43.25 Under original design conditions a fan using $5.5hp$ rotates at $750rpm$ against a static pressure loss of $2in\,wg$. Due to a design change, the length of the duct served by the fan increases, adding an additional $0.5in$ of static pressure. What is the fan speed after the system modification?

A. $810rpm$

B. $840rpm$

C. $920rpm$

D. $940rpm$

Make a quick table to organize the original and new operating conditions for the fan:

	Original (1)	New (2)
$W\ [hp]$	5.5	W_2
$N\ [rpm]$	750	N_2
$P\ [in\,wg]$	2	2.5

The fan speed and power will both increase to meet the new static pressure requirements; however, the horsepower is extra information and may be ignored. Look up Fan Affinity Laws or Fan Laws and select formula 1b from the table. Since the diameter and density are not changing from one case to the next, ratios of those parameters are equal to 1 and may be omitted.

$$P_1 = P_2 \left(\frac{N_1}{N_2}\right)^2$$

It may be advisable to internalize the most common fan laws such as the relationships between speed, volume flow rate, pressure, and power.

Rearrange the formula to isolate N_2 and solve:

$$\left(\frac{N_2}{N_1}\right)^2 = \frac{P_2}{P_1} \rightarrow \frac{N_2}{N_1} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{2}} \rightarrow N_2 = N_1 \left(\frac{P_2}{P_1}\right)^{\frac{1}{2}}$$

$$N_2 = (750rpm)\left(\frac{2.5in\,wg}{2in\,wg}\right)^{\frac{1}{2}} = 839rpm$$

Answer B

44 Systems and Components

44.1 During winter operation an outside air handler pre-heats and humidifies $20°F$ air with 50% relative humidity to $65°F$ and 40% relative humidity. The humidification process consumes $1/2 gpm$ of water. What volume flow rate is required by the fan?

A. $11,000cfm$

B. $12,000cfm$

C. $13,000cfm$

D. $14,000cfm$

Both states are fully defined, however there is no information about the sensible or total load. Therefore focus on the humidification process. Use the Psychrometric Chart to obtain the humidity ratio for the outside air and the preheated air. Also note the specific volume for the entering air condition.

For State 1:

$$T_1 = 20°F$$

$$\phi_1 = 50\%$$

$$\omega_1 = .00107\frac{lb_w}{lb_{da}}$$

$$v_1 = 12.16\frac{ft^3}{lb}$$

For State 2:

$$T_2 = 65°F$$

$$\phi_2 = 40\%$$

$$\omega_2 = .00524\frac{lb_w}{lb_{da}}$$

Calculate the change in humidity ratio:

$$\Delta\omega = \omega_2 - \omega_1 = .00524\frac{lb_w}{lb_{da}} - .00107\frac{lb_w}{lb_{da}} = .00417\frac{lb_w}{lb_{da}}$$

Convert the mass flow rate of water from gpm to $\frac{lb}{min}$:

$$\dot{m} = \rho\dot{V}$$

$$\dot{m}_w = \left(62.4\frac{lb}{ft^3}\right)\left(\frac{1ft^3}{7.48gal}\right)\left(.5\frac{gal}{min}\right) = 4.17\frac{lb}{min}$$

Apply the definition of the humidity ratio and solve for the mass flow rate of air. Isolate $\dot{m}_a$ and solve:

$$\dot{m}_w = \dot{m}_a\Delta\omega \rightarrow \dot{m}_a = \frac{\dot{m}_w}{\Delta\omega} = \frac{4.17\frac{lb_w}{min}}{.00417\frac{lb_w}{lb_{da}}} = 1000\frac{lb_{da}}{min}$$

Use the specific volume to change the mass flow rate of air to a volume flow rate:

$$\dot{V} = \dot{m}_a v = \left(1000\frac{lb}{min}\right)\left(12.16\frac{ft^3}{lb}\right) = 12,160cfm$$

Answer B

44.2 **$5000 cfm$ of outside air at $90°F$ and 80% RH enters the cooling coil of a dedicated outside air handling unit. The unit supplies tempered air at $62°F$ dry bulb and $60°F$ wet bulb. What is the volume flow rate of condensate removed by the unit?**

A. $0.4 gpm$

B. $0.5 gpm$

C. $0.6 gpm$

D. $0.7 gpm$

Both states are fully defined. Use the Psychrometric Chart to obtain the humidity ratio for both the entering outside air and the tempered leaving air. Also look up the specific volume for the entering air:

For State 1:

$$T_1 = 90°F$$

$$\phi_1 = 80\%$$

$$\omega_1 = 0.02469 \frac{lb_w}{lb_{da}}$$

$$v_1 = 14.46 \frac{ft^3}{lb}$$

For State 2:

$$T_{2,db} = 62°F$$

$$T_{2,wb} = 60°F$$

$$\omega_2 = 0.01062 \frac{lb_w}{lb_{da}}$$

Calculate the change in humidity ratio:

$$\Delta\omega = \omega_1 - \omega_2 = 0.02469 \frac{lb_w}{lb_{da}} - 0.01062 \frac{lb_w}{lb_{da}} = 0.01407 \frac{lb_w}{lb_{da}}$$

Use the specific volume at state 1 to solve for the mass flow rate of air entering the coil:

$$\dot{m}_a = \rho Q = \frac{Q}{v} = \frac{5000 \frac{ft^3}{min}}{14.46 \frac{ft^3}{lb}} = 345.8 \frac{lb_a}{min}$$

Apply the definition of the humidity ratio to solve for the mass flow rate of water i.e. condensate removed from the air:

$$\dot{m}_w = \dot{m}_a \Delta\omega$$

$$\dot{m}_w = \left(345.8\frac{lb}{min}\right)\left(0.01407\frac{lb_w}{lb_{da}}\right) = 4.865\frac{lb_w}{min}$$

Use the density of water to convert the mass flow rate to a volume flow rate:

$$Q_{condensate} = \frac{\dot{m}_w}{\rho} = \left(\frac{4.865\frac{lb}{min}}{62.4\frac{lb}{ft^3}}\right)\left(7.48\frac{gal}{ft^3}\right) = 0.583gpm$$

Answer C

44.3 The compressor for a water cooled chiller draws $40KW$. The chiller delivers $100gpm$ with a $10°F$ delta T. A cooling tower serving the chiller provides $80gpm$ of $80°F$ condenser water. What is the temperature of the condenser water leaving the chiller?

A. $74°F$

B. $78°F$

C. $93°F$

D. $96°F$

Use the sensible heating/cooling rule of thumb for water to determine the total load on the evaporator, which corresponds to the water *delivered* by the chiller:

$$\dot{Q}_{in} = 500 gpm \Delta T = 500\,(100)\,(10) = 500,000 \frac{Btu}{hr}$$

Determine the total heat to be rejected by the condenser, which is the sum of the evaporator load and the compressor power. Be sure to align units.

$$\dot{Q}_{out} = \dot{Q}_{in} + \dot{W}_{in}$$

$$\dot{Q}_{out} = 500,000 \frac{Btu}{hr} + 40KW \left(3412 \frac{Btu}{hr \cdot KW} \right) = 636,480 \frac{Btu}{hr}$$

Apply the sensible heating/cooling rule of thumb for water again, this time for the condenser, to determine the condenser water return temperature. Note the naming may be counter-intuitive since the water *leaving* the chiller's condenser is *returning* to the cooling tower. The nomenclature for condenser water is typically considered from the perspective of the cooling tower.

$$\dot{Q}_{out} = 500 gpm \Delta T = 500 gpm \,(CWR - CWS)$$

$$\dot{Q}_{out} = 500\,(80)\,(CWR - 80°F) = 636,480 \frac{Btu}{hr}$$

$$CWR - 80°F = 15.9°F$$

$$CWR = 95.9°F$$

Answer D

44.4 An unoccupied $3000ft^2$ technology room with $12ft$ ceilings is located at the perimeter of a building and experiences excessive infiltration from the outdoors amounting to $2ACH$. On a summer design day the outside conditions are $95°F$ dry bulb and 80% RH. The equipment load is $50KW$ sensible and the space is to be maintained at $72°F$ and 50% RH. What is the total cooling demand?

A. $2tons$

B. $13tons$

C. $14tons$

D. $27tons$

To determine the infiltration load, use the Psychrometric Chart to obtain the enthalpy for the outside air and the enthalpy for the internal space, both of which are fully defined.

For the outside air, State 1:

$$T_1 = 95°F$$

$$\phi_1 = 80\%$$

$$h_1 = 54.83\frac{Btu}{lb}$$

For the internal space, State 2:

$$T_2 = 72°F$$

$$\phi_2 = 50°F$$

$$h_2 = 26.43\frac{Btu}{lb}$$

Calculate the change in enthalpy required to condition the outside air:

$$\Delta h = h_1 - h_2 = 54.83\frac{Btu}{lb} - 26.43\frac{Btu}{lb}$$

Based on the ACH and dimensions of the space, find the volume flow rate for the infiltration:

$$\dot{V} = \left(3000ft^2\right)(12ft)\left(\frac{2\,air\,changes}{hr}\right)\left(\frac{1hr}{60min}\right) = 1200cfm$$

Use the total heating/cooling rule of thumb for air to determine the cooling load due to infiltration:

$$\dot{Q}_{infiltration} = 4.5cfm\Delta h$$

$$\dot{Q}_{infiltration} = 4.5\,(1200)\,(28.4) = 153,360\frac{Btu}{hr}$$

Determine the total cooling load including the internal heat load as well as the infiltration. Align units to $\frac{Btu}{hr}$, then convert to refrigeration tons:

$$\dot{Q}_{total} = \dot{Q}_{infiltration} + \dot{Q}_{internal}$$

$$\dot{Q}_{total} = 153,360\frac{Btu}{hr} + (50KW)\left(3412\frac{Btu}{hr \cdot KW}\right) = 323,960\frac{Btu}{hr}$$

$$\dot{Q}_{total} = 323,960\frac{Btu}{hr}\left(\frac{1ton}{12000\frac{Btu}{hr}}\right) = 27tons$$

Answer D

44.5 A pumping system delivers water to a factory through a standard weight steel piping supply line (surface roughness $C = 120$) with 3 outlets delivering $100gpm$ to each outlet. The main pipe initially has a $5in$ nominal diameter, reducing to $4in$ and $3in$ after each branch outlet. The first outlet is located $50ft$ from the pumping station; the second outlet is $100ft$ downstream of the first, and the third outlet is $100ft$ downstream of the second. What is the pressure loss for the system? Ignore minor losses.

A. $7ft$

B. $10ft$

C. $14ft$

D. $20ft$

The pressure loss is based on the flow rate, diameter, surface roughness, and the length of the pipe. Break the problem into 3 sections and use the Steel Pipe Friction Tables to look up the head loss per 100 ft for each section. The surface roughness may be considered at the end.

For the 5 inch section:

$$D = 5in$$

$$L = 50ft$$

$$Q = 300gpm$$

$$h_{d.loss} = 3ft/100ft$$

$$h_f = (50ft)\left(\frac{3ft}{100ft}\right)$$

For the 4 inch section, the flow is reduced by $100gpm$ after the first branch:

$$D = 4in$$

$$L = 100ft$$

$$Q = 200gpm$$

$$h_{d.loss} = 4.3ft/100ft$$

$$h_f = (100ft)\left(\frac{4.3ft}{100ft}\right)$$

For the 3 inch section, the flow is reduced again by $100gpm$ after the second branch:

$$D = 3in$$

$$L = 100ft$$

$$Q = 100gpm$$

$$h_{d.loss} = 4.5ft/100ft$$

$$h_f = (100ft)\left(\frac{4.5ft}{100ft}\right)$$

Look up Surface Roughness Factors in the Reference Handbook under the Steel Pipe Friction Tables and refer to the correction factors. For a surface roughness of $C = 120$, it is necessary to multiply the total head loss by .71. Take the sum of the losses from the 3 sections and apply the correction factor to determine the total pressure loss for the system:

$$h_f = (.71)\left[(50ft)\left(\frac{3ft}{100ft}\right) + (100ft)\left(\frac{4.3ft}{100ft}\right) + (100ft)\left(\frac{4.5ft}{100ft}\right)\right] = 7.3$$

Answer A

44.6 A locker room has 12 showers supplied with hot water from a steam heat exchanger. The shower heads are rated for $5gpm$ each. Expected demand can be estimated as 25% of maximum. Cold water enters the heat exchanger at $55°F$ and leaves at $115°F$. $500\frac{lb}{hr}$ of $5psig$ steam is supplied to the heat exchanger and leaves saturated. What is the efficiency of the heat exchanger?

A. 90%

B. 92%

C. 94%

D. 96%

The heat transferred to the water is less than the heat given up by the steam due to losses. The efficiency is determined by calculating both quantities.

For the water side of the heat exchanger, use the sensible heating rule of thumb for water to find the heat added. Before solving, apply the diversity in the flow rate demand. It is not necessary to size the heat exchanger for all 12 shower heads to supply the full $5gpm$ simultaneously.

$$Demand = (12showers)\left(5\frac{gpm}{shower}\right)(.25) = 15gpm$$

$$\dot{Q}_w = 500gpm\Delta T$$

$$\dot{Q}_{water} = 500\,(15)\,(115 - 55) = 450,000\frac{Btu}{hr}$$

For the steam side of the heat exchanger, look up the heat of vaporization for $20psia$ steam in the steam table, Properties of Saturated Water (by Pressure). Make sure to convert psig to psia before obtaining values. Calculate the energy given up by the steam using $Q = m\Delta h$:

$$\dot{Q}_{steam} = \dot{m}\Delta h = \dot{m}h_{fg}$$

$$\dot{Q}_{steam} = \left(500\frac{lb}{hr}\right)\left(960\frac{Btu}{lb}\right) = 480,000\frac{Btu}{hr}$$

Calculate the efficiency of the heat exchanger:

$$\eta = \frac{\dot{Q}_{water}}{\dot{Q}_{steam}} = \frac{450,000\frac{Btu}{hr}}{480,000\frac{Btu}{hr}} = 93.75\%$$

Answer C

44.7 Due to acoustical considerations, the compressor and condenser for a $2ton$ refrigerator with a COP of 5 are located remotely in a nearby storage closet. Neglecting lights and other ancillary heat sources, what is the required cooling capacity for the storage closet?

A. $24,000\frac{Btu}{hr}$

B. $25,000\frac{Btu}{hr}$

C. $29,000\frac{Btu}{hr}$

D. $33,000\frac{Btu}{hr}$

The cooling system for the closet needs to be able to support the full heat rejection from the system, which includes the compressor and the condenser. As with all refrigeration cycles, the compressor energy is added to the refrigerant, therefore the heat rejection at the condenser is already exhaustive, with the possible minor exception of local heat loss from the compressor due to any inefficiency. However, even in that case, any local heat generation is being added to the room directly rather than the refrigerant loop, and will no longer need to be rejected from the condenser. Ultimately, the sum of the heat generated, and thus the cooling required for the room, is nothing more or less than Q_{out} for the cycle.

Apply the Coefficient of Performance (COP) for a refrigerator to calculate the compressor power:

$$COP_R = \frac{\dot{Q}_{in}}{\dot{W}_{in}} \rightarrow \dot{W}_{in} = \frac{\dot{Q}_{in}}{COP_R} = \frac{2tons}{5} = .4tons$$

Calculate the heat rejection from the condenser, and convert to $\frac{Btu}{hr}$:

$$\dot{Q}_{out} = \dot{Q}_{in} + \dot{W}_{in} = 2tons + .4tons = 2.4tons$$

$$\dot{Q}_{out} = 2.4tons\left(\frac{12,000\frac{Btu}{hr}}{ton}\right) = 28,800\frac{Btu}{hr}$$

Answer C

44.8 A counterflow heat exchanger is used to remove heat from steam condensate prior to discharge and for pre-heating cold water. Cold water enters at $50°F$ and leaves at $70°F$. Condensate enters at $160°F$ and leaves at $100°F$. What is the log mean temperature difference?

A. $62°F$

B. $68°F$

C. $76°F$

D. $90°F$

For a counterflow heat exchanger, the hot stream enters on the opposite side from the cold stream such that the ΔT along the length is close to the average ΔT. (Contrast this with the temperature profile for a parallel flow heat exchanger which varies dramatically along the length.) Arbitrarily call the hot entering end "Side A" and cold entering end "Side B." Calculate the temperature differences at both ends. It may be useful to draw the temperature profile on a *Temperature vs. Length* diagram.

$$\Delta T_A = 160°F - 70°F = 90°F$$

$$\Delta T_B = 100°F - 50°F = 50°F$$

Look up Log Mean Temperature Difference (LMTD) in the Reference Handbook. Consider applying the simplified version of this formula initially introduced during in the Heat Transfer section of this book:

$$LMTD = \frac{\Delta T_A - \Delta T_B}{ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{90°F - 50°F}{ln\left(\frac{90°F}{50°F}\right)} = 68°F$$

Answer B

44.9 An outside air handler mixes $2000cfm$ of $90°F$ db / $80°F$ wb fresh air with recirculated return air at $76°F$ / 50% relative humidity. The unit supplies $10,000cfm$ of $58°F$ air to the space. What is the enthalpy of the mixed air entering the cooling coil?

A. $31\frac{Btu}{lb}$

B. $32\frac{Btu}{lb}$

C. $33\frac{Btu}{lb}$

D. $34\frac{Btu}{lb}$

It may be helpful to draw and label a typical outside air handling arrangement. The supply air temperature downstream of the cooling coil is extra information.

Since the volume flow rate of outside air is $2000cfm$ and a total of $10,000cfm$ is being supplied, the volume flow rate of recirculated air is given by:

$$Q_{recirculation} = 10,000cfm - 2000cfm = 8,000cfm.$$

To find the enthalpy of mixed air (prior to the coil), perform a mixing calculation using the outside air stream and return (recirculated) air stream, both of which are fully defined. Use the Psychrometric Chart to obtain the enthalpy values for both states:

$$T_{OA,db} = 90°F$$

$$T_{OA,wb} = 80°F$$

$$h_{OA} = 43.57\frac{Btu}{lb}$$

$$T_{RA} = 76°F$$

$$\phi_{RA} = 50\%$$

$$h_{RA} = 28.74\frac{Btu}{lb}$$

$$h_{MA} = \frac{(2000cfm)\left(43.57\frac{Btu}{lb}\right) + (8000cfm)\left(28.74\frac{Btu}{lb}\right)}{2000cfm + 8000cfm} = 31.7\frac{Btu}{lb}$$

Answer B

44.10 A hydronic piping system is re-designed to improve efficiency. The $250gpm$ pump is re-selected from $200ft$ TDH to $175ft$ TDH to suit the reduction in pressure loss throughout the system and capture savings. Both the old and new pump selections have an efficiency of 85% and are driven by a 94% efficient motor. The pump will run 9AM-5PM Monday through Friday year round. Electricity costs $0.18 per kWh. What are the annual savings?

A. $550

B. $950

C. $1250

D. $1650

Consider the original pump selection as Case 1 and the new pump selection as Case 2. Find the water horsepower, WHP, for both scenarios:

$$WHP = \frac{Q\Delta h}{3960}$$

$$WHP_1 = \frac{(250)(200)}{3960} = 12.63hp$$

$$WHP_2 = \frac{(250)(175)}{3960} = 11.05hp$$

Find the electrical power for each scenario by applying the pump and motor efficiency and converting units to KW:

$$P_1 = \frac{WHP_1}{\eta_p \eta_m} = \frac{12.63hp}{(.85)(.94)}\left(.7457\frac{KW}{hp}\right) = 11.8KW$$

$$P_2 = \frac{WHP_2}{\eta_p \eta_m} = \frac{11.05hp}{(.85)(.94)}\left(.7457\frac{KW}{hp}\right) = 10.34KW$$

Calculate the annual costs for each scenario by applying the annual run time and electricity rate:

$$Cost_1 = (11.8KW)\left(8\frac{hr}{day}\right)\left(5\frac{days}{wk}\right)\left(52\frac{wk}{yr}\right)\left(\frac{\$0.18}{kW \cdot hr}\right) = \$4,418/year$$

$$Cost_2 = (10.34KW)\left(8\frac{hr}{day}\right)\left(5\frac{days}{wk}\right)\left(52\frac{wk}{yr}\right)\left(\frac{\$0.18}{kW \cdot hr}\right) = \$3,871/year$$

Calculate the savings:

$$Savings = \$4,418/year - \$3,871/year = \$547/year$$

Answer A

44.11 Water enters a $100ton$ cooling tower at $130°F$ and leaves at $105°F$. Air enters at $88°F$ and 60% RH and leaves at $104°F$ and 80% RH. What quantity of make up water is required? Assume no losses.

A. $0.25gpm$

B. $0.5gpm$

C. $1gpm$

D. $2gpm$

The cooling tower entering and leaving water temperatures are extra information and not needed to solve the problem. The rate of heat transfer *to* the air is equivalent to the rate of heat transfer *from* the condenser water:

$$\dot{Q}_{cw} = \dot{Q}_{air} = 100tons\left(12,000\frac{Btu}{hr \cdot ton}\right) = 1,200,000\frac{Btu}{hr}$$

Set this quantity equal to a $m\Delta h$ expression, where entering air is State 1 and the leaving air is State 2. Both states are fully defined and enthalpy values as well as humidity ratios may be obtained using the Psychrometric Chart and High Temperature Psychrometric Chart, where required.

$$\dot{Q}_{air} = \dot{m}_{air}\Delta h$$

For the entering air, State 1:

$$T_1 = 88°F$$

$$\phi_1 = 60\%$$

$$h_1 = 40.03\frac{Btu}{lb}$$

$$\omega_1 = .01719\frac{lb_w}{lb_{da}}$$

For the leaving air, State 2:

$$T_2 = 104°F$$

$$\phi_2 = 80\%$$

$$h_2 = 67.76\frac{Btu}{lb}$$

$$\omega_2 = .03866\frac{lb_w}{lb_{da}}$$

Solve for the mass flow rate of air. Convert units to $\frac{lb}{min}$:

$$\dot{Q}_{air} = \dot{m}_{air}\Delta h \rightarrow \dot{m}_{air} = \frac{\dot{Q}_{air}}{h_2 - h_1} = \frac{1,200,000\frac{Btu}{hr}}{\left(67.76\frac{Btu}{lb} - 40.03\frac{Btu}{lb}\right)} = 43,274\frac{lb}{hr}$$

$$\dot{m}_{air} = 43,274\frac{lb}{hr}\left(\frac{1hr}{60min}\right) = 721.2\frac{lb}{min}$$

Find the mass flow rate of water being added to the air stream and convert to gpm. Note, the formula used is derived from the definition of the humidity ratio and is best memorized rather than looked up or derived:

$$\dot{m}_w = \dot{m}_a\left(\omega_2 - \omega_1\right)$$

$$\dot{m}_w = \left(721.2\frac{lb}{min}\right)\left(.03866\frac{lb_w}{lb_{da}} - .01719\frac{lb_w}{lb_{da}}\right) = 15.5\frac{lb}{min}$$

$$\dot{m}_w = 15.5\frac{lb}{min}\left(\frac{1ft^3}{62.4lb}\right)\left(\frac{7.48gal}{1ft^3}\right) = 1.86gpm$$

Answer D

44.12 R-410a is used in a chiller with a suction pressure of $60psia$ and a discharge pressure of $185psia$. The refrigeration cycle operates with $20°F$ of sub cooling and $20°F$ of superheating. The load on the chiller is $200tons$. What is the mass flow rate of refrigerant?

A. $420\frac{lb}{min}$

B. $440\frac{lb}{min}$

C. $460\frac{lb}{min}$

D. $480\frac{lb}{min}$

Look up Pressure Versus Enthalpy Curves for Refrigerant 410A in the Reference Handbook and draw the refrigeration cycle directly on the screen. If drawing on the screen is unworkable, sketch on scrap paper and mark key values obtained from the chart on the axes. Note the vertical axis is nonlinear so take special care to identify the low and high pressure conditions for the evaporator and condenser.

The load on the chiller is the refrigeration effect, $\dot{Q}_{in}$. Express the refrigeration effect as the mass flow rate times the change in enthalpy across the evaporator, typically represented as $h_1 - h_4$.

$$\dot{Q}_{in} = \dot{m}\left(h_1 - h_4\right)$$

State 1, leaving the evaporator and entering the condenser, must be selected to the right of the saturation curve in the superheated region to account for 20°F of superheat.

State 3, leaving the condenser and entering the expansion valve, must be selected to the left of the saturation curve in the subcooled region to account for 20°F of subcooling. Since the expansion process $3 \to 4$ is isenthalpic, assume $h_4 = h_3$.

Solve for mass flow rate, substitute enthalpy values, and convert units where necessary:

$$\dot{Q}_{in} = \dot{m}\,(h_1 - h_4) = \dot{m}\,(h_1 - h_3)$$

$$\dot{m} = \frac{\dot{Q}_{in}}{(h_1 - h_3)} = \frac{(200 tons)\left(12,000\frac{Btu}{hr \cdot ton}\right)}{\left(122\frac{Btu}{lb} - 28\frac{Btu}{lb}\right)} = 25,532\frac{lb}{hr}$$

$$\dot{m} = 25,532\frac{lb}{hr}\left(\frac{1hr}{60min}\right) = 425\frac{lb}{min}$$

Answer A

44.13 R-134a is used in a chiller with an evaporator pressure of $30psia$ and a condenser pressure of $150psia$. There is $20°F$ of superheat. What is the coefficient of performance?

A. 3

B. 4

C. 5

D. 6

Look Up Pressure Versus Enthalpy Curves for Refrigerant 134a in the Reference Handbook and draw the refrigeration cycle directly on the screen. If drawing on the screen is unworkable, sketch on scrap paper and mark key values obtained from the chart on the axes. Assume State 3, leaving the condenser and entering the expansion valve, is a saturated liquid since there is no mention of subcooling. Locate State 1 to the right of the saturation curve in the superheated region to account for 20°F of superheat. The enthalpy at State 4 is equal to the enthalpy at State 3 assuming isenthalpic expansion. Note the vertical axis is nonlinear so take special care to identify the low and high pressure conditions for the evaporator and condenser.

Calculate the Coefficient of Performance (COP) for the refrigeration cycle:

$$COP_R = \frac{\dot{Q}_{in}}{\dot{W}_{in}} = \frac{\dot{m}\,(h_1 - h_4)}{\dot{m}\,(h_2 - h_1)} = \frac{(h_1 - h_3)}{(h_2 - h_1)} = \frac{\left(109\frac{Btu}{lb} - 47\frac{Btu}{lb}\right)}{\left(122\frac{Btu}{lb} - 109\frac{Btu}{lb}\right)} = 4.8$$

Answer C

44.14 A $2ton$ AC unit with remote compressor using R-134a operates with a condenser pressure of $150psia$ and an evaporator pressure of $50psia$. The suction line is a $5/8in$ diameter type L copper tube with a length of $30ft$. What is the pressure drop for the suction line?

A. $0.5psi$

B. $1.3psi$

C. $1.9psi$

D. $5.8psi$

Look up Suction Line Capacities in Tons for Refrigerant 134a in the Reference Handbook. Using the Pressure Versus Enthalpy Curves for Refrigerant 134a, determine the evaporator temperature that corresponds to an evaporator pressure of $50psia$. Use the evaporator temperature and the diameter of the suction line to obtain the capacity from the table. Also note the corresponding pressure drop from the table.

$$P_{evap} = 50psia$$

$$T_{evap} = 40°F$$

$$Capacity = 0.66tons$$

$$\Delta P = 1.93psi/100ft$$

Use the equation from Note 3 below the table to adjust for the actual length and capacity given:

$$\Delta t = Table\,\Delta t \left(\frac{Actual\,L_e}{Table\,L_e}\right) \times \left(\frac{Actual\,Capacity}{Table\,Capacity}\right)^{1.8}$$

$$\Delta t = (2°F)\left(\frac{30ft}{100ft}\right) \times \left(\frac{2tons}{0.66tons}\right)^{1.8} = 4.41°F$$

The actual pressure drop is linearly related to the actual temperature drop. Set up a proportion and solve, using the actual length:

$$\frac{\Delta P_{actual}}{\Delta P_{table}} = \frac{\Delta T_{actual}}{\Delta T_{table}}$$

$$\Delta P_{actual} = \Delta P_{table}\left(\frac{\Delta T_{actual}}{\Delta T_{table}}\right) = \left(1.93\frac{psi}{100ft}\right)\left(\frac{4.41°F}{2°F}\right) = 4.25\frac{psi}{100ft}$$

$$\Delta P = \left(4.25\frac{psi}{100ft}\right)(30ft) = 1.3psi$$

Answer B

44.15 Air at $85°F$ and 40% relative humidity enters a direct evaporative cooler with a saturation efficiency of 60%. What is the leaving air temperature?

A. $62°F$

B. $68°F$

C. $74°F$

D. $78°F$

The efficiency (Saturation Efficiency) of an Evaporative Cooler is the ratio of the actual temperature reduction achieved compared with the temperature differential if the air was cooled to the wet bulb temperature, i.e. fully *saturated*.

The entering conditions, State 1, are fully defined. Use the Psychrometric Chart to obtain the wet bulb temperature:

$$T_{1,db} = 85°F$$

$$\phi_1 = 40\%$$

$$T_{1,wb} = 67.3°F$$

Write the equation for the Saturation Efficiency and solve for the leaving air temperature, T_2:

$$\varepsilon_e = \frac{T_1 - T_2}{T_1 - T_{wb}}$$

$$.6 = \left(\frac{85°F - T_2}{85°F - 67.3°F}\right) \rightarrow T_2 = 74.4°F$$

Answer C

44.16 **$1000cfm$ of outside air at $92°F$ and 85% RH and $6000cfm$ of return air at $76°F$ and 55% RH are cooled by an air handling unit supplying $54°F$ dry bulb and $53°F$ wet bulb air. $60gpm$ of chilled water enters the cooling coil at $46°F$. What is the leaving water temperature?**

A. $54°F$

B. $58°F$

C. $62°F$

D. $66°F$

The outside air and return air conditions are both fully defined and volume flow rates are known. Use the Psychrometric Chart to look up the enthalpy values and perform a mixing calculation to determine the enthalpy of the mixed air entering the cooling coil.

$$T_{OA} = 92°F$$

$$\phi_{OA} = 85\%$$

$$h_{OA} = 53\frac{Btu}{lb}$$

$$T_{RA} = 76°F$$

$$\phi_{RA} = 55\%$$

$$h_{RA} = 29.8\frac{Btu}{lb}$$

$$h_{MA} = \frac{(1000cfm)\left(53\frac{Btu}{lb}\right) + (6000cfm)\left(29.8\frac{Btu}{lb}\right)}{1000cfm + 6000cfm} = 33.1\frac{Btu}{lb}$$

The air leaving the coil, the supply air, is also fully defined. Use the Psychrometric Chart to look up the enthalpy value for the supply air. Then use the total cooling rule of thumb to determine the rate of heat removal from the air stream.

$$T_{SA,db} = 54°F$$

$$T_{SA,wb} = 53°F$$

$$h_{SA} = 22\frac{Btu}{lb}$$

$$\dot{Q}_t = 4.5cfm\Delta h = 4.5\,(7000)\,(33.1-22) = 349,650\frac{Btu}{hr}$$

Since the heat removed from the air is added to the chilled water flowing in the coil, set the total cooling of the air equal to the heating of the water, using the sensible heating rule of thumb for water. Solve for the unknown leaving water temperature.

$$\dot{Q}_t = \dot{Q}_w = 500gpm\Delta T$$

$$\Delta T = \frac{349,650}{(500)\,(60)} = 11.7^\circ F$$

$$\Delta T = LWT - EWT = LWT - 46^\circ F = 11.7^\circ F$$

$$LWT = 57.7^\circ F$$

Answer B

44.17 During a chiller plant upgrade, an oversized fixed speed pump, producing $200gpm$ and $80ft$ of total dynamic head with a 70% pump efficiency and 80% motor efficiency, is replaced with a duplex parallel pump set with variable frequency drives. The two replacement pumps provide $60gpm$ each at $45ft$ TDH which is sufficient to meet operational demands. The new pump efficiency is 75% and the new motor efficiency is 93%. The system operates continuously 24 hours per day 365 days per year. The average cost of electricity is $0.12/ kWh. What are the annual savings?

A. $3100

B. $4100

C. $4900

D. $5500

Make a table to organize the given information for the two scenarios:

	Existing	New
Qty of Pumps	1	2
Flow Rate	$200gpm$	$2 \times 60gpm$
TDH	$80ft$	$45ft$
Pump Efficiency	70%	75%
Motor Efficiency	80%	93%
Run Hours	7/24/365	7/24/365
Electricity Rate	$\$0.12/kW \cdot hr$	$\$0.12/kW \cdot hr$

Calculate the Hydraulic Horsepower for both scenarios:

$$WHP = \frac{Q\Delta h}{3960}$$

$$WHP_1 = \frac{(200)\,(80)}{3960} = 4.04hp$$

$$WHP_2 = \frac{(2)\,(60)\,(45)}{3960} = 1.36hp$$

Apply the pump and motor efficiencies to determine the electrical power demand, and convert units to KW:

$$P = \frac{WHP}{\eta_p \eta_m}$$

$$P_1 = \frac{(4.04hp)}{(.7)\,(.8)}\left(.7457\frac{KW}{hp}\right) = 5.38KW$$

$$P_2 = \frac{(1.36hp)}{(.75)\,(.93)}\left(.7457\frac{KW}{hp}\right) = 1.46KW$$

Calculate the reduction in electrical demand:

$$Demand\,Reduction = 5.38KW - 1.46KW = 3.92KW$$

Apply the annual run hours and electricity rate to determine the annual cost savings:

$$Cost\,Savings = (3.92KW)\left(24\frac{hrs}{day}\right)\left(365\frac{days}{yr}\right)\left(\frac{\$0.12}{kW \cdot hr}\right) = \$4120$$

Answer B

44.18 A $10ft \times 10ft$ exterior wall is made of $4in$ brick $\left(\rho = 120\frac{lb}{ft^3}\right)$, $3.5in$ mineral fiber insulation, and $5/8in$ gypsum board. There is a single $3ft \times 6ft$ operable window comprised of double glazing with $1/2in$ air space and emissivity of 0.6. The window frame is made of insulated fiberglass. The temperature differential between inside and outside is $20°F$. What is the average heat flux through the wall?

A. $0.9\frac{Bu}{hr \cdot ft^2}$

B. $1.4\frac{Bu}{hr \cdot ft^2}$

C. $2.7\frac{Bu}{hr \cdot ft^2}$

D. $8.6\frac{Bu}{hr \cdot ft^2}$

Find the total resistance of the composite wall. Look up Thermal Resistance of Building Materials.

For brick with a density of $120\frac{lb}{ft^3}$, take the average resistance per inch from the range given and multiply by the thickness:

$$R_{brick} = \left(0.165\frac{hr \cdot ft^2 \cdot °F}{Btu \cdot in}\right)(4in) = .66\frac{hr \cdot ft^2 \cdot °F}{Btu}$$

For the mineral fiber insulation, the resistance is listed for the nominal thickness of $3.5in$:

$$R_{insulation} = 13\frac{hr \cdot ft^2 \cdot °F}{Btu}$$

For the gypsum board, the resistance is listed for the thickness of $\frac{5}{8}in$:

$$R_{gypsum} = .56\frac{hr \cdot ft^2 \cdot °F}{Btu}$$

Calculate the total resistance for the composite wall, then determine the overall heat transfer coefficient:

$$R_{wall} = R_{brick} + R_{insulation} + R_{gypsum}$$

$$R_{wall} = .66\frac{hr \cdot ft^2 \cdot °F}{Btu} + 13\frac{hr \cdot ft^2 \cdot °F}{Btu} + .56\frac{hr \cdot ft^2 \cdot °F}{Btu} = 14.22\frac{hr \cdot ft^2 \cdot °F}{Btu}$$

$$U_{wall} = \frac{1}{R_{wall}} = \frac{1}{14.22\frac{hr \cdot ft^2 \cdot °F}{Btu}} = .07\frac{Btu}{hr \cdot ft^2 \cdot °F}$$

Find the heat transfer coefficient for the window. Look up U-Factors for Fenestration and use the frame type (insulated fiberglass), glazing type (double glazing with with $e = 0.60$), thickness of the air space ($\frac{1}{2}in$), and operability to obtain the U Factor:

$$U_{window} = .43 \frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$$

Determine the total overall coefficient of heat transfer for the wall *inclusive* of the window by taking a weighted average of the U factors by area.

$$A_{window} = (3ft)(6ft) = 18ft^2$$

$$A_{wall} = (10ft)(10ft) - 18ft^2 = 82ft^2$$

$$U_{total} = \frac{\left(.07 \frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}\right)(82ft^2) + \left(.43 \frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}\right)(18ft^2)}{82ft^2 + 18ft^2} = .135 \frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$$

Find the heat flux by diving the overall heat transfer formula by area:

$$\dot{Q} = UA\Delta T$$

$$\dot{q} = \frac{\dot{Q}}{A} = U\Delta T$$

$$\dot{q} = \left(.135 \frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}\right)(20^\circ F) = 2.7 \frac{Btu}{hr \cdot ft^2}$$

Answer C

44.19 An R-1234yf chiller operates between $50psia$ on the low pressure side and $150psia$ on the high pressure side with no subcooling and no superheat. What is the quality of refrigerant entering the evaporator?

A. 0

B. 0.12

C. 0.22

D. 0.32

Look up Pressure Versus Enthalpy Curves for Refrigerant 1234yf in the Reference Handbook and draw the refrigeration cycle on the diagram, either using on-screen drawing tools or scratch paper. Carefully locate State 3, the condition leaving the condenser prior to expansion, on the left side of the saturation curve. Assume the expansion is isenthalpic, therefore the enthalpy of State 4, after the expansion and before entering the evaporator, is known to be equal to the enthalpy at State 3.

For State 3:

$$P_3 = 150psia$$

$$\chi_3 = 0$$

$$h_3 = 45\frac{Btu}{lb}$$

For State 4:

$$P_4 = 50psia$$

$$h_4 = h_3 = 45\frac{Btu}{lb}$$

On the next page after the Pressure Enthalpy curves, refer to the table for Refrigerant 1234yf listing Properties of Saturated Liquid and Saturated Vapor. Since the pressure at State 4 is between two rows, it is necessary to interpolate to find h_f and h_g for R-1234yf at $P_4 = 50psia$. Make a table to organize the data collected and help set up for the interpolation:

$Pressure[psia]$	$h_f(liquid)\ [\frac{Btu}{lb}]$	$h_g(vapor)\ [\frac{Btu}{lb}]$
48.45	21.98	91.77
50	$h_f \approx 22.5$	$h_g \approx 92$
53.12	23.54	92.54

Calculate the quality at State 4:

$$\chi_4 = \frac{h_4 - h_f}{h_g - h_f} = \frac{45\frac{Btu}{lb} - 22.5\frac{Btu}{lb}}{92\frac{Btu}{lb} - 22.5\frac{Btu}{lb}} = .32$$

Answer D

44.20 An outside air handler tempers outside air of $90°F$ dry bulb and $80°F$ wet bulb using return air at $74°F$ and 50% relative humidity using an air-to-air heat exchanger. The heat exchanger effectiveness is 72%. What is the enthalpy of the air leaving the heat exchanger?

A. $31\frac{Btu}{lb}$

B. $33\frac{Btu}{lb}$

C. $41\frac{Btu}{lb}$

D. $43\frac{Btu}{lb}$

An air to air heat exchanger in a tempering application will drive only sensible cooling of the outside air stream being treated. A 100% efficient heat exchanger would cool the outside air all the way to the temperature of the return air, $74°F$ in this case. Apply the given efficiency to determine the dry bulb temperature actually achieved as the result of tempering. Let State 1 be the outside air, State 2 be the Return Air, and State 3 be the Tempered Air. Ignore the Exhaust Air (after the Return Air has collected heat from the outside air.

$$\eta = \frac{T_1 - T_3}{T_1 - T_2}$$

$$.72 = \frac{90^{\circ}F - T_3}{90^{\circ}F - 74^{\circ}F}$$

$$T_3 = 78.5^{\circ}F$$

In order to find the enthalpy at State 4, a second parameter must be determined. Use the Psychrometric Chart to look up the dew point for State 1:

$$T_{1,db} = 90^{\circ}F$$

$$T_{1,wb} = 80^{\circ}F$$

$$T_{1,dp} = 76.7^{\circ}F$$

Since the outside air was not cooled past the dew point ($T_3 > T_{1,dp}$), it is confirmed that only *sensible* cooling has been performed. No moisture has been removed and the process from $1 \rightarrow 3$ is purely horizontal such that dew point is unchanged. (The humidity ratio is also unchanged). This fully defines State 3. Use the Psychrometric Chart once more to obtain the enthalpy at State 3.

$$T_{3,dp} = T_{1,dp} = 76.7^{\circ}F$$

$$T_{3,db} = 78.5^{\circ}F$$

$$h_3 = 40.7\frac{Btu}{lb}$$

Answer C

44.21 What is the friction loss for $1000cfm$ being delivered by a $14in \times 8in$ duct? Assume a friction factor of 0.015.

A. $0.15^{in\,wg}/_{100ft}$

B. $0.25^{in\,wg}/_{100ft}$

C. $0.40^{in\,wg}/_{100ft}$

D. $0.50^{in\,wg}/_{100ft}$

This problem is straightforward using the Frictions Loss chart for ductwork; however, if not supplied within the problem statement, since the chart is not included in the Reference Handbook, a manual solution is required using the Darcy Equation.

Calculate the Circular Equivalent diameter of a round duct by using the formula in the Reference Handbook under Rectangular Ducts. Round up to a nominal duct size.

$$D_e = \frac{1.30\,(ab)^{0.625}}{(a+b)^{0.250}}$$

$$D_e = \frac{1.30\,[(14in)\,(8in)]^{0.625}}{(14in + 8in)^{0.250}} = 11.46in \approx 12in$$

Calculate the velocity using the volume flow rate and area:

$$Q = vA \rightarrow v = \frac{Q}{A}$$

$$v = \frac{1000\frac{ft^3}{min}}{\frac{\pi}{4}\,(1ft)^2} = 1273\frac{ft}{min}\left(\frac{1min}{60s}\right) = 21.2\frac{ft}{s}$$

Find the friction loss per 100 ft, to align with the answer choices:

$$h_f = \frac{fLv^2}{2Dg}$$

$$h_f = \frac{(.015)\,(100ft)\left(21.2\frac{ft}{s}\right)^2}{2\,(1ft)\left(32.2\frac{ft}{s^2}\right)} = 10.5ft\left(\frac{12in}{1ft}\right) = 126in\,(air)$$

The pressure loss should be measured in inches of water rather than inches of air. To approximate the height of a water column that would support an air column of a given height, multiply by the ratio of the densities of air and water. As an intuitive check, the density of air is about 0.1% of the density of water.

$$h_f = 126in\,air\left(\frac{.075\frac{lb}{ft^3}}{62.4\frac{lb}{ft^3}}\right) = .15in\,wg$$

Answer A

44.22 **$30\frac{lb}{hr}$ of $5psig$ steam is supplied to a heating coil for an air handler delivering $1000cfm$ of outside air. The entering outside air is $50°F$ dry bulb and $45°F$ wet bulb. The coil bypass factor is 0.1. What is the temperature of the air leaving the heating coil?**

A. $74°F$

B. $75°F$

C. $77°F$

D. $78°F$

Look up the enthalpy of vaporization for steam at $5psig \approx 20psia$ in the steam table, Properties of Saturated Water, in the Reference Handbook. Calculate the heat being added by the steam:

$$\dot{Q}_{steam} = \dot{m}\Delta h = \dot{m}h_{fg}$$

$$\dot{Q}_{steam} = \left(30\frac{lb}{hr}\right)\left(960\frac{Btu}{lb}\right) = 28,800\frac{Btu}{hr}$$

The heating coil adds only sensible heat to the air stream. Use the sensible heating rule of thumb to calculate the leaving air temperature i.e. supply air temperature. Assume the coil efficiency is 100% for the time being.

$$\dot{Q}_{steam} = \dot{Q}_{air} = 1.08cfm\Delta T$$

$$1.08\,(1000)\,(T_{SA,\eta100} - 50) = 28,800\frac{Btu}{hr}$$

$$T_{SA,\eta100} = 76.7°F\,(\eta = 100\%)$$

Account for the bypass factor, which is the complement of coil efficiency. The air would be heated to a temperature of $76.7°F$ if the heating process were 100% efficient; therefore, it is expected that the final supply air temperature will be slightly lower.

$$\eta_{coil} = 1 - BF = 1 - 0.1 = 0.9 = 90\%$$

$$\eta_{coil} = \frac{T_{SA,\eta90} - T_{EA}}{T_{SA,\eta100} - T_{EA}}$$

$$0.9 = \frac{T_{SA,\eta90} - 50°F}{76.7°F - 50°F}$$

$$T_{SA,\eta90} = 74°F\,(\eta = 90\%)$$

Answer A

44.23 A cooling coil with a sensible capacity of $10tons$ is designed for a $20°F$ delta T. The air handler is installed in a facility at $5000ft$ elevation and must produce a total static pressure of $2.5in\,wg$. Assuming the fan is 92% efficient, what should be the nominal size of the fan motor?

A. $1^1/_2hp$

B. $2hp$

C. $2^1/_2hp$

D. $3hp$

Convert the sensible capacity to units of $\frac{Btu}{hr}$:

$$\dot{Q}_s = (10tons)\left(12,000\frac{Btu}{hr \cdot ton}\right) = 120,000\frac{Btu}{hr}$$

The sensible heating and cooling rule of thumb is not valid due to the elevation; however, the section Heat Gain Calculations Using Standard Air Values offers a slight adaptation for air at 5,000 ft. Update the constant in the rule of thumb and proceed with calculating the cfm. Note, the section for Elevation Correction may be useful for other nonstandard elevations.

$$\dot{Q}_s = 0.92cfm\Delta T$$

$$cfm = \frac{\dot{Q}_s}{(.92)(\Delta T)} = \frac{120,000}{(.92)(20)} = 6522cfm$$

Look up Efficiency of Fan in the Reference Handbook and use the formula right above the search result to calculate the air horsepower needed to provide the required volume flow rate against the pressure drop given. Units need not be shown provided the volume flow rate is in cfm and the pressure drop is in $in\,wg$. In a separate step, consider the efficiency to determine the brake horsepower.

$$AHP = \frac{Q_{[cfm]}\Delta P_{[in\,wg]}}{6356}$$

$$AHP = \frac{(6522)(2.5)}{6356} = 2.57hp$$

$$\eta_{fan} = \frac{AHP}{BHP} \rightarrow BHP = \frac{AHP}{\eta_{fan}}$$

$$BHP = \frac{2.57hp}{.92} = 2.79hp$$

Motor sizes are always rated in BHP. Round up to the nearest nominal motor size. For a list of standard motor sizes and efficiencies, look up Average Efficiencies Representing Typical Electric Motors in the Reference Handbook. $3HP$ is included in the list.

Answer D

44.24 What is the size of a refrigeration system required to freeze $100lbs$ of raspberries initially at $65°F$ to $15°F$ in $3hrs$?

A. $1,300\frac{Btu}{hr}$

B. $4,000\frac{Btu}{hr}$

C. $5,500\frac{Btu}{hr}$

D. $16,500\frac{Btu}{hr}$

Look up Refrigeration Properties of Foods and find raspberries. Obtain the freezing point temperature, the specific heat capacity above and below freezing, and the latent heat of fusion from the table. Determine the total heat to be removed from the fruit by calculating the sensible cooling above and below freezing and the latent heat removed (during phase change) at the freezing point.

Above the freezing point:

$$Q_{s,above} = mc_{p,above}\Delta T$$

$$Q_{s,above} = (100lb)\left(.95\frac{Btu}{lb \cdot °F}\right)(65°F - 30.9°F) = 3,240Btu$$

At the freezing point:

$$Q_{L,@FP} = mh_{fusion}$$

$$Q_{L,@FP} = (100lb)\left(124\frac{Btu}{lb}\right) = 12,400Btu$$

Below the freezing point:

$$Q_{s,below} = mc_{p,below}\Delta T$$

$$Q_{s,below} = (100lb)\left(.46\frac{Btu}{lb \cdot °F}\right)(30.9°F - 15°F) = 731Btu$$

Find the total heat removed. Then divide by the time in which that energy is to be removed to determine the capacity of the refrigeration system.

$$Q_{total} = 3,240Btu + 12,400Btu + 731Btu = 16,371Btu$$

$$\dot{Q} = \frac{Q}{t} = \frac{16,371Btu}{3hr} = 5,457\frac{Btu}{hr}$$

Answer C

44.25 The top of the waterline of an open cooling tower basin is located $13ft$ above the centerline of the associated $50gpm$ condenser water pump. The entering condenser water for the tower is $92°F$. The outdoor conditions are $68°F$ and 60% relative humidity. The cooling tower effectiveness is 70%. The suction piping between the basin and the condenser pump is comprised of an equivalent length of $25ft$ of $2^1/_2in$ standard weight steel pipe. What is the net positive suction head available to the condenser water pump in feet of water?

A. $27ft$

B. $36ft$

C. $45ft$

D. $49ft$

Look up Net Positive Suction Head in the Reference Handbook and use the formula for $NPSH_A$:

$$NPSH_A = h_p + h_z - h_{vpa} - h_f$$

where h_p is atmospheric pressure, h_z is the height of the column of water above the suction inlet (negative if the height of the reservoir is below the pump centerline), h_{vpa} is the vapor pressure which is a function of temperature, and h_f is the friction losses associated with the suction side piping path. Consider each term one at a time.

Atmospheric pressure is readily known to be $14.7psia$. For consistency, convert units to ft of head by applying by the rule of thumb conversion factor for water $2.31ft = 1psi$.

$$h_p = 14.7psi\left(\frac{2.31ft}{psi}\right) = 33.96ft$$

The height of the water column on the suction side is given:

$$h_z = 13ft$$

The vapor pressure of water is a function of temperature. The warmer the water, the higher the vapor pressure because more water molecules are likely to undergo phase change and become vapor. The water on the suction side of the condenser water pump is leaving the cooling tower, and the temperature is unknown. However, the entering water temperature is known, the wet bulb temperature can be determined using the outside conditions and the Psychrometric Chart, and the cooling tower effectiveness is known. Find the leaving water temperature.

$$T_{OA,db} = 68°F$$

$$\phi_{OA} = 60\%$$

$$T_{OA,wb} = 59.2°F$$

The wet bulb temperature is the minimum possible leaving water temperature that could be achieved if the cooling tower effectiveness was 100%. Since the effectiveness is only 70%, the leaving water temperature will be slightly greater.

$$\varepsilon = \frac{EWT - LWT}{EWT - T_{wb}}$$

$$.7 = \frac{92°F - LWT}{92°F - 59.2°F}$$

$$LWT = 69°F$$

Look up the steam table, Properties of Saturated Water by Temperature, and obtain the saturation pressure for $69°F$ water. Convert units to ft of water.

$$P_{sat@69°F} = .35psi$$

$$h_{vpa} = (.35psi)\left(\frac{2.31ft}{psi}\right) = .81ft$$

For the friction loss, look up Steel Pipe Friction Tables and use the diameter and flow rate given to find the head loss per unit length. Apply the equivalent length given to solve for the total friction loss.

$$D = 2.5in$$

$$Q = 50gpm$$

$$\Delta h_{d,loss} = 3.6\frac{ft}{100ft}$$

$$h_f = \left(3.6\frac{ft}{100ft}\right)(25ft) = .9ft$$

Calculate the net positive suction head available:

$$NPSH_A = h_p + h_z - h_{vpa} - h_f$$

$$NPSH_A = 33.96ft + 13ft - .81ft - .9ft = 45.25ft$$

Answer C

44.26 On a day with outside conditions of $80°F$ dry bulb and 50% relative humidity, a cooling tower operates with an effectiveness of 70%. The return condenser water enters the tower at $96°F$. What is the approach?

A. $9°F$

B. $15°F$

C. $21°F$

D. $29°F$

Use the outside conditions and the Psychrometric Chart in the Reference Handbook to obtain the wet bulb temperature.

$$T_{OA,db} = 80°F$$

$$\phi_{OA} = 50\%$$

$$T_{OA,wb} = 66.6°F$$

Use the cooling tower effectiveness to solve for the leaving water temperature (condenser water supply).

$$\varepsilon = \frac{EWT - LWT}{EWT - T_{wb}}$$

$$.7 = \frac{96°F - LWT}{96°F - 66.6°F}$$

$$LWT = 75.4°F$$

Look up Cooling Tower Approach, which is defined as the difference between the cooling tower leaving water temperature and the entering air wet bulb temperature. Apply this definition to find the approach.

$$Approach = LWT - T_{wb} = 75.4°F - 66.6°F = 8.8°F$$

Note, another term worth knowing is the range of a cooling tower which is the difference between the entering and leaving water temperatures. In this case, $Range = EWT - LWT = 96°F - 75.4°F = 10.6°F$.

Answer A

44.27 An energy efficiency initiative being evaluated for a $2500ton$ chiller plant running 24/7 is expected to improve the total average annualized COP from 4 to 5. The project budget is $800,000. Capital can be borrowed at an interest rate of 5%. Electricity costs are estimated at $0.14 per kwH. What is the loan duration that should be used if the initiative is required to be cash flow neutral?

A. 17 months

B. 18 months

C. 19 months

D. 20 months

The electricity to run the chiller plant consists of the power to run the compressors, which is $\dot{W}_{in}$ in the Coefficient of Performance (COP) formula. Rearrange the COP and solve the input power before and after the initiative. Arbitrarily call these Option 1 and Option 2. Convert units to KW.

$$COP_R = \frac{\dot{Q}_{in}}{\dot{W}_{in}} \rightarrow \dot{W}_{in} = \frac{\dot{Q}_{in}}{COP_R}$$

$$\dot{W}_{in,1} = \frac{(2500tons)\left(12,000\frac{Btu}{hr \cdot ton}\right)}{(4)\left(3412\frac{Btu}{hr \cdot KW}\right)} = 2198KW$$

$$\dot{W}_{in,2} = \frac{(2500tons)\left(12,000\frac{Btu}{hr \cdot ton}\right)}{(5)\left(3412\frac{Btu}{hr \cdot KW}\right)} = 1758KW$$

Calculate the annual cost savings associated with the reduction in demand. Multiply by time and the rate of electricity.

$$Annual\,Cost\,Savings = (2198KW - 1758KW)(8760hr)\left(\frac{\$0.14}{KW \cdot hr}\right) = \$539,600$$

Look up Economic Factor Conversions and find the option for Capital Recovery which converts to A given P, where A is an annualized payment and P is a lump sum of principal borrowed. The value of the conversion factor is a function of the interest rate and term length and is written as $(A/P, i\%, n)$. Since A and P are known, solve for the value of the factor.

$$A = (A/P, 5\%, n)\,P$$

$$(A/P, 5\%, n) = \frac{A}{P} = \frac{\$539,600}{\$800,000} = .6739$$

Set the value of the factor equal to the expression used for calculating when both interest rate and term are known. In this case, the interest rate is known and the term length needs to be determined.

$$(A/P, 5\%, n) = \frac{i\,(1+i)^n}{(1+i)^n - 1} = .6739$$

Substitute $i = .05$:

$$\frac{(.05)(1.05)^n}{(1.05)^n - 1} = .6739$$

Rather than tackle the challenging algebra and potentially wasting time (see alternate solution below), consider an iterative trial and error approach where some answers may be quickly eliminated. As a starting point, determine the simple payback for the initiative:

$$Simple\ Payback = \frac{\$800,000}{\$539,600} = 1.48 years \left(\frac{12 months}{year}\right) \approx 18 months$$

The simple payback does not account for any interest paid over time, therefore it is a more favorable representation of the financials from the perspective of the borrower. Answer choice A, $n = 17 months$, can be eliminated on the basis that the term cannot be more favorable than the simple payback would imply.

It is difficult to eliminate any other choices; try all remaining answer choices to see which term length comes closest to the calculated value for $(A/P, 5\%, n)$. The units for the term length should be years to align with the interest rate, which is annual.

$$n = 18 months \left(\frac{1 year}{12 months}\right) = 1.5 years$$

$$\frac{(.05)(1.05)^{1.5}}{(1.05)^{1.5} - 1} = .7085$$

$$n = 19 months \left(\frac{1 year}{12 months}\right) = 1.58 years$$

$$\frac{(.05)(1.05)^{1.58}}{(1.05)^{1.58} - 1} = .6726$$

Since $.6726 < .6739 < .7085$, there is no need to try $n = 20 months$.
.6739 is closer to .6726, so choose $n = 19 months$.
Alternate Solution:

$$\frac{(.05)(1.05)^n}{(1.05)^n - 1} = .6739$$

Divide by .05:

$$\frac{(1.05)^n}{(1.05)^n - 1} = 13.478$$

Take the inverse of both sides:

$$\frac{(1.05)^n - 1}{(1.05)^n} = .0742$$

Break left side into two terms:

$$1 - \frac{1}{(1.05)^n} = .0742$$

Simplify:

$$\frac{1}{(1.05)^n} = .9258$$

Take the inverse of both sides:

$$(1.05)^n = 1.08$$

Recall from algebra that solving for an exponent involves a logarithm. Write an equivalent relationship to the above using logs:

$$n = log_{1.05}1.08$$

In order to solve a log with a base other than 10 or e, rewrite as a ratio of two logs with base 10:

$$n = \frac{log_{10}1.08}{log_{10}1.05} = 1.58years$$

Convert to months:

$$n = 1.58years\left(\frac{12months}{1year}\right) = 19months$$

Answer C

44.28 An engineer is specifying a $1000 cfm$ dedicated outside air unit for a 24 hour gym which is to be maintained at $72°F$ with 50% relative humidity by supplying $55°F$ saturated supply air. The average outdoor conditions for the region are $88°F$ and 55% relative humidity. The unit manufacturer offers an option to include an enthalpy wheel with 60% effectiveness for an additional cost of $10,000. If it costs the tenant $0.50 per ton hour to produce chilled water, what is the simple payback for the enthalpy wheel? Neglect maintenance and assume installation and commissioning add no additional upfront cost.

A. 3 months

B. 10 months

C. 2 years

D. 3 years

An enthalpy wheel is capable of recovering both sensible and latent heat. Contrast this with an air-to-air heat exchanger which captures only sensible heat. The enthalpy wheel provides the opportunity to cool and dehumify the entering outside air by rejecting heat and moisture to the room air being exhausted. If the enthalpy wheel had 100% effectivenss, the enthalpy of the air supplied by the enthalpy wheel would be equal to the enthalpy of the room air. Further cooling and dehumfication would always have to be provided by the outside air handling unit's cooling coil. Therefore, the effectiveness of the enthalpy wheel, and thus the opportunity to produce savings, applies only to the enthalpy differential between the outside air and the room air. The OAHU discharge conditions are to be ignored.

Consider the outside air as State 1 and the room air as State 2. Use the Psychrometric Chart to look up the enthalpy for both states. Use the total cooling rule of thumb to calculate the amount of energy removed by the enthalpy wheel if it was 100% effective, and take 60% of that value to account for the given effectiveness.

$$T_1 = 88°F$$

$$\phi_1 = 55\%$$

$$h_1 = 38.4\frac{Btu}{lb}$$

$$T_2 = 72°F$$

$$\phi_2 = 50\%$$

$$h_2 = 26.4\frac{Btu}{lb}$$

$$\dot{Q}_t = 4.5 cfm \Delta h$$

$$\dot{Q}_t = (0.6)\,(4.5)\,(1000)\,(38.4 - 26.4) = 32,400 \frac{Btu}{hr}$$

This is the total avoided cooling load. Convert this value to $refrigeration\,tons$ and calculate the annual $ton \cdot hours$:

$$Avoided\,Cooling\,Demand = \left(32,400 \frac{Btu}{hr}\right)\left(\frac{1 ton}{12,000 \frac{Btu}{hr}}\right)(8760 hours) = 23,652 ton \cdot hours$$

Calculate the annual cost savings:

$$Cost\,Savings = (23,652 ton \cdot hours)\left(\frac{\$0.50}{ton \cdot hour}\right) = \$11,826$$

Calculate the simple payback:

$$Simple\,Payback = \frac{\$10,000}{\$11,826} = 0.8456 years \left(\frac{12 months}{1 year}\right) = 10.1 months$$

Answer B

44.29 A low-stage refrigeration system using R-22 operates with a saturated suction temperature of $-50°F$ and a discharge temperature of $10°F$. The discharge line is a $1^3/_8in$ type L copper tube with a length of $100ft$. What is the capacity of the discharge line?

A. $4.5tons$

B. $5.6tons$

C. $6.6tons$

D. $7.9tons$

Look up Discharge and Liquid Line Capacities in the Reference Handbook and find the table for Refrigerant 22, specifically Intermediate or Low-Stage Duty. The suction temperature is extra information and is not needed for determining the capacity of the discharge line.

Based on Type L Copper tube with the diameter given, obtain the discharge line capacity from the table as $6.6tons$. This assumes a 100ft length which is consistent with the problem statement.

Read note #5 below the table and recognize the condensing temperature is assumed to be $0°F$. However, there is a small table of correction factors for other condensing temperatures. For the condensing temperature given, $10°F$, it is necessary to multiply the table capacity by a factor of 1.2.

$$Discharge\,Capacity = (6.6tons)\,(1.2) = 7.92tons$$

Answer D

45 Supporting Topics

45.1 Machine A produces a sound pressure of $58dB$, and machine B produces a sound pressure of $52dB$. What is the combined sound pressure?

A. $53dB$

B. $58dB$

C. $59dB$

D. $61dB$

Refer to the table for Combining Two Sound Levels. Note that when the difference between the dB levels of the two sources is between 5 and 9, the number of dB to be added to the highest source is $1dB$. Since Machine A is the higher source, add $1dB$ to its sound pressure level.

$$58dB + 1dB = 59dB$$

Answer C

45.2 The background noise in an office has a sound pressure level of $38dB$. An overhead fan coil unit with a sound pressure level of $43dB$ turns on. What is the combined sound pressure level?

A. $39dB$

B. $44dB$

C. $46dB$

D. $52dB$

Refer to the table for Combining Two Sound Levels. Note that when the difference between the dB levels of two sources is between 5 and 9, the number of dB to be added to the highest source is $1dB$.

Combine the two sources.

$$43dB + 1dB = 44dB$$

Answer B

45.3 Four identical fans produce a combined sound pressure level of $90dBA$ as measured at a point that is equidistant from each fan. What is the sound pressure level if three fans are shut down?

A. $70dB$

B. $80dB$

C. $84dB$

D. $87dB$

Refer to the table for Combining Two Sound Levels and note that when the difference between two source's sound levels is $0dB$, the number of decibels to be added to the highest level is 3dB. In this situation, sources are being removed as fans are shut down, but the same principle applies in reverse. To be clear, the table does not offer a way to add 3 or more sources together directly, therefore it is necessary to find an approach that allows adding the sources in pairs only.

First, imagine shutting 2 of the 4 fans down. One pair of fans may be treated as one source and the other pair treated as a second source. The sound pressure level will be reduced by $3dB$ when have the sources are removed. This reasoning can be confirmed by imagining re-enabling the 2 fans, thereby combining two pairs of sources, and adding back the $3dB$.

$$90dB - 3dB = 87dB$$

Next imagine shutting down one of the two remaining fans, thereby removing half the sources. By the same reasoning, another $3dB$ reduction will be observed.

$$87dB - 3dB = 84dB$$

Again, sense check this answer by adding two $84dB$ sources together to get $87dB$, then adding the two pair of sources to get back to $90dB$.

Answer C

45.4 The background noise in a factory prior to any equipment turning on has a sound pressure level of $40dB$. Once the equipment is operating, the sound pressure level is $46dB$. What is the sound pressure level attributable to the machinery only?

A. $6dB$

B. $41dB$

C. $43dB$

D. $45dB$

Refer to the table for Combining Two Sound Levels. The process for combining sound levels involves adding up to $3dB$ to the *highest* source, depending on the difference in sound level between the two sources. In this case, it is not immediately clear whether the background noise or the machinery is the louder source. Since the most that could be added to arrive at the combined sound pressure level is $3dB$, it can be inferred that the background noise is not as loud at the machinery, as combining two $40dB$ sources would result in a combined level of only $43dB$. Therefore, the machinery must be louder.

Test values for the machinery between $41dB$ and $45dB$.

$$SPL_{machinery} = 41dB \rightarrow Difference = 1dB \rightarrow Combined\,SPL = 41dB + 3dB = 44dB \neq 46dB$$

$$SPL_{machinery} = 42dB \rightarrow Difference = 2dB \rightarrow Combined\,SPL = 42dB + 2dB = 44dB \neq 46dB$$

$$SPL_{machinery} = 43dB \rightarrow Difference = 3dB \rightarrow Combined\,SPL = 43dB + 2dB = 45dB \neq 46dB$$

$$SPL_{machinery} = 44dB \rightarrow Difference = 4dB \rightarrow Combined\,SPL = 44dB + 2dB = 46dB = 46dB$$

$$SPL_{machinery} = 45dB \rightarrow Difference = 5dB \rightarrow Combined\,SPL = 45dB + 1dB = 46dB = 46dB$$

Note there are two viable answer choices, $44dB$ and $45dB$. However, only $45dB$ is an answer choice.

Answer D

45.5 The octave band measurements of a fan are: $63Hz$, $64dB$; $125Hz$, $67dB$; $250Hz$, $63dB$; $500Hz$, $63dB$; $1000Hz$, $59dB$; $2000Hz$, $54dB$; $4000Hz$, $50dB$; $8000Hz$, $46dB$. What is the NC rating?

A. NC-45

B. NC-50

C. NC-55

D. NC-60

Refer to the Noise Criteria curves and use the figure to plot the sound pressure level in dB for each octave band frequency. The NC rating is the lowest curve which all measured values fall below.

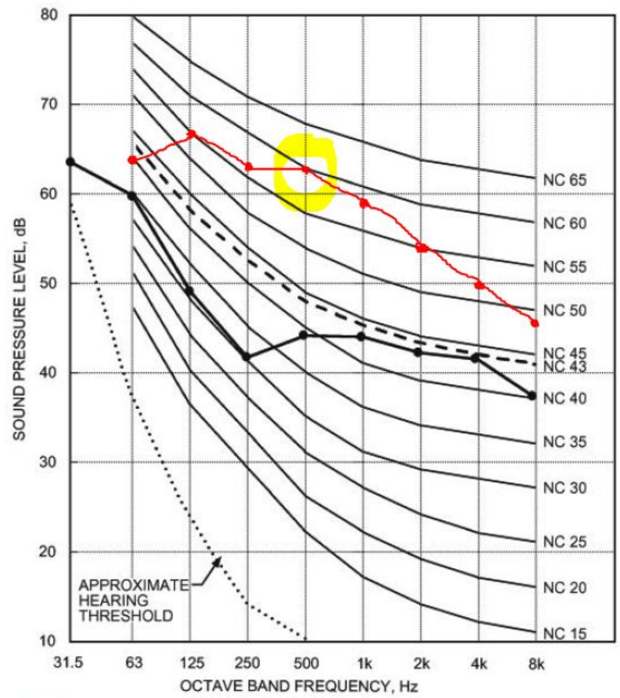


Fig. 7 NC (Noise Criteria) Curves and Sample Spectrum (Curve with Symbols)

In this case, the worst case octave band is the $500Hz$ frequency, and the rating is NC-60.
Answer D

45.6 A $5000lb_m$ machine rotates at $1800rpm$ and is mounted on vibration isolators with a combined stiffness of $40,000\frac{lb_f}{in}$. In parallel with the springs, a damper has been included. The damping ratio is 0.3. An unbalanced force of $2000lb_f$ is caused by the machine. What is the maximum force transmitted through the base?

A. $550lb_f$

B. $950lb_f$

C. $1050lb_f$

D. $1450lb_f$

Start by finding the natural frequency of the machine which is a function of the total combined spring stiffness and the mass. Note that g_c must be included to make the units consistent.

$$\omega_n = \sqrt{\frac{kg_c}{m}} = \sqrt{\frac{\left(40,000\frac{lb_f}{in}\right)\left(12\frac{in}{ft}\right)\left(32.2\frac{lb_m \cdot ft}{lb_f \cdot s^2}\right)}{5,000lb_m}} = 55.6\frac{rad}{s}$$

Find the forcing frequency, which is a function of the rotational speed.

$$\omega = \left(1800\frac{rev}{min}\right)\left(\frac{1min}{60s}\right)\left(\frac{2\pi rad}{rev}\right) = 188.5\frac{rad}{s}$$

Find the frequency ratio, r.

$$r = \frac{\omega}{\omega_n} = \frac{55.6\frac{rad}{s}}{188.5\frac{rad}{s}} = 3.39$$

Determine the vibration transmissibility, $\frac{F_T}{F_o}$, where F_T is the transmitted force and F_o is the unbalanced force. The damping ratio is given as $\varsigma = 0.3$.

$$\frac{F_T}{F_o} = \left[\frac{1 + (2\varsigma r)^2}{(1-r^2)^2 + (2\varsigma r)^2}\right]^{\frac{1}{2}} = \left[\frac{1 + [2(0.3)(3.39)]^2}{\left(1-(3.39)^2\right)^2 + [2(0.3)(3.39)]}\right]^{\frac{1}{2}} = 0.72$$

Solve for the transmitted force.

$$F_T = (0.72)\,F_o = (0.72)\,(2000lb_f) = 1440lb_f$$

Answer D

45.7 A $1.5in$ diameter steel shaft ($E = 2.9\times10^7 psi$) is $4ft$ long and supported by two frictionless bearings at its ends. A $200lb_m$ flywheel is mounted on the center of the shaft. The shaft weight is negligible and there is no damping. What is the critical speed of the shaft?

A. $4Hz$

B. $12Hz$

C. $78Hz$

D. $590Hz$

The critical speed depends on the linear natural frequency of the shaft which can be determined from the static deflection due to the mass of the flywheel modeled as a point load applied to the center of a simple beam.

Start by calculating the area moment of inertia for a the shaft.

$$I = \frac{\pi r^4}{4} = \frac{\pi\,(0.75in)^4}{4} = 0.2485in^4$$

Find the formula for the static deflection of a simple beam with a concentrated load at center. Calculate the maximum static deflection.

$$\delta_{st} = y = \frac{Pl^3}{48EI} = \frac{(200lb_f)\,(48in)^3}{48\left(2.9\times10^7\frac{lb_f}{in^2}\right)(0.2485in^4)} = 0.064in$$

The undamped natural circular frequency can then be determined as a function of the static deflection.

$$\omega_n = \sqrt{\frac{g}{\delta_{st}}} = \sqrt{\frac{\left(32.2\frac{ft}{s^2}\right)\left(\frac{12in}{1ft}\right)}{0.064in}} = 77.7\frac{rad}{s}$$

Find the linear natural frequency.

$$f_n = \frac{\omega_n}{2\pi} = \frac{77.7\frac{rad}{s}}{2\pi} = 12.4Hz$$

Answer B

45.8 A $200lb_m$ compressor rotates at $1750rpm$ and generates a disturbing force due to unbalance during each rotation. The compressor is mounted on 4 identical, equally loaded springs at the corners of its base. What individual spring stiffness is required to limit the transmitted force to 70% of the disturbing force?

A. $10,000\frac{lb_f}{in}$

B. $15,000\frac{lb_f}{in}$

C. $17,000\frac{lb_f}{in}$

D. $41,000\frac{lb_f}{in}$

Start with the vibration transmissibility formula. The ratio of the transmitted force to the unbalanced force, $\frac{F_T}{F_o} = 0.7$. Since there is no mention of damping, set the damping ratio, $\varsigma = 0$. Solve for r, which is the ratio of the forcing frequency to the natural frequency.

$$\frac{F_T}{F_o} = \left[\frac{1 + (2\varsigma r)^2}{(1 - r^2)^2 + (2\varsigma r)^2}\right]^{\frac{1}{2}}$$

$$0.7 = \left[\frac{1}{(1 - r^2)^2}\right]^{\frac{1}{2}}$$

$$0.49 = \frac{1}{(1 - r^2)^2}$$

$$\left(1 - r^2\right)^2 = 2.04$$

$$\left(1 - r^2\right) = 1.43$$

$$r^2 = -0.43$$

Although the Reference Handbook does not address this issue, it is valid and expected that it will be necessary to take the absolute value of the right side before taking the square root. Other references such as the Mechanical Engineering Reference Manual show a version of the vibration transmissibility formula which includes absolute value symbols for precisely this reason.

$$r^2 = |-0.43| = 0.43$$

$$r = 0.65$$

Determine the forcing frequency, which is a function of the unbalanced force being exerted as the compressor rotates. The Reference Handbook uses ω, however to avoid ambiguity it may be useful to use ω_f.

$$\omega_f = \left(1750\frac{rev}{min}\right)\left(\frac{1min}{60s}\right)\left(\frac{2\pi rad}{rev}\right) = 183.3\frac{rad}{s}$$

Since r is the ratio of the forcing frequency to the natural frequency, rearrange to calculate the natural frequency required to limit the transmissibility to 70%, or in other words, to drive the value of r to 0.65.

$$r = \frac{\omega_f}{\omega_n}$$

$$\omega_n = \frac{\omega_f}{r} = \frac{183.3\frac{rad}{s}}{0.65} = 278\frac{rad}{s}$$

Rearrange the formula for natural frequency to find the total spring constant, k_t.

$$\omega_n = \sqrt{\frac{kg_c}{m}}$$

$$k_t = \frac{\omega_n^2 m}{g_c} = \frac{\left(278\frac{rad}{s}\right)^2(200lb_m)}{\left(32.2\frac{lb_m\cdot ft}{lb_f\cdot s^2}\right)\left(\frac{12in}{1ft}\right)} = 40,578\frac{lb_f}{in}$$

Since there are 4 springs in parallel, divide by 4 to find the individual spring constant.

$$k_s = \frac{k_t}{4} = \frac{40,578\frac{lb_f}{in}}{4} = 10,144\frac{lb_f}{in}$$

Answer A

45.9 A $\frac{3}{8}in$ diameter steel threaded rod (Poisson's Ratio $= 0.3$) has been installed to support a $300lb$ load to be hung $4ft$ below. The lateral strain on the rod is -0.1%. How much will the rod elongate when the load is added?

A. $0.05in$

B. $0.1in$

C. $0.2in$

D. $0.5in$

Recall that Poisson's Ratio is lateral strain divided by longitudinal strain. The negative sign is included because the rod contracts laterally and expands longitudinally (axially).

Find the logitudinal strain:

$$\nu = -\frac{lateral\ strain}{longitudinal\ strain} = 0.3$$

$$\nu = \frac{-0.001}{\varepsilon_{long}} = 0.3 \rightarrow \varepsilon = 0.00333$$

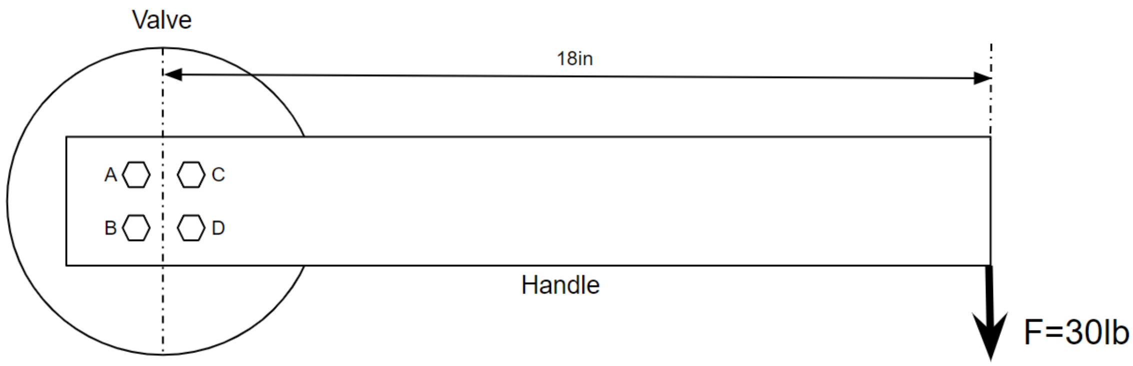
Under Uniaxial Loading and Deformation, find the formula relating strain, elastic longitudinal deformation, and the original length of the rod. The elongation is the longitudinal deformation.

$$\varepsilon = \frac{\delta}{L}$$

$$\delta = \varepsilon L = (.00333)\,(4ft)\left(\frac{12in}{1ft}\right) = 0.16in$$

Answer C

45.10 The handle of a large manual valve is secured with a square bolt pattern, as shown. The handle is $18in$ long and the force applied to the end of the handle during valve opration is $30lb_f$. The bolts have a nominal diameter of $1/4in$ and a cross-sectional area of $0.03in^2$. When the valve is being closed, which statement can be made about the shear stress experienced by the bolts?



A. Bolts A and B experience higher shear stress than bolts C and D.

B. Bolts C and D experience higher shear stress than bolts A and B.

C. Bolts A and C experience higher shear stress than bolts B and D.

D. Bolts B and D experience higher shear stress than bolts A and C.

This is a qualitative problem, so there is no need to quantify the loads applied to the bolts. Since all bolts have the same diameter and cross-sectional area, the maximum shear stress will be a direct outcome of the resultant force experienced due to the applied load and moment.

Since the applied load is downward, the reaction forces on the bolts from the applied load are all upward.

Since the load is applied a distance away from the bolts, it produces a clockwise moment, generating reaction forces perpendicular to lines drawn through each bolt and the center of the bolt pattern. In othwer words, the forces resulting from the moment are tangent to a circle drawn through all four bolts.

Adding the vectors for the reaction forces from the applied load and the moment, notice the directions of the reaction forces partially offset for bolts A and B. However, the forces are partially additive for bolts C and D. Therefore, bolts C and D have larger resultant reaction forces and more shear stress than bolts A and B.

Answer B

45.11 A nominal $2in$ chilled water pipe ($D_o = 2.375in$, $D_i = 2.067in$) is filled with water and simply supported with pipe hangers located $18ft$ apart. Steel has a specific weight of $0.284\frac{lb_f}{in^3}$ and a modulus of elasticity of $29 \times 10^6 \frac{lb_f}{in^2}$. What is the maximum deflection of the pipe?

A. $0.03in$

B. $0.26in$

C. $0.43in$

D. $0.63in$

Search for the table for Deflection of Beams of Uniform Cross Section, Under Various Conditions of Loading. The pipe can be modeled as a Simple Beam with a Uniform Load. The maxmum deflection occurs at the center of the span and is given by the formula below where W is the uniform load per unit length, l is the length of the span, E is the modulus of elasticity for the pipe, and I is the moment of inertia.

$$y = \frac{5Wl^4}{384EI}$$

The span and modulus of elasticity are given.

$$l = 18ft$$

$$E = 29 \times 10^6 \frac{lb_f}{in^2}$$

The uniform load can be determined by finding the weight of the pipe and the water contained within it and dividing by the span. However, it is more convenient and faster to use the table Schedule 40 Steel Pipe which provides the total weight per linear foot for various pipe sizes. Convert to weight per inch for ease of use in the deflection formula.

$$W = \left(5.11\frac{lb_f}{ft}\right)\left(\frac{1ft}{12in}\right) = 0.426\frac{lb_f}{in}$$

The moment of inertia can be determined using the geometry of the pipe cross section and a formula found in the table Properties of Various Shapes under the column Area Moment of Inertia. However, again the Schedule 40 Steel Pipe table saves time by providing the moment of inertia directly. Note the moment of inertia is a function of the cross sectional area only, so there is no need to consider the length. The value from the table should be taken and used directly.

$$I = 0.666in^4$$

Find the maximum deflection.

$$y = \frac{5Wl^4}{384EI} = \frac{5\left(0.426\frac{lb_f}{in}\right)(216in)^4}{384\left(29\times 10^6\frac{lb_f}{in^2}\right)(0.666in^4)} = 0.625in$$

Answer D

45.12 The displacement of a hydraulic press is $3in^3$ per revolution and the pump speed is $1800rpm$. The hydraulic pressure is $600psig$. The positive displacement pump is 80% efficient and is driven by a 3-phase, 208V AC motor that is 95% efficient. The power factor is 0.9. What size circuit breaker should be selected to protect the system?

A. $20A$

B. $30A$

C. $40A$

D. $50A$

By default, it is common practice to apply the formulas for hydraulic horsepower based on rules of thumb. However, fundamentally the power produced by a pump is the product of the pressure added by the pump, ΔP, and the volume flow rate, Q. The other details are unit conversions and efficiencies. It is possible and occassionally necessary to build up the formulation from this fundamental concept, as with this problem.

Suppose hydraulic horsepower may be expressed simply as below, provided we address units and efficiencies later on.

$$WHP = \Delta P \times Q$$

In this case, the hydraulic pressure is generated entirely by the pump and ΔP may be taken as $600psi$. The volume flow rate is not given, however the displacement of the hydraulic press, i.e. volume, is given as well as the rotational speed. This can be developed into volume per unit time, i.e. volume flow rate.

Determine the hydraulic horsepower delivered. Convert units to KW for convenience in the subsequent step.

$$WHP = \left(600\frac{lb_f}{in^2}\right)\left(3\frac{in^3}{rev}\right)\left(1800\frac{rev}{min}\right)\left(\frac{1min}{60s}\right)\left(\frac{1ft}{12in}\right)\left(\frac{1hp}{550\frac{ft\cdot lb_f}{s}}\right)\left(\frac{0.7457KW}{1hp}\right) = 6.1KW(delivered)$$

Apply the pump and motor efficiencies to determine the electrical power consumed by the motor in producing the power which was delivered.

$$\dot{W}_{elec} = P_{KW} = \frac{WHP}{\eta_p\eta_m} = \frac{6.1KW}{(0.8)(0.95)} = 8.03KW(consumed)$$

Search for Power for Different Motor Phases and select the formula for specifying the current for a 3-phase motor where the power consumed in KW is known.

$$I_{amps} = \frac{P_{KW}\left(1000\frac{W}{KW}\right)}{\sqrt{3}V\left(pf\right)} = \frac{\left(8.03KW\right)\left(1000\frac{W}{KW}\right)}{\sqrt{3}\left(208V\right)\left(0.9\frac{W}{VA}\right)} = 24.8A$$

Select the circuit breaker the next size up. An undersized breaker will trip anytime the motor draws its full load current, therefore it is not appropriate to round down.

Answer B

45.13 $90°F$, 20% relative humidity air is cooled using a 75% effective evaporative cooler. What is the temperature of the air after being cooled?

A. $55°F$

B. $63°F$

C. $70°F$

D. $76°F$

The effectiveness of an evaporative cooler is given by the formula below where t_1 represents the entering air dry bulb temperature, t_2 represents the leaving air dry bulb temperature, and t'_s is the wet bulb temperature of the entering air. The wet bulb temperature is the minimum temperature which could theoretically be achieved in a 100% efficient evaporative cooler.

$$\varepsilon_e = \frac{t_1 - t_2}{t_1 - t'_s}$$

Use the Psychrometric Chart to find the wet bulb temperature of the entering air.

$$t_1 = 90°F$$

$$\phi = 20\%$$

$$t'_s = 62.8°F$$

Substitute into the effectiveness formula and solve for t_2.

$$0.75 = \frac{90°F - t_2}{90°F - 62.8°F}$$

$$t_2 = 69.6°F$$

Answer C

45.14 A company is considering whether to invest in a piece of equipment that will have an initial cost of $100,000 and will produce $50,000 per year in revenue for the next 3 years before maintenance costs and taxes. Maintenence will cost $5000 per year. The tax rate is 30% and straight line depreciation is used for the equipment. The equipment has a salvage value of $20,000 to be realized at the end of year 3. What is the present value of the initiaitve using a 10% rate of return?

A. -$62K

B. $18K

C. $46K

D. $211K

Draw a cash flow diagram and make a list of cash flows.

Year 0: -$100K

Years 1 & 2: Revenue = 50K and Cost = 5K. The profit before tax is 45K. The taxes may be addressed separately.

Year 3: The cash flow is the same as for years 1 & 2 except for an additional $20K in salvage value which will be included a separate one-off future payment.

For tax purposes, the profit which is considered taxable is reduced by the depreciation for that year even though the cash was actually spent in year 0. For straight line depreciation, the depreciated amount for years 1, 2, and 3 is the same.

$$D = \frac{\$100,000}{3years} = \$33,333\, per\ year$$

Determine the profit for tax purposes.

$$Profit = Revenue - (Expenses + Depreciation)$$

$$Profit = \$50,000 - (\$5,000 + \$33,333) = \$11,667$$

Apply the tax rate to determine the tax liability.

$$Tax = (\$11,667)\,(0.3) = \$3,500$$

Subtract the tax from the before-tax profit (excluding depreciation) to determine the after-tax profit. This is the net cash flow for years 1 & 2.

$$After\, tax\ Profit = \$45,000 - \$3,500 = \$41,500$$

For year 3, the salvage value, which is not subject to taxes, will be handled as a separate future payment in our present value calculation. In other words, the $41,500 will be considered part of an annualized cash flow with a 3 year period.

Calculate the present value. Use the Economic Factor Tables to look up the cash flow factors for P/A and P/F based on an interest rate of 10%.

$$PV = -\$100,000 + (\$41,500)\,(P/A, 10\%, 3) + (\$20,000)\,(P/F, 10\%, 3)$$

$$PV = -\$100,000 + (\$41,500)\,(2.4869) + (\$20,000)\,(0.7513) = \$18,232$$

Answer B

45.15 A company purchases a factory for \$1M. The factory will generate a gross annual revenue of \$140K and incur annual expenses of \$60K. The facility has an expected life of 20 years and no salvage value. Assuming straight-line depreciation and a 30% effective tax rate, what is the after tax rate of return if the company sells the factory for \$800K and exits the investment after 5 years? Ignore tax implications of capital losses at the time of sale.

A. 1.5%

B. 3.5%

C. 5.5%

D. 7.5%

Draw a cash flow diagram or make a list of cash flows. The cash flow in year 0 is -\$1M. The cash flow in year 5 is +\$800K in addition to the net profit after tax.

To determine the net profit after tax for years 1 through 5, start by subtracting the expenses from the revenue.

$$Profit\,Before\,Tax = Revenue - Expenses = \$140K - \$60K = \$80K$$

Because there is depreciation, the taxes are not assessed against the \$80K. The taxable amounnt is reduced by the depreciation. Essentially, depreciation is applied as an expense even though the cash left the business in year 0. For straight line deprecation of \$1M of initial cost spread over 20 years:

$$D = \frac{\$1,000,000}{20} = \$50K$$

The taxable income is therefore:

$$Taxable\,Income = \$80K - \$50K = \$30K$$

The tax liability based on a 30% tax rate is:

$$Tax = (0.3)\,(\$30K) = \$9K$$

Determine the Net Profit After Tax:

$$Net\,Profit\,After\,Tax = Profit\,Before\,Tax - Tax = \$80K - \$9K = \$71K$$

Write an expression for the present value of the investment accounting for the initial cost, the net profit after tax for years 1 through 5, and the salvage value in year 5. Set the present value equal to zero. By definition, the interest rate that gives the investment a present value of zero is the rate of return.

$$PV = -\$1,000,000 + \$71,000\,(P/A, i, 5) + \$800,000\,(P/F, i, 5) = 0$$

The math required for a direct solution becomes complex, so it is faster and equally reliable to use trial an error and interpolation to determine the interest rate. Guesses are best made in the vicinity of the answer choices with a strong preference for values offered in the Economic Factor Tables.

Try $i = 6\%$. Refer to the relevant Factor Table in the Economic Analysis section.

$$(P/A, 6\%, 5) = 4.2124$$

$$(P/F, 6\%, 5) = 0.7473$$

$$PV = -\$1,000,000 + \$71,000\,(4.2124) + \$800,000\,(0.7473) = -\$103,080$$

A negative present value implies the future cash flows, which are positive, are being discounted too much, therefore the 6% interest rate is too high.

Try $i = 2\%$.

$$(P/A, 2\%, 5) = 4.7135$$

$$(P/F, 2\%, 5) = 0.9057$$

$$PV = -\$1,000,000 + \$71,000\,(4.7135) + \$800,000\,(0.9057) = \$59,220$$

A positive present value implies the future cash flows, which are positive, are not being discounted enough, therefore the 2% interest rate guessed is too low.

Make a table and interpolate between $i = 6\%$ and $i = 2\%$

Interest Rate [%]	Present Value [$]
2	59,220
i	0
6	−103,080

$$\frac{59,220 - 0}{59,220 - (-103,080)} = \frac{2 - i}{2 - 6}$$

$$0.3649 = \frac{2 - i}{2 - 6}$$

$$-1.46 = 2 - i$$

$$i = 3.46\%$$

Answer B

45.16 A project has an initial cost of $200K and generates $30K per year in net profits. After 15 years there is a salvage value of $40K. What is the return on investment for the project?

A. 13.3%

B. 14.2%

C. 15.1%

D. 16.0%

Draw a cash flow diagram or make a list of cash flows.

For year 0 there is an initial cost of -$200K.

For years 1 through 15 there is an annual profit of $30K.

For year 15 there is a salvage value of $40K.

Write an expressions for the present value of the project. Set the present value equal to zero. The return on investment (ROI) is the interest rate that gives the initiative a present value of zero.

$$PV = -\$200,000 + \$30,000\,(P/A, i\%, 15) + \$40,000\,(P/F, i\%, 15) = 0$$

The math involved in solving for the interest rate is challenging and time consuming, therefore a trial and error method is often the best way forward from this point. One way to get an approximate answer to look at the answer choices and notice they are all between 12% and 18%. Another way is to notice that the one time salvage value is much less significant (though not negligible) than the annual profit, so it can be temporarily ignored as a first pass.

$$PV = -\$200,000 + \$30,000\,(P/A, i\%, 15) \approx 0$$

$$(P/A, i\%, 15) \approx \frac{\$200K}{\$30K} \approx 6.7$$

Refering to the $i = 12\%$ Factor Table, the value for $(P/A, i\%, 15)$ is 6.8109 which is slightly higher than 6.7. Since P/A gets smaller as interest rates increase, the ROI must be greater than 12%. Also, the salvage value (previously ignored) is positive and drives the present value up which means future cash flows will need to be discounted slightly more and the interest rate is going to be greater than 12%. This is about as far as qualitative judgment goes. To arrive at a precice answer, it is necessary to find the PV using interest rates of 12% and 18%, then interpolate.

$$PV_{i=12} = -\$200,000 + \$30,000\,(P/A, 12\%, 15) + \$40,000\,(P/F, 12\%, 15)$$

$$PV_{i=12} = -\$200,000 + \$30,000\,(6.8109) + \$40,000\,(0.1827) = \$11,635 > 0$$

Therefore, $ROI > 12\%$

$$PV_{i=18} = -\$200,000 + \$30,000\,(P/A, 18\%, 15) + \$40,000\,(P/F, 18\%, 15)$$

$$PV_{i=18} = -\$200,000 + \$30,000\,(5.0916) + \$40,000\,(0.0835) = -\$43,912 < 0$$

Therefore, $ROI < 18\%$
Interpolate and solve for i.

i [%]	PV [$]
12	11,635
i	0
18	−43,912

$$\frac{i-12}{18-12} = \frac{0-11,635}{-43,912-11,635} = 0.2095$$

$$i - 12 = 1.257$$

$$i = 13.3\%$$

Answer A

45.17 A $100,000 investment today pays back $10,000 in years 1 through 9 and $100,000 in year 10. What is the rate of return?

A. 7.8%

B. 8.6%

C. 9.4%

D. 10.3%

The rate of return is the interest rate that makes the present value zero. Draw a cash flow diagram or make a list of cash flows.

There is an initial outlay of $100,000 in year zero (negative).
In years 1-9 there is a return of $10,000 per year.
In year 10, there is a return of the original $100,000 principle.
Write an expressions for the present value and set it equal to zero.

$$PV = -\$100,000 + \$10,000\,(P/A, i, 9) + \$100,000\,(P/F, i, 10) = 0$$

Direct solutions are challenging when the interest rate is unknown. The fastest approach is to guess values for i in close proximity to the answer choices. It is also possible to try the answer choices by trial and error; however, since only certain integer percentages can be found in the Economic Factor Tables, this would require using the Economic Factor Conversions to derive the cash flow factors. This solution will describe the process without testing answer choices.

Assume $i = 8\%$.

$$PV = -\$100,000 + \$10,000\,(6.2469) + \$100,000\,(0.4632) = \$8,789 > 0$$

Since the present value is *greater* than zero, the interest rate must be *higher*, thereby discounting the future (positive) cash flows *more* and *reducing* the present value.

Assume $i = 10\%$.

$$PV = -\$100,000 + \$10,000\,(5.7590) + \$100,000\,(0.3855) = -\$3,860 < 0$$

Since the present value is *less* than zero, the interest rate must be *lower*, thereby discounting the future (positive) cash flows *less* and *increasing* the present value.

Looking at the answer choices, it is possible at this stage to eliminate choices A and D as they are outside the range of 8-10% which is now known to contain the interest rate that drives the present to zero. Furthermore, it is possible to infer that the interest rate will be closer to 10% than 8% since the resulting present value obtained for $i = 10\%$ was closer to zero.

If time allows, interpolate and solve for i.

i [%]	PV [\$]
8	8,789
i	0
10	−3,860

$$\frac{i-8}{10-8} = \frac{0-8,789}{-3,860-8,789} = 0.695$$

$$i - 8 = 1.39$$

$$i = 9.4\%$$

Answer C

45.18 A contractor leases a piece of equipment for \$50K down and \$30K per year for a project expected to take 3 years. After the third year, the equipment is still needed due to a schedule delay and the contractor must pay \$40K per year to continue to lease for the fourth and fifth years. After the fifth year, the project is completed and the equipment is returned. How much annual revenue is required to ensure the project has a 18% return on investment?

A. \$33K

B. \$44K

C. \$49K

D. \$56K

Draw a cash flow diagram or make a list of cash flows.

For year 0 there is a payment (negative cash flow) of -\$50K.

For years 1 through 3 there is a negative cash flow of -\$30K.

For years 4 and 5 there is a negative cash flow of -\$40K.

For years 1 through 5 there is a positive cash flow of R, the unknown revenue.

Write an expression for the present value. For convenience, overstate the costs in years 1 through 3 by showing a negative -\$40K cash flow for the entire 5 years, then offset with a *positive* cash flow of \$10K for the first 3 years only. (Annualized cash flows can only be used if they start in year 1. Otherwise years 4 and 5 would have to be dealt with as independent future payments of an additional \$10K which is equally valid but creates a bit more work.) Set the present value equal to zero and determine the revenue that will make the ROI 18%. Use the 18% Factor Table as needed.

$$PV = -\$50,000 - \$40,000\,(P/A, 18\%, 5) + \$10,000\,(P/A, 18\%, 3) + R\,(P/A, 18\%, 5) = 0$$

$$PV = -\$50,000 - \$40,000\,(3.1272) + \$10,000\,(2.1743) + R\,(3.1272) = 0$$

$$-\$50,000 - \$125,088 + \$21,743 + R\,(3.1272) = 0$$

$$R\,(3.1272) = \$153,345$$

$$R = \$49,036$$

Answer B

45.19 A company undertakes an energy saving initiative that costs \$100,000 up front and \$1000 per month for recurring service. The project will save \$30,000 per year. The equipment involved in the upgrade will have a salvage value of \$40,000 after 12 years. What is the annual savings for the project if the interest rate is 7%?

A. \$3,200

B. \$7,600

C. \$18,600

D. \$32,800

Draw a cash flow diagram or make a list of cash flows. Since the problem is asking for annual savings, this solution treats costs as negative and revenues as positive.

For year 0 there is a payment for the original purchase of -\$100K.

For years 1 through 12 there is an annualized cost of \$1K per month which equals \$12K per year and a savings of \$30K per year for a net annual savings of \$18K per year.

For year 12 there is a positive cash flow of \$40K for the salvage value.

Write an expression for the annualized savings. Only the initial cost and salvage value need to be transformed to annualized figures.

$$EUAC = \$18,000 - \$100,000\,(A/P, 7\%, 12) + \$40,000\,(A/F, 7\%, 12)$$

Since there is no Factor Table for 7%, there are two workarounds for calulating the cash flow factors needed. The first is to use the 6% and 8% tables and interpolate i.e. take the average to get the 7% cash flow factors.

$N = 12$	A/P	A/F
6%	0.1193	.0593
7%	0.1260	0.0560
8%	0.1327	0.0527

The alternative is to use the Economic Factor Conversions table to find A/F and A/P.

$$(A/P, 7\%, 12) = \frac{i\,(1+i)^n}{(1+i)^n - 1} = \frac{0.07\,(1.07)^{12}}{(1.07)^{12} - 1} = 0.1259$$

$$(A/F, 7\%, 12) = \frac{i}{(1+i)^n - 1} = \frac{0.07}{(1.07)^{12} - 1} = 0.0559$$

Determine the annual savings.

$$EUAC = \$18,000 - \$100,000\,(0.1259) + \$40,000\,(0.0559) = \$7646$$

Answer B

45.20 A company invests \$100K to make a product which will generate \$25K of annual revenue over the next 12 years. Expenses will be \$5,000 per year. The manufactured product is depreciated over the 12 years using straight-line depreciation. There is no salvage value as all the product is expected to be sold. The income tax rate is 35%. What is the after-tax rate of return?

A. −0.5%

B. 5.9%

C. 11.7%

D. 18.3%

Draw a cash flow diagram or make a list of cash flows.

In Year 0, there is an initial payment of \$100K (negative).

In Years 1-12, there is a net profit before tax of $\$25K - \$5K = \$20K$. To calculate the tax, it is necessary to consider the depreciation. Depreciation is not an actual cash flow; rather, it is applied as a deduction from the profits, thereby lowering the taxable income for that year. Depreciation is like a fictitious expense which provides tax benefits of offsetting income without actually spending in that year. Straight line deperciation is calculated using the formula below, where C is the initial cost, S_n is the salvage value (if applicable), and n is the number of years.

$$D_j = \frac{C - S_n}{n} = \frac{\$100,000 - \$0}{12} = \$8333$$

Determine the tax basis (i.e. taxable income).

$$Tax\,basis = \$20,000 - \$8333 = \$11,667$$

Apply the tax rate to calculate the tax.

$$Tax = (0.35)(\$11,667) = \$4083$$

Since tax is an acutal expense, subtract the tax from the net profit before tax to obtain the net profit after tax. This figure summarizes the annualized cash flows for years 1 through 12.

$$Net\,profit\,after\,tax = \$20,000 - \$4083 = \$15,917$$

Write an expression for the present value. The after-tax rate of return is the interest rate that makes the present value equal zero. Solve for cash flow factor $(P/A, i, 12)$.

$$PV = -\$100,000 + \$15,917\,(P/A, i, 12) = 0$$

$$(P/A, i, 12) = 6.2827$$

Review the Economic Factor Tables and note that the cash flow factor P/A with a duration of 12 years decreases as the interest rate increases, because future cash flows are discounted more as the interest rate increases. At an interest rate $i = 10$, $(P/A, 10, 12) = 6.8137$. At an interest rate $i = 12$, $(P/A, 12, 12) = 6.1944$. The interest rate must be within the range if $10 - 12\%$, which is sufficient information to select a final answer based on the choices. If time permits, make a table and interpolate to drill down on the answer.

$i[\%]$	$(P/A, i, 12)$
10	6.8137
i	6.2827
12	6.1944

$$\frac{i - 10}{12 - 10} = \frac{6.2827 - 6.8137}{6.1944 - 6.8137}$$

$$i - 10 = 1.71$$

$$i = 11.7\%$$

Answer C

45.21 A new piece of equipment costs \$100,000 and increases revenue by \$15,000 per year for the next 6 years, and by \$20,000 per year (from the original baseline) for the following 6 years. Assuming no maintenance costs and no salvage value, what is the present value of investing in this equipment if the effective annual interest rate is 6%?

A. \$43,000

B. \$56,000

C. \$145,000

D. \$195,000

Draw a cash flow diagram or make a list of cash flows.

In year zero, there is an initial cost of \$100,000 (negative).

In years 1 through 6, there is an annual revenue of \$15,000.

In years 7-12, there is an annual revenue of \$20,000.

Rather than handle the (6) additional \$5,000 cash flows in years 7-12 as individual future cash flows, it is faster to assume and annual revenue of \$20,000 for the entire 12 years, then compensate for overstating the revenue in years 1-6 by *subtracting* \$5,000 per year over 6 years from the outset. This can be handled as an annualized cash flow over 6 years.

The present value can be determined with the following expression.

$$PV = -\$100,000 + (\$20,000)\,(P/A, 6\%, 12) - (\$5,000)\,(P/A, 6\%, 6)$$

Use the 6% Factor Table to look up the cash flow factors needed to translate the cash flows into present value. Solve for the present value.

$$PV = -\$100,000 + (\$20,000)\,(8.3838) - (\$5,000)\,(4.9173) = \$43,090$$

Answer A

45.22 A piece of equipment is purchased for \$20K and will be sold 5 years later for \$5K. The first year maintenance costs \$2500, then increases by \$500 per year. The effective interest rate is 8%. What is the present worth?

A. $-\$30K$

B. $-\$23K$

C. $-\$10K$

D. $-\$3K$

Draw a cash flow diagram or make a list of cash flows.

In Year 0, there is an initial payment of \$20K (negative).

In Years 1-5, there is an annual maintenance cost of \$2500 (negative) which escalates by an additional \$500 per year. This can be treated as a uniform series of payments *plus* a uniform gradient.

In Year 5, there is a \$5K future cash payment (positive) for the salvage value.

Write an expression for the present value. Use the $i = 8\%$ Factor Table to retreive the cash flow factors.

$$PV = -\$20,000 - \$2500\,(P/A, 8\%, 5) - \$500\,(P/G, 8\%, 5) + \$5000\,(P/F, 8\%, 5)$$

$$PV = -\$20,000 - \$2500\,(3.9927) - \$500\,(7.3724) + \$5000\,(0.6806) = -\$30,264$$

Answer A

45.23 What is the partial pressure of water in atmostpheric air at $120°F$ and 70% RH?

A. $0.3psi$

B. $0.8psi$

C. $1.2psi$

D. $1.7psi$

There are 3 alternative approaches to this problem.

Approach #1: Search for Properties of Saturated Water by temperature and find $120°F$ in the steam table. The saturation pressure at $120°F$ is:

$$p_{ws@120°F} = 1.7psia$$

Since the relative humidity is 70%, the partial pressure of water vapor in the air is only 70% of the saturation pressure. Recall that saturation pressure is the maximum possible pressure water vapor can have in air at a given temperature. Apply the definition of relative humidity to find the partial pressure of water.

$$\phi = \frac{p_w}{p_{ws}}$$

$$p_w = p_{sat}\phi = (1.7psia)(.7) = 1.19psia$$

Approach #2: This method involves looking up the dew point temperature on the Psychrometric Chart for High Temperature air. Recall that the dew point is the temperature at which the air would be saturated if it were sensibly cooled until reaching the saturation curve.

$$T_{dp} \approx 107°F$$

Return to the steam table and look up the saturation pressure at the dew point temperature. By definition, the partial pressure of water vapor in moist air is the saturation pressure at the dew point temperature.

$$p_w = p_{ws@T_{dp}} = 1.17psia$$

Approach #3: This method involves looking up the humidity ratio on the Psychrometric Chart for High Temperature air.

$$\omega \approx .055\frac{lb_{H2O}}{lb_{da}}$$

Since the humidity ratio is a ratio of the mass of water vapor to the mass of dry air, it is possible to work out the mole fraction of water vapor in the air. There are $0.055lb_{H2O}$ for every $1lb_{da}$. Find the corresponding number of moles for water and dry air using the molecular weights. Refer to the periodic table as needed. Rounding is permissible.

$$MW_{H20} = (2)(1) + (16) = 18\frac{lb}{mol}$$

$$MW_{da} = (2)(14)(.79) + (2)(16)(.21) \approx 29\frac{lb}{mol}$$

Determing the number of moles of water vapor and dry air.

$$N_{H2O} = \frac{0.055lb}{18\frac{lb}{mol}} = 0.00305mol$$

$$N_{da} = \frac{1lb}{29\frac{lb}{mol}} = 0.03448mol$$

Find the mole fraction of water vapor.

$$x_{H2O} = \frac{N_{H2O}}{N_{H2O} + N_{da}} = \frac{0.00305mol}{0.00305mol + 0.03448mol} = .081$$

The ratio of the partial pressure of water vapor to the total pressure is the same as the ratio of the number of moles of water vapor to the total number of moles i.e. the mole fraction. (Note: This holds true for any mixture of gases. The contribution of any one gas in the mixture to the total pressure - its partial pressure - is equal to its mole fraction!)

$$\frac{p_w}{p_t} = x_{H2O}$$

$$p_w = (x_{H2O})(p_t) = (.081)(14.7psia) = 1.19psia$$

Answer C

45.24 A $2500ft^2$ conference center with $14ft$ ceilings is maintained at $72°F$ and 50% relative humidity. What is the total mass of water vapor in the air?

A. $15lb$

B. $22lb$

C. $140lb$

D. $290lb$

Find the total volume of the room by multiplying the area and the height.

$$V = \left(2500ft^2\right)(14ft) = 35,000ft^3$$

Find the humidity ratio and specific volume for the room conditions using the Psychrometric Chart.

$$T = 72°F$$

$$\phi = 50\%$$

$$\omega = 0.0084 \frac{lb_w}{lb_{da}}$$

$$v = 13.6 \frac{ft^3}{lb_{da}}$$

Recall the definition of the humidity ratio as described under Psychrometric Properties. Rearrange to solve for the mass of water.

$$\omega = \frac{m_w}{m_{da}}$$

$$m_w = (m_{da})(\omega)$$

The mass of air can be expressed as density times volume, or volume over specific volume.

$$m_{da} = \rho V = \frac{V}{v} = \frac{35,000 ft^3}{13.6 \frac{ft^3}{lb_{da}}} = 2574 lb_{da}$$

Determine the mass of water.

$$m_w = (m_{da})(\omega) = (2574 lb_{da}) \left(0.0084 \frac{lb_w}{lb_{da}}\right) = 21.6 lb_w$$

Answer B

45.25 Condenser water returns to a cooling tower at $95°F$ and leaves at $85°F$. The outside conditions are $84°F$ and 60% relative humidity. What is the cooling tower effectiveness?

A. 9%

B. 46%

C. 54%

D. 91%

To find the Cooling Tower effectiveness, start by using the Psychrometric Chart to determine the wet bulb temperature of the outdoor conditions.

$$T_{db} = 84°F$$

$$\phi = 60\%$$

$$T_{wb} = 73.1°F$$

Cooling tower effectiveness is defined by the equation below where range and approach are defined in terms of the entering and leaving water temperatures and the wet bulb temperature as shown.

$$\varepsilon = \frac{range}{range + approach}$$

$$range = EWT - LWT$$

$$approach = LWT - T_{wb}$$

$$\varepsilon = \frac{EWT - LWT}{(EWT - LWT) + (LWT - T_{wb})} = \frac{EWT - LWT}{EWT - T_{wb}} = \frac{95°F - 85°F}{95°F - 73.1°F} = 45.7\%$$

Answer B

45.26 A cooling tower has a range of $15°F$ and a volume flow rate of $50gpm$. Air enters at $88°F$ dry bulb and $75°F$ wet bulb and exits at $92°F$ and 75% relative humidity. Assuming no losses, what is the required volume flow rate of air?

A. $3,300cfm$

B. $7,700cfm$

C. $8,200cfm$

D. $10,900cfm$

The heat rejected by the condenser water is absorbed into the air. Use the sensible heat rule of thumb for water to determine the quantity of heat removed from the condenser water.

$$\dot{Q}_{cw} = \dot{Q}_{air}$$

$$\dot{Q}_{cw} = 500GPM\Delta T = (500)(50)(15) = 375,000\frac{Btu}{hr}$$

$$\dot{Q}_{air} = \dot{m}\Delta h = 375,000\frac{Btu}{hr}$$

Use the Psychrometric Chart to determine the enthalpy for the entering and leaving air as well as the specific volume for the entering air. Let State 1 represent the entering condition and State 2 represent the leaving condition.

$$T_{1,db} = 88°F$$

$$T_{1,wb} = 75°F$$

$$h_1 = 38.47\frac{Btu}{lb}$$

$$v_1 = 14.2\frac{ft^3}{lb_{da}}$$

$$T_2 = 92°F$$

$$\phi_2 = 75\%$$

$$h_2 = 49.23\frac{Btu}{lb}$$

Solve for the mass flow rate of air using the enthalpy values.

$$\dot{m} = \frac{\dot{Q}}{\Delta h} = \frac{\dot{Q}}{h_2 = h_1} = \frac{375,000\frac{Btu}{hr}}{49.23\frac{Btu}{lb} - 38.47\frac{Btu}{lb}} = 34,851\frac{lb}{hr}$$

Use the specific volume for State 1 to determine the volume flow rate in cfm.

$$\dot{V} = \dot{m}v_1 = \left(34,851\frac{lb}{hr}\right)\left(\frac{1hr}{60min}\right)\left(14.2\frac{ft^3}{lb}\right) = 8,248cfm$$

Answer C

45.27 What is the relative humidity of moist air at $6000ft$ above sea level with a dry bulb temperature of $70°F$ and a partial pressure of dry air of $11.5psia$?

A. 48%

B. 58%

C. 68%

D. 78%

Use the table Altitude Correction for Air to find the Density Factor at $6,000ft$ of elevation, and use it to determine the total pressure of moist air at that altitude.

$$DF = 0.801$$

$$p_t = (14.7psia)(0.801) = 11.78psia$$

The pressure of moist air is the sum of the pressure of partial pressure of water vapor in the air and the partial pressure of dry air. Since the partial pressure of dry air is given, subtract to find the partial pressure of water vapor.

$$p_w = p_t - p_{da} = 11.78psia - 11.5psia = 0.28psia$$

Use the steam table by searching Properties of Saturated Water organized by temperature and look up the saturation pressure at $70°F$. The saturation pressure is the maximum pressure water vapor can have at a given temperature.

$$p_{ws@70°F} = 0.36psia$$

Apply the definition of relative humidity, which is the actual partial pressure of water as compared to the saturatin pressure at that temperature.

$$\phi = \frac{p_w}{p_{ws}} = \frac{0.28psia}{0.36psia} = 78\%$$

Answer D

46 Practice Exam #1

46.1 A fan supplies air through a $12in$ by $18in$ rectangular sheet metal duct with $1in$ fiberglass insulation. The duct run is $15ft$ long. Local octave band measurements of the sound power level for the fan are $125Hz$, $95dB$; $250Hz$, $94dB$; $500Hz$, $92dB$; $1000Hz$, $90dB$; $2000Hz$, $85dB$; $4000Hz$, $69dB$. What is the expected sound power level for the $1000Hz$ octave band at the end of the duct run?

A. $35dB$

B. $52dB$

C. $69dB$

D. $86dB$

Refer to the table Insertion Loss for Rectangular Sheet Metal Ducts with 1 in. Fiberglass Lining. Look up dimensions $12in$ by $18in$ and note the insertion loss for the $1000Hz$ octave band is $3.7\frac{dB}{ft}$. Multiply the loss per foot times the length of the duct to obtain the total dB reduction.

$$\left(3.7\frac{dB}{ft}\right)(15ft) = 55.5dB$$

Subtract the dB reduction from the measured sound power level for the $1000Hz$ octave band to obtain the final sound power level with the indulated duct inserted.

$$90dB - 55.5dB = 34.5dB$$

Answer A

46.2 A normal shock wave in air has a Mach number of 3. The pressure upstream is $1atm$, what is the pressure downsteam?

A. 2 psi

B. 10 psi

C. 60 psi

D. 150 psi

There are two possible approaches for this problem, the first using the Normal Shock Relationships table and the second using equations relating downstream flow conditions to upstream flow conditions for a normal shock wave. In both cases, the subscript 1 is used to represent the upstream conditions and the subscript 2 is used to represent the downstream conditions.

Using the table, for $M_1 = 3$, find the corresponding pressure ratio.

$$\frac{P_2}{P_1} = 10.3333$$

Since the upstream pressure is known, substitute for P_1 and convert from atm to psi.

$$P_2 = 10.3333\,(P_1) = 10.3333\,(1atm)\left(\frac{14.7psi}{atm}\right) = 152psi$$

Alternatively, since the table values have been generated for convenience, it is also valid to use the underlying formulas to solve for the pressure ratio. The ratio of specific heats, k, is assumed to be 1.4.

$$\frac{P_2}{P_1} = \left(\frac{1}{k+1}\right)\left[2kM_1^2 - (k-1)\right]$$

$$\frac{P_2}{P_1} = \left(\frac{1}{1.4+1}\right)\left[2\,(1.4)\,(3)^{\,2} - (1.4-1)\right] = 10.3333$$

The rest of the solution follows from the first approach.
Answer D

46.3 A company purchases a factory for $1M with a salvage value of $300K in 15 years. Operations and maintenance costs are $40K/year. At an interest rate of 8%, what is the equivalent uniform annual cost of the factory over the next 15 years?

A. $70K

B. $90K

C. $150K

D. $170K

Draw a cash flow diagram or make a list of cash flows. Since the problem is asking for EUAC, this solution treats costs as positive.

For year 0 there is a payment for the original purchase of $1M.

For years 1 through 15 there is an annualized payment for operation and maintenance of $40K per year.

For year 15 there is a positive cash flow of $300K for the salvage value which partially offsets the costs.

Since the O&M cost in years 1 through 15 is already annualized, there is no need for further manipulation.

The initial cost and the salvage value need to be transformed into annualized cash flows and added to the O&M. Use the Factor Table for 8% to look up the required cash flow factors. Solve for the EUAC.

$$EUAC = \$40,000 + \$1,000,000\,(A/P, 8\%, 15) - \$300,000\,(A/F, 8\%, 15)$$

$$EUAC = \$40,000 + \$116,800 - 11,040 = \$145,760$$

Answer C

46.4 A commercial tenant entering into a 17 year lease has the option to make a down payment to lower the monthly rent. Assuming a 6% interest rate, which option has the best present value?

A. \$0 down, \$12,500/month

B. \$250K down, \$10,000/month

C. \$500K down, \$8,000/month

D. \$1M down, \$5,000/month

Find the present value for each option. The the $i = 6\%$ Factor Table to find P/A. The minimum present value is the best choice.

$$PV_1 = (12)\,(\$12,500)\,(P/A, 6\%, 17)$$

$$PV_1 = (12)\,(\$12,500)\,(10.4773) = \$1,571,595$$

$$PV_2 = \$250,000 + (12)\,(\$10,000)\,(P/A, 6\%, 17)$$

$$PV_2 = \$250,000 + (12)\,(\$10,000)\,(10.4773) = \$1,507,276$$

$$PV_3 = \$500,000 + (12)\,(\$8,000)\,(P/A, 6\%, 17)$$

$$PV_3 = \$500,000 + (12)\,(\$8,000)\,(10.4773) = \$1,505,821$$

$$PV_4 = \$1,000,000 + (12)\,(\$5,000)\,(P/A, 6\%, 17)$$

$$PV_4 = \$1,000,000 + (12)\,(\$5,000)\,(10.4773) = \$1,628,638$$

Answer C

46.5 A group of machines are maintained under a contract which costs $50,000 this year. The contract cost will inrease by $1000 per year over the next 10 years. What is the present value of the entire 10 years of maintenance using an effctive annual interest rate of 12%.

A. $303,000

B. $336,000

C. $352,000

D. $370,000

The present value can be represented as the sum of two cash flows: a recurring annual cost of $50,000 and a uniform gradient of $1,000. The gradient has a value of zero in the first year, such that the first year cost is $50,000, second year is $51,000, third year is $52,000, etc. There is no initial cost reflected in year 0 as it is customary in engineering economics to reflect costs that occur throughout the year at the end of the year.

Write an expression for the present value.

$$PV = A\left(P/A, 12\%, 10\right) + G\left(P/G, 12\%, 10\right)$$

Use the 12% Factor Table to look up the cash flow factors needed to translate the cash flows into present value. Solve for the present value.

$$PV = (\$50,000)\left(5.6502\right) + (\$1,000)\left(20.2541\right) = \$302,764$$

Answer A

46.6 A pump delivers 200 GPM of water at 130 feet of total dynamic head, operating from 7am-7pm Monday through Friday. The pump is 80% efficient and the motor is 93% efficient. What is the annual cost of operation at $0.13 per kWh?

A. $2670

B. $3490

C. $3750

D. $5030

The cost is a function of electrical power and time, and electrical power is a function of hydraulic horsepower (aka water horsepower i.e. whp) and efficiency. Start by calculating the water horsepower based on volume flow rate and feet of head provided by the pump:

$$whp = \frac{Q\Delta h}{3960} = \frac{(200)\,(130)}{3960} = 6.566hp$$

Note the volume and head units must be in GPM and ft, respectively, to use this "rule of thumb" equation. Therefore units need not be shown, provided they are confirmed to be correct prior to use.

Recall that brake horsepower, bhp, depends on water horsepower, whp, and the efficiency of the pump, η_p. Similarly, the electrical power, $\dot{W}$,depends on brake horsepower, bhp, and motor efficiency, η_m.

$$bhp = \frac{whp}{\eta_p}$$

$$\dot{W} = \frac{bhp}{\eta_m}$$

Put these together, substitute, solve, and convert to KW:

$$\dot{W} = \frac{whp}{\eta_p \eta_m} = \frac{6.566hp}{(.8)(.93)} \left(\frac{.746KW}{1hp}\right) = 6.58KW$$

To find the annual cost, multiply by time and the unit rate of electricity:

$$Cost = (6.58KW) \left(\frac{12hrs}{day}\right) \left(\frac{5days}{wk}\right) \left(\frac{52wks}{yr}\right) \left(\frac{\$0.13}{KWH}\right) = \$2669\, per\, year$$

Answer A

46.7 A $7.5hp$ single phase $230V$ motor drawing $40A$ at full load is located $50\, meters$ from the voltage source. The motor is wired with $8AWG$ wire which has a cross sectional area of $16,509\, circular\, mils$ ($1\, circular\, mil = 5.066 \times 10^{-10} m^2$) and a resistivity of $1.724 \times 10^{-8} \Omega \cdot m$. What is the percent voltage drop for the wiring in the circuit?

A. 1%

B. 2%

C. 3%

D. 4%

The electrical resistance attributable to the wiring is the result of copper's resistivity, which is an intrinsic material property, and the length and gauge of the wire. The formula for resistivity can be rearranged to solve for the total resistance.

$$\rho = \frac{RA}{L}$$

$$R = \frac{\rho L}{A}$$

Since the motor is $50ft$ from the voltage source, a sufficient length of wire must be provided to make a round trip from the source to the load and back. Therefore, the total length is given by:

$$L = 2(50m) = 100m$$

Determine the resistance.

$$R = \frac{\rho L}{A} = \frac{\left(1.724 \times 10^{-8}\Omega \cdot m\right)(100m)}{(16,509cmil)\left(5.066 \times 10^{-10}\frac{m^2}{cmil}\right)} = 0.206\Omega$$

Find the voltage drop due to the wire by applying Ohm's Law.

$$V_{drop} = IR = (40A)(0.206\Omega) = 8.25V$$

Determine the percentage voltage drop by dividing by the nominal voltage of the source.

$$\frac{V_{drop}}{V_{source}} = \frac{8.25V}{230V} = 0.036 = 3.6\%$$

Answer D

46.8 $1000cfm$ of $350°F$, $80psia$ air is supplied by an air compressor. What is the standard volume flow rate (SCFM)?

A. $100cfm$

B. $300cfm$

C. $3500cfm$

D. $8500cfm$

Since the air being supplied is at an elevated temperature and pressure, it is necessary to make Temperature and Altitude Corrections for Air. This can be achieved using the factors in the table; however, the pressure is given in psia rather than as an elevation, therefore it is more straightforward to multiply by the ratio of the pressure as compared to standard atmosphereic pressure. Similarly, a temperature ratio multiplier is also convenient to use, provided absolute temperature units are used. Standard temperature and pressure may be considered $60°F$ and $14.7psia$.

In terms of qualitative expectations, a higher than standard pressure implies the standard CFM (SCFM) will be higher than the actual CFM. A higher than standard temperature implies the standard CFM will be lower than the actual CFM. In concept, SCFM is attempt to explain how much volume the compressor would move if pumping air at STP.

$$SCFM = (1000cfm)\left(\frac{80psia}{14.7psia}\right)\left(\frac{60°F + 460°R}{350°F + 460°R}\right) = 3,493cfm$$

Answer C

46.9 **$40gpm$ of water flows through a parallel piping network with two branches, A and B. Branch A consists of $100ft$ of straight Schedule 40 $2in$ steel pipe. Branch B consists of $60ft$ of Schedule 40 $2in$ steel pipe, several valves with a total equivalent length of $35ft$, and six 90-degree elbows. What is the flow rate through branch A?**

A. $19gpm$

B. $21gpm$

C. $23gpm$

D. $25gpm$

Sketch the piping network. Since there are two branches in parallel, the head loss through each branch must be equal. Write the Darcy equation for both sides and set them equal.

$$h_{f,A} = h_{f,B}$$

$$\frac{fL_A v_A^2}{2D_A g} = \frac{fL_B v_B^2}{2D_B g}$$

Assume the friction factor is approximately the same for both branches and will cancel out, along with the constants, 2 and g. Also, $D_A = D_B$,so the diameters will cancel out.

$$L_A v_A^2 = L_B v_B^2$$

Rearrange the relation to express the ratio of the velocities through the two branches as a function of the equivalent lenghts of the branches.

$$\frac{v_B}{v_A} = \sqrt{\frac{L_A}{L_B}}$$

Recognize from the Continuity Equation, $Q = Av$, since the diameters are the same, the areas of the two branches are also the same, therefore the ratio of the velocities is equal to the ratio of the volume flow rates.

$$Q_A = A_A v_A \rightarrow v_A = \frac{Q_A}{A_A}$$

$$Q_B = A_B v_B \rightarrow v_B = \frac{Q_B}{A_B}$$

$$A_A = A_B$$

$$\frac{v_B}{v_A} = \frac{\left(\frac{Q_B}{A_B}\right)}{\left(\frac{Q_A}{A_A}\right)} = \frac{Q_B}{Q_A} = \sqrt{\frac{L_A}{L_B}}$$

The total volume flow rate is the sum of both branches and is given as $40gpm$.

$$Q_A + Q_B = 40gpm$$

If both equivalent lengths, L_A and L_B, were known, it would be possible to solve the system of two equations with two unknowns, Q_A and Q_B, to specify Q_B. However, only L_A is known. $L_A = 100ft$. The length of branch B is a function of the linear footage, the equivalent length of valves, and the eqivalent length of elbows. The latter two are known, however the equivalent length of the elbows is a function of both the diameter and the velocity. Since the velocity is unknown, there is a circular dependency making a direct solution impossible.

As a workaround, refer to the table Equivalent Lengths for Elbows and note that for a typical range of velocities, for instance $2 - 5fps$, the equivalent length per elbow for a $2in$ diameter ranges from $5.1 - 5.9ft$. Since this will only make up about a quarter of the total length of branch B regardless of where in that range, it is reasonable to guess the volume flow rate through branch B, find the corresponding velocity through branch B and the equivalent length of the elbows, and then use the system of equations to confirm the guess, or recalibrate and perform a second iteration.

Looking at the answer choices, it is clear that more than half of the flow is going to flow through branch A because branch B has a greater total equivalent length (i.e. more resistance, even if the velocity through branch B is fairly low this remains true.) For convenience, select a volume flow of $22gpm$ for branch A which is intentionally in between choices B and C, and available in the Steel Pipe Friction Tables to save time calculating the velocity.

$$Q_A = 22gpm$$

$$Q_B = 40gpm - 22gpm = 18gpm$$

$$v_B = 1.72fps$$

$$L_{elbow} \approx 5ft$$

$$L_B = 60ft + 35ft + (6)(5ft) = 125ft$$

$$\frac{Q_B}{Q_A} = \sqrt{\frac{L_A}{L_B}} = \sqrt{\frac{100ft}{125ft}} = 0.8944$$

$$\frac{Q_B}{Q_A} = \frac{18gpm}{22gpm} = 0.8182$$

To close the gap between the ratio $\frac{Q_B}{Q_A}$ computed using both methods, it would be necessary to try a larger value for Q_B and therefore a smaller value for Q_A. Since only one answer choice is smaller, select $Q_A = 21gpm$.

If time allows, perform a second iteration for full reassurance.

$$Q_A = 21gpm$$

$$Q_B = 40gpm - 21gpm = 19gpm$$

$$v_B \approx 1.8fps$$

$$L_{elbow} \approx 5ft$$

$$L_B = 60ft + 35ft + (6)(5ft) = 125ft$$

$$\frac{Q_B}{Q_A} = \sqrt{\frac{L_A}{L_B}} = \sqrt{\frac{100ft}{125ft}} = 0.8944$$

$$\frac{Q_B}{Q_A} = \frac{19gpm}{21gpm} = 0.9048$$

These ratios are within about 1%, therefore no further iteration is required.
Answer B

46.10 What is the maximum COP of a Carnot refrigerator operating between $40°F$ and $95°F$?

A. 0.7

B. 1.7

C. 9.1

D. 10.1

The maximum Coefficient of Performance, or COP, for any heat engine, including all heat pumps and refrigerators, is the Carnot cycle. Select the formula for Carnot COP for a refrigerator. The numerator should be the temperature of the *cold* reservoir. Remember to use absolute temperature units i.e. degrees Rankine.

$$T_L = 40°F + 460 = 500°R$$

$$T_H = 95°F + 460 = 555°R$$

$$COP_c = \frac{T_L}{T_H - T_L} = \frac{500°R}{555°R - 500°R} = 9.1$$

Answer C

46.11 **$10,000 cfm$ of air enters a cooling coil at $78°F$ and 60% relative humidity and exits at $58°F$ db / $54°F$ wb. At what rate is condensate removed?**

A. $0.5 \frac{gal}{hr}$

B. $6 \frac{gal}{hr}$

C. $23 \frac{gal}{hr}$

D. $190 \frac{gal}{hr}$

Consider the air entering the coil as State 1 and the air leaving the coil as State 2. Both states are fully defined. Use the Psychrometric Chart to look up the humidity ratio for both states. Also obtain the specific volume for the entering air condition.

$$T_{1,db} = 78°F$$

$$\phi_1 = 60\%$$

$$\omega_1 = 0.01235 \frac{lb_w}{lb_{da}}$$

$$v_1 = 13.88 \frac{ft^3}{lb_{da}}$$

$$T_{2,db} = 58°F$$

$$T_{2,wb} = 54°F$$

$$\omega_2 = 0.00798 \frac{lb_w}{lb_{da}}$$

Use the formula under Moist-Air Cooling and Dehumidification to quantify the mass flow rate of water vapor being condensed from the air stream as it flows through the cooling coil.

$$\dot{m}_w = \dot{m}_a (\omega_1 - \omega_2)$$

Express the mass flow rate of air entering the coil as the product of the density and volume flow rate. Substitute for density using $\rho_1 = \frac{1}{v_1}$.

$$\dot{m}_a = \rho Q = \frac{Q}{v_1} = \frac{10,000 \frac{ft^3}{min}}{13.88 \frac{ft^3}{lb_{da}}} = 720.46 \frac{lb_{da}}{min}$$

Substitute and solve for the mass flow rate of condensate removed. Convert *minutes* to *hours* and lb_w to gal.

$$\dot{m}_w = \left(720.46 \frac{lb_{da}}{min}\right)\left(\frac{60min}{1hr}\right)\left(0.01235 \frac{lb_w}{lb_{da}} - 0.00798 \frac{lb_w}{lb_{da}}\right)\left(\frac{1gal}{8.34 lb_w}\right) = 22.65 \frac{gal}{hr}$$

Answer C

46.12 **$55°F$ chilled water at $150psig$ enters a $10ton$ cooling coil and leaves at $65°F$ and $135psig$ after passing through the coil and the control valve located on the return side. Under these conditions, the cooling coil control valve is backed off by 50% and the coil is providing half of its rated capacity . The pressure drop through the coil is $10ft$ of water. What is the required control valve flow coefficient?**

A. 1.1

B. 2.4

C. 3.7

D. 5.4

The total pressure drop is the sum of the pressure drop through the coil and the pressure drop through the valve. Solve for the pressure drop through valve only. Use the conversion factor rule of thumb for water to align units to *psi*.

$$\Delta P_{total} = \Delta P_{coil} + \Delta P_{valve}$$

$$\Delta P_{valve} = \Delta P_{total} - \Delta P_{coil} = 15psi - (10ft)\left(\frac{1psi}{2.31ft}\right) = 10.67psi$$

Use the formula under Valve Flow Coefficient which depends on the volume flow rate and pressure drop.

$$C_v = \frac{Q}{\sqrt{\Delta P}}$$

Use the sensible cooling rule of thumb for water to determine the volume flow rate. Since the coil is operating at half its rated capacity, use $5tons$ rather than $10tons$. Provided $\dot{Q}$ is in $\frac{Btu}{hr}$ and the temperature range is in $°F$, the volume flow rate will be in gpm as required and units need not be written.

$$\dot{Q} = 500gpm\Delta T$$

$$gpm = \frac{\dot{Q}}{500 \cdot \Delta T} = \frac{5\,(12,000)}{500\,(65-55)} = 12gpm$$

Solve for the valve flow coefficient, C_v. The volume flow rate must be in gpm and the pressure drop must be in psi. C_v is unitless.

$$C_v = \frac{12}{\sqrt{10.67}} = 3.67$$

Answer C

46.13 $2000cfm$ **of** $55°F$ **conditioned air with 40% relative humidity enters a kitchen where it collects heat and moisture before being extracted as** $80°F$ **air with 70% relative humidity. What is the rate of moisture removal from the kitchen?**

A. $1.8\frac{lb_m}{min}$

B. $2.4\frac{lb_m}{min}$

C. $2.8\frac{lb_m}{min}$

D. $3.4\frac{lb_m}{min}$

Let state 1 be the entering air conditions and state 2 be the leaving air conditions. Use the Psychrometric Chart to find the humidity ratio for both states. Note the specific volume for the entering air condition.

$$T_1 = 55°F$$

$$\phi_1 = 40\%$$

$$\omega_1 = 0.0037\frac{lb_{h2o}}{lb_{da}}$$

$$v_1 = 13.1\frac{ft^3}{lb_{da}}$$

$$T_2 = 80°F$$

$$\phi_2 = 70\%$$

$$\omega_2 = 0.0155\frac{lb_{h2o}}{lb_{da}}$$

Although this problem is about adding moisture to air, the formula found by searching Moist-Air Cooling and Dehumidification can be used with the expectation that the humidity ratio for the leaving air at state 2 will be greater than that of the entering air at state 1. It is valid to interchange ω_2 and ω_1 to reflect this understanding.

$$\dot{m}_w = \dot{m}_{da}\left(\omega_2 - \omega_1\right)$$

The mass flow rate of dry air entering at state 1 can be expressed as volume flow rate times density or volume flow rate divided by specific volume.

$$\dot{m}_{da} = \rho Q = \frac{Q}{v_1} = \frac{2000\frac{ft^3}{min}}{13.1\frac{ft^3}{lb_{da}}} = 152.7\frac{lb_{da}}{min}$$

Determine the mass flow rate of water being added to the air.

$$\dot{m}_w = \left(152.7\frac{lb_{da}}{min}\right)\left(0.0155\frac{lb_{h2o}}{lb_{da}} - 0.0037\frac{lb_{h2o}}{lb_{da}}\right) = 1.8\frac{lb_m}{min}$$

Answer A

46.14 Water traveling at $2fps$ in a nominal $5in$ pipe is combined with water traveling at $5fps$ in a nominal $3in$ pipe at a tee connection. Downstream of the tee, the piping has a nominal $6in$ diameter. What is the velocity downstream of the tee?

A. $1.3fps$

B. $1.9fps$

C. $2.7fps$

D. $3.9fps$

Sketch and label the tee connection with the given information. Designate the entering flows as 1 & 2 and the exiting flow as 3. The volume flow rate exiting the tee is equal to the sum of the volume flow rates entering the tee.

$$Q_1 + Q_2 = Q_3$$

Apply the Continuity Equation and replace the volume flow rates with the products of their respective velocities and areas.

$$Q = Av$$

$$A_1v_1 + A_2v_2 = A_3v_3$$

Solve for the the velocity downstream of the tee, v_3.

$$v_3 = \frac{A_1v_1 + A_2v_2}{A_3}$$

Express area as a function of internal diameter for each connection to the tee and substitute accordingly, cancelling the $\frac{\pi}{4}$ which is common to all terms.

$$A = \frac{\pi}{4}D^2$$

$$v_3 = \frac{\frac{\pi}{4}D_1^2v_1 + \frac{\pi}{4}D_2^2v_2}{\frac{\pi}{4}D_3^2} = \frac{D_1^2v_1 + D_2^2v_2}{D_3^2}$$

Gather inside diameter values from the table by searching Schedule 40 Steel Pipe. Substitute and solve for the velocity, v_3.

$$v_3 = \frac{(5.047in)^2\left(2\frac{ft}{s}\right) + (3.068in)^2\left(5\frac{ft}{s}\right)}{(6.065in)^2} = 2.66\frac{ft}{s}$$

Answer C

46.15 A $100lb_m$ mass rests on 4 springs, each with a spring constant of $15\frac{lb_f}{in}$. The mass is initially displaced from its equilibrium position, then released. What is the resulting period of oscillation?

A. $0.03s$

B. $0.1s$

C. $0.4s$

D. $2.3s$

Refer to the section on Free Vibration. Recognize that the spring constant for springs in parallel add linearly, therefore the total spring constant for the system can be determined as follows.

$$k_{total} = 4\left(k_{spring}\right) = (4)\left(15\frac{lb_f}{in}\right) = 60\frac{lb_f}{in}$$

Find the natural frequency, which is a function of the total spring contant and the mass. The relevant formula may be found by searching undamped natural circular frequency. Note g_c must be included to change lb_m to lb_f for consistency of units. This is not given in the reference handbook and must be inferred by the inconsistency of the units if not addressed. Also note the appearance of radians in the result for this application. Be assured this is valid and expected with analysis of vibrating sytems.

$$\omega_n = \sqrt{\frac{kg_c}{m}} = \sqrt{\frac{\left(60\frac{lb_f}{in}\right)\left(32.2\frac{lb_m \cdot ft}{lb_f \cdot s^2}\right)\left(\frac{12in}{ft}\right)}{100lb_m}} = 15.2\frac{rad}{s}$$

Find the period. The relevant formula may be found by searching undamped natural period of vibration.

$$\tau_n = \frac{2\pi}{\omega_n} = \frac{2\pi\, rad}{15.2\frac{rad}{s}} = 0.4s$$

Answer C

46.16 Methane is burned with 20% excess air. What is the air-to-fuel ratio?

A. $14\frac{lb}{lb}$

B. $17\frac{lb}{lb}$

C. $21\frac{lb}{lb}$

D. $24\frac{lb}{lb}$

Look up the table Combustion Reactions of Common Fuel Constituents and find the combustion reaction for methane burned stoichiometrically in air. Include 3.76 nitrogen molecules for every 1 oxygen molecule since nitrogen has been omitted in the table. Nitrogen does not participate in the reaction; however, it does contribute mass to the air and thus impacts the air-to-fuel ratio.

$$CH_4 + 2O_2 + 2\left(3.76\right)N_2 \rightarrow CO_2 + 2H_2O + 2\left(3.76\right)N_2$$

Add 20% excess air. Air-to-fuel ratio applies only to the reactants, so it is not necessary to balance the reaction and write out the product side.

$$CH_4 + 1.2\left[2O_2 + 2\left(3.76\right)N_2\right] \rightarrow products$$

$$CH_4 + \left(2.4\right)O_2 + \left(9.02\right)N_2 \rightarrow products$$

Calculate the air-to-fuel ratio by multiplying the number of moles of each constituent times the atomic weight and dividing the air mass by the fuel mass. Use the Periodic Table to look up atomic weights as needed.

$$\frac{m_{air}}{m_{fuel}} = \frac{n_{O_2}M_{O_2} + n_{N_2}M_{N_2}}{n_{CH_4}M_{CH_4}} = \frac{\left(2.4\right)\left(32\right) + \left(9.02\right)\left(28\right)}{\left(1\right)\left(16\right)} = 20.6\frac{lb}{lb}$$

Alternatively, in the Combustion Reactions table, notice the heading for Stoichiometric Oxygen and Air Requirements. The amount of air required to burn methane stoichiometrically is given as $17.24\frac{lb}{lb}$. Increase this value by 20% to account for excess air.

$$\left(1.2\right)\left(17.24\frac{lb}{lb}\right) = 20.7\frac{lb}{lb}$$

Answer C

46.17 A refrigeration cycle using R-134a has a refrigeration effect of $8000\frac{Btu}{hr}$ and a coefficient of performance of 11. What is the power required to run the compressor?

A. $210W$

B. $730W$

C. $28KW$

D. $90KW$

Use the definition of Coefficient of Performance for Refrigerators and Air Conditioners. Solve for the work of the compressor. Convert units to Watts.

$$COP = \frac{Q_L}{W}$$

$$W = \frac{Q_L}{COP} = \frac{8000\frac{Btu}{hr}}{11}\left(\frac{1W}{3.412\frac{Btu}{hr}}\right) = 213W$$

Answer A

46.18 $100,000\frac{lb_m}{hr}$ of steam at $5psig$ with quality $\chi = 0.9$ flows through a pipe with an inside diameter of $20in$. What is the velocity?

A. $230\frac{ft}{s}$

B. $255\frac{ft}{s}$

C. $850\frac{ft}{s}$

D. $940\frac{ft}{s}$

Since the steam is a saturated mixture, use the quality to determine the specific volume at $5psig$. Use the steam table by searching Properties of Saturated Water and Steam by pressure. $5psig \approx 20psia$. Collect the values for specific volume of a liquid, v_f, and specific volume change during phase change, v_{fg}.

$$v_f = 0.0168\frac{ft^3}{lb}$$

$$v_{fg} = 20.09\frac{ft^3}{lb}$$

Use the equation for specific volume of a two-phase system.

$$v = v_f + \chi v_{fg} = 0.0168\frac{ft^3}{lb} + (0.9)\left(20.09\frac{ft^3}{lb}\right) = 18.1\frac{ft^3}{lb}$$

Next find the area of a pipe with an inside diameter of $20in$ in ft^2.

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}\left(\frac{20in}{\left(\frac{12in}{1ft}\right)}\right)^2 = 2.182ft^2$$

Mass flow rate is the product of density and volume flow rate: $\dot{m} = \rho Q$.

Volume flow rate is the product of velocity and area: $Q = VA$.

Combine the above and solve for velocity. Substite specific volume in the numerator for density in the denominator, since they are inverses. Substitute known values and solve for the velocity, converting units as needed to drive the final answer to $\frac{ft}{s}$.

$$\dot{m} = \rho VA$$

$$V = \frac{\dot{m}}{\rho A} = \frac{\dot{m}v}{A} = \frac{\left(100,000\frac{lb}{hr}\right)\left(\frac{1hr}{3600s}\right)\left(18.1\frac{ft^3}{lb}\right)}{2.182ft^2} = 230\frac{ft}{s}$$

Answer A

46.19 What is the maximum theoretical efficiency of a power cycle operating with a minimum temperature of $70°F$ and a maximum temperature of $900°F$?

A. 39%

B. 61%

C. 64%

D. 92%

The maximum efficiency possible is based on the Carnot Cycle and depends entirely upon the temperatures of the hot and cold reservoirs which heat is being transfered from and to. Be sure to use absolute temperatures when applying the efficiency formula for a Carnot cycle.

$$\eta_c = \frac{(T_H - T_L)}{T_H} = \frac{1360°R - 530°R}{1360°R} = 61\%$$

Answer B

46.20 What is the thermal efficiency of a reversible heat engine operating between a cold and hot reservoir with temperatures of $100°F$ and $500°F$, respectively?

A. 42%

B. 58%

C. 71%

D. 80%

For a heat engine to be reversible, it must be operating as a Carnot Cycle, which achieves the maximum theoretical efficiency and depends entirely upon the temperatures of the hot and cold reservoirs which heat is being transfered from and to. Be sure to use absolute temperatures when applying the efficiency formula for a Carnot cycle.

$$\eta_c = \frac{(T_H - T_L)}{T_H} = \frac{960°R - 560°R}{960°R} = 42\%$$

Answer A

46.21 $10,000cfm$ of atmospheric air is compressed adiabatically to $40psia$ by a 70% efficient compressor. What brake horsepower is required to drive the compressor?

A. $370hp$

B. $530hp$

C. $760hp$

D. $1060hp$

Look up Adiabatic Compression and use the formula provided.

$$\dot{W}_{comp} = \frac{\dot{m}P_i k}{(k-1)\,\rho_i \eta_c}\left[\left(\frac{P_e}{P_i}\right)^{1-\frac{1}{k}} - 1\right]$$

The problem statement gives a volume flow rate rather than a mass flow rate, recall that mass flow rate is the product of density and volume flow rate.

$$\dot{m} = \rho Q$$

Substituting into the equation, the density cancels out. All other inputs are known. Substitute, and solve for $\dot{W}_{comp}$. Convert units to hp.

$$\dot{W}_{comp} = \frac{QP_i k}{(k-1)\,\eta_c}\left[\left(\frac{P_e}{P_i}\right)^{1-\frac{1}{k}} - 1\right]$$

$$\dot{W}_{comp} = \frac{\left(10,000\frac{ft^3}{min}\right)\left(14.7\frac{lb_f}{in^2}\right)(1.4)\left(\frac{144in^2}{ft^2}\right)}{(1.4-1)(0.7)}\left[\left(\frac{40psia}{14.7psia}\right)^{1-\frac{1}{1.4}} - 1\right] = 3.5\times10^7\frac{ft\cdot lb_f}{min}$$

$$\dot{W}_{comp} = 3.5\times10^7\frac{ft\cdot lb_f}{min}\left(\frac{1min}{60s}\right)\left(\frac{1hp}{550\frac{ft\cdot lb_f}{s}}\right) = 1062hp$$

Answer D

46.22 A $1.5hp$ motor drives a re-circulation fan serving a room with a $7500ft^3$volume of room temperature air. The fan and fan motor are located in an adjacent mechanical room which is a return plenum for the conditioned space. What is the maximum possible increase in the room air temperature if the fan is left to run for 30 minutes?

A. $1°F$

B. $3°F$

C. $8°F$

D. $14°F$

In a worst-case scenario, assume all of the motor's energy heats the air. This drives the maximum possible increase in the room air temperature. Determine the amount of energy produced by the motor during a half hour.

$$(1.5hp)\left(\frac{0.7457KW}{hp}\right)(0.5hr)\left(3412\frac{\frac{Btu}{hr}}{KW}\right) = 1908Btu$$

Assume a typical density for air of $0.075\frac{lb_m}{ft^3}$ and find the mass of air based on the volume given.

$$m = \rho V = \left(0.075\frac{lb_m}{ft^3}\right)\left(7500ft^3\right) = 562.5lb_m$$

Find ΔT based on the heat transfer, mass, and specific heat capacity of air.

$$Q = mc_p\Delta T$$

$$\Delta T = \frac{Q}{mc_p} = \frac{(1908Btu)}{(562.5lb_m)\left(0.24\frac{Btu}{lb_m°F}\right)} = 14.1°F$$

Answer D

46.23 In a steam heat exchanger, $750 \frac{lb}{hr}$ of $500°F$ steam at atmospheric pressure is used to heat $80gpm$ of cold water initally at $50°F$. If the steam exits as a saturated liquid, what is the final temperature of the water assuming there are no losses?

A. $52°F$

B. $64°F$

C. $71°F$

D. $76°F$

Consider the entering steam as State 1 and leaving saturated liquid as State 2. Consider the entering water as State 3 and the leaving water as State 4.

Use the Properties of Superheated Steam table to obtain the enthalpy at State 1.

$$P_1 = 14.7psia$$

$$T_1 = 500°F$$

$$h_1 = 1287.3 \frac{Btu}{lb}$$

Use the Properties of Saturated Water and Steam table to obtain the saturated liquid enthalpy at State 2.

$$P_2 = 14.7psia\,(saturated)$$

$$h_2 = 180.18 \frac{Btu}{lb}$$

Use the mass flow rate to calculate the heat provided by the steam.

$$\dot{Q}_{steam} = \dot{m}_{steam}\,(h_1 - h_2) = 750 \frac{lb}{hr}\left(1287.3 \frac{Btu}{lb} - 180.18 \frac{Btu}{lb}\right) = 830,340 \frac{Btu}{hr}$$

The quantity of heat added to the water is equal to the quantity of heat provided by the steam. Use the sensible heat rule of thumb for water to calculate the increase in temperature, and then specify the leaving water temperature at State 4. Note $\dot{Q}$ must have units of $\frac{Btu}{hr}$ for the rule of thumb to work properly, with temperatures having units of $°F$.

$$\dot{Q}_{water} = \dot{Q}_{steam}$$

$$500gpm\Delta T = \dot{Q}_{steam}$$

$$\Delta T = T_4 - T_3 = \frac{\dot{Q}_{steam}}{500gpm} = \frac{830,340}{(500)\,(80)} = 20.8°F$$

$$T_4 = T_3 + 20.8°F = 70.8°F$$

Answer C

46.24 Air enters a compressor at $80°F$ and $14.7psia$ and exits at $180psia$. What is the change in enthalpy during the compression process?

A. $115\frac{Btu}{lb}$

B. $135\frac{Btu}{lb}$

C. $155\frac{Btu}{lb}$

D. $175\frac{Btu}{lb}$

Consider the entering conditions as State 1 and the leaving conditions as State 2. Use the Air at Low Pressure tables to obtain the enthalpy at State 1. The air tables assume that for low pressure air, enthalpy is a function of temperature only. Also obtain the relative pressure at State 1.

$$T_1 = 80°F$$

$$h_1 \approx 129\frac{Btu}{lb}$$

$$p_{r,1} = 1.386$$

Use the ratio of the pressures to find the relative pressure at State 2.

$$\frac{p_{r,2}}{p_{r,1}} = \frac{P_2}{P_1} = \frac{180psia}{14.7psia} = 12.24$$

$$p_{r,2} = (12.24)\,(1.386) = 16.97$$

Use the air tables again to obtain the enthalpy at State 2 using the relative pressure at State 2.

$$h_2 \approx 264\frac{Btu}{lb}$$

Calculate the change in enthalpy.

$$\Delta h = h_2 - h_1 = 264\frac{Btu}{lb} - 129\frac{Btu}{lb} = 135\frac{Btu}{lb}$$

Answer B

46.25 A steam boiler uses $50\frac{lb}{hr}$ of $40psia$ saturated steam to heat $10gpm$ of water. What is the expected increase in temperature for the water?

A. $7°F$

B. $8°F$

C. $9°F$

D. $10°F$

There is no mention of any losses in the problem statement, so assume the heat exchange process is 100% efficient. Set the heat provided by the steam equal to the heat gained by the water. Ensuring both sides of the equation have units of $\frac{Btu}{hr}$, it is valid to use the sensible heating rule of thumb for water on the right side.

$$\dot{Q}_{steam} = \dot{Q}_{water}$$

$$\dot{m}_{steam}\Delta h = 500gpm\Delta T$$

The change in enthalpy for the steam may be assumed as the latent heat of vaporization for steam at 40psia. Since no quality or leaving enthalpy was given, it is reasonable to assume the steam condenses fully and gives up all of its latent heat in the process.

$$\dot{m}_{steam}h_{fg} = 500gpm\Delta T$$

Use the Properties of Saturated Water and Steam table to obtain the latent heat of vaporization.

$$P = 40psia$$

$$h_{fg} = 933.68\frac{Btu}{lb}$$

Solve the left side of the equation and confirm the units are $\frac{Btu}{hr}$.

$$\dot{m}_{steam}h_{fg} = \left(50\frac{lb}{hr}\right)\left(933.68\frac{Btu}{lb}\right) = 46,684\frac{Btu}{hr}$$

Since the units are confirmed and the right side of the equation is a "rule of thumb," it is implied that the change in temperature will be in degrees Farenheit, as desired. Solve for ΔT.

$$46,684 = (500)(10)\Delta T$$

$$\Delta T = \frac{46,684}{(500)(10)} = 9.3°F$$

Answer C

46.26 $200\frac{lb}{hr}$ **of** $5psig$ **saturated steam enters a heating coil which supplies** $100MBH$**. What percent of the exiting steam is in a liquid phase?**

A. 44%

B. 48%

C. 52%

D. 56%

Consider the saturated steam entering the coil as State 1 and the saturated mixture leaving the coil as State 2.

Use the Properties of Saturated Water and Steam table to obtain the enthalpy at State 1.

$$P_1 = 5psig \approx 20psia$$

$$h_1 = h_g = 1156.19\frac{Btu}{lb}$$

The total heat transfer and mass flow rate are given. Determine the enthalpy at State 2.

$$\dot{Q} = \dot{m}\Delta h = \dot{m}\left(h_1 - h_2\right)$$

$$h_2 = h_1 - \frac{\dot{Q}}{\dot{m}} = 1156.19\frac{Btu}{lb} - \frac{100,000\frac{Btu}{hr}}{200\frac{lb}{hr}} = 656.19\frac{Btu}{lb}$$

Determine the quality at State 2. Use the steam table to obtain enthalpy values h_f and h_{fg}. The quality is the fraction of the saturated mixture that is in a *vapor* phase.

$$h_f = 196.25\frac{Btu}{lb}$$

$$h_{fg} = 959.94\frac{Btu}{lb}$$

$$\chi_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{656.19\frac{Btu}{lb} - 196.25\frac{Btu}{lb}}{959.94\frac{Btu}{lb}} = 0.479$$

The fraction of the water that is in a *liquid* phase is the complement of the quality.

$$1 - \chi_2 = 1 - 0.479 = 0.521 \approx 52\%$$

Answer C

46.27 A $5lbm$ mass hangs from a spring with a spring constant of $15\frac{lbf}{in}$. What is the linear frequency of vibration for the system?

A. $1Hz$

B. $5Hz$

C. $11Hz$

D. $34Hz$

Sketch and label the system. Search for Free Vibration and apply the formula for the natural frequency which is a function of the mass and the spring constant. Since the problem uses US Customary units, it will be necessary to include the gravitational constant, g_c, for consistency. This is not required for similar problems using SI units. Solve for the natural frequency.

$$\omega_n = \sqrt{\frac{kg_c}{m}} = \sqrt{\frac{\left(15\frac{lbf}{in}\right)\left(12\frac{in}{ft}\right)\left(32.2\frac{ft\cdot lb_m}{s^2\cdot lb_f}\right)}{5lb_m}} = 34.05\frac{rad}{s}$$

Infer the relationship between linear frequency, f, and natural frequency, ω_n, using the equations for the period shown on the same page under the phrase: Undamped Natural Period of Vibration. Solve for the linear frequency, f. The units associated with 2π are implied to be radians per cycle, such that the linear frequency ultimately has units of cycles (or oscillations) per second aka Hz.

$$\frac{2\pi}{\omega_n} = \frac{1}{f}$$

$$f = \frac{\omega_n}{2\pi} = \frac{34.05\frac{rad}{s}}{2\pi\frac{rad}{cycle}} = 5.42\frac{cycles}{s} = 5.42Hz$$

Answer B

46.28 A museum is maintained at $68°F$ and 45% relative humidity. What is the vapor pressure of the space?

A. $0.15in\,Hg$

B. $0.31in\,Hg$

C. $0.34in\,Hg$

D. $0.69in\,Hg$

Use the definition of Relative Humidity, which is the ratio of the vapor pressure and the maximum possible pressure of water vapor in air at a given temperature, the saturation pressure.

$$\phi = \frac{p_w}{p_{ws}}$$

Use the table Properties of Saturated Water and Steam (Temperature) to obtain the saturation pressure for $68°F$ water.

$$T = 68°F$$

$$p_{ws} = 0.34psia$$

Solve for the vapor pressure.

$$p_w = \phi p_{ws} = (0.45)\,(0.34psia) = 0.153psia$$

Convert from $psia$ to $in\,Hg$. Refer to Measurement Relationships for necessary converstions.

$$p_w = (0.153psia)\left(\frac{2.036in\,Hg}{1psi}\right) = 0.31in\,Hg$$

Answer B

46.29 Saturted liquid water at $50psig$ is boiled in a sealed vessel at constant pressure until one third of the water by mass has changed to a vapor phase. What is the change in entropy of the mixture during this process?

A. $0.40\frac{Btu}{lb_m \cdot °R}$

B. $0.42\frac{Btu}{lb_m \cdot °R}$

C. $0.80\frac{Btu}{lb_m \cdot °R}$

D. $0.83\frac{Btu}{lb_m \cdot °R}$

Start by finding the entropy for the initial condition, State 1. Since the water is a saturated liquid, the entropy at State 1 corresponds to s_f for the pressure given. Use the table Properties of Saturated Water and Steam (Pressure) to obtain the entropy, s_1.

$$P_1 = 50psig \approx 65psia$$

$$s_1 = s_f = 0.4344\frac{Btu}{lb_m \cdot °R}$$

Also obtain the entropy of vaporation, s_{fg}, from the same line in the steam table for use in the following step.

$$s_{fg} = 1.2035\frac{Btu}{lb_m \cdot °R}$$

Since the water is boiled at constant pressure until a third of the mass has changed to vapor, the quality at State 2, χ_2, is $\frac{1}{3}$. This is the definition of quality.

$$\chi_2 = \frac{m_{vapor}}{m_{vapor} + m_{liquid}} = \frac{m_{vapor}}{m_{total}} = \frac{1}{3}$$

Use one of the formulas under Properties for Two-Phase (Vapor-Liquid) Systems to solve for s_2.

$$s_2 = s_f + \chi_2 s_{fg} = 0.4344\frac{Btu}{lb_m \cdot {}^\circ R} + \left(\frac{1}{3}\right)\left(1.2035\frac{Btu}{lb_m \cdot {}^\circ R}\right) = 0.8356\frac{Btu}{lb_m \cdot {}^\circ R}$$

Calculate the change in entropy, Δs.

$$\Delta s = s_2 - s_1 = 0.8356\frac{Btu}{lb_m \cdot {}^\circ R} - 0.4344\frac{Btu}{lb_m \cdot {}^\circ R} = 0.401\frac{Btu}{lb_m \cdot {}^\circ R}$$

Alternatively, a faster solution would be to recognize that the change in entropy will be one third of the entropy of vaporiation, s_{fg}, since one third of the total mass is changing phase.

$$\Delta s = \left(\frac{1}{3}\right) s_{fg} = \left(\frac{1}{3}\right)\left(1.2035\frac{Btu}{lb_m \cdot {}^\circ R}\right) = 0.401\frac{Btu}{lb_m \cdot {}^\circ R}$$

Answer A

46.30 A counterflow heat exchanger is used to cool a fluid from $180^\circ F$ to $140^\circ F$. The cooling medium temperature increases from $60^\circ F$ to $120^\circ F$. What is the log mean temperature difference?

A. $56^\circ F$

B. $60^\circ F$

C. $64^\circ F$

D. $70^\circ F$

Sketch the heat exchanger or draw a Temperature vs. Length diagram to depict the direction of flow, and label all temperatures. The fluids flow in opposite directions because it is a *counterflow* heat exchanger.

$$180^\circ F \longrightarrow 140^\circ F$$

$$120^\circ F \longleftarrow 60^\circ F$$

Calculate the temperature differential on each physical side of the exchanger, arbitrarily labeling the sides A & B.

$$\Delta T_A = 180^\circ F - 120^\circ F = 60^\circ F$$

$$\Delta T_B = 140^\circ F - 60^\circ F = 80^\circ F$$

Calculate the Log Mean Temperature Difference, ΔT_{lm}. The formula below is consistent with the formula shown in the reference handbook, but may be easier to correctly apply once the temperature differentials are properly defined. Note that interchanging ΔT_A and ΔT_B leads to the same correct result!

$$\Delta T_{lm} = \frac{\Delta T_A - \Delta T_B}{ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$$

$$\Delta T_{lm} = \frac{60°F - 80°F}{ln\left(\frac{60°F}{80°F}\right)} = 69.5°F$$

Answer D

46.31 A heat sink is designed to remove $25W$ from a computer CPU. The ambient air inside the machine is $90°F$ and the surface temperature of the heat sink is not to exceed $140°F$. The combined heat transfer coefficient, including both convection and radiation, is $3\frac{Btu}{hr \cdot ft^2 \cdot °F}$. What is the minimum required surface area for the heat sink?

A. $7in^2$

B. $24in^2$

C. $82in^2$

D. $148in^2$

The overall heat transfer is given by the equation below, where the overall coefficient of heat transfer, U, *includes* both convection and radiation.

$$\dot{Q} = UA\Delta T$$

Solve for the area. Substitute the amount of heat to be removed, the overall heat transfer coefficient, and the temperatures to determine the surface area. Since the area calculation is based on the *largest* allowable temperature differential, the value obtained represents the *minimum* area required to ensure the upper temperature limit is not exceeded. Convert to square inches.

$$A = \frac{\dot{Q}}{U\Delta T} = \frac{(25W)\left(3.412\frac{Btu}{hr \cdot W}\right)}{\left(3\frac{Btu}{hr \cdot ft^2 \cdot °F}\right)(140°F - 90°F)} = 0.57ft^2$$

$$A = 0.57ft^2\left(\frac{12in}{1ft}\right)^2 = 82in^2$$

Answer C

46.32 **$5000 cfm$ of air at $75°F$ db / $68°F$ wb enters a spray chamber using $90°F$ water. The bypass factor for the spray chamber is 0.15. What is the dry bulb temperature of the leaving air?**

A. $69°F$

B. $74°F$

C. $77°F$

D. $88°F$

The spray chamber is heating the air, so the wet bulb temperature of the entering air has no bearing on the problem. If the process was 100% efficient, the air would leave at the same temperature as the water, $90°F$. However, due to the bypass factor, the efficiency of the heating process is only 85%.

$$\eta = 1 - BF = 1 - 0.15 = 0.85$$

Perform a mixing calculation using 85% of the airflow having been heated to $90°F$, and the balance having been unaffected because it bypassed the spray.

$$T_2 = (0.85)(90°F) + (0.15)(75°F) = 87.75°F$$

Alternatively, set up the efficieny as the ratio of the change in dry bulb temperature actually observed compared to the maximum possible delta T if there was no bypass, i.e. 100% efficiency.

$$\eta = \frac{T_2 - T_1}{T_{spray} - T_1}$$

$$0.85 = \frac{T_2 - 75°F}{90°F - 75°F}$$

$$T_2 = 87.75°F$$

Answer D

46.33 A pizza oven has a flame temperature of $1000°F$ and the internal walls are $700°F$. Assuming all surfaces are considered to be black, what is the rate of heat transfer per square foot due to radiation?

A. $1300\frac{Btu}{hr \cdot ft^2}$

B. $4700\frac{Btu}{hr \cdot ft^2}$

C. $8800\frac{Btu}{hr \cdot ft^2}$

D. $13,000\frac{Btu}{hr \cdot ft^2}$

The energy exchange due to Radiation is given by the equation below.

$$\dot{Q}_r = \varepsilon \sigma A \left(T_1^4 - T_2^4\right)$$

Since all surfaces are considered to be black, the emissivity is assumed to be 1.

$$\varepsilon = 1$$

The question asks for the heat transfer per square foot, so divide both sides by area.

$$\frac{\dot{Q}_r}{A} = \dot{q}_r = \sigma \left(T_1^4 - T_2^4\right)$$

σ is the Stefan-Boltzmann Constant. In order for the units to work out, absolute temperatures must be used i.e. Rankine. Solve for $\dot{q}_r$.

$$\dot{q}_r = \left(0.1713 \times 10^{-8} \frac{Btu}{hr \cdot ft^2 \cdot {}^{\circ}R^4}\right) \left[(1460°R)^4 - (1160°R)^4\right] = 4682\frac{Btu}{hr \cdot ft^2}$$

Answer B

46.34 **A $50ft$ length of hot water piping with $1\,in\,O.D.$ runs uninsulated through an open basement. The ambient temperature and average temperature of the walls and other surfaces is $60°F$. The convective heat transfer coefficient is $6\frac{Btu}{hr\cdot ft^2\cdot °F}$. The average surface temperature of the pipe is $120°F$. The emissivity for the pipe is 0.9. What is the total heat loss?**

A. $800\frac{Btu}{hr}$

B. $4680\frac{Btu}{hr}$

C. $5520\frac{Btu}{hr}$

D. $9640\frac{Btu}{hr}$

Heat is lost from the pipe through both Convection and Radiation. For combined heat transfer, add the convection and radiation equations together.

$$\dot{Q}_{conv} = hA\Delta T$$

$$\dot{Q}_{rad} = \sigma\varepsilon A\left(T_s^4 - T_\infty^4\right)$$

$$\dot{Q}_t = \dot{Q}_{conv} + \dot{Q}_{rad} = hA\Delta T + \sigma\varepsilon A\left(T_s^4 - T_\infty^4\right)$$

Area is common to both equations and may be factored out of the combined equation.

$$\dot{Q}_t = A\left(h\Delta T + \sigma\varepsilon\left(T_s^4 - T_\infty^4\right)\right)$$

Calculate the external surface area of the pipe.

$$A_s = \pi DL = \pi\left(\frac{1in}{12\frac{in}{ft}}\right)(50ft) = 13.1ft^2$$

Substitute the convection coefficient, surface temperature, and surrounding air temperature into the convection portion of the equation. Substitute the Stefan-Boltzmann Constant, emissivity, pipe surface temperature, and the temperature of the surrounding surfaces in the radiation portion of the equation. Be sure to use absolute temperatures ie. Rankine for radiation. Determine the total heat loss.

$$\dot{Q}_t = \left(13.1ft^2\right)\times$$

$$\left[\left(6\frac{Btu}{hr\cdot ft^2\cdot °F}\right)(120°F - 60°F) + \left(0.1713\times 10^{-8}\frac{Btu}{hr\cdot ft^2\cdot °R^4}\right)(0.9)\left((580°R)^4 - (520°R)^4\right)\right]$$

$$\dot{Q}_t = 5525\frac{Btu}{hr}$$

Answer C

46.35 A variable frequnecy drive producing $100W$of waste heat during continuous operation is housed in an insulated sheet matal enclosure mounted in a machine room. The insulation is $\frac{1}{8}in$ thick with a thermal conductivity of $0.2\frac{Btu}{hr\cdot ft\cdot °F}$. The thermal resistance of the sheet metal is negligible. The surface area of the enclosure is $8ft^2$. The machine room is maintained at $76°F$. The film coefficients both inside and outside the enclosure are $4\frac{Btu}{hr\cdot ft^2\cdot °F}$. What is the steady state temperature inside the enclosure?

A. $52°F$

B. $88°F$

C. $100°F$

D. $112°F$

Model the enclosure as a Composite Wall with 3 layers: 2 films and the insulation. Negligible thermal resistance is provided by the sheet metal. The total heat transfer through the composite wall may be described by the equation $\dot{Q} = UA\Delta T$, where the overall coefficient of heat transfer, $U = \frac{1}{R_T}$, and where R_T is the total thermal resistance. Determine the total thermal resistance by adding the individual thermal resistenaces in series.

$$R_T = \frac{1}{h_i} + \frac{L_{ins}}{k_{ins}} + \frac{1}{h_o}$$

$$R_T = \frac{1}{\left(4\frac{Btu}{hr\cdot ft^2\cdot °F}\right)} + \frac{\left(\frac{1}{8}in\right)\left(\frac{1ft}{12in}\right)}{0.2\frac{Btu}{hr\cdot ft\cdot °F}} + \frac{1}{\left(4\frac{Btu}{hr\cdot ft^2\cdot °F}\right)} = 0.55\frac{hr\cdot ft^2\cdot °F}{Btu}$$

Calculate the overall heat transfer coefficient from the total thermal resistance.

$$U = \frac{1}{R_T} = \frac{1}{0.55\frac{hr\cdot ft^2\cdot °F}{Btu}} = 1.8\frac{Btu}{hr\cdot ft^2\cdot °F}$$

Calculate the temperature differential using the total heat transfer, the overall heat transfer coefficient, and the surface area.

$$\Delta T = \frac{\dot{Q}}{UA} = \frac{(100W)\left(3.412\frac{Btu}{hr\cdot W}\right)}{\left(1.8\frac{Btu}{hr\cdot ft^2\cdot °F}\right)(8ft^2)} = 23.7°F$$

Use the temperature differential to calculate the temperature inside the encolsure based on the room temperature.

$$\Delta T = T_{enclosure} - T_{room}$$

$$T_{enclosure} = \Delta T + T_{room} = 23.7°F + 76°F = 99.7°F$$

Answer C

46.36 In a counterflow heat exchanger, the cold fluid increases in temperature from $50°F$ to $100°F$ and the warm fluid is cooled from $180°F$ to $145°F$. What is the logarithmic mean temperature difference?

A. $45°F$

B. $87°F$

C. $115°F$

D. $119°F$

It is valid to use the Reference Handbook formula for Log Mean Temperature Difference. There is also a generalized version of the LMTD equation not provided in the reference handbook which is easier to remember and applies to both Counterflow and Parallel Flow heat exchangers, provided the flow directions are drawn out first. Note the opposite direction for the arrows for a counterflow heat exchanger.

$$Cold\,Fluid:\ 50°F \longrightarrow 100°F$$

$$Hot\,Fluid:\ 145°F \longleftarrow 180°F$$

Define one *physical* side of the heat exchanger as 'A' and the other side as 'B' and determine the respective temperature differences. Conveniently, the assignment of labels A and B turns out to be arbitrary. However, the *direction* of the flows is critical.

$$\Delta T_A = 145°F - 50°F = 95°F$$

$$\Delta T_B = 180°F - 100°F = 80°F$$

Use the formula below to calculate the log mean temperature difference.

$$LMTD = \frac{\Delta T_A - \Delta T_B}{ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$$

$$LMTD = \frac{95°F - 80°F}{ln\left(\frac{95°F}{80°F}\right)} = 87.3°F$$

Answer B

46.37 A composite wall is composed of $\frac{3}{4}in$ of stucco, $8in$ normal weight concrete blocks, and $\frac{1}{2}in$ gypsum board. The inside and outside surface conductances are $6\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$ and $1.5\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$, respectively. What is the U-factor for the wall?

A. $0.11\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$

B. $0.41\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$

C. $0.62\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$

D. $2.4\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$

Stetch the Composite Plane Wall and label with given information. There are five sources of resistance, the two surface conductances and the three layers of building materials. The U-factor, or overall coefficient of heat transfer, is the inverse of the total resistance.

$$U = \frac{1}{R_{total}}$$

Write an expression for R_{total} for this specific situation.

$$R_{total} = \frac{1}{h_i} + R_{stucco} + R_{concrete} + R_{gypsum} + \frac{1}{h_o}$$

Use the table Thermal Resistance of Building Materials to look up the resistance values for each of the materials. In some cases the resistance may be provided per unit thickness and in others it may be given for a particular, typical thickness. Be sure to account for such nuances by ensuring correct units before taking the sum. For concrete, use the average value from the range provided for 8in blocks.

$$R_{stucco} = \left(0.15\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu\cdot in}\right)(0.75in) = 0.1125\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$$

$$R_{concrete} = 1.04\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$$

$$R_{gypsum} = 0.45\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$$

Calculate R_{total}.

$$R_{total} = \frac{1}{6\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}} + 0.1125\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu} + 1.04\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu} + 0.45\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu} + \frac{1}{1.5\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}}$$

$$R_{total} = 2.436\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$$

Calculate the U-factor.

$$U = \frac{1}{R_{total}} = \frac{1}{2.436\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}} = 0.41\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$$

Answer B

46.38 A fluid with a kinematic viscosity of $3centistokes$ and a specific gravity of 0.88 flows through a nominal $3in$ pipe at $4fps$. What is the Reynolds number?

A. $32,000$

B. $104,000$

C. $380,000$

D. $3,700,000$

Reynolds Number is a function of velocity, diameter, and kinematic viscosity. Specific gravity has no bearing on Reynolds number.

$$Re = \frac{vD}{\nu}$$

The kinematic viscosity has been given in cSt which is best converted to $\frac{ft^2}{s}$ since the problem is otherwise specified in US Customary units. Use the table Measurement Relationships to find the relevant conversion factors from cSt to $\frac{m^2}{s}$ and from $meters$ to ft. Substitute directly into the Reynolds number formula and solve. Use the table Schedule 40 Steel Pipe to look up the internal diameter of a nominal $3in$ pipe.

$$Re = \frac{\left(4\frac{ft}{s}\right)\left(\frac{3.068}{12}ft\right)}{(3cSt)\left(\frac{1\times10^{-6}\frac{m^2}{s}}{1cSt}\right)\left(\frac{3.281ft}{1m}\right)^2} = 31,666$$

Answer A

46.39 What is the quality of $1300 psia$ steam produced by a boiler that adds $600 \frac{Btu}{lb}$ to $250°F$ saturated liquid feedwater?

A. 0.22

B. 0.39

C. 0.61

D. 0.78

Consider the feedwater as State 1 and the saturated mixture leaving the boiler as State 2. Use the Properties of Saturated Water and Steam table by temperature to obtain the enthalpy at State 1.

$$T_1 = 250°F\,(saturated)$$

$$h_1 = h_f = 218.6 \frac{Btu}{lb}$$

Calculate the enthalpy at State 2 by accounting for the heat added by the boiler.

$$\Delta h = h_2 - h_1 = 600 \frac{Btu}{lb}$$

$$h_2 = h_1 + 600 \frac{Btu}{lb} = 218.6 \frac{Btu}{lb} + 600 \frac{Btu}{lb} = 818.6 \frac{Btu}{lb}$$

Use the steam table by pressure to obtain the enthalpy values h_f and h_{fg} at $1300 psia$. Then calculate the quality at State 2.

$$P_2 = 1300 psia$$

$$h_f = 585.6 \frac{Btu}{lb}$$

$$h_{fg} = 593.9 \frac{Btu}{lb}$$

$$\chi_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{818.6 \frac{Btu}{lb} - 585.6 \frac{Btu}{lb}}{593.9 \frac{Btu}{lb}} = 0.39$$

Answer B

46.40 Equal mass flow rates of water and a 50/50 glycol-water mixture with specific heat capacity $0.75\frac{Btu}{lb_m{}^\circ F}$ flow on either side of a shell and tube heat exchanger. Water enters at $90^\circ F$ and the glycol mixture enters at $38^\circ F$. What could be the leaving temperatures of the water and glycol-water mixture, respectively?

A. $74^\circ F$ / $50^\circ F$

B. $74^\circ F$ / $54^\circ F$

C. $78^\circ F$ / $50^\circ F$

D. $78^\circ F$ / $54^\circ F$

Assuming 100% efficiency, all the heat extracted from the water is added to the glycol mixture. Equate the heat transfer for the two sides of the heat exchanger. The mass flow rates are the same and thus cancel out. Derive a ratio of the temperature differentials.

$$\dot{Q}_{water} = \dot{Q}_{glycol}$$

$$(\dot{m}c_p\Delta T)_{water} = (\dot{m}c_p\Delta T)_{glycol}$$

$$c_{p,water}\Delta T_{water} = c_{p,glycol}\Delta T_{glycol}$$

$$\frac{\Delta T_{water}}{\Delta T_{glycol}} = \frac{c_{p,glycol}}{c_{p,water}} = \frac{0.75\frac{Btu}{lb_m{}^\circ F}}{1\frac{Btu}{lb_m{}^\circ F}} = 0.75$$

$$\Delta T_{water} = 0.75 \times \Delta T_{glycol}$$

To validate this result against intution, consider that water has a *greater* specific heat capacity than the glycol mixture, and as such, it will have a *smaller* ΔT. Examine the answer choices and note that only one option produces ΔT values in the correct proportion.

$$\Delta T_{water} = 90^\circ F - 78^\circ F = 12^\circ F$$

$$\Delta T_{glycol} = 54^\circ F - 38^\circ F = 16^\circ F$$

These values make the established relation true. Note there are an infinite number of possible solutions, and without multiple choice options being provided, this problem would be underdefined.

Answer D

46.41 A $7lb_m$ cast iron pan ($c_p = 0.1\frac{Btu}{lb_m{}^\circ F}$) is heated uniformly to $500^\circ F$ during cooking, then placed in a sink filled with 4 *gallons* of $60^\circ F$ water. Neglecting losses, what is the final equilibrium temperature?

A. $69^\circ F$

B. $79^\circ F$

C. $89^\circ F$

D. $99^\circ F$

All of the heat released from the pan is added to the water. Express both quantities of heat as the product of mass, specific heat capacity, and ΔT. Set them equal.

$$(mc_p\Delta T)_{iron} = (mc_p\Delta T)_{water}$$

In the case of water, the volume was given instead of the mass. Use the density of water to calculate the mass.

$$m_{water} = \rho V = \left(62.4\frac{lb_m}{ft^3}\right)\left(\frac{1ft^3}{7.48gal}\right)(4gal) = 33.4lb_m$$

Substitute into the first equation and solve for the final equilibrium temperature, T_f, which is the same for the pan and the water.

$$(7lb_m)\left(0.1\frac{Btu}{lb_m{}^\circ F}\right)(500^\circ F - T_f) = (33.4lb_m)\left(1\frac{Btu}{lb_m{}^\circ F}\right)(T_f - 60^\circ F)$$

Since the units are all consistent, it is fine to ignore the units while solving for the unknown temperature.

$$(0.7)(500 - T_f) = (33.4)(T_f - 60)$$

$$350 - 0.7T_f = 33.4T_f - 2002$$

$$2352 = 34.1T_f$$

$$T_f = 69^\circ F$$

Answer A

46.42 A refrigeration system using R-22 operates between $80°F$ condensing and $0°F$ evaporation. The refrigerant exits the evaporator as a dry, saturated vapor. What is the specific work done by the compressor assuming isentropic compression?

A. $9\frac{Btu}{lb}$

B. $11\frac{Btu}{lb}$

C. $15\frac{Btu}{lb}$

D. $18\frac{Btu}{lb}$

Draw the refrigeration cycle on the Pressure-Enthalpy diagram for Refrigerant 22, labelling all 4 States. The compression process is from State 1 to State 2. The specific work done by the compressor is the difference between the enthalpy at State 2 and the enthalpy at State 1. Specific work is distinct from 'Work' in that its units are $\frac{Btu}{lb}$ (as opposed to $\frac{Btu}{hr}$) and it does not require the mass flow rate.

$$Work = \dot{W}_{comp} = \dot{m}\Delta h = \dot{m}\left(h_2 - h_1\right)$$

$$Specific Work = w = h_2 - h_1$$

Start by analyzing State 1 which is a dry, saturated vapor with a known Temperature. Use the Refrigerant 22 table to obtain the enthalpy at State 1.

$$T_1 = 0°F$$

$$h_1 = h_f = 104.6\frac{Btu}{lb}$$

Use the Pressure Versus Enthalpy Curves for Refrigerant 22 to locate State 1. Since the compression process is isentropic, draw a line of constant entropy up and to the right.

The condensing temperature is $80°F$, which is implied to refer to the segment of the condensing process line which lies inside the vapor dome. The condensing process is constant *pressure* throughout the entire process, however it is only constant *temperature* inside the vapor dome. Extend a horizontal line to the right from the $80°F$ line.

Graphically locate State 2 as the intersection of the extended $80°F$ line and the constant entropy line previously drawn from State 1. Read the enthalpy at State 2 along the top horizontal axis. Some uncertainty and imprecision is to be expected due to graphical nature of this approach.

$$h_2 \approx 120\frac{Btu}{lb}$$

Calculate the specific work.

$$w = 120\frac{Btu}{lb} - 104.6\frac{Btu}{lb} = 15.4$$

Answer C

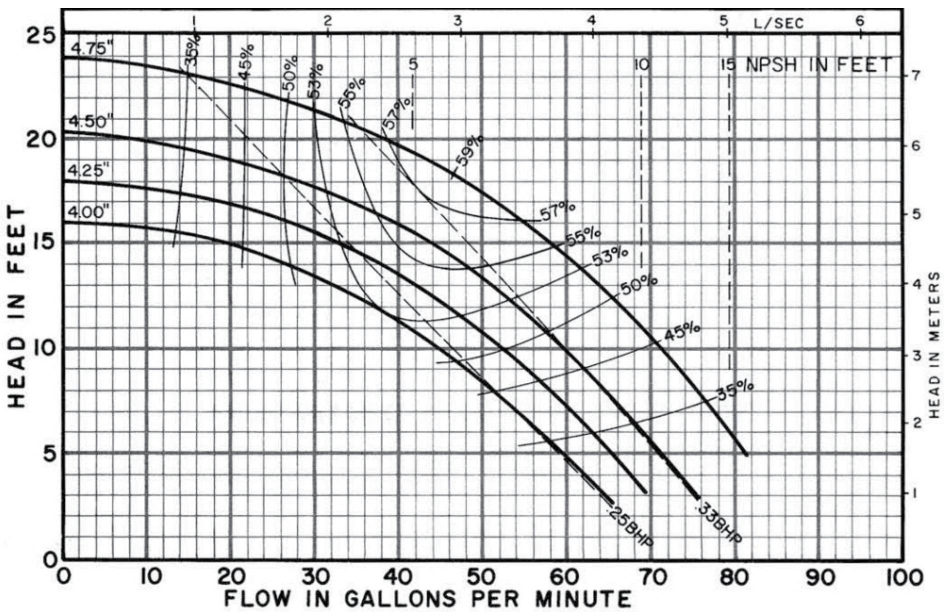
46.43 The operating pressure in a hydronic system is $15ft$ of head and the required flow is $120gpm$. The system has been designed with 3 pumps operating in parallel. Referring to the pump curves below, what is the minimum impeller size sufficient for the system?

A. $4.00in$

B. $4.25in$

C. $4.50in$

D. $4.75in$



Refer to Pump Performance Curves.
Since the 3 pumps are in parallel, the head added is the same across each pump.

$$\Delta h = 15ft$$

The volume flow rate will be split equally across all 3 pumps.

$$Q = \frac{120gpm}{3} = 40gpm$$

Find the operating point on the chart for $40gpm, 15ft$ and choose the next size up, which is the $4.5in$ impeller.

Answer C

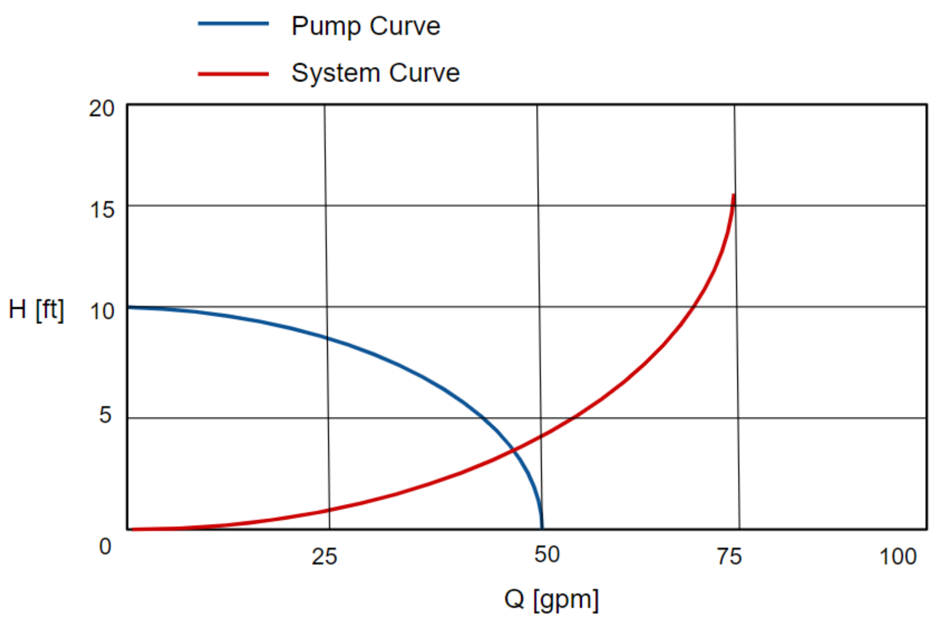
46.44 A hydronic system operates accorinding to the system curve shown below. The system is being designed to include two pumps in parallel, each with the characteristics of the pump curve shown below. What is the maximum hydraulic horsepower available to the system?

A. $0.05hp$

B. $0.13hp$

C. $0.19hp$

D. $0.29hp$



Reference the graph titled Operating Conditions for Parallel Operation and sketch a second pump in parallel. The curve for two pumps in parallel should connect $10ft$ on the vertical axis with $100gpm$ on the horizonatal axis, and roughly parallel the single pump curve. Make a best approximation of the volume flow rate and head at the intersection of the new parallel pump curve and the existing system curve.

$$Q \approx 63gpm$$

$$\Delta h \approx 8ft$$

Calculate the maximum hydraulic horsepower by assuming 100% pumping efficiency. For the Water Horsepower formula selected, the units for the flow rate, Q, must be gpm. The units for head, h, must be ft.

$$whp = \frac{Q\Delta h}{3960}$$

$$whp = \frac{(63)\,(8)}{3960} = 0.13hp$$

Answer B

46.45 A 70% efficient pump driven by a 93% efficient motor delivers $150gpm$ of $120°F$ hot water at a head of $40ft$ with a rotational speed of $1800rpm$. The pump runs from 7am-7pm Monday-Friday year round. The average cost of electricity is $0.12/kWh. What is the annual cost to run the pump?

A. $275

B. $300

C. $650

D. $700

Calculate the Water Horsepower.

$$whp = \frac{Q\Delta h}{3960}$$

$$whp = \frac{(150)\,(40)}{3960} = 1.5hp$$

Calculate the electrical power required to drive the pump by dividing by the pump efficiency and motor efficiency. Convert units from hp to KW.

$$\dot{W} = \frac{whp}{\eta_{pump}\eta_{motor}} = \frac{1.5hp}{(0.7)\,(0.93)} = 1.7KW$$

Calculate the cost of running based on the power, the annual run time, and the cost of electricity.

$$C = (1.7KW)\left(\frac{12hr}{day}\right)\left(\frac{5days}{wk}\right)(52wks)\left(\frac{\$0.12}{kWh}\right) = \$636$$

Answer C

46.46 A condenser water pump is located $5ft$ below the top of the waterline of a cooling tower basin. The leaving water temperature is $75°F$. The friction loss on the suction side of the pump is $9ft$ of head. What is the net positive suction head available?

A. $4ft$

B. $9ft$

C. $29ft$

D. $37ft$

Refer to the first formula in the Reference Handbook for Net Positive Suction Head Available. Calculate the NPSHA by taking the sum of the atmospheric pressure, h_p, and the height of the fluid column on the suction side of the pump, h_z, minus the vapor pressor, h_{vpa}, and the losses on the suction side, h_f. The vapor pressure is the saturation pressure at the temperature of the water and can be found using the Properties of Saturated Water and Steam table by temperature.

$$h_{vpa} = P_{sat@75°F} = 0.43psi\left(2.31\frac{ft}{psi}\right) \approx 1ft$$

$$NPSH_A = h_p + h_z - h_{vpa} - h_f$$

$$NPSH_A = 34ft + 5ft - 1ft - 9ft = 29ft$$

Answer C

46.47 The flow of a centrifugal pump developing $150ft$ of head is reduced from $500gpm$ to $300gpm$. After the speed reduction, what is the head added by the pump?

A. $32ft$

B. $54ft$

C. $90ft$

D. $250ft$

Refer to the Pump Affinity Laws. For a change in speed, the change in volume flow rate is proportional to the change in speed. Calculate the ratio of the new speed to the old speed.

$$\frac{N_2}{N_1} = \frac{Q_2}{Q_1} = \frac{300gpm}{500gpm} = 0.6$$

The change in head is a function of the *square* of the change in speed. Calculate the new head after the speed change.

$$\frac{h_2}{h_1} = \left(\frac{N_2}{N_1}\right)^2$$

$$h_2 = h_1 \left(\frac{N_2}{N_1}\right)^2 = (150ft)(0.6)^2 = 54ft$$

Answer B

46.48 A manometer uses mercury to measure the pressure inside a gas storage tank. One end of the manometer is open to the atmosphere. The height of the column of mercury is $18in$. What is the pressure inside the tank?

A. $9psia$

B. $18psia$

C. $24psia$

D. $37psia$

Refer to the Commonly Used Equivalents, taking note of the relationship between inches of mercury and psi.

$$1in\,of\,mercury = 0.491psi$$

Since the manometer is open to the atmosphere on one side, the height of the column of mercury measures the gauge pressure only. The absolute pressure must account for atmospheric pressure which is exerted on the open manometer in addition to the mercury. Determine the pressure of the column of mercury and add $14.7psi$ for the atmosphere.

$$P_g = (18in)(0.491psi) = 8.84psig$$

$$P_a = 8.84psig + 14.7psi = 23.5psia$$

Answer C

46.49 The SR-71 Blackbird aircraft travels at $2193mph$ at an an altitude of $70,000ft$ where the temperature is $-70°F$. What is the Mach number?

A. 2.8

B. 3.3

C. 7.7

D. 18.9

The Mach Number is the ratio of velocity of the air to the speed of sound.

$$M = \frac{V}{c}$$

The Speed of Sound, c, is a function of the ratio of specific heats, k, the Specific Gas Constant, R, and the temperature, T, in absolute terms i.e. Rankine. The gravitational constant, g_c, also needs to be included to make the units work out, which must be inferred since it is not shown in the reference handbook.

Calculate the speed of sound in air at $-70°F$.

$$c = \sqrt{kRT}$$

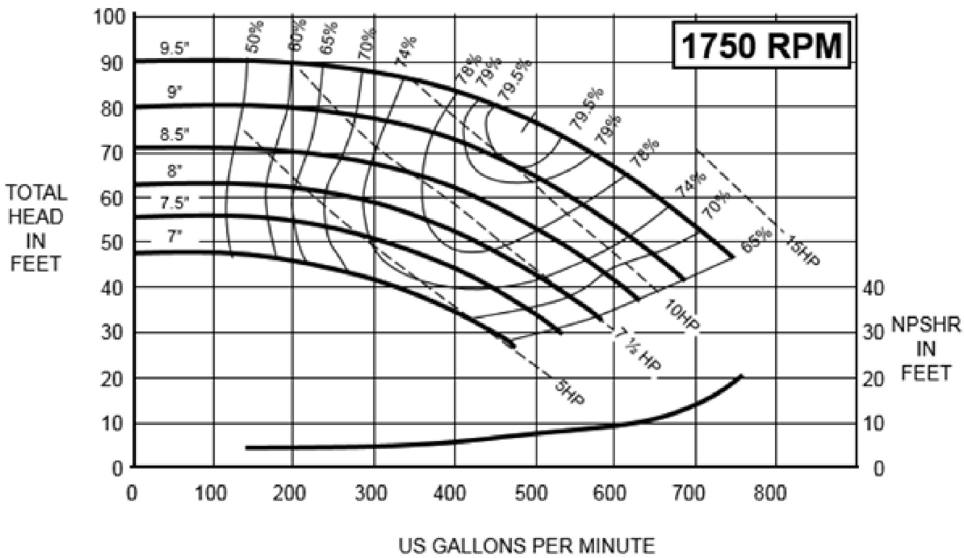
$$c = \sqrt{(1.4)\left(53.3\frac{ft \cdot lb_f}{lb_m \cdot R}\right)(390R)\left(32.2\frac{ft \cdot lb_m}{s^2 \cdot lb_f}\right)} = 968\frac{ft}{s}$$

Determine the Mach number. Convert mph to $\frac{ft}{s}$ such that the final result is unitless.

$$M = \frac{(2193mph)\left(88\frac{ft}{min \cdot mph}\right)\left(\frac{1min}{60s}\right)}{968\frac{ft}{s}} = 3.3$$

Answer B

46.50 The flow rate at the operating point of a $7\frac{1}{2}HP$ pump described by the pump curve below is $300gpm$. What is the amount of pump head needed at the pump shaft?



A. $59ft$

B. $69ft$

C. $74ft$

D. $79ft$

Reading the Pump Performance Curve, follow the $7\frac{1}{2}HP$ curve until it intersects with $300gpm$. This is the operating point. Use the vertical axis to obtain the total head in ft at the operating point. This represents the head added to the fluid by the pump.

$$h_{added} \approx 59ft$$

The head needed *at the shaft* is greater than the head added to the fluid because the pump is not 100% efficient. Read the efficiency at the operating point.

$$\eta_{pump} \approx 75\%$$

Find the amount of head needed at the pump shaft.

$$h_{shaft} = \frac{h_{added}}{\eta_{pump}} = \frac{59ft}{0.75} = 78.7ft$$

Answer D

46.51 A pump is driven by a 4-pole synchronous motor. What is the nominal rotational speed? Ignore slip.

A. $1200rpm$

B. $1800rpm$

C. $2400rpm$

D. $3600rpm$

The number of poles of a Synchronous Speed Motor determines the speed in rpm. Read directly from the table for 4 poles.

$$N = 1800rpm$$

Answer B

46.52 The pressure drop through a chilled water coil at the design flow rate of $25gpm$ is $8psi$. During normal operation, the actual flow rate is $4gpm$. What is the pressure drop in normal operation?

A. $0.2psi$

B. $1.3psi$

C. $4.1psi$

D. $8.0psi$

The pressure drop is a function of the physical design of the coil and the velocity pressure from the water. Static pressure in a hydronic system tends to be relatively stable and gravitational effects are likely to be minimal in the vicinity of the coil. The primary driver is the operation of the control valve which allows more or less flow into the coil. Recall $Q = vA$. Since the coil cross-sectional area is constant, the velocity is proportional to the volume flow rate. Since velocity pressure depends on the *square* of the velocity, relate the ratio of the pressure drops to the ratio of the velocities *squared*. Then substitute flow rate for velocity since flow rates are given. Substitute and solve for ΔP_{actual}.

$$\frac{\Delta P_{actual}}{\Delta P_{design}} = \left(\frac{v_2}{v_1}\right)^2 = \left(\frac{Q_2}{Q_1}\right)^2 = \left(\frac{4gpm}{25gpm}\right)^2 = 0.0256$$

$$\Delta P_{actual} = 0.0256\left(\Delta P_{design}\right) = 0.0256\left(8psi\right) = 0.2psi$$

Answer A

46.53 Air exits a nozzle at $500\frac{ft}{s}$ into a $70°F$ room at atmospheric pressure. What is the Mach number?

A. 0.39

B. 0.44

C. 2.3

D. 2.5

The Mach Number is the velocity of the air divided by the speed of sound in air. The speed of sound in air can be determined in at least three ways. First, it can be memorized. $c \approx 1130\frac{ft}{s}$

Second, it can be looked up in the Properties of Air at Low Pressure table. Interpolate or estimate as necessary.

Third, it can be calculated using the equation below. However, to make the units work, the gravitational constant, g_c, must also be included for US customary units. Substitute the ratio of specific heats for air, the Specific Gas Constant for air, and the absolute temperature in degrees Rankine.

$$c = \sqrt{kRT}$$

$$c = \sqrt{kRTg_c}$$

$$c = \sqrt{(1.4)\left(53.35\frac{ft \cdot lb_f}{lb_m \cdot R}\right)(530R)\left(32.2\frac{lb_m \cdot ft}{lb_f \cdot s^2}\right)} = 1128\frac{ft}{s}$$

Calculate the Mach number.

$$M = \frac{V}{c}$$

$$M = \frac{500\frac{ft}{s}}{1128\frac{ft}{s}} = 0.44$$

Answer B

46.54 **$20gpm$ of oil with specific gravity 0.88 flows through a valve with a valve coefficient of 4.5. What is the pressure drop across the valve?**

A. $3.9psi$

B. $4.4psi$

C. $17psi$

D. $20psi$

The Valve Flow Coefficient for a fluid other than water is given by the equation below which accounts for the specific gravity. The volume flow rate must be in gpm and the pressure drop must be in psi. Rearrange to isolate ΔP, substitute, and solve.

$$C_v = Q\sqrt{\frac{SG}{\Delta P}}$$

$$C_v^2 = Q^2 \frac{SG}{\Delta P}$$

$$\Delta P = \left(\frac{Q}{C_v}\right)^2 SG = \left(\frac{20}{4.5}\right)^2 (0.88) = 17.4psi$$

Answer C

46.55 **$1000gpm$ of water is pumped up an incline of $200ft$. The suction pressure is $50psig$ and the pressure at the extent of the discharge piping is $250psig$. The head loss through the discharge piping is $40ft$, and losses through the suction piping are negligible. The suction and discharge piping diameters are $12in$ and $8in$, respectively. How much horsepower is supplied by the pump?**

A. $111hp$

B. $132hp$

C. $177hp$

D. $410hp$

Use the modified Bernoulli Equation for head added by a pump.

$$h_A = \frac{P_2 - P_1}{\gamma} + \frac{v_2^2 - v_1^2}{2g} + z_2 - z_1 + h_f$$

Neglect the velocity term. Use the rule of thumb conversion factor to convert the differential static pressure from psi to ft.

$$h_A = (250psig - 50psig)\left(2.31\frac{ft}{psi}\right) + (200ft) + 40ft = 702ft$$

Calculate the Water Horsepower added by the pump.

$$whp = \frac{Q\Delta h}{3960}$$

$$whp = \frac{(1000)(702)}{3960} = 177hp$$

Answer C

46.56 A threaded $\frac{3}{4}in$ pipe has (4) 90-degree long radius elbows and (6) 45-degree elbows. The volume flow rate is $5gpm$. What is the minor head loss for the system?

A. $0.2ft$

B. $0.3ft$

C. $0.7ft$

D. $0.8ft$

Use the equation for head loss from Fittings Losses.

$$h_{f,minor} = K\left(\frac{v^2}{2g}\right)$$

Use the Steel Pipe Friction Tables to find the velocity for $5gpm$ flowing in a nominal $\frac{3}{4}in$ pipe.

$$v = 3.01\frac{ft}{s}$$

Look up the K-Factors for Threaded Pipe Fittings and obtain the values for 90-degree long radius elbows and 45-degree elbows. Take the sum accounting for the quantities to find the value of K in total.

$$K = 4(0.92) + 6(0.35) = 5.78$$

Solve for the minor losses.

$$h_{f,minor} = (5.78)\frac{\left(3.01\frac{ft}{s}\right)^2}{2\left(32.2\frac{ft}{s^2}\right)} = 0.8ft$$

Answer D

46.57 A $6in$ gate valve with flow coefficient 150 permits $500gpm$ of oil $(SG = 0.88)$ to flow through a piping system. What is the pressure drop across the valve?

A. $2.9psi$

B. $3.3psi$

C. $9.8psi$

D. $11.1psi$

Use the equation for the Valve Flow Coefficient for fluids other than water to account for the specific gravity of oil. Rearrange to isolate ΔP.

$$C_v = Q\sqrt{\frac{SG}{\Delta P}}$$

$$\Delta P = \left(\frac{Q}{C_v}\right)^2 SG$$

Substitute and solve. Make sure the volume flow rate, Q, is in gpm, and the pressure drop will be obtained in psi.

$$\Delta P = \left(\frac{500}{150}\right)^2 (0.88) = 9.8psi$$

Answer C

46.58 An air handler uses $52°F$ chilled water to cool and dehumidify a room which is maintained at $78°F$ and 50% relative humidity. The AHU has a single chilled water coil from which air is discharged at $60°F$ db / $58°F$ wb. The unit also has a bypass damper which is modulated to allow 25% of the required airflow to bypass the coil under normal operating conditions. The unit provides $10,000cfm$ of supply air to the space. Prior to returning to the unit, 10% of the air is exhausted and outside air at $95°F$ db / $75°F$ wb is mixed into the return stream for ventilation. What is the total cooling load provided by the air handler?

A. $13tons$

B. $16tons$

C. $18tons$

D. $21tons$

Sketch the system and label all given information. Consider the air entering the coil as State 1 and the air being discharged from the coil as State 2. The total cooling load provided by the air handler is a function of airflow over the coil only, as the bypass air is neither cooled nor dehumified. Since the unit provides a total volume flow rate of $10,000cfm$, and the bypass damper allows 25% of the airflow to bypass the coil, the volume flow rate over the coil is the remaining 75%.

$$Q = (0.75)\,(10,000cfm) = 7500cfm$$

Use the total cooling rule of thumb.

$$\dot{Q}_t = 4.5cfm\Delta h$$

The coil discharge condition is fully defined. Use the Psychrometric Chart to obtain the enthalpy of the discharge air coming off the coil.

$$T_{2,db} = 60°F$$

$$T_{2,wb} = 58°F$$

$$h_2 = 25.1\frac{Btu}{lb}$$

The entering condition is a mixture of return air and outside air. 10% of the return air is exhausted and replaced by outside air. Use the Psychrometric Chart again to find the enthalpy for the room/return condition, and the enthalpy of the outside air. Then perform a mixing calculation to find the enthalpy of the mixed air. This is the entering coil condition.

$$T_R = 78°F$$

$$\phi_R = 50\%$$

$$h_R = 29.96 \frac{Btu}{lb}$$

$$T_{OA,db} = 95^\circ F$$

$$T_{OA,wb} = 75^\circ F$$

$$h_{OA} = 38.4 \frac{Btu}{lb}$$

$$h_1 = (0.9)\left(29.96 \frac{Btu}{lb}\right) + (0.1)\left(38.4 \frac{Btu}{lb}\right) = 30.8 \frac{Btu}{lb}$$

Solve for the total cooling load. Units need not be shown when applying a "rule of thumb" formula provided the input units are as expected, the outcome will be $\frac{Btu}{hr}$. Convert the final answer to refrigeration *tons*.

$$\dot{Q}_t = 4.5 cfm \left(h_1 - h_2\right)$$

$$\dot{Q}_t = 4.5\left(7500\right)\left(30.8 - 25.1\right) = 192,375 \frac{Btu}{hr}$$

$$\dot{Q}_t = \frac{192,375 \frac{Btu}{hr}}{12,000 \frac{Btu}{hr \cdot ton}} = 16 tons$$

Answer B

46.59 A fan rated for $15bhp$ is controlled by a variable frequency drive and runs at $900rpm$ which is 50% of its maximum speed, supplying $20,000cfm$ of air against a system pressure of $1.5in\,wg$. The existing filters are replaced with new high efficiency filters increasing the pressure drop by $0.75in\,wg$. What is the required fan speed following this upgrade?

A. $1100rpm$

B. $1350rpm$

C. $2030rpm$

D. $3040rpm$

Consider the original operating conditions as State 1 and the final operating conditions as State 2. Use the Fan Affinity Laws to find the new speed, N_2. Pressure changes with the *square* of the change in speed. Therefore, speed changes with the *square root* of the change in pressure. Select equation '1b' and cross out the diameter and density ratios which are not changing and may be assumed to equal 1.

$$P_1 = P_2 \left(\frac{N_1}{N_2}\right)^2$$

$$N_2 = N_1\sqrt{\frac{P_2}{P_1}} = (900rpm)\sqrt{\frac{2.25in\,wg}{1.5in\,wg}} = 1102rpm$$

Answer A

46.60 An atypical hydronic system permits the velocity of water to reach a maximum of $12\frac{ft}{s}$ when required. What is the smallest nominal schedule 40 steel pipe size that should be selected for a flow rate of $50gpm$?

A. $1in$

B. $1.25in$

C. $1.5in$

D. $2in$

Use the relation $Q = vA$ to specify the required area. Express area as $A = \frac{\pi}{4}D^2$ and solve for the minimum diameter.

$$A = \frac{Q}{v}$$

$$A = \frac{\pi}{4}D^2$$

$$\frac{\pi}{4}D^2 = \frac{Q}{v}$$

$$D = \sqrt{\frac{4Q}{\pi v}} = \sqrt{\frac{4\left(50\frac{gal}{min}\right)\left(\frac{1ft^3}{7.48gal}\right)\left(\frac{1min}{60s}\right)}{\pi\left(12\frac{ft}{s}\right)}} = 0.109ft\left(\frac{12in}{1ft}\right) = 1.30in$$

Refer to the Schedule 40 Steel Pipe table. The inside diameter of a $1.25in$ nominal pipe size is physically $1.38in$. There is no need to choose a larger size.

Answer B

46.61 $1200gpm$ of water flows through a $50ft$ length of pipe with a $8in$ inside diameter and a friction factor of 0.02. What is the pressure drop?

A. $0.2psi$

B. $0.6psi$

C. $1.4psi$

D. $5.9psi$

Determine the velocity of water flowing in the pipe. The Steel Pipe Friction Tables provide a reasonable approximation, however the problem does not state 'nominal' or 'standard weight' or 'schedule 40.' Therefore, it is recommended to calculate the values manually.

$$Q = vA$$

$$v = \frac{Q}{A} = \frac{\left(1200\frac{gal}{min}\right)\left(\frac{1ft^3}{7.48gal}\right)\left(\frac{1min}{60s}\right)}{\frac{\pi}{4}\left(\frac{8in}{12\frac{in}{ft}}\right)^2} = 7.66\frac{ft}{s}$$

Use the Darcy-Weisbach Equation to find the head loss in ft. Then use the rule of thumb conversion factor for water to convert the units to psi for the pressure drop.

$$h_f = \frac{fLv^2}{2Dg}$$

$$h_f = \frac{(0.02)(50ft)\left(7.66\frac{ft}{s}\right)^2}{2\left(\frac{8in}{12\frac{in}{ft}}\right)\left(32.2\frac{ft}{s^2}\right)} = 1.37ft$$

$$\Delta P = \frac{1.37ft}{2.31\frac{ft}{psi}} = 0.59psi$$

Answer B

46.62 A pump delivers $250gpm$ and produces $125ft$ of head. The fluid being distributed has a density of $71\frac{lb_m}{ft^3}$ and the pump is 80% efficient. What is the brake horsepower required to drive the pump?

A. $9.0hp$

B. $9.9hp$

C. $11.2hp$

D. $25.9hp$

Use the formula for Brake HP. The volume flow rate, head, and efficiency are given. Use the density of the fluid along with the standard density of water to determine the Specific Gravity, then solve for the bhp.

$$bhp = \frac{Q\Delta h \cdot SG}{3960\eta_p}$$

$$SG = \frac{\rho}{\rho_{water}} = \frac{71\frac{lb_m}{ft^3}}{62.4\frac{lb_m}{ft^3}} = 1.14$$

$$bhp = \frac{(250gpm)(125ft)(1.14)}{3960(0.8)} = 11.2hp$$

Answer C

46.63 A heat pump operated in cooling mode has a capacity of 2 refrigeration tons and uses a $1500W$ compressor. What is the coefficient of performance?

A. 4.7

B. 5.7

C. 8.1

D. 10.4

Since the heat pump is being operated in cooling mode, use the formula for refrigerators and air conditioners under Coefficient of Performance. Substitute the cooling capacity for Q_L and the compressor energy for W. Align the units in the numerator and denominator such that the final result is unitless.

$$COP = \frac{Q_L}{W}$$

$$COP = \frac{(2tons)\left(12,000\frac{Btu}{hr\cdot ton}\right)}{(1500W)\left(3.412\frac{Btu}{hr\cdot W}\right)} = 4.69$$

Answer A

46.64 A centrifugal pump consumes $200hp$ when operating at $1800rpm$. What is the electrical power demand when the pump speed is reduced to $1200rpm$? Assume 100% motor efficiency.

A. $44KW$

B. $59KW$

C. $66KW$

D. $89KW$

The motor output, typically expressed in bhp, is the input to the pump. Therefore, if the pump initially *consumes* $200hp$, this represents the motor output. Since the motor efficiency is assumed to be 100%, the motor's electrical power demand (input) is equal in magnitude to its bhp (output) and differs only in its units. Electrical power input is typically expressed in KW.

To account for the reduction in speed, the Pump Affinity Laws can be used to find the new power. Select the equation under the column "Speed Change" on the row "Horsepower." Let the subscript '1' denote the original operating conditions and '2' denote the new conditions. Substitute and solve for the new bhp.

$$bhp_2 = bhp_1 \left(\frac{N_2}{N_1}\right)^3 = (200hp)\left(\frac{1200rpm}{1800rpm}\right)^3 = 59.26hp$$

Since there are assumed to be no motor losses, simply convert the units of the output power from hp to KW to determine the electrical input power.

$$\dot{W} = 59.26hp\left(\frac{745.7W}{hp}\right)\left(\frac{1KW}{1000W}\right) = 44.2KW$$

Answer A

46.65 During initial operating conditions, the cooling coil in a computer room air conditioning unit cools $90°F$ entering air to $65°F$. The unit uses $56°F$ supply chilled water to drive the coil temperature to an apparatus dew point of $60°F$. The coil is designed for a maximum air side delta T of $25°F$. After an increase in heat load, the same unit is met with $95°F$ return air. In order to stay safely within the coil's temperature limits, operators raise the chilled water supply temperature to $63°F$ such that the apparatus dew point becomes $67°F$. What is the expected discharge air temperature based on the new operating conditions?

A. $68.3°F$

B. $70.0°F$

C. $71.7°F$

D. $72.5°F$

Consider the original operating conditions as Case A and the final operating conditions as Case B. Calculate the coil efficiency for Case A. Coil efficiency is the ratio of the actual ΔTaccross the coil as compared to the maximum possible ΔT which occurs when the discharge air has been cooled to the apparatus dew point (ADP).

$$\eta_A = \frac{T_{return,A} - T_{discharge,A}}{T_{return,A} - ADP_A} = \frac{90°F - 65°F}{90°F - 60°F} = 0.833$$

Assume the coil efficiency remains constant for the new set of operating conditions.

$$\eta_B = \eta_A = 0.833$$

Use the new return temperature and new ADP for Case B to determine the new discharge temperature, $T_{discharge,B}$, after the change.

$$\eta_B = \frac{T_{return,B} - T_{discharge,B}}{T_{return,B} - ADP_B} = \frac{95°F - T_{discharge,B}}{95°F - 67°F} = 0.833$$

$$T_{discharge,B} = 71.7°F$$

While it is not required for the solution, it is noteworthy that the reduction in ΔT on the air side will require an increase in cfm to satisfy the same cooling demand, and since the problem states that the heat load has been *increased*, this compounds the need for additional airflow!

Answer C

46.66 Water flows at $4fps$ through a $200ft$ pipe with inside diameter of $1.45in$. The Moody friction factor is 0.028. What is the pressure drop?

A. $1.2psi$

B. $5.0psi$

C. $11.5psi$

D. $59.8psi$

Use the Darcy equation for Head Loss Due to Flow to calculate the head loss based on the given information.

$$h_f = \frac{fLv^2}{2Dg} = \frac{(0.028)(200ft)\left(4\frac{ft}{s}\right)^2}{2\left(\frac{1.45}{12}ft\right)\left(32.2\frac{ft}{s^2}\right)} = 11.51ft$$

Convert the head loss in ft to a pressure drop in psi. These terms are often used interchangably. Converting between pressure units and length units is trivial provided the fluid is water.

$$\Delta p = 11.51ft\left(\frac{1psi}{2.31ft}\right) = 4.98psi$$

Answer B

46.67 An energy recovery device is used to pre-cool $5000cfm$ of outside air at $95°F$ db / $75°F$ wb. An equivalent volume of return air enters the device at $76°F$ and 50% relative humidity. After passing through the device the exhaust air is discharged outside at $84°F$ db / $70°F$ wb. What is the reduction in cooling demand provided by the energy recovery wheel?

A. $4tons$

B. $8tons$

C. $10tons$

D. $18tons$

Sketch the energy recovery device, considering the outside air as State 1, the supply air as State 2, the exhaust air as State 3, and the return air as State 4. Since the problem statement makes no reference to any losses or effectiveness, assume 100% of the heat absorbed by the exhaust stream from $4 \rightarrow 3$ is removed from the supply stream $1 \rightarrow 2$. For an energy recovery device, both sensible and latent heat are transferred, so it is appropriate to quantify the total heat gained by the exhaust path using the change in enthalpy which accounts for both sensible and latent energy. State 3 and State 4 are both fully defined, so use the Psychrometric Chart to obtain the enthalpies, h_3 and h_4.

$$T_{3,db} = 84°F$$

$$T_{3,wb} = 70°F$$

$$h_3 = 33.96\frac{Btu}{lb}$$

$$T_4 = 76°F$$

$$\phi_4 = 50\%$$

$$h_4 = 28.74\frac{Btu}{lb}$$

Use the total heating rule of thumb to calculate the total heat added to the exhaust stream, and thus removed from the supply stream. Convert to refrigeration *tons*.

$$\dot{Q}_t = 4.5cfm\Delta h = 4.5\,(5000)\,(33.96 - 28.74) = 117,450\frac{Btu}{hr}$$

$$\dot{Q}_t = \frac{117,450\frac{Btu}{hr}}{12,000\frac{Btu}{hr\cdot ton}} = 9.8tons$$

Answer C

46.68 A 75% effective enthalpy wheel supplies $2000cfm$ of tempered air by recovering energy from a return air stream at $74°F$ and 50% relative humidity. The entering outside air is $96°F$ db / $76°F$ wb. What is the dry bulb temperature of the tempered air?

A. $76°F$

B. $79°F$

C. $82°F$

D. $85°F$

An enthalpy wheel is an example of an Energy-Recovery Ventilator (ERV). Therefore, both sensible and latent energy are transferred through the device. However, the question is concerned only with the *dry bulb temperature* of the tempered air, therefore it is not necessary to consider the enthalpy values in this case. (To be clear, it wouldn't be incorrect or inappropriate to explore the enthalpies as both sensible and latent heat are being conveyed when using an enthalpy wheel; it simply is not necessary in this case.) The effectiveness of the enthalpy wheel applies to both the sensible and latent heat being transfered in an equal manner. In other words, 75% of the possible sensible heat is being transferred, and 75% of the possible latent heat is being transferred.

Sketch the enthalpy wheel and label with all given information. Equate the effectiveness to the ratio of the actual delta T achieved between the outside air and the tempered air as compared to the maximum delta T possible, which would be the difference between the outside air and the return air. It is recommended to arrive at this relation through reasoning since the HRV/ERV formulas in the Reference Handbook are unecessarily convoluted.

$$\varepsilon = \frac{T_{OA} - T_{TA}}{T_{OA} - T_{RA}}$$

$$0.75 = \frac{96°F - T_{TA}}{96°F - 74°F}$$

$$T_{TA} = 79.5°F$$

Answer B

46.69 $10,000 cfm$ **of air at** $90°F$ **db /** $54°F$ **wb enters an evaporative cooler using a** $50°F$ **water spray to produce** $60°F$ **leaving air. What is the saturation efficiency?**

A. 62%

B. 67%

C. 75%

D. 83%

Sketch the evaporative cooler and label the entering and leaving air conditions. Consider the entering condition as State 1 and the leaving condition as State 2. Use the formula for Saturation Efficiency. The numerator is the actual ΔT observed, and the denominator is the maximum possible ΔT achievable if the leaving air was reduced to the wet bulb temperature of the entering air. This would imply 100% saturation efficiciency. The volume flow rate of the air and and the spray temperature are excess information.

$$\varepsilon_e = \frac{T_1 - T_2}{T_1 - T_{1,wb}} = \frac{90°F - 60°F}{90°F - 54°F} = 0.833 = 83.3\%$$

Answer D

46.70 Steam enters a 75% efficient turbine at a pressure of $800psia$ and a temperature of $700°F$ and exits at atmospheric pressure. What is the specific work produced by the turbine?

A. $250\frac{Btu}{lb}$

B. $330\frac{Btu}{lb}$

C. $1010\frac{Btu}{lb}$

D. $1190\frac{Btu}{lb}$

Consider the entering steam as State 1 and the exiting steam as State 2. Use the properties of Superheated Steam tables to obtain the enthalpy and entropy at State 1.

$$P_1 = 800psia$$

$$T_1 = 700°F$$

$$h_1 = 1338.4\frac{Btu}{lb}$$

$$s_1 = 1.548\frac{Btu}{lb \cdot R}$$

Find the *ideal* entropy and enthalpy at State 2 by imagining the turbine was isentropic i.e. 100% efficient. Use the properties of Saturated Water and Steam table to look up entropy values to determine the ideal quality for State 2, and use the quality to find the ideal enthalpy at State 2.

$$s_2 = s_1 = 1.548\frac{Btu}{lb \cdot R}$$

$$P_2 = 14.7psia$$

$$s_f = 0.3122\frac{Btu}{lb \cdot R}$$

$$s_{fg} = 1.4443\frac{Btu}{lb \cdot R}$$

$$h_f = 180.18\frac{Btu}{lb}$$

$$h_{fg} = 970.07\frac{Btu}{lb}$$

$$\chi_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{1.548\frac{Btu}{lb \cdot R} - 0.3122\frac{Btu}{lb \cdot R}}{1.4443\frac{Btu}{lb \cdot R}} = 0.856$$

$$h_2 = h_f + \chi_2 h_{fg} = 180.18\frac{Btu}{lb} + (0.856)\left(970.07\frac{Btu}{lb}\right) = 1010.2\frac{Btu}{lb}$$

Determine the *actual* change in enthalpy by applying the efficiency. This is the specific work produced by the turbine.

$$\eta = \frac{h_1 - h_2^{'}}{h_1 - h_2}$$

$$w = h_1 - h_2^{'} = \eta\left(h_1 - h_2\right) = 0.75\left(1338.4\frac{Btu}{lb} - 1010.2\frac{Btu}{lb}\right) = 246.2\frac{Btu}{lb}$$

Answer A

46.71 The overall efficiency of a gas turbine combined cycle is 55%. The gas turbine cycle standing alone has an efficiency of 40%. What is the efficiency of the Rankine cycle?

A. 9%

B. 25%

C. 75%

D. 91%

Refer to the Brayton Cycle for the gas turbine standing alone. Refer to the Combined Cycle when waste heat recovery is included. The heat recovery section can be modeled as a Rankine Cycle. The product of the *losses* from the Brayton Cycle and the *losses* from the Rankine Cycle equals the *losses* from the Combined Cycle. Solve for the efficiency of the Rankine Cycle.

$$\left(1 - \eta_{Brayton}\right)\left(1 - \eta_{Rankine}\right) = \left(1 - \eta_{Combined}\right)$$

$$\left(1 - 0.4\right)\left(1 - \eta_{Rankine}\right) = \left(1 - 0.55\right)$$

$$1 - \eta_{Rankine} = \left(\frac{0.45}{0.6}\right) = 0.75$$

$$\eta_{Rankine} = 0.25$$

Another way to conceptualize this scenario is to notice that since the standalone Brayton Cycle has 40% efficiency, that implies 60% losses. Reason that to increase the overall efficiency of the combined cycle to from 40% to 55%, 15% of the wasted 60% must be converted into useful work, which is one fourth or 25% of the waste energy from the Brayton Cycle which is heat input to the Rankine Cycle.

Answer B

46.72 Water is pumped from an open tank by a pump located $15ft$ below the top of the tank's waterline. The pump adds $50ft$ of total head. The discharge pressure is $28psig$. Neglecting losses on the suction side of the pump, what is the velocity of the flowing water?

A. $5\frac{ft}{s}$

B. $11\frac{ft}{s}$

C. $18\frac{ft}{s}$

D. $47\frac{ft}{s}$

Sketch the reservoir and pump. Consider the reservoir as State 1 and the pump discharge as State 2. Write the modified Bernoulli equation for the total head added by a pump. A useful version may be obtained by starting with the Mechanical Energy Equation in section 9.6.4 of the Reference Handbook.

$$h_A = \frac{P_2 - P_1}{\gamma} + \frac{v_2^2 - v_1^2}{2g} + (z_2 - z_1)$$

The head added by the pump is given as $h_A = 50ft$. The static pressure at the source, State 1, is atmospheric pressure and the static pressure at the pump discharge, State 2, is measured by a gauge as $28psig$. Since the difference in pressure is needed, it is not necessary to convert to absolute pressure terms. Simply subtract and use the conversion factor rule of thumb, $2.31\frac{ft}{psi}$ to convert the units of the static pressure term from psi to ft.

$$\frac{P_2 - P_1}{\gamma} = (28psig - 0psig)\left(2.31\frac{ft}{psi}\right)$$

For the velocity term, the velocity of the water in the reservoir is zero. The velocity at the pump discharge, State 2, is the unknown being sought in this problem.

$$\frac{v_2^2 - v_1^2}{2g} = \frac{v_2^2}{2g}$$

For the elevation term, the pump is $15ft$ below the top of the reservoir, therefore the Δz term will be negative, which aligns with the expectation that *less* work will need to be done by the pump since the source water on the suction side is at a relatively higher elevation.

$$z_2 - z_1 = 0ft - 15ft = -15ft$$

Substitute and solve for the velocity term, then solve for the discharge velocity, v_2.

$$50ft = (28psig - 0psig)\left(2.31\frac{ft}{psi}\right) + \frac{v_2^2}{2g} - 15ft$$

$$\frac{v_2^2}{2g} = 0.32ft$$

$$v_2^2 = (0.32ft)(2)\left(32.2\frac{ft}{s^2}\right) = 20.6\frac{ft^2}{s^2}$$

$$v_2 = \sqrt{20.6\frac{ft^2}{s^2}} = 4.5\frac{ft}{s}$$

Answer A

46.73 A boiler produces saturated steam at atmospheric pressure. $20gpm$ of feedwater enters at $160°F$ and $14.7psia$. What is the boiler horsepower rating?

A. $270 boiler\ hp$

B. $280 boiler\ hp$

C. $290 boiler\ hp$

D. $300 boiler\ hp$

Consider the feedwater entering the boiler as State 1 and the steam leaving the boiler as State 2. To find the enthalpy at State 1, recall from Thermodynamics that the change in enthalpy is the product of the specific heat capacity and the change in termperature. State 1 is compressed water which has been cooled sensibly past the saturation temperature of $212°F$. Use the properties of Saturated Water and Steam table to obtain the enthalpy for a saturated liquid at $14.7psia$, and determine h_1.

$$P_1 = 14.7psia$$

$$T_1 = 160°F$$

$$\Delta h = c_p \Delta T$$

$$h_{sat} - h_1 = c_p (T_{sat} - T_1)$$

$$h_1 = h_{sat} - c_p (T_{sat} - T_1) = 180.18\frac{Btu}{lb} - \left(1\frac{Btu}{lb \cdot °F}\right)(212°F - 160°F) = 128.2\frac{Btu}{lb}$$

Use the properties of Saturated Water and Steam table again to obtain the enthalpy for State 2.

$$P_2 = 14.7psia\ (saturated)$$

$$h_2 = 1150.25\frac{Btu}{lb}$$

Find the mass flow rate in $\frac{lb}{hr}$. Use the Properties of Water table to obtain the density at State 1.

$$\dot{m} = \rho Q$$

$$\dot{m} = \left(61\frac{lb}{ft^3}\right)\left(20\frac{gal}{min}\right)\left(\frac{1ft^3}{7.48gal}\right)\left(\frac{60min}{1hr}\right) = 9786\frac{lb}{hr}$$

Determine the heat added by the boiler. Find the converstion factor from $\frac{Btu}{hr}$ to *boiler hp* in the Measurement Relationships table.

$$\dot{Q} = \dot{m}\Delta h$$

$$\dot{Q} = \frac{\left(9786\frac{lb}{hr}\right)\left(1150.25\frac{Btu}{lb} - 128.2\frac{Btu}{lb}\right)}{\left(33,470\frac{Btu}{hp\cdot boiler\ hp}\right)} = 299 boiler\ hp$$

Answer D

46.74 A three-phase AC generator supplies $700A$ at $480V$ with a power factor of 0.8 and an efficiency of 90%. The engine speed is $3600rpm$. What is the torque needed to drive the generator?

A. $610ft \cdot lb_f$

B. $750ft \cdot lb_f$

C. $820ft \cdot lb_f$

D. $1010ft \cdot lb_f$

Adapt the last formula in the table Power for Different Motor Phases for a generator. Normally the formula is used to calculate the output horsepower from a motor that receives a certain input of electricity, hence the efficiency is placed in the numerator to account for the motor's losses. However, in this case the generator receives horsepower as its input and produces electricity as its output, therefore it is appropriate to *divide* by the efficiency to account for the generator's losses.

$$P_{[hp]} = \frac{\sqrt{3}IV\,(pf)}{746\eta}$$

$$P = \frac{\sqrt{3}\,(700A)\,(480V)\,(0.8)}{(746)\,(0.9)} = 693.4hp$$

On the same page in reference handbook under Torques, use the formula relating the torque to the horsepower and rotational speed. Provided the speed is in rpm, the torque will be in $ft \cdot lb_f$. No additional unit conversion is neeeded. Calculate the torque.

$$T = 5250\left(\frac{hp}{rpm}\right)$$

$$T = 5250\left(\frac{693.4}{3600}\right) = 1011 ft \cdot lb_f$$

Answer D

46.75 The output shaft of an engine accelerates from $1000rpm$ at idle to $6000rpm$ at red line in $5seconds$. What is the rotational acceleration?

A. $105\frac{rad}{s^2}$

B. $521\frac{rad}{s^2}$

C. $727\frac{rad}{s^2}$

D. $1000\frac{rad}{s^2}$

Use the definition for rotational acceleration under Rigid Body Rotation. Re-write the derivative expression as a change in rotational velocity over time. No calculus is required.

$$\alpha = \frac{d\omega}{dt}$$

$$\alpha = \frac{\Delta\omega}{t}$$

Subtract to find the change in rotational velocity and convert units to $\frac{rad}{s}$.

$$\Delta\omega = \omega_2 - \omega_1 = 6000rpm - 1000rpm = 5000rpm$$

$$\Delta\omega = 5000\frac{rev}{min}\left(\frac{2\pi rad}{rev}\right)\left(\frac{1min}{60s}\right) = 523.6\frac{rad}{s}$$

Divide by the time to determine the rotational acceleration.

$$\alpha = \frac{523.6\frac{rad}{s}}{5s} = 104.7\frac{rad}{s^2}$$

Answer A

46.76 Superheated steam at $400psia$ and $700°F$ is expanded in a 85% efficient turbine to atmospheric pressure. What is the enthalpy of the saturated mixture exiting the turbine?

A. $1120\frac{Btu}{lb}$

B. $1130\frac{Btu}{lb}$

C. $1140\frac{Btu}{lb}$

D. $1150\frac{Btu}{lb}$

Sketch the turbine. Consider the entering superheated steam as State 1 and the exiting saturated mixture as State 2. Use the Properties of Superheated Steam table to determine the enthalpy and entropy at State 1, which is fully defined since the temperature and pressure are both known.

$$P_1 = 400psia$$

$$T_1 = 700°F$$

$$h_1 = 1362.9\frac{Btu}{lb}$$

$$s_1 = 1.641\frac{Btu}{lb°R}$$

Initially assume isentropic expansion to find the ideal exit quality at State 2.

$$s_2 = s_1 = 1.641\frac{Btu}{lb°R}$$

Use the Properties of Saturated Water and Steam (Pressure) table to look up s_f and s_{fg} at $P_2 = 1atm = 14.7psia$.

$$s_f = 0.3122\frac{Btu}{lb°R}$$

$$s_{fg} = 1.4443\frac{Btu}{lb°R}$$

Rearrange the formula relating entropy and quality from Properties for Two-Phase (Vapor-Liquid) Systems.

$$s_2 = s_f + \chi_2 s_{fg} \rightarrow \chi_2 = \frac{s_2 - s_f}{s_{fg}}$$

$$\chi_2 = \frac{1.641\frac{Btu}{lb°R} - 0.3122\frac{Btu}{lb°R}}{1.4443\frac{Btu}{lb°R}} = 0.92$$

Use the ideal quality at State 2 to determine the ideal enthalpy at State 2. Return to the Properties of Saturated Water and Steam (Pressure) table to obtain the enthalpies h_f and h_{fg} at $P_2 = 14.7psia$.

$$h_f = 180.18\frac{Btu}{lb}$$

$$h_{fg} = 970.07\frac{Btu}{lb}$$

$$h_{2,ideal} = h_f + \chi_2 h_{fg} = 180.18\frac{Btu}{lb} + 0.92\left(970.07\frac{Btu}{lb}\right) = 1072.7\frac{Btu}{lb}$$

Apply the turbine efficiency to determine the actual enthalpy at State 2, $h_2^{'}$. Recognize the actual change in enthalpy, $\Delta h_{actual} = h_1 - h_2^{'}$, is less than the ideal change in enthalpy, $\Delta h_{ideal} = h_1 - h_2$, as dictated by the turbine efficiency. Rearrange for $h_2^{'}$, substitute, and solve.

$$\eta = \frac{\Delta h_{actual}}{\Delta h_{ideal}} = \frac{h_1 - h_2^{'}}{h_1 - h_2}$$

$$h_2^{'} = h_1 - \eta\left(h_1 - h_2\right)$$

$$h_2^{'} = 1362.9\frac{Btu}{lb} - 0.85\left(1362.9\frac{Btu}{lb} - 1072.7\frac{Btu}{lb}\right) = 1116\frac{Btu}{lb}$$

Answer A

46.77 A room with a volume of $50,000ft^3$is maintained at $72°F$ and 40% relative humidity. The space requires five air changes per hour of ventilation. On a winter design day, the outdoor temperature is $0°F$. What is the required humidification capacity to satisfy this application?

A. $2\frac{lb}{hr}$

B. $60\frac{lb}{hr}$

C. $140\frac{lb}{hr}$

D. $1300\frac{lb}{hr}$

Use the air changes per hour and the volume of the room to calculate the volume flow rate being supplied and exhausted from the space.

$$Q = \left(5\frac{air\,changes}{hr}\right)\left(50,000\frac{ft^3}{air\,change}\right)\left(\frac{1hr}{60min}\right) = 4167cfm$$

The room condition is fully defined. Use the Psychrometric Chart to obtain the humidity ratio for the indoor conditions.

$$T_r = 72°F$$

$$\phi_r = 40\%$$

$$\omega_r = 0.00668 \frac{lb_w}{lb_{da}}$$

To find the required humidification, it is necessary to quantify the change in humidity ratio, which requires specifying the humidity ratio for the outdoor conditions, ω_{OA}. However, the Reference Handbook does not furnish a low temperature psychrometric chart, and the problem statement provides only the temperature without a second data point to better define the state. Fortunately, the Reference Handbook does provide a table underneath the Psychrometric Charts called Thermodynamic Properties of Moist Air which provides the humidity ratio for fully saturated $0°F$ air. From the perspective of sizing the humidification system, saturated outside air would be a best-case scenario.

$$\omega_{OA,sat} = 0.000788 \frac{lb_w}{lb_{da}}$$

Altenratively, the worst-case scenario would be completely dry outside air.

$$\omega_{OA,dry} = 0 \frac{lb_w}{lb_{da}}$$

By establishing a bounded range for the outside moisture levels, recognize the limited capacity of cold air to hold moisture, and conclude that the change in humidity is largely driven by the *internal* requirements and little contribution is being made from the outside regardless of relative humidity. Calculate the change in the humidity ratio using both values to observe the negligible difference in the results.

$$\Delta\omega_{min} = \omega_r - \omega_{OA,sat} = 0.00668 \frac{lb_w}{lb_{da}} - 0.000788 \frac{lb_w}{lb_{da}} = 0.0059 \frac{lb_w}{lb_{da}}$$

$$\Delta\omega_{max} = \omega_r - \omega_{OA,dry} = 0.00668 \frac{lb_w}{lb_{da}} - 0 \frac{lb_w}{lb_{da}} = 0.0067 \frac{lb_w}{lb_{da}}$$

Calculate the average value, $\Delta\omega_{avg}$, and set the expectation of up to ~6% error in the final answer, which should be sufficient since the answer choices are generously spaced.

$$\Delta\omega_{avg} = \frac{\Delta\omega_{min} + \Delta\omega_{max}}{2} = \frac{0.0059 \frac{lb_w}{lb_{da}} + 0.0067 \frac{lb_w}{lb_{da}}}{2} = 0.0063 \frac{lb_w}{lb_{da}}$$

Using the equation under Moist-Air Cooling and Dehumidification, calculate the mass flow rate of water that must be added to the air to achieve the desired internal moisture levels as a function of the mass flow rate of entering air and the change in humidity ratio. When finding the mass flow rate of entering outside air, use the specific volume from the table Thermodynamic Properties of Moist Air, recognizing that the variance between dry and saturated conditions is minimal since air's capacity for holding moisture is negligible at low temperatures. Suggest taking a rough average of the table values for convenience.

$$\dot{m}_w = \dot{m}_a \Delta\omega_{avg}$$

$$\dot{m} = \rho Q = \frac{Q}{v_{OA}} = \frac{\left(4167\frac{ft^3}{min}\right)\left(\frac{60min}{1hr}\right)}{11.585\frac{ft^3}{lb_{da}}} = 21,581\frac{lb_{da}}{hr}$$

$$\dot{m}_w = \left(21,581\frac{lb_{da}}{hr}\right)\left(0.0063\frac{lb_w}{lb_{da}}\right) = 136\frac{lb_w}{hr}$$

Answer C

46.78 A $7.5hp$ motor is 93% efficient. How much waste heat is generated due to losses?

A. $810\frac{Btu}{hr}$

B. $1340\frac{Btu}{hr}$

C. $1440\frac{Btu}{hr}$

D. $2580\frac{Btu}{hr}$

The heat losses from the motor result from input electrical power that is not converted into brake horsepower. Since motors are rated in bhp, the mechanical output power is always equal to the nominal rating of the motor, in this case $7.5hp$. Therefore, the losses do not come out of the $7.5hp$, but rather, come out of the input electrical power leaving (precisely) the bhp left to be delivered.

Calculate the electrical input power to the motor.

$$\dot{W}_{in} = \frac{bhp}{\eta_{motor}} = \frac{7.5hp}{0.93} = 8.065hp$$

The waste heat is the difference between the input electrical power and the output shaft power. Calculate the losses. Convert units to $\frac{Btu}{hr}$.

$$\dot{Q}_{losses} = (0.565hp)\left(\frac{0.7457KW}{hp}\right)\left(\frac{3412\frac{Btu}{hr}}{KW}\right) = 1437\frac{Btu}{hr}$$

Answer C

46.79 **$25gpm$ of water at $300psia$ and $250°F$ goes through a boiler where it is converted to $500psia$ steam at $1000°F$. What is the heat load being delivered by the boiler?**

A. $360 boiler\ hp$

B. $420 boiler\ hp$

C. $460 boiler\ hp$

D. $490 boiler\ hp$

Consider the water entering the boiler as a State 1 and the superheated steam exiting the boiler as State 2. Determine the enthalpy at State 1. Use the properties of Saturated Water and Steam table by pressure and obtain h_f at $P_1 = 300psia$. Since $T_1 < T_{sat}$, the water is subcooled. Solve for the enthalpy at T_1.

$$T_{sat@300psia} = 417.33°F$$

$$h_{sat} = h_{f@300psia} = 393.93\frac{Btu}{lb}$$

$$h_{sat} - h_1 = c_p\left(T_{sat} - T_1\right)$$

$$h_1 = h_{sat} - c_p\left(T_{sat} - T_1\right) = 393.93\frac{Btu}{lb} - \left(1\frac{Btu}{lb°F}\right)(417.33°F - 250°F) = 226.6\frac{Btu}{lb}$$

Approximate the density at State 1 using the Properties of Water table and extrapolating to $250°F$. The pressure is much higher than atmospheric pressure, but this approach yields a fairly accurate result since water incompressible.

$T\,[°F]$	$\rho\left[\frac{lb}{ft^3}\right]$
200	60.1
212	59.83
250	ρ

$$\frac{212°F - 200°F}{250°F - 200°F} = \frac{59.83\frac{lb}{ft^3} - 60.1\frac{lb}{ft^3}}{\rho - 60.1\frac{lb}{ft^3}}$$

$$0.24 = \frac{-0.27\frac{lb}{ft^3}}{\rho - 60.1\frac{lb}{ft^3}}$$

$$\rho - 60.1\frac{lb}{ft^3} = -1.125\frac{lb}{ft^3}$$

$$\rho = 58.98\frac{lb}{ft^3}$$

The density value obtained from compressed water tables not available in the Reference Handbook is $58.8 \frac{lb}{ft^3}$ for a deviation of only 0.3%.

Find the heat load for the boiler. Replace mass flow rate with the product of density and volume flow rate. Convert units to $\frac{Btu}{hr}$, then finally to *boiler hp*.

$$\dot{Q} = \dot{m}\Delta h = \rho Q \Delta h$$

$$\dot{Q} = \left(58.98 \frac{lb}{ft^3}\right)\left(25 \frac{gal}{min}\right)\left(\frac{1 ft^3}{7.48 gal}\right)\left(\frac{60 min}{1 hr}\right)\left(1521 \frac{Btu}{lb} - 226.6 \frac{Btu}{lb}\right) = 1.53 \times 10^7 \frac{Btu}{hr}$$

$$\dot{Q} = \frac{1.53 \times 10^7 \frac{Btu}{hr}}{33,470 \frac{Btu}{hr \cdot boiler\ hp}} = 457 boiler\ hp$$

Answer C

46.80 **$1 \frac{lb_m}{s}$ of saturated liquid water at $50 psia$ enters a mixing chamber along with $1 \frac{lb_m}{s}$ of superheated steam at $50 psia$ and $500°F$. $2 \frac{lb_m}{s}$ of the resulting mixture is discharged after thorough mixing. What is the quality of the mixture?**

A. 0.44

B. 0.50

C. 0.56

D. 0.62

Sketch the mixing chamber. Let State 1 represent the entering saturated liquid, State 2 represent the entering saturated steam, and State 3 represent the exiting mixture. Write the energy balance for the mixing process.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

All mass flow rates are known. Use the Properties of Saturated Water and Steam (Pressure) table to obtain the enthalpy at State 1, h_1.

$$P_1 = 50 psia$$

$$h_1 = h_f = 250.2 \frac{Btu}{lb}$$

Use the Properties of Superheated Steam table to obtain the enthalpy at State 2.

$$P_2 = 50 psia$$

$$T_2 = 500°F$$

$$h_2 = 1284.1 \frac{Btu}{lb}$$

Solve for h_3.

$$h_3 = \frac{\dot{m}_1 h_1 + \dot{m}_2 h_2}{\dot{m}_3} = \frac{\left(1 \frac{lb}{s}\right)\left(250.2 \frac{Btu}{lb}\right) + \left(1 \frac{lb}{s}\right)\left(1284.1 \frac{Btu}{lb}\right)}{\left(2 \frac{lb}{s}\right)} = 767.15 \frac{Btu}{lb}$$

Return to the Properties of Saturated Water and Steam (Pressure) table to obtain the enthalpy of vaporaization, h_{fg}, at $50 psia$.

$$h_{fg} = 924.03 \frac{Btu}{lb}$$

Find the quality at State 3 using the equation from Properties for Two-Phase (Vapor-Liquid) Systems.

$$h_3 = h_f + \chi h_{fg} \rightarrow \chi = \frac{h_3 - h_f}{h_{fg}}$$

$$\chi = \frac{767.15 \frac{Btu}{lb} - 250.2 \frac{Btu}{lb}}{924.03 \frac{Btu}{lb}} = 0.56$$

Answer C

47 Practice Exam #2

47.1 A plant room contains a generator with a noise level of $95dBA$, an air compressor with a noise level of $88dBA$, and a pump with a noise level of $77dBA$. What is the overall noise level?

A. $87dB$

B. $95dB$

C. $96dB$

D. $98dB$

Refer to the table for Combining Two Sound Levels. Note that when the difference between the dB levels of two sources is between 5 and 9, the number of dB to be added to the highest source is $1dB$. Also recall that only two sources may be added at once; the table provides no guidance on adding more than two sources.

Start by combining the two loudest sources.

$$95dB + 1dB = 96dB$$

Regarding the pump noise, recognize that the difference between the noise levels between the pump and combined generator and compressor fall into the '$10dB$ or more' range, therefore, there is no meaningful difference to the combined level.

Answer C

47.2 A data center developer has a choice between (1) building a \$50M data center that will have a 30 year lifespan and cost \$1M per year to maintain, and (2) building a \$15M data center that will have a 10 year lifespan and cost \$3M per year to maintain. If the interest rate is 8%, which alternative is superior?

A. Option 1

B. Option 2

C. Neither, the options are comparable.

D. There is not enough information.

In engineering economics, when evaluating alternatives, there are two basic approaches: comparing the present value, and comparing the equivalent uniform annual cost (EUAC). When the two options have the same life cycle, present value is a viable option. However, when the two options have different life cycles as is the case here, EUAC is the preferred approach. The maintenance costs are given as annual costs already, so the main task is annualizing the up front cost. Write expressions for the EUAC for both options. Use the $i = 8\%$ Factor Table to retreive the cash flow factors.

$$EUAC_1 = \$50M\,(A/P, 8\%, 30) + \$1M = \$50M\,(0.0888) + \$1M = \$5.44M$$

$$EUAC_2 = \$15M\,(A/P, 8\%, 10) + \$3M = \$15M\,(0.1490) + \$3M = \$5.23M$$

Option 2 is superior.
Answer B

47.3 A company with a tax rate of 30% makes a $50,000 one time purchase that drives $8,000 of annual revenue and carries $1200 of annual maintenance costs. The salvage value after 10 years is $5000. What is the present value of the investment over 10 years at a 6% interest rate?

A. $-\$12,200$

B. $-\$6,000$

C. $\$11,700$

D. $\$52,800$

Draw a cash flow diagram or make a list of cash flows.

In Year 0, there is an initial payment of $50K (negative).

In Years 1-10, there is a net profit before tax of $\$8000 - \$1200 = \$6800$ and a net profit after tax of $\$6800\,(1 - 0.3) = \$4760$.

In Year 10, there is also a future payment for the salvage value of $5K in addition to the after-tax profit.

Note the tax rate is applied only to the annual profits and not to the initial cost or salvage value, and there is no reference to depreciation in the problem statement.

Write an expression for the present value. Use the $i = 6\%$ Factor Table to retreive the cash flow factors.

$$PV = -\$50,000 + \$4760\,(P/A, 6\%, 10) + \$5000\,(P/F, 6\%, 10)$$

$$PV = -\$50,000 + \$4760\,(7.3601) + \$5000\,(0.5584) = -\$12,174$$

Answer A

47.4 A company pays $500K for a warehouse that it plans to hold for 15 years. The warehouse will save the company $5000 per month in shipping costs, boosting profit. Maintenance and taxes cost $10,000 per year. At the end of 15 years, what sale price is needed to realize an 8% rate of return?

A. $\$23K$

B. $\$230K$

C. $\$780K$

D. $\$1.7M$

Draw a cash flow diagram or make a list of cash flows.

In Year 0, there is an initial payment of $500K (negative).

In Years 1-15, there is a monthly savings of $5K which translates to a $60K increase to the annual revenue. There is also $10K in annual costs, included taxes. Therefore, the net profit after tax is $(12)(\$5K) - \$10K = \$50K$ per year.

In Year 15, there is a salvage value of unknown magnitude which is being sought in this problem.

Write an expression for the present value. The rate of return is the interest rate that makes the present value equal to zero, in this case, $i = 8\%$. Use the $i = 8\%$ Factor Table to retreive the cash flow factors. Solve for S, the salvage value.

$$PV = -\$500K + \$50K\,(P/A, 8\%, 15) + S\,(P/F, 8\%, 15) = 0$$

$$-\$500K + \$50K\,(8.5595) + S\,(0.3152) = 0$$

$$S = \$228,506$$

Answer B

47.5 A power plant upgrade project takes two years to implement and has an initial cost of $500,000 plus an additional $250,000 at the end of year 1 and year 2. An additional $100,000 retainage will be paid at the end of the one-year defects & liability period following project completion. The life cycle of the upgrade is expected to be 20 years from completion and the salvage value will be $300,000. At an interest rate of 6%, what is the annualized cost of the venture?

A. $83,000

B. $91,000

C. $99,000

D. $107,000

Draw a cash flow diagram or make a summary of cash flows. This solution treats costs as positive.
Year 0: $500K
Year 1: $250K
Year 2: $250K
Year 3: $100K
Year 20: -$300K

The cash flows in years 1 through 3 can be expressed as an annual cost of $100K for 3 years plus an annual cost of an additional $150K for the first 2 years only.

Use the 6% Factor Table in the Economic Analysis section to find the present value:

$$\$500,000 + \$100,000\,(P/A, 6\%, 3) + \$150,000\,(P/A, 6\%, 2) - \$300,000\,(P/F, 6\%, 20)$$

$$\$500,000 + \$100,000\,(2.673) + \$150,000\,(1.8334) - \$300,000\,(.3118) = \$948,770$$

Find the equivalent annualized cost spread over 20 years at 6%:

$$\$948,770\,(A/P, 6\%, 20) = \$948,770\,(.0872) = \$82,733$$

Alternate Approach: Discount each cash flow back to its present value individually:

$$PV_0 = \$500,000$$

$$PV_1 = \$250,000\left(\frac{1}{1+i}\right)^n = \$250,000\left(\frac{1}{1.06}\right)^1 = \$235,849$$

$$PV_2 = \$250,000\left(\frac{1}{1+i}\right)^n = \$250,000\left(\frac{1}{1.06}\right)^2 = \$222,499$$

$$PV_3 = \$100,000\left(\frac{1}{1+i}\right)^n = \$250,000\left(\frac{1}{1.06}\right)^3 = \$83,962$$

$$PV_{20} = -\$300,000\left(\frac{1}{1+i}\right)^n = -\$300,000\left(\frac{1}{1.06}\right)^{20} = -\$93,541$$

Take the sum to find the present value:

$$PV_0 + PV_1 + PV_2 + PV_3 + PV_{20}$$

$$\$500,000 + \$235,849 + \$222,499 + \$83,962 - \$93,541 = \$948,769$$

Use the same approach as in the original solution to find the annualized cost:

$$\$948,769\,(A/P, 6\%, 20) = \$948,770\,(.0872) = \$82,733$$

Answer A

47.6 The air horsepower produced by a fan is $6.3hp$. The fan has a mechanical efficiency of 80% and the fan motor has an efficiency of 95%. The fan runs for 12 hours per day. What is annual electricity consumption for the fan?

A. $21,000kWh$

B. $27,000kWh$

C. $36,000kWh$

D. $54,000kWh$

To find the electrical consumption, start by finding the electrical demand by dividing the air horsepower by both the fan efficiency and the motor efficiency and converting from hp to KW.

$$\dot{W} = \frac{AHP}{\eta_f \eta_m} = \frac{(6.3hp)\left(0.7457\frac{KW}{hp}\right)}{(0.8)\,(0.95)} = 6.18KW$$

Find the annual consumption by multiplying the demand by the amount of time the fan runs throughout the year.

$$Consumption = (6.18KW)\left(12\frac{hr}{day}\right)(365days) = 27,074kWh$$

Answer B

47.7 A fan delivers $10,000cfm$ of $70°F$ air at sea level. How much volume will the same fan deliver when used at $4000ft$ elevation to distribute $50°F$ air?

A. $8,000cfm$

B. $9,000cfm$

C. $11,000cfm$

D. $12,000cfm$

Qualitatively, it stands to reason that increasing the elevation at which the fan is used will increase the capacity of the fan in terms of volume flow rate because air is less dense higher in the atmosphere. However, reducing the temperature of the air makes it more dense, and reduces the capacity of the fan. These factors will compete and must be considered separately.

Search for Temperature and Altitude Corrections and use the table to look up the Density Factors for both the temperature and elevation change.

The Density Factor for the temperature requires interpolation.

Temperature [$°F$]	Density Factor
0	1.152
50	DF_T
70	1

$$\frac{70-50}{70-0} = \frac{1-DF_T}{1-1.152} = 0.2857$$

$$1 - DF_T = -0.0434 \rightarrow DF_T = 1.043$$

Look up the Density Factor for the altitude.

$$DF_A = 0.864$$

Although it is not explicitly stated in the reference handbook whether the original cfm should be multiplied or divided by the density factors, the previous reasoning provides the expectation that the decreased temperature will tend to reduce the fan capacity and the increased altitude will tend to increase the fan capacity. Therefore, the original cfm should be *divided* by the density factors.

$$Q_{4000ft} = \frac{Q_{sea\ level}}{DF_T \cdot DF_A} = \frac{10,000cfm}{(1.043)\,(0.864)} = 11,097cfm$$

Answer C

47.8 A heat recovery ventilator is used to pre-heat $30°F$, 40% RH outside air with $75°F$, 50% RH exhaust air. The HRV effectiveness is 60%. What quantity of heat is recovered?

A. $4.3\frac{Btu}{lb}$

B. $6.5\frac{Btu}{lb}$

C. $10.8\frac{Btu}{lb}$

D. $27.1\frac{Btu}{lb}$

Let State 1 refer to the entering outside air condition. Let State 2 refer to the leaving outside air after being heated through the ventilator. Let State 3 refer to the entering return air condition. Ignore the leaving exhaust air as it is not relevant.

Recall the distinction between *heat* recovery and *energy* recovery. Energy recovery devices transmit latent energy in addition to sensible heat. Heat-Recovery devices drive exclusively Sensible Energy Recovery and the humidity need not be considered. Therefore, the effectivenss of a heat recovery ventilator is given by a the ratio of ΔT_{actual} to ΔT_{ideal}. (Energy recovery effectiveness would depend on changes in enthalpy rather than temperature.)

$$\varepsilon = \frac{\Delta T_{actual}}{\Delta T_{ideal}} = \frac{T_2 - 30°F}{75°F - 30°F} = 0.6$$

$$T_2 = 57°F$$

The total heat transfer by the heat recovery device is given by the equation below. Sicne there is no mass flow rate or volume rate given and the problem is asking for the quantity of heat rather than the rate of heat transfer, divide both sides by $\dot{m}$ and solve for q, heat per unit mass. The delta T is the actual increase in temperature experienced by the outside air.

$$\dot{Q} = \dot{m} c_p \Delta T$$

$$\frac{\dot{Q}}{\dot{m}} = q = c_p \Delta T = \left(0.24 \frac{Btu}{lb \cdot °F}\right)(57°F - 30°F) = 6.48\frac{Btu}{lb}$$

Answer B

47.9 The maximum pressure achieved in the cylinder of a car engine is $800psi$. How much force will be exerted on a $3.7in$ piston?

A. $700lb_f$

B. $2,200lb_f$

C. $4,300lb_f$

D. $8,600lb_f$

A useful representation of pressure is the amount of force applied over an area. This can be expressed through the formula below and rearranged to solve for the force, F.

$$P = \frac{F}{A}$$

$$F = PA$$

Determine the area of the piston.

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(3.7in)^2 = 10.75in^2$$

Solve for the force.

$$F = PA = \left(800\frac{lb_f}{in^2}\right)\left(10.75in^2\right) = 8600lb_f$$

Answer D

47.10 A spring with 10 coils has squared ends and a shear modulus of $10 \times 10^6 psi$. The diameter of the wire is $0.15in$ and the average coil diameter is $1in$. What is the spring constant?

A. $52\frac{lb_f}{in}$

B. $63\frac{lb_f}{in}$

C. $79\frac{lb_f}{in}$

D. $105\frac{lb_f}{in}$

The Spring Constant for a Helical Compression Spring can be determined using the following formula, where k is the spring constant, d is the diameter of the wire, G is the shear modulus, D is the coil diameter, and $N$is the number of *active* coils.

$$k = \frac{d^4 G}{8D^3 N}$$

Using the table Type of Spring Ends, note that for squared ends the total number of coils N_t is the number of active coils plus two. Solve for the number of active coils.

$$N_t = N + 2$$

$$N = N_t - 2 = 10 - 2 = 8$$

Solve for the spring constant.

$$k = \frac{d^4 G}{8 D^3 N} = \frac{(0.15in)^4 \left(10 \times 10^6 \frac{lb_f}{in^2}\right)}{8\,(1in)^3\,(8)} = 79 \frac{lb_f}{in}$$

Answer C

47.11 An air handling unit uses 10% outside air at $88°F$ and 60% RH and 90% recirculated air returned from the space, which is maintained at $76°F$ and 50% RH. What is the dew point temperature of the air entering the coil?

A. $56°F$

B. $58°F$

C. $63°F$

D. $65°F$

Define State 1 as the outside air, State 2 as the return air, and State 3 as the mixed air. The question does not concern the supply/discharge air after the coil.

Use the Psychrometric Chart to look up the humidity ratio for State 1 and State 2 which are fully defined.

$$T_1 = 88°F$$

$$RH_1 = 60\%$$

$$\omega_1 = .0172 \frac{lb_{H2O}}{lb_{da}}$$

$$T_2 = 76°F$$

$$RH_2 = 50\%$$

$$\omega_2 = .0096 \frac{lb_{H2O}}{lb_{da}}$$

Perform a mixing calculation to find the humidity ratio at State 3.

$$\omega_3 = (.1)\left(.0172\frac{lb_{H2O}}{lb_{da}}\right) + (.9)\left(.0096\frac{lb_{H2O}}{lb_{da}}\right) = .01036\frac{lb_{H2O}}{lb_{da}}$$

Follow the psychrometric chart horizonally to the left from ω_3 to the saturation curve to read the corresponding dew point temperature.

$$T_{DP,3} \approx 58°F$$

Answer B

47.12 $2000cfm$ of outside air at $95°F$ dry bulb and $78°F$ wet bulb is cooled to $68°F$ and 60% relative humidity. What quantity of latent heat is removed?

A. $60,000\frac{Btu}{hr}$

B. $70,000\frac{Btu}{hr}$

C. $80,000\frac{Btu}{hr}$

D. $90,000\frac{Btu}{hr}$

Let state 1 be the entering air conditions and state 2 be the leaving air conditions. Use the Psychrometric Chart to find the humidity ratio for both states.

$$T_{1,db} = 95°F$$

$$T_{1,wb} = 78°F$$

$$\omega_1 = 0.0169\frac{lb_{h2o}}{lb_{da}}$$

$$T_2 = 68°F$$

$$\phi_2 = 60\%$$

$$\omega_2 = 0.0088\frac{lb_{h2o}}{lb_{da}}$$

Even though this problem is about calculating the latent heat removed from the air, it is appropriate to use the Latent Heat Gain rule of thumb formula provided the smaller humidity ratio is subtracted from the larger humidity ratio such that $\Delta\omega$ has a positive value. As long as the correct units are used for all inputs, q_l will be specified in the desired units, $\frac{Btu}{hr}$.

$$q_l = 4840Q_s\Delta\omega = 4840\,(2000)\,(0.0169 - 0.0088) = 78,408\frac{Btu}{hr}$$

Answer C

47.13 What is the equivalent diameter of a $18in \times 24in$ rectangular duct?

A. $20in$

B. $21in$

C. $22in$

D. $23in$

Use the formula under Rectangular Ducts to find the circular equivalent of a rectangular duct with sides lengths a and b. Substitute into the equation the known side lengths in in and the final result will be determined in in as well. Assignment of a and b is arbitrary as both addition and multiplication are commutative.

$$D_e = \frac{1.30\,(ab)^{0.625}}{(a+b)^{0.25}}$$

$$D_e = \frac{1.30\,(18 \cdot 24)^{0.625}}{(18+24)^{0.25}} = \frac{1.3\,(432)^{0.625}}{(42)^{0.25}} = 22.7in$$

Answer D

47.14 An unoccupied space has $10KW$ of computer equipment and lighting and a moisture load of $12\frac{lb}{hr}$ of water vapor. What is the sensible heat ratio?

A. 0.25

B. 0.34

C. 0.75

D. 2.93

Use the formula for the Sensible Heat Ratio. The total heat gain is the sum of the sensible load and latent load.

$$SHR = \frac{sensible\ heat\ gain}{total\ heat\ gain} = \frac{\dot{Q}_S}{\dot{Q}_S + \dot{Q}_L}$$

The sensible load is composed of the computer equipment and lighting. Convert the units of KW to $\frac{Btu}{hr}$.

$$\dot{Q}_S = (10KW)\left(3412\frac{Btu}{hr \cdot KW}\right) = 34,120\frac{Btu}{hr}$$

The latent load (i.e. moisture load) is a function of the mass flow rate of water vapor being added to the air and the latent heat of vaporation, h_{fg}, of that water vapor, which depends on temperature and pressure. Since no temperature or pressure information is given, assume standard atmospheric conditions. Use the Properties of Saturated Water and Steam (Pressure) table to obtain the value of h_{fg} at atmospheric pressure.

$$P = 14.7psia$$

$$h_{fg} \approx 970\frac{Btu}{lb}$$

Hint: When making approximations of latent load due to moisture, consider assuming $h_{fg} \approx 1000\frac{Btu}{lb}$ to save time.

Calculate the latent load.

$$\dot{Q}_L = \dot{m}\Delta h = \dot{m}\Delta h_{fg} = \left(12\frac{lb}{hr}\right)\left(970\frac{Btu}{lb}\right) = 11,640\frac{Btu}{hr}$$

Solve for SHR.

$$SHR = \frac{\dot{Q}_S}{\dot{Q}_S + \dot{Q}_L} = \frac{34,120\frac{Btu}{hr}}{34,120\frac{Btu}{hr} + 11,640\frac{Btu}{hr}} = 0.746$$

Answer C

47.15 A $10lb_m$ mass hangs from a spring and damper assembly. The spring has a spring constant of $100\frac{lb_f}{in}$. The damping ratio is 0.6. What is the damped frequency of the system?

A. $6Hz$

B. $8Hz$

C. $10Hz$

D. $12Hz$

Find the natural frequency of the system as though no damping was present. The undamped natural circular frequency is given by the equation below.

$$\omega_n = \sqrt{\frac{kg_c}{m}} = \sqrt{\frac{\left(100\frac{lb_f}{in}\right)\left(12\frac{in}{ft}\right)\left(32.2\frac{lb_m \cdot ft}{lb_f \cdot s^2}\right)}{10lb_m}} = 62.2\frac{rad}{s}$$

Find the Damped Natural Frequency which accounts for the damping ratio.

$$\omega_d = \omega_n\sqrt{1-\varsigma^2} = \left(62.2\frac{rad}{s}\right)\sqrt{1-(0.6)^2} = 49.7\frac{rad}{s}$$

Since the answer choices are in Hz, find the corresponding damped *linear* frequency. Note the final units of "cycles per second" is the same as Hz.

$$f_d = \frac{\omega_d}{2\pi} = \frac{49.7\frac{rad}{s}}{2\pi\frac{rad}{cycle}} = 7.9Hz$$

Answer B

47.16 A carnot heat pump operates during winter when the outisde air temperature is $20°F$ and inside temperature is $68°F$. During summer, the unit runs in reverse to provide cooling when the outisde air temperature is $100°F$ and inside temperature is $72°F$. What is the coefficient of performance during summer operation?

A. 3

B. 4

C. 17

D. 19

Recall that a Carnot heat pump has the maximum theorteical Coefficient of Performance based on the temperatures of the reservoirs heat is being removed from and rejected to. In this case, winter operation may be ignored since the question is asking about the COP for summer operation only.

The COP for refrigeration for a carnot cycle is given by:

$$COP_c = \frac{T_L}{T_H - T_L}$$

Temperature units must be absolute (Rankine). The denominator is a temperature differential and therefore may be left in Farenheit.

$$COP_c = \frac{72°F + 460°}{100°F - 72°F} = 19$$

Answer D

47.17 A refrigeration cycle using R-123 operates between $30psia$ and $125psia$ with no subcooling and isenthalpic expansion. What is the quality of the mixture entering the evaporator?

A. 0.20

B. 0.26

C. 0.32

D. 0.38

Look up the R-123 properties table and Pressure Versus Enthalpy Curves for Refrigerant 123. Consider the high pressure side of the refrigeration cycle after the refrigerant passes through the condenser, it is expected to be a saturated liquid at $125psia$. Let this be considered State 3. Use either the table or the chart to determine the enthalpy of saturated liquid, h_f. The table lends itself to slightly higher precision but may take a bit more time. Formal interpolation is not necessary. Beware of the logarithmic scale on the vertical axis if using the P-H chart. Since the expansion process in a typical refrigeration cycle is isenthalpic, the enthalpy after expansion is the same as the enthalpy prior to expansion. Let the low pressure condition after expansion be considered State 4.

$$h_4 = h_3 = h_{f@125psia} \approx 64.3\frac{Btu}{lb}$$

Use the table to obtain h_f and h_g at the low pressure condition of $30psia$.

$$h_{f@30psia} \approx 38.14\frac{Btu}{lb}$$

$$h_{g@30psia} \approx 107.4\frac{Btu}{lb}$$

Calculate the enthalpy at State 4.

$$\chi_4 = \frac{h_4 - h_f}{h_g - h_f} = \frac{64.3\frac{Btu}{lb} - 38.14\frac{Btu}{lb}}{107.4\frac{Btu}{lb} - 38.14\frac{Btu}{lb}} = 0.378$$

Answer D

47.18 A kitchen contains lighting and cooking equipment which draws $30KW$. There is also a moisture load of $2\frac{lb}{min}$. What is the sensible heat ratio?

A. 0.02

B. 0.45

C. 0.55

D. 0.98

Change the units of the sensible heat load from KW to $\frac{Btu}{hr}$.

$$Q_S = (30KW)\left(\frac{3412\frac{Btu}{hr}}{KW}\right) = 102,360\frac{Btu}{hr}$$

Calculate the latent load. Use the steam table by looking up Properties of Saturated Water by temperature. Assume the kitchen is around $80°F$. Note the latent heat of vaporazation for steam, $h_{fg} \approx 1050\frac{Btu}{lb}$ at this approximate temperature.

$$Q_L = \dot{m}\Delta h = \dot{m}h_{fg} = \left(2\frac{lb}{min}\right)\left(1050\frac{Btu}{lb}\right)\left(\frac{60min}{1hr}\right) = 126,000\frac{Btu}{hr}$$

Find the Sensible Heat Ratio.

$$SHR = \frac{Q_S}{Q_T} = \frac{Q_S}{Q_S + Q_L} = \frac{102,360\frac{Btu}{hr}}{102,360\frac{Btu}{hr} + 126,000\frac{Btu}{hr}} = 0.448$$

Answer B

47.19 How much power is required to isentropically compress $100\frac{lb}{min}$ of air at atmospheric pressure and $80°F$ to $150psia$? Assume air is an ideal gas with constant specific heat capacity.

A. $50hp$

B. $200hp$

C. $290hp$

D. $1920hp$

Look up Constant Entropy Processes and find the formula relating temperature and pressure. Determine the temperature after the compression process, T_2. The ratio of specific heats may be taken as $k = 1.4$ since air is to be considered an ideal gas. Be sure to use the absolute temperature scale ie. Rankine rather than Farenheit.

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = (540°R)\left(\frac{150psia}{14.7psia}\right)^{\frac{1.4-1}{1.4}} = 1048.6°R = 588.6°F$$

The power for a compressor can be expressed most generally as the product of the mass flow rate and the change in enthalpy. If the gas being compressed has constant specific heats, it is valid to express the enthalpy change in terms of the change in temperature. Calculate the power required and convert the final units to horsepower to be consistent with the answer choices. Look up Measurement Relationships for unit conversions that may be useful.

$$\dot{W} = \dot{m}\Delta h = \dot{m}c_p\Delta T = \left(100\frac{lb}{min}\right)\left(0.24\frac{Btu}{lb°F}\right)(588.6°F - 80°F) = 12,207\frac{Btu}{min}$$

$$\dot{W} = 12,207\frac{Btu}{min}\left(\frac{1hp}{42.4\frac{Btu}{min}}\right) = 288hp$$

Answer C

47.20 A refrigeration cycle using R-123 operates between $75psia$ and $220psia$ with no sub-cooling. During isenthalpic expansion, what is the change in entropy of the refrigerant?

A. $0.001\frac{Btu}{lb\cdot^\circ F}$

B. $0.003\frac{Btu}{lb\cdot^\circ F}$

C. $0.01\frac{Btu}{lb\cdot^\circ F}$

D. $0.04\frac{Btu}{lb\cdot^\circ F}$

Sketch the process line from State 3 to State 4 representing the expansion process within a typical refrigeration cycle. Use the table for Refrigerant 123 to obtain the enthalpy and entropy at State 3. Since there is no sub-cooling, the refrigerant is a saturated liquid at State 3.

$$P_3 = 220psia$$

$$h_3 = h_f = 78.66\frac{Btu}{lb}$$

$$s_3 = s_f = 0.138\frac{Btu}{lb^\circ R}$$

The expansion from $3 \rightarrow 4$ is isenthalpic, therefore the enthalpy at State 4 is the same as the enthalpy at State 3.

$$h_4 = h_3 = 78.66\frac{Btu}{lb}$$

Since the expansion process line from $3 \rightarrow 4$ is vertically down on the Pressure-Enthalpy diagram, State 4 is observed to be a saturated mixture, as it is within the vapor dome. Use the Refrigerant 123 table again to obtain the enthalpy values h_f and h_{fg} at the lower pressure of State 4. Calculate the quality at State 4. Refer to Properties for Two-Phase (Vapor-Liquid) Systems for a reminder of the formulas involving quality.

$$P_4 = 75psia$$

$$h_f = 53.58\frac{Btu}{lb}$$

$$h_{fg} = 115.68\frac{Btu}{lb}$$

$$h_4 = h_f + \chi_4 h_{fg}$$

$$\chi_4 = \frac{h_4 - h_f}{h_{fg}} = \frac{78.66\frac{Btu}{lb} - 53.58\frac{Btu}{lb}}{115.68\frac{Btu}{lb}} = 0.404$$

Use the same line in the table to obtain the entropy values s_f and s_{fg}. Calculate the entropy at State 4 using the quality, χ_4.

$$s_f = 0.102 \frac{Btu}{lb^\circ R}$$

$$s_{fg} = 0.199 \frac{Btu}{lb^\circ R}$$

$$s_4 = s_f + \chi_4 s_{fg} = \left(0.102 \frac{Btu}{lb^\circ R}\right) + (0.404) \left(0.199 \frac{Btu}{lb^\circ R}\right) = 0.182 \frac{Btu}{lb^\circ R}$$

Finally, calculate the change in entropy during the expansion process.

$$\Delta s = s_4 - s_3 = 0.182 \frac{Btu}{lb^\circ R} - 0.138 \frac{Btu}{lb^\circ R} = 0.044 \frac{Btu}{lb^\circ R}$$

Answer D

47.21 A flash distilation vessel boils seawater to make potable water. The pressure in the vessel is held at $10\ in\ Hg$ vacuum. What temperasure does the seawater boil at?

A. $162^\circ F$

B. $192^\circ F$

C. $212^\circ F$

D. $228^\circ F$

Convert the pressure in the vessel to absolute terms of $psia$, using conversions from the Measurement Relationships table as needed. Recall that vacuum pressure reads negative on a gauge, but pressure is always positive in absolute terms.

$$P_g = (-10 in\, Hg) \left(\frac{1 psi}{2.036 in\, Hg}\right) = -4.91 psig$$

$$P_a = P_g + 14.7 psi = -4.91 psig + 14.7 psi = 9.8 psia$$

Use the Properties of Saturated Water and Steam table to look up the saturation temperature at $9.8 psia$. The saturation temperature is the boiling point of water at a given pressure. As a sense check, the boiling point should be *lower* than at standard conditions since there is less pressure holding the molecules from escaping.

$$T_{sat@9.8psia} \approx 192^\circ F$$

Ignore boiling point elevation; salinity accounts for only about $+1^\circ F$ and is outside the intended scope of the problem.

Answer B

47.22 $5lb_m$ of $80°F$ air is compressed at constant temperature from $15psia$ to $90psia$. How much work is done on the closed system?

A. $50Btu$

B. $110Btu$

C. $220Btu$

D. $330Btu$

For a Constant Temperature Process in a Closed System, with the initial and final pressures known, select the equation below. Make sure to use absolute temperature. Look up the Gas Constant for air.

$$w = RTln\left(\frac{P_1}{P_2}\right)$$

$$w = \left(53.35\frac{ft \cdot lb_f}{lb_m°R}\right)(540°R)\,ln\left(\frac{15psia}{90psia}\right) = -51,619\frac{ft \cdot lb_f}{lb_m}$$

Convert units to $\frac{Btu}{lb_m}$. Search Measurement Relationships for relevant conversions.

$$w = \left(-51,619\frac{ft \cdot lb_f}{lb_m}\right)\left(\frac{1Btu}{778ft \cdot lb_f}\right) = -66\frac{Btu}{lb_m}$$

Note this result is the *specific* work i.e. the work per unit mass. Multiply by the mass to determine the total work. The negative sign implies work done *on the system* and may be omitted since the problem statement calls for the work on the system.

$$W = mw = (5lb_m)\left(66\frac{Btu}{lb}\right) = 330Btu$$

Answer D

47.23 $300psia$ superheated steam enters an isentropic turbine and exits at $170°F$ with 10% moisture content. What is the temperature of the entering steam?

A. $420°F$

B. $690°F$

C. $960°F$

D. $1230°F$

Consider the entering consitions to be State 1, and exit conditions to be State 2. Since there is some moisture content at State 2, it can be inferred that the steam is a saturated mixture. 10% moisture content implies a quality of $\chi_2 = 0.9$. Use the Properties of Saturated Water and Steam table to look up the entropies s_f and s_{fg}. Calculate the entropy at State 2.

$$T_2 = 170°F$$

$$\chi_2 = 0.9$$

$$s_f = 0.2474 \frac{Btu}{lb°F}$$

$$s_{fg} = 1.5816 \frac{Btu}{lb°F}$$

$$s_2 = 0.2474 \frac{Btu}{lb°F} + 0.9 \left(1.5816 \frac{Btu}{lb°F}\right) = 1.671 \frac{Btu}{lb°F}$$

Since the turbine is isentropic, the entropy for State 1 is the same as the entropy for State 2. The pressure at State 1 has been given. Use the Properties of Superheated Steam table to determine the temperature at State 1. Interpolate or estimate as appropriate.

$$s_1 = s_2 = 1.671 \frac{Btu}{lb°F}$$

$$P_1 = 300psia$$

$$T_1 = 690°F$$

Answer B

47.24 Outside air conditions are $85°F$ and 50% relative humidity. What is the partial pressure of water vapor in the air?

A. $0.3psia$

B. $0.6psia$

C. $1.3psia$

D. $7.4psia$

Use the definition of Relative Humidity found under Psychrometric Properties. Relative humidity is a function of the partial pressure of water vapor in air, p_w, and the maximum possible partial pressure for water vapor in air,p_{ws}, which occurs at fully saturated conditions i.e. 100% relative humidity. The saturation pressure of water vapor in air is a function of temperature. Warmer air has a greater capacity for absorbing moisture, and therefore a higher saturation pressure.

$$\phi = \frac{p_w}{p_{ws}} \rightarrow p_w = \phi p_{ws}$$

Use the Properties of Saturated Water and Steam (Temperature) table to obtain the saturation pressure of water vapor at $85°F$.

$$T = 85°F$$

$$p_{ws} = 0.6psia$$

Substitute and solve for the partial pressure of water vapor at 50% relative humidity.

$$p_w = (0.5)(0.6psia) = 0.3psia$$

Answer A

47.25 $2000gpm$ of $68°F$ water is transported to an open reservoir $140ft$ above the pump via $1500ft$ of $12in$ nominal steel pipe. Pressure on the suction side of the pump is measured as $15psig$. The Darcy friction factor for this application is assumed to be approximately 0.015. What is the operating head of the pump?

A. $20ft$

B. $120ft$

C. $220ft$

D. $240ft$

Draw a sketch of the pump and reservoir and label all given information. Consider the suction side of the pump as State 1 and the top of the reservoir as State 2. Use the modified Bernoulli equation aka Mechanical Energy Equation arranged for total head added by a pump. Make all terms have units of ft.

$$h_A = \frac{P_2 - P_1}{\gamma} + \frac{v_2^2 - v_1^2}{2g} + z_2 - z_1 + h_f$$

The static pressure at the pump inlet, P_1, is given in gauge pressure, $15psig$. The reservoir is at atmospheric pressure which by definition is $0psig$ near sea level. There is no need to convert to absolute pressure, $psia$, in order to find the pressure difference. Convert from $psia$ to ft by using the conversion factor rule of thumb for water, $2.31\frac{ft}{psi}$. The velocity term may be neglected. Using the pump centerline as the datum, the Δz term may be determined.

The only unknown is the losses through the discharge piping from the pump to the reservoir, h_f. Since the friction factor is provided, use the Darcy equation rather than the Steel Pipe Friction Tables. Use the table to obtain the velocity and inside diameter.

$$h_f = \frac{fLv^2}{2Dg} = \frac{(0.015)(1500ft)\left(5.73\frac{ft}{s}\right)^2}{2\left(\frac{11.938}{12}ft\right)\left(32.2\frac{ft}{s^2}\right)} = 11.5ft$$

Solve for the total head added by the pump.

$$h_A = (0psi - 15psi)\left(2.31\frac{ft}{psi}\right) + 140ft + 11.5ft = 116.9ft$$

Answer B

47.26 $1000\frac{Btu}{lb}$ **of heat is added to** $70°F$ **,** $14.7psia$ **air. What is the temperature after heating?**

A. $3665°F$

B. $3815°F$

C. $3965°F$

D. $4125°F$

Consider the condition of the air before heating as State 1 and the condition of air after heating as State 2. Use the Air at Low Pressure tables to look up the enthalpy of air at $70°F$. For low pressure air, enthalpy may be reasonably approximated as a function of temperature only.

$$h_1 \approx 126\frac{Btu}{lb}$$

Calculate the enthalpy after heating.

$$h_2 = 126\frac{Btu}{lb} + 1000\frac{Btu}{lb} = 1126\frac{Btu}{lb}$$

Return to the low pressure air table to look up the corresponding temperature for State 2. Without interpolating, notice h_2 is about halfway between two values, making the temperature straightforward to obtain.

$$T_2 \approx 3665°F$$

Answer A

47.27 $400\frac{lbm}{hr}$ **of** $62°F$**, 60% relative humidity air is heated to** $96°F$ **without changing the moisture content. How much heat is needed?**

A. $3300\frac{Btu}{hr}$

B. $6700\frac{Btu}{hr}$

C. $10,100\frac{Btu}{hr}$

D. $13,600\frac{Btu}{hr}$

Since the moisture content is not changing, the heat transfer depends on the the mass flow rate, specific heat capacity of air, and the dry bulb temperature differential only. There is no need to account for humidity ratio or enthalpy.

$$\dot{Q} = \dot{m}c_p\Delta T$$

$$\dot{Q} = \left(400\frac{lb}{hr}\right)\left(0.24\frac{Btu}{lb°F}\right)(96°F - 62°F) = 3624\frac{Btu}{hr}$$

Answer A

47.28 Air at $75°F$ db / $64°F$ wb enters a cooling coil with an ADP of $45°F$ and a bypass factor of 15%. What is the wet bulb temperature of the leaving air?

A. $45°F$

B. $48°F$

C. $50°F$

D. $61°F$

Use the Psychrometric Chart to plot the process line from the room condition to the ADP.

Determine the coil efficiency using the bypass factor.

$$\eta_{coil} = 1 - BF = 1 - 0.15 = 0.85$$

Set the coil efficiency equal to the ratio of the actual reduction in wet bulb temperature from $1 \rightarrow 2$ to the maximum possible reduction which would be achieved only when State 2 is the ADP, corresponding to 100% coil efficiency. Substitute and solve for $T_{2,wb}$.

$$\eta_{coil} = \frac{T_{1,wb} - T_{2,wb}}{T_{1,wb} - ADP}$$

$$0.85 = \frac{64°F - T_{2,wb}}{64°F - 45°F}$$

$$T_{2,wb} = 47.9°F$$

Answer B

47.29 A 230V, single-phase, 5-hp motor operates at full load with a power factor of 0.8. The motor efficiency is 75%. What is the current drawn?

A. $10A$

B. $13A$

C. $15A$

D. $27A$

The current drawn by an AC motor is a function of the number of phases, power, voltage, motor efficiency, and power factor. Search for Motor Phases and find the table Power for Different Motor Phases. Select the first equation in the "Single-Phase" column. Substitute and solve using the values given.

$$I_{amps} = \frac{P_{hp}\left(746\frac{W}{hp}\right)}{V\eta\,(pf)}$$

$$I_{amps} = \frac{(5hp)\left(746\frac{W}{hp}\right)}{(230V)(0.75)\left(0.8\frac{W}{VA}\right)} = 27A$$

Answer D

47.30 The bedroom of a pre-war apartment contains a steam radiator which provides up to $40,000\frac{Btu}{hr}$ at full load. Building steam is supplied at $4psig$ saturated. The radiator discharge is a saturated liquid. Neglecting losses, what mass flow rate of steam is required to satisfy the heating demand?

A. $34.6\frac{lb}{hr}$

B. $35.5\frac{lb}{hr}$

C. $39.8\frac{lb}{hr}$

D. $41.6\frac{lb}{hr}$

Since the steam enters the radiator as a saturated vapor and leaves as a saturated liquid, the amount of heat provided as the steam condenses is by definition the latent heat of vaporaization, h_{fg}. Use the table Properties of Saturated Water and Steam (Pressure) to obtain h_{fg} at the operating pressure given. Rough interpolation is sufficient.

$$P = 4psig \approx 19psia$$

$$h_{fg} \approx 962\frac{Btu}{lb}$$

Set the heating demand equal to the product of the mass flow rate of steam and the latent heat of vaporization which released as the steam condenses. Rearrange for mass flow rate, substitute, and solve.

$$\dot{Q} = \dot{m}h_{fg}$$

$$\dot{m} = \frac{\dot{Q}}{h_{fg}} = \frac{40,000\frac{Btu}{hr}}{962\frac{Btu}{lb}} = 41.6\frac{lb}{hr}$$

A quick and easy rule of thumb worth considering for steam applications is $\Delta h \approx 1000\frac{Btu}{lb}$, however if the answers are close together as they are here, it's worth the time to look up the particular h_{fg} value from the steam table.

Answer D

47.31 A heated indoor swimming pool is maintained at $78°F$. Evaporation of pool water introduces moisture into the surrounding space at a rate of $4\frac{lb}{min}$. The room is maintained at $80°F$ and 60% relative humidity by exhausting a constant volume of room air and replacing it with outside air at $85°F$ db / $65°F$ wb. What volume flow rate of outside air is required to achieve the intended dehumidification?

A. $9800 cfm$

B. $11,600 cfm$

C. $12,300 cfm$

D. $18,100 cfm$

Sketch the pool room and label the outside air and room air. The primary driver for the required volume flow rate of outside air is the difference in humidity ratio between the inside and outside conditions, both of which are fully defined states. Use the Psychrometric Chart to obtain both humidity ratios. Also obtain the specific volume for the outside air condition.

$$T_r = 80°F$$

$$\phi_r = 60\%$$

$$\omega_r = 0.01321\frac{lb_w}{lb_{da}}$$

$$T_{OA,db} = 85°F$$

$$T_{OA,wb} = 65°F$$

$$\omega_{OA} = 0.00865\frac{lb_w}{lb_{da}}$$

$$v_{OA} = 13.97\frac{ft^3}{lb_{da}}$$

Using the equation under Moist-Air Cooling and Dehumidification, then substitute for the mass flow rate of air, $\dot{m}_a$, and rearrange for the volume flow rate of outside air, Q_{OA}. The mass flow rate of water, $\dot{m}_w$, is the evaporation rate of pool water into the room air, which is given. Substitute and solve.

$$\dot{m}_w = \dot{m}_a \Delta\omega$$

$$\dot{m}_a = \rho_{OA} Q_{OA} = \frac{Q_{OA}}{v_{OA}}$$

$$\dot{m}_w = \frac{Q_{OA}}{v_{OA}} \Delta\omega \rightarrow Q_{OA} = \frac{\dot{m}_w v_{OA}}{\Delta\omega}$$

$$Q_{OA} = \frac{\left(4\frac{lb_w}{min}\right)\left(13.97\frac{ft^3}{lb_{da}}\right)}{\left(0.01321\frac{lb_w}{lb_{da}} - 0.00865\frac{lb_w}{lb_{da}}\right)} = 12,254\frac{ft^3}{min}$$

Answer C

47.32 A refrigeration cycle provides $8tons$ of cooling with a COP of 4.2. What is the required compressor horsepower?

A. $9hp$

B. $12hp$

C. $31hp$

D. $38hp$

Recall from Thermodynamics the formula for Coefficient of Performance for a refrigeration cycle.

$$COP_R = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} = \frac{\dot{Q}_L}{\dot{W}_{in}}$$

Rearrange for the compressor work, $\dot{W}_{in}$. Substitute, solve, and convert units to hp.

$$\dot{W}_{in} = \frac{\dot{Q}_L}{COP} = \frac{8tons}{4.2}\left(12,000\frac{Btu}{hr \cdot ton}\right)\left(\frac{1W}{3.412\frac{Btu}{hr}}\right)\left(\frac{1hp}{745.7W}\right) = 9hp$$

Answer A

47.33 A $4in$ thick composite wall has an R-value of of $8\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$. The inside and outside convective heat transfer coefficients are $1.5\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$ and $3\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$, respectively. What is the total thermal resistance?

A. $0.1\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$

B. $0.9\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$

C. $1.1\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$

D. $9.0\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$

The R-value for a Composite Wall is the thermal resistance for all materials from which the wall is composed. Film coefficients are an outcome of the orientation, air velocity, and other fluid characteristics, and not a function of the wall construction. Therefore, when calulating the total thermal resistance, the effect of films must be added separately if they are able to be known. In this case, the film coefficients for inside and outside are both given. Write an expression for the total resistance, substitute, and solve.

$$R_t = \frac{1}{h_i} + R + \frac{1}{h_o}$$

$$R_t = \frac{1}{1.5\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}} + 8\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu} + \frac{1}{3\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}} = 9\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$$

Answer D

47.34 An object with a surface area of $10ft^2$ and a surface temperature of $40^\circ F$ gains $1000\frac{Btu}{hr}$ through a combination of radiation and convection. The ambient temperature as well as the temperature of the surrounding surfaces is $80^\circ F$. The emmissivity is 0.8. What is the convection film coefficient?

A. $1.7\frac{Btu}{hr\cdot ft^2{}^\circ F}$

B. $3.1\frac{Btu}{hr\cdot ft^2{}^\circ F}$

C. $3.8\frac{Btu}{hr\cdot ft^2{}^\circ F}$

D. $5.6\frac{Btu}{hr\cdot ft^2{}^\circ F}$

Radiation and Convection are both applicable and together make up the total heat gain.

$$\dot{Q}_t = \dot{Q}_{conv} + \dot{Q}_{rad}$$

$$\dot{Q}_{conv} = hA\Delta T$$

$$\dot{Q}_{rad} = \sigma \varepsilon A \left(T_s^4 - T_\infty^4 \right)$$

$$\dot{Q}_t = \dot{Q}_{conv} + \dot{Q}_{rad} = hA\Delta T + \sigma \varepsilon A \left(T_s^4 - T_\infty^4 \right)$$

Calculate the heat transfer resulting from radiation. Be sure to use absolute temperatures i.e. degrees Rankine.

$$\dot{Q}_{rad} = \sigma \varepsilon A \left(T_s^4 - T_\infty^4 \right)$$

$$\dot{Q}_{rad} = \left(0.1713 \times 10^{-8} \frac{Btu}{hr \cdot ft^2 {}^\circ R} \right) (0.8) \left(10 ft^2 \right) \left[(540^\circ R)^4 - (500^\circ R)^4 \right] = 308.8 \frac{Btu}{hr}$$

Subtract the radiation from the total heat gain to determine the heat gain from convection.

$$\dot{Q}_{conv} = \dot{Q}_t - \dot{Q}_{rad} = 1000 \frac{Btu}{hr} - 308.8 \frac{Btu}{hr} = 691.2 \frac{Btu}{hr}$$

Solve for the convection coefficient.

$$\dot{Q}_{conv} = hA\Delta T$$

$$h = \frac{\dot{Q}_{conv}}{A\Delta T} = \frac{\left(691.2 \frac{Btu}{hr} \right)}{\left(10 ft^2 \right) (80^\circ F - 40^\circ F)} = 1.7 \frac{Btu}{hr \cdot ft^2 {}^\circ F}$$

Answer A

47.35 A hot water heat exchanger is supplied with $55^\circ C$ LTHW which is used to heat $2 \frac{L}{s}$ of domestic water from $20^\circ C$ to $50^\circ C$. The return LTHW temperature is $47^\circ C$. What is the volume flow rate of LTHW required?

A. $0.5 \frac{L}{s}$

B. $3.0 \frac{L}{s}$

C. $7.5 \frac{L}{s}$

D. $11.0 \frac{L}{s}$

Assuming 100% efficiency, the heat supplied to the domestic hot water is removed from the low temperature hot water (LTHW). Set these quantities equal and represent each using $Q = \dot{m} c_p \Delta T$.

$$\dot{Q}_{LTHW} = \dot{Q}_{DHW}$$

$$\left[\dot{m} c_p \Delta T \right]_{LTHW} = \left[\dot{m} c_p \Delta T \right]_{DHW}$$

Substitute the product of density and volume flow rate for the mass flow rate on both sides.

$$\dot{m} = \rho Q$$

$$[\rho Q c_p \Delta T]_{LTHW} = [\rho Q c_p \Delta T]_{DHW}$$

Since both sides of the heat exchanger are using liquid water as a medium, the density and specific heat capacity cancel out.

$$[Q\Delta T]_{LTHW} = [Q\Delta T]_{DHW}$$

Rearrange for the volume flow rate on the LTHW side. Substitute and solve.

$$Q_{LTHW} = Q_{DHW}\left(\frac{\Delta T_{DHW}}{\Delta T_{LTHW}}\right) = \left(2\frac{L}{s}\right)\left(\frac{50°C - 20°C}{55°C - 47°C}\right) = 7.5\frac{L}{s}$$

Answer C

47.36 $500,000\frac{L}{s}$ of water is discharged from a reservoir and falls $30 meters$. How much power is released due to the change in elevation?

A. $60MW$

B. $150MW$

C. $310MW$

D. $480MW$

Power is released when the potential energy stored in the water is converted into kinetic energy as the water descends from high elevation. Search for Potential Energy and use the formula for potential energy due to gravity.

$$PE = mgh$$

Work is a form of energy, and power is work per unit time. On the left side, potential energy, PE, can be replaced with work, $\dot{W}$, and on the right side use the mass flow rate, $\dot{m}$, instead of the mass, m. Both sides then have time in the denominator.

$$\dot{W} = \dot{m}gh$$

$1L$ of water has a mass of $1kg$. This can be confirmed by searching Properties of Water at Standard Conditions which states that $\rho_{water} = 1000\frac{kg}{m^3}$. Since $1000L = 1m^3$, then converting the density to $\frac{kg}{L}$.

$$\rho_{water} = 1000\frac{kg}{m^3}\left(\frac{1m^3}{1000L}\right) = 1\frac{kg}{L}$$

Apply the Continuity Equation to determine the mass flow rate as a function of density and volume flow rate.

$$\dot{m} = \rho Q = \left(1\frac{kg}{L}\right)\left(500,000\frac{L}{s}\right) = 500,000\frac{kg}{s}$$

Substitute and solve for power.

$$\dot{W} = \dot{m}gh = \left(500,000\frac{kg}{s}\right)\left(9.81\frac{m}{s^2}\right)(30m) = 1.47 \times 10^8 \frac{kg \cdot m^2}{s^3}$$

To get the final answer in MW, use the following unit conversions.

$$1N = 1\frac{kg \cdot m}{s^2}$$

$$1J = 1N \cdot m = 1\frac{kg \cdot m^2}{s^2}$$

$$1W = 1\frac{J}{s} = 1\frac{kg \cdot m^2}{s^3}$$

$$1MW = 10^6 W = 10^6 \frac{kg \cdot m^2}{s^3}$$

Finally, solve for power, $\dot{W}$, in MW.

$$\dot{W} = \left(1.47 \times 10^8 \frac{kg \cdot m^2}{s^3}\right)\left(\frac{1MW}{10^6 \frac{kg \cdot m^2}{s^3}}\right) = 147MW$$

Answer B

47.37 An air handling unit uses a hot water coil to produce $20,000cfm$ of $120°F$ supply air. The entering air is composed of $5000cfm$ of $25°F$ outside air and $15,000cfm$ of $75°F$ return air. The hot water supply and return temperatures to and from the coil are $135°F$ and $105°F$, respectively. What volume flow rate of hot water is required?

A. $14gpm$

B. $83gpm$

C. $119gpm$

D. $345gpm$

Use the sensible heating rule of thumb for air to quantify the amount of heat added to the air.

$$\dot{Q}_{s,air} = 1.08cfm\Delta T$$

The discharge air temperature is given, but the entering air is a mixture of outside air and return air. Perform a mixing calculation to find the temperature of the air entering the coil. For convenience, use the known volume flow rates as the states are not fully defined and it will be implausible to determine the mass flow rates.

$$T_{MA} = \frac{(5000cfm)\,(25^{\circ}F) + (15,000cfm)\,(75^{\circ}F)}{20,000cfm} = 62.5^{\circ}F$$

Calculate the sensible heating of the air.

$$\dot{Q}_{s,air} = 1.08\,(20,000)\,(120 - 62.5) = 1,242,000\frac{Btu}{hr}$$

Equate the quantity of heat added to the air with the quantity of heat given up by the hot water flowing through the coil. The hot water undergoes an equal amount of sensible cooling. Use the sensible heating/cooling rule of thumb for water to solve for the volume flow rate of hot water. The temperature range is given.

$$\dot{Q}_{s,water} = \dot{Q}_{s,air}$$

$$500gpm\Delta T = 1,242,000\frac{Btu}{hr}$$

$$gpm = \frac{1,242,000}{(500)\,(135 - 105)} = 82.8gpm$$

Answer B

47.38 A radiator is designed for $100^{\circ}F$ entering air and $150^{\circ}F$ leaving air. The inlet water is expected to enter at $212^{\circ}F$ and leave at $195^{\circ}F$. The radiator may be treated as a counterflow heat exchanger with a heat transfer surface area of $10ft^2$ and an overall coeffieient of heat transfer of $11\frac{Btu}{hr \cdot ft^2 \cdot {}^{\circ}F}$. What is the rate of heat transfer?

A. $5000\frac{Btu}{hr}$

B. $8100\frac{Btu}{hr}$

C. $8500\frac{Btu}{hr}$

D. $10,500\frac{Btu}{hr}$

Calculate the log mean temperature difference for the radiator modeled as a Counterflow heat exchanger. Draw the heat exchanger and label the temperatures.

$$Hot\,Fluid:\ 212^{\circ}F \longrightarrow 195^{\circ}F$$

$$Cold\,Fluid:\ 150^{\circ}F \longleftarrow 100^{\circ}F$$

Define one *physical* side of the heat exchanger as 'A' and the other side as 'B' and determine the respective temperature differences.

$$\Delta T_A = 212°F - 150°F = 62°F$$

$$\Delta T_B = 195°F - 100°F = 95°F$$

Use the formula below to calculate the log mean temperature difference.

$$LMTD_{counterflow} = \frac{\Delta T_A - \Delta T_B}{ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$$

$$LMTD_{counterflow} = \frac{62°F - 95°F}{ln\left(\frac{62°F}{95°F}\right)} = 77.3°F$$

Calculate the heat transfer for the heat exchanger:

$$\dot{Q} = UA\Delta T_{lm} = \left(11\frac{Btu}{hr \cdot ft^2 \cdot °F}\right)\left(10ft^2\right)(77.3°F) = 8506\frac{Btu}{hr}$$

Answer C

47.39 An $8ft$ long, $1in$ diameter solid aluminum alloy rod with coefficient of linear thermal expansion of $12.8 \times 10^{-6}\frac{1}{°F}$ is heated from $70°F$ to $230°F$. What is the change in cross-sectional area?

A. $-3.2 \times 10^{-3} in^2$

B. $-2.1 \times 10^{-3} in^2$

C. $+2.1 \times 10^{-3} in^2$

D. $+3.2 \times 10^{-3} in^2$

The change in cross-sectional area of the rod is dependent upon the change in diameter, which is linear with the change in temperature. To obtain the change in the diameter, multiple the original diameter by the linear coefficient of thermal expansion and the ΔT.

$$\Delta D = D_0 \alpha \Delta T$$

$$\Delta D = (1in)\left(12.8 \times 10^{-6}\frac{1}{°F}\right)(230°F - 70°F) = 0.00205in$$

Calculate the new diameter.

$$D_1 = D_0 + \Delta D = 1in + 0.00205in = 1.00205in$$

Calculate the new difference between the new and old cross-sectional areas.

$$A_1 - A_0 = \frac{\pi}{4}\left[D_1^2 - D_0^2\right]$$

$$A_1 - A_0 = \frac{\pi}{4}\left[(1.00205in)^2 - (1in)^2\right] = 3.2 \times 10^{-3} in^2$$

Answer D

47.40 A $25ft$ long hot water pipe with a $3in$ O.D. has an an average surface temperature of $175°F$ in a room with an ambient temperature of $60°F$. The convection coefficient is $2\frac{Btu}{hr\cdot ft^2\cdot °F}$. What is the total heat loss from the pipe, assuming all surfaces are considered to be black, and no insulation is used?

A. $3000\frac{Btu}{hr}$

B. $4500\frac{Btu}{hr}$

C. $7500\frac{Btu}{hr}$

D. $15,000\frac{Btu}{hr}$

Consider both Convection and Radiation. The total heat loss is found by combining the two.

$$\dot{Q}_{combined} = \dot{Q}_{convection} + \dot{Q}_{radiation}$$

Write the formula for convection found by searching Newton's Law of Cooling. The convection coefficient is given. The surface area of the pipe is defined as $A = \pi DL$. The temperatures are known. Substitute and solve for the heat loss due to convection.

$$\dot{Q}_{conv} = hA\Delta T$$

$$\dot{Q}_{conv} = \left(2\frac{Btu}{hr\cdot ft^2\cdot °F}\right)\left[\pi\left(\frac{3}{12}ft\right)(25ft)\right](175°F - 60°F) = 4516\frac{Btu}{hr}$$

Write the formula for radiation. Since all surfaces are black, assume $\varepsilon = 1$. σ is the Stefan-Boltzmann Constant. Surface area is the same as in the convection analysis. Temperatures must be in absolute terms i.e. Rankine.

$$\dot{Q}_{rad} = \varepsilon\sigma A\left(T_1^4 = T_2^4\right)$$

$$\dot{Q}_{rad} = (1)\left(0.1713\times10^{-8}\frac{Btu}{hr\cdot ft^2\cdot °R^4}\right)\left(\left[\pi\left(\frac{3}{12}ft\right)(25ft)\right]\right)\left[(635°R)^4 - (520°R)^4\right] = 3009\frac{Btu}{hr}$$

Solve for the combined heat loss by taking the sum of the heat loss due to convection and radiation.

$$\dot{Q}_{combined} = 4516\frac{Btu}{hr} + 3009\frac{Btu}{hr} = 7525\frac{Btu}{hr}$$

Answer C

47.41 Saturated steam at $300psia$ enters a closed feedwater heater and heats entering water with a temperature of $60°F$. The steam leaves as a saturated liquid. If the mass flow rate of water is 10 times the mass flow rate of steam, what is the exit temperature of the water?

A. $99°F$

B. $101°F$

C. $139°F$

D. $141°F$

Assuming 100% efficiency, all of the heat provided by the steam is added to the water. Set the heat removed from the steam equal to the heat gained by the water.

$$\dot{Q}_{steam} = \dot{Q}_{water}$$

Write an expression for the steam based on mass flow rate and the change in enthalpy, and express the heat gain by the water using mass flow rate, specific heat capacity, and change in temperature.

$$\dot{m}_{steam}\Delta h = \dot{m}_{water}c_p\Delta T$$

Since the mass flow rate of water is 10 times the mass flow rate of steam, substitute for the mass flow rate of water, then cancel $\dot{m}_{steam}$ on both sides.

$$\dot{m}_{water} = 10\dot{m}_{steam}$$

$$\dot{m}_{steam}\Delta h = 10\dot{m}_{steam}c_p\Delta T$$

$$\Delta h = 10c_p\Delta T$$

Solve for ΔT. Use the Properties of Saturated Water and Steam table by pressure to obtain the change in enthalpy for $300psia$ steam. The steam enters as saturated steam and therefore has enthalpy h_g, and leaves as saturated liquid and therefore has enthalpy h_f. For convenience, recall that the change in enthalpy is provided in the table directly, and $h_{fg} = h_g - h_f$.

$$\Delta T = \frac{\Delta h}{10c_p} = \frac{h_g - h_f}{10c_p} = \frac{h_{fg}}{10c_p} = \frac{809.42\frac{Btu}{lb}}{10\left(1\frac{Btu}{lb\cdot°F}\right)} = 80.9°F$$

Expand the water ΔT and solve for the leaving water temperature, T_2.

$$\Delta T = T_2 - T_1$$

$$T_2 = T_1 + \Delta T$$

$$T_2 = 60°F + 80.9°F = 140.9°F$$

Answer D

47.42 An exterior wall is constructed from $\frac{5}{8}in$ plaster board $\left(R = 0.56\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}\right)$, $3.5in$ batt insulation ($R = 13\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$), and $3.5in$ brick ($k = 6\frac{Btu\cdot in}{hr\cdot ft^2\cdot{}^\circ F}$). The inside surface of the plasterboard is maintained at $72°F$. The outside film coefficient is $1.5\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}$ and the outside temperature is $20°F$. What is the temperature at the interface of the brick and the insulation?

A. $24°F$

B. $36°F$

C. $56°F$

D. $68°F$

Find the total resistance for the Composite Wall, accouting for all resistances in series including the plasterboard, insulation, brick, and outside film coefficient. Note the inside surface is maintained at a specific temperature, so there is no need to account for an inside film coefficient. Make sure the units for each term are the same before adding.

$$R_{total} = R_{plasterboard} + R_{insulation} + \frac{L_{brick}}{k_{brick}} + \frac{1}{h_o}$$

$$R_{total} = 0.56\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu} + 13\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu} + \frac{3.5in}{6\frac{Btu\cdot in}{hr\cdot ft^2\cdot{}^\circ F}} + \frac{1}{1.5\frac{Btu}{hr\cdot ft^2\cdot{}^\circ F}} = 14.8\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}$$

Write an expression for the total heat flux through the wall. The total heat transfer, $\dot{Q}$, cannot be determined without the area of the wall being known, but the heat transfer per unit area i.e. heat flux, $\dot{q}$, can be found.

$$\dot{Q} = UA\Delta T$$

$$\frac{\dot{Q}}{A} = \dot{q} = U\Delta T$$

The overall heat transfer coefficient, U, is the inverse of the total resistance, R_{total}. $U = \frac{1}{R_t}$. Express heat flux in terms of total resistance. Substitute and solve.

$$\dot{q} = \frac{\Delta T}{R_t} = \frac{72°F - 20°F}{14.8\frac{hr\cdot ft^2\cdot{}^\circ F}{Btu}} = 3.5\frac{Btu}{hr\cdot ft^2}$$

The heat flux is the rate at which heat is conducted through the entire composite wall based on the total resistance of the wall. However, heat travels quickly through layers with minimal insulating properties and slowly through good insulators. Therefore, the temperature gradient throughout the composite wall is not uniform. To find the temperature at the interface of any two layers of the wall, find the resistance of all layers on one side of the interface. In this case, consider the interface between the insulation and the brick as location X. Find the combined resistance of the plasterboard and insulation.

$$R_{pb+ins} = R_{plasterboard} + R_{insulation} = 0.56 \frac{hr \cdot ft^2 \cdot {}^\circ F}{Btu} + 13 \frac{hr \cdot ft^2 \cdot {}^\circ F}{Btu} = 13.56 \frac{hr \cdot ft^2 \cdot {}^\circ F}{Btu}$$

Using the previously determined heat flux for the entire wall, but only the partial resistance of the layers to the left of location X, find the temperature differential between the inside wall and location X. Note this is not the same as the previous delta T which is for the entire wall.

$$\dot{q} = \frac{\Delta T}{R_t}$$

$$\Delta T = \dot{q} R_{pb+ins} = \left(3.5 \frac{Btu}{hr \cdot ft^2}\right) \left(13.56 \frac{hr \cdot ft^2 \cdot {}^\circ F}{Btu}\right) = 47.6^\circ F$$

Solve for the temperature at location X.

$$\Delta T = 72^\circ F - T_x = 47.6^\circ F$$

$$T_x = 72^\circ F - 47.6^\circ F = 24.4^\circ F$$

Answer A

47.43 A building has 8 office floors and a basement chiller plant, with $15ft$ of vertical spacing per floor. The chiller plant houses a set of pumps distributing chilled water via a central core riser to air handling units located in the building core on each floor of the building. Each floor has one air handling unit designed for $100gpm$ and $8ft$ of head pressure drop for the coil and $4psi$ of pressure drop for the control valve. The chillers are piped in parallel and have a maximum pressure drop of $15ft$ of head in all modes of operation. The head loss for the piping at the maximum flow rate is $4ft$ per $100ft$ of pipe. What is the head pressure that must be added by the pump set?

A. $39ft$

B. $44ft$

C. $59ft$

D. $152ft$

The total head pressure added by the pumps must be sufficient to overcome the pressure drop through the chillers, air handling units, and the piping losses through the longest run. It is not necessary to consider all floors individually as the pressure required is determined by the the *longest run* which is to the top floor.

Determine the vertical distance between the basement and the top floor. The total length of piping is double the height to account for losses in both the supply and return piping. Horizontal distance may be neglected since the piping distribution is through a central core riser and the AHUs are located in the core.

$$L = 8\,(15ft) \times 2 = 240ft$$

Calculate the losses associated with the length of the longest run.

$$h_f = \left(\frac{4ft}{100ft}\right)(240ft) = 9.6ft$$

Next, find the head pressure required to overcome the pressure drop for one air handler. Convert the pressure drop for the valves to ft by multiplying by the conversion factor $2.31\frac{ft}{psi}$. Refer to Commonly Used Equivalents.

$$h_{AHU} = 8ft + (4psi)\left(2.31\frac{ft}{psi}\right) = 17.24ft$$

Lastly, consider the pressure drop for the chillers. Since the chillers are piped in parallel, the pressure drop is the same regardless of the number of chillers.

$$h_{chillers} = 15ft$$

Calculate the total pressure drop for the longest run in feet of head. This is the minimum head pressure that must be added by the pump set.

$$h_A = h_f + h_{AHU} + h_{chillers}$$

$$h_A = 9.6ft + 17.24ft + 15ft \approx 44ft$$

Answer B

47.44 A 75% efficient fuel pump supplies $50gpm$ of No. 2 diesel fuel ($SG = 0.88$). The differential pressure across the pump is $30psi$. The motor driving the pump is 82% efficient. What is the electrical demand to run the pump?

A. $930W$

B. $1.1KW$

C. $1.2KW$

D. $1.4KW$

First determine the hydraulic horsepower produced by the pump, then use the efficiencies to determine the electrical demand to run the pump.

The specific gravity is required only when the differential pressure is given in feet of head. When the pressure added by the pump is already in *psi*, select the formula for Water Horsepower that uses ΔP directly. For this formula, the units for the flow rate, Q, must be *gpm*. The units for differential pressure, ΔP, must be *psi*.

$$whp = \frac{Q\Delta P}{1714}$$

$$whp = \frac{(50)(30)}{1714} = 0.875hp$$

The brake horsepower, *bhp*, is the water horsepower divided by the pump efficiency.

$$bhp = \frac{whp}{\eta_{pump}}$$

The electrical demand, $\dot{W}$, is the brake horsepower divided by the motor efficiency.

$$\dot{W} = \frac{bhp}{\eta_{motor}}$$

By substitition the electrical demand can be expressed as the water horsepower divided by both the pump and motor efficiencies. Calculate the power required to run the pump. Convert units to KW.

$$\dot{W} = \frac{whp}{\eta_{pump}\eta_{motor}}$$

$$\dot{W} = \frac{0.875hp}{(0.75)(0.82)} \left(0.7457 \frac{KW}{hp}\right) = 1.06KW$$

Answer B

47.45 A 90% efficient pump normally delivers $50gpm$ of $50°F$ chilled water at a head of $20ft$ of water with a rotational speed of $900rpm$. What is the percent increase in brake horsepower required to increase the volume flow rate by 10%? Assume the pump is oversized and has sufficient capacity in reserve to deliver the additional flow.

A. 10%

B. 21%

C. 33%

D. 46%

Refer to the Pump Affinity Laws. Change in speed and change in volume flow rate are proportional. Therefore, when the volume flow inceases by 10%, the speed also increases by 10%. Establish the ratio of new to old volume flow rate and speed.

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} = 1.1$$

The percent increase in brake horsepower is a function of the cube of the change in speed (or volume flow rate).

$$\frac{bhp_2}{bhp_1} = \left(\frac{N_2}{N_1}\right)^3 = (1.1)^3 = 1.33$$

Therefore, a 33% increase in power is required to support a 10% increase in the speed / volume flow rate.

Note there is no need to caclulate the actual brake horsepower to determine the percent change. The specific value of various parameters given are additional information not required to answer the fundamental question put forth, which is purely an application of the pump affinty laws.

Answer C

47.46 $100gpm$ of a liquid with a specific gravity of 0.8 is supplied by a pump operating with a differential pressure of $10psi$. What is the hydraulic horsepower?

A. $0.2hp$

B. $0.3hp$

C. $0.5hp$

D. $0.6hp$

Calculate the Water Horsepower. Use the differential pressure given in psi directly. Ignore the specific gravity which is only needed when the head added by the pump is given in ft.

$$whp = \frac{Q\Delta p}{1714} = \frac{(100)(10)}{1714} = 0.58hp$$

Answer D

47.47 Waste water flows to a common drain from 3 upstream sources. The pipes have inside diameters of $1in$, $2in$, and $3in$. The velocity in each upstream pipe is $3\frac{ft}{s}$. If the main drain downstream is sized such that the velocity in is not to exceed $2\frac{ft}{s}$, what is the minimum diameter?

A. $3in$

B. $4in$

C. $5in$

D. $6in$

Calculate the volume flow rate through the drain by finding the sum of the volume flow rate from each of the 3 sources. Use the relation that volume flow rate is the product of velocity and area for each source. Area is a function of the inside diameter. Label the sources as 1, 2, and 3, and the drain as 4.

$$Q_4 = Q_1 + Q_2 + Q_3$$

$$Q_4 = V_1A_1 + V_2A_2 + V_3A_3$$

Substitute known velocities and diameters. Convert in to ft.

$$Q_4 = \left(3\frac{ft}{s}\right)\left(\frac{\pi}{4}\right)\left(\frac{1in}{\left(\frac{12in}{ft}\right)}\right)^2 + \left(3\frac{ft}{s}\right)\left(\frac{\pi}{4}\right)\left(\frac{2in}{\left(\frac{12in}{ft}\right)}\right)^2 + \left(3\frac{ft}{s}\right)\left(\frac{\pi}{4}\right)\left(\frac{3in}{\left(\frac{12in}{ft}\right)}\right)^2 = 0.229\frac{ft^3}{s}$$

Solve for the area of the drain.

$$Q_4 = V_4A_4$$

$$A_4 = \frac{Q_4}{V_4} = \frac{0.229\frac{ft^3}{s}}{2\frac{ft}{s}} = 0.1145ft^2$$

Calculate the diameter of the drain. Convert to in.

$$A_4 = \frac{\pi}{4} D_4^2$$

$$D_4 = \sqrt{\frac{4}{\pi} A_4} = 0.38 ft \left(\frac{12 in}{ft} \right) = 4.6 in$$

Answer C

47.48 What is the Reynolds number for $1500 gpm$ of $70°F$ water flowing in a standard weight steel pipe with a diameter of $10 in$?

A. 32,000

B. 380,000

C. 480,000

D. 5,800,000

Use the Schedule 40 Steel Pipe table or the Steel Pipe Friction Tables to find the diameter of nominal $10 in$ pipe.

$$D = 10.02 in$$

Use the Steel Pipe Friction Tables to find the velocity for $1500 gpm$ flowing in a $10 in$ pipe. This saves time as compared with calulating $v = \frac{Q}{A}$, which is equally valid.

$$v = 6.1 \frac{ft}{s}$$

Look up the kinematic viscosity for $70°F$ water in the Properties of Water table.

$$\nu_{@70°F} = 1.059 \times 10^{-5} \frac{ft^2}{s}$$

Calculate the Reynolds Number.

$$Re = \frac{vD}{\nu} = \frac{\left(6.1 \frac{ft}{s}\right) \left(\frac{10.02 in}{12 \frac{in}{ft}} \right)}{1.059 \times 10^{-5} \frac{ft^2}{s}} = 480,000$$

Answer C

47.49 A gauge reads the static pressure for air flowing in a pipe as $1 psig$. A pitot tube reads the total pressure as $60 mm$ of mercury. What is the velocity of the air?

A. $5600 fpm$

B. $8400 fpm$

C. $11,800 fpm$

D. $16,300 fpm$

Total Pressure is the sum of static pressure and velocity pressure. Rearrange the formula for velocity pressure.

$$p_t = p_s + p_v$$

$$p_v = p_t - p_s$$

Both the total pressure and the static pressure are measured by gauges and therefore report gauge pressure. It is the *difference* between the two which is relevant in this scenario, which is the same regardless of whether gauge or absolute pressures are used, since atmospheric pressure washes out in the subtraction. In summary, there is no need for converting to absolute pressure.

Use Commonly Used Equivalents to find the conversion from mm of mercury to psi. Calculate the total pressure minus the static pressure. Convert to inches of water.

$$p_v = (60mm\,Hg)\left(\frac{1in}{25.4mm}\right)\left(0.491\frac{psi}{in\,Hg}\right) - 1psi = 0.16psi$$

$$p_v = 0.16psi\left(\frac{2.31ft\,H_2O}{psi}\right)\left(\frac{12in\,H_2O}{ft\,H_2O}\right) = 4.43in\,H_2O$$

Since no temperautre is given, assume air is at standard conditions. Solve the Velocity Pressure equation for velocity in fpm.

$$p_v = \left(\frac{V_{[fpm]}}{4005}\right)^2 = 4.43in\,H_2O$$

$$V = 8430fpm$$

Answer B

47.50 An open loop condenser water system holds $20,000\ gallons$. The system is to be treated with a 45% by volume biocide solution until the average concentration after mixing is $10ppm$. Ignoring evaporation and the addition of make-up water, what volume of the solution is required?

A. $0.2gal$

B. $0.4gal$

C. $2gal$

D. $4gal$

The final concentration of biocide is 10 parts per million (ppm). Calculate the volume of biocide needed to achieve this concentration.

$$20,000gal\left(\frac{10}{10^6}\right) = 0.2gal$$

If the solution being added is only 45% biocide, the volume of the *solution* required is larger than the volume of the active chemical. It is inferred that the remaining 55% of the solution is inactive, probably water. Calculate the volume of the solution needed to provide $0.2gal$ of biocide.

$$\frac{0.2gal}{0.45} = 0.44gal$$

Answer B

47.51 The flow of $20°C$ water through a hose with an inside diameter of $25mm$ is at the lower boundary of the fully turbulent range. How long will it take to fill a $50,000L$ swimming pool?

A. $8\,hours$

B. $27\,hours$

C. $38\,hours$

D. $59\,hours$

Pipe flow is considered Fully Turbulent once the Reynolds Number is greater than 12,000. Since the flow is at the lower boundary of the turbulent range, find the velocity which corresponds to $Re = 12,000$. Use the Properties of Water table to obtain the kinematic viscosity at $20°C$.

$$Re > 12,000$$

$$Re = \frac{vD}{\nu}$$

$$v = \frac{Re \cdot \nu}{D} = \frac{(12,000)\left(0.000001003\frac{m^2}{s}\right)}{(0.025m)} = 0.481\frac{m}{s}$$

Calculate the volume flow rate based on velocity and area. Since the pool volume is in liters, and the answer choices are in hours, convert to $\frac{L}{hr}$.

$$Q = vA = \left(0.481\frac{m}{s}\right)\left(\frac{\pi}{4}\right)(0.025m)^2 = 2.36 \times 10^{-4}\frac{m^3}{s}\left(\frac{1000L}{1m^3}\right)\left(\frac{3600s}{hr}\right) = 849.6\frac{L}{hr}$$

By definition, volume flow rate is volume per unit time. Rearrange to solve for the time to fill the desired volume.

$$Q = \frac{Volume}{t}$$

$$t = \frac{Volume}{Q} = \frac{50,000L}{849.6\frac{L}{hr}} = 58.9hr$$

Answer D

47.52 $800gpm$ **of gasoline** $(SG = 0.72)$ **is transported through an** $18in$ **steel pipe. The kinematic viscosity of gasoline is** $6 \times 10^{-6}\frac{ft^2}{s}$**. What is the Reynolds number?**

A. 1,800

B. 180,000

C. 250,000

D. 350,000

Use the volume flow rate and diameter to calculate the velocity of gasoline through the pipe. For larger pipes, there is no need to distinguish nominal from actual size.

$$Q = vA$$

$$v = \frac{Q}{A} = \frac{\left(800\frac{gal}{min}\right)\left(\frac{1ft^3}{7.48gal}\right)\left(\frac{1min}{60s}\right)}{\frac{\pi}{4}\left(1.5ft\right)^2} = 1.01\frac{ft}{s}$$

Use the kinematic viscosity, diameter, and velocity to determine the Reynolds Number. The specific gravity is extra information and should be ignored.

$$Re = \frac{vD}{\nu}$$

$$Re = \frac{\left(1.01\frac{ft}{s}\right)(1.5ft)}{\left(6 \times 10^{-6}\frac{ft^2}{s}\right)} = 252,177$$

Answer C

47.53 **A water main is required to transport** $8000gpm$ **of water. What is the smallest diameter of pipe that should be used?**

A. $12in$

B. $18in$

C. $24in$

D. $32in$

Start by checking the Steel Pipe Friction Tables. The largest diameter provided is $12in$ and the maximum volume flow rate is $4000gpm$. Eliminate choice A.

Since there is no additional information aside from the flow rate, use a rule of thumb. One handy option is to divide gpm by 20 and take the square root. This is only for getting a ballpark answer.

$$D_{[in]} \approx \sqrt{\frac{Q_{[gpm]}}{20}} = \sqrt{\frac{8000}{20}} = 20in$$

Eliminate choice D as $32in$ is likely excessive. Since $20in$ is only slightly larger than $18in$, answer B is still worth considering.

Another approach is to assume a typical maximum velocity, such as $5\frac{ft}{s}$, and solve for the required area.

$$Q = vA$$

$$A = \frac{Q}{v} = \frac{\left(8000\frac{gal}{min}\right)\left(\frac{1ft^3}{7.48gal}\right)\left(\frac{1min}{60s}\right)}{5\frac{ft}{s}} = 3.56ft^2$$

Solve for the diameter.

$$A = \frac{\pi}{4}D^2$$

$$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4\left(3.56ft^2\right)}{\pi}} = 2.13ft\left(\frac{12in}{1ft}\right) = 25.6in$$

Since the diameter is only slightly larger than $24in$, and the first rule of thumb gave a 20% smaller answer, choose $24in$.

Answer C

47.54 A pressurized tank contains air at $300psia$. What is the Mach number of air exiting to the atmosphere through a hole in the tank?

A. 0.8

B. 2.6

C. 4.2

D. 5.5

Determine the ratio of the pressure downstream of the opening to the pressure inside the tank.

$$\frac{P}{P_0} = \frac{14.7psia}{300psia} = 0.049$$

Use the One-Dimensional Isentropic Compressible-Flow Functions table to look up the pressure ratio and obtain the corresponding Mach Number, M.

$$M \approx 2.6$$

Alternatively, use the equation from Isentropic Flow Relationships. Solve for M. Assume the ratio of specific heats $k = 1.4$.

$$\frac{P_0}{P} = \left(1 + \frac{k-1}{2}M^2\right)^{\frac{k}{k-1}}$$

$$M = \sqrt{\left(\frac{2}{k-1}\right)\left[\left(\frac{P_0}{P}\right)^{\frac{k-1}{k}} - 1\right]}$$

$$M = \sqrt{\left(\frac{2}{1.4-1}\right)\left[\left(\frac{300psia}{14.7psia}\right)^{\frac{1.4-1}{1.4}} - 1\right]} = 2.61$$

Answer B

47.55 A pump requires $120hp$ to transport $1400gpm$. What percent reduction in power will be realized when the flow rate is reduced to $800gpm$?

A. 19%

B. 33%

C. 67%

D. 81%

Reference the Pump Affinity Laws and use the equation for horsepower as a function of speed. Speed and volume flow rate are linearly proportional, therefore the ratio of the volume flow rates may be substituted for the ratio of the speeds.

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1}$$

$$bhp_2 = bhp_1\left(\frac{N_2}{N_1}\right)^3$$

$$bhp_2 = bhp_1\left(\frac{Q_2}{Q_1}\right)^3$$

Consider the original operating conditions as State 1, and the new conditions as State 2. Substitute and solve for the new power.

$$bhp_2 = (120hp)\left(\frac{800gpm}{1400gpm}\right)^3 = 22.4hp$$

Calculate the percent reduction relative to the original power.

$$\frac{(120hp - 22.4hp)}{120hp} = 81\%$$

Answer D

47.56 A fluid with a specific gravity of 1.1 is pumped by a 150hp pump which generates 300ft of head. What is the increase in pressure observed at the pump outlet?

A. 130psi

B. 143psi

C. 3300psi

D. 20,600psi

Refer to the section under the Bernoulli Equation. The change in pressure is essentially the head added by the pump converted from ft to psi, and after adjusting for the specific weight of fluids other than water, as is the case in this problem.

$$\Delta p = \gamma h$$

Head added by the pump, h, is given. The specific weight is a function of the Specific Gravity. Solve for γ and substitute into the original equation.

$$SG = \frac{\gamma}{\gamma_w}$$

$$\gamma = SG \cdot \gamma_w$$

$$\Delta p = SG \cdot \gamma_w h$$

Evaluate the increase in pressure, Δp, and convert units to psi.

$$\Delta p = (1.1)\left(62.4\frac{lb_f}{ft^3}\right)(300ft)\left(\frac{1ft^2}{144in^2}\right) = 143psi$$

Answer B

47.57 A pump running at $1750rpm$ delivers $250gpm$ and generates $150ft$ of head. What is the head generated by the pump after the impeller is trimmed by 25%, assuming the speed remains the same?

A. $84ft$

B. $113ft$

C. $150ft$

D. $267ft$

Use the Pump Affinity Laws for Impeller Diameter Change. Consider the original pump conditions as State 1 and pump attributes after modification as State 2. A 25% reduction in diameter retains 75% of the original diameter such that $\frac{D_2}{D_1} = 0.75$. The speed is unchanged and the volume flow rate is extra information. Selet the formula below and determine the head for the new conditions.

$$h_2 = h_1 \left(\frac{D_2}{D_1}\right)^2$$

$$h_2 = (150ft)(0.75)^2 = 84.4ft$$

Answer A

47.58 A pump is used to distribute $90°F$ water from an open tank at $5gpm$. The centerline of the pump is located $8ft$ above the surface of the water. The manufacturer's specifications state the inlet pressure for this arrangement must be at least $30psi$. What is the net positive suction head required?

A. $35ft$

B. $61ft$

C. $69ft$

D. $103ft$

Net Positive Suction Head Required, or $NPSH_R$, is always provided by the pump manufacturer. In this case, the manufacturer has provided the required inlet pressure, which is the same information given in *psi* rather than *ft* of head. The additional information in the problem statement will impact the net positive suction head *available*, but the net positive suction head *required* is purely a specification from the manufacturer. Simply convert the units from *psi* to ft. There is no need to add atmospheric pressure. The atmosphere may help contribute to the required head / pressure.

$$NPSH_R = (30psi)\left(2.31\frac{ft}{psi}\right) = 69ft$$

Answer C

47.59 A water-cooled chiller produces $500 gpm$ of $45°F$ supply chilled water from $56°F$ return chilled water. The chiller has a coefficient of performance of 4.8. What is the load on the condenser?

A. $181 tons$

B. $229 tons$

C. $277 tons$

D. $325 tons$

Use the sensible cooling rule of thumb for water to determine the refrigeration effect, $\dot{Q}_{in}$.

$$\dot{Q}_{in} = 500 gpm \Delta T_{CHW}$$

$$\dot{Q}_{in} = 500\,(500)\,(56 - 45) = 2,750,000 \frac{Btu}{hr}$$

Use the Coefficient of Performance for a refrigeration cycle to determine the work done by the compressor.

$$COP_R = \frac{\dot{Q}_{in}}{\dot{W}_{in}}$$

$$\dot{W}_{in} = \frac{\dot{Q}_{in}}{COP} = \frac{2,750,000 \frac{Btu}{hr}}{4.8} = 572,917 \frac{Btu}{hr}$$

The condenser load is the total heat rejected by the condenser which is the sum of the heat absorbed by the evaporator and the compressor input energy. Calculate $\dot{Q}_{out}$. Convert units from $\frac{Btu}{hr}$ to $tons$.

$$\dot{Q}_{out} = \dot{Q}_{in} + \dot{W}_{in}$$

$$\dot{Q}_{out} = 2,750,000 \frac{Btu}{hr} + 572,917 \frac{Btu}{hr} = 3,322,917 \frac{Btu}{hr}$$

$$\dot{Q}_{out} = 3,322,917 \frac{Btu}{hr} \left(\frac{1 ton}{12,000 \frac{Btu}{hr}} \right) = 277 tons$$

Answer C

47.60 A single phase $240V$ motor drives a pump that supplies $100\frac{lb_m}{min}$ of $80°F$ water and adds $400ft$ of pressure head. The pump is 70% efficient and the motor is 90% efficient. What is the current drawn by the motor?

A. $3A$

B. $4A$

C. $5A$

D. $6A$

Use the Properties of Water table to look up the density of water at $80°F$. Use the density and the mass flow rate to find the volume flow rate. Convert units to gpm.

$$\rho = 62.2\frac{lb_m}{ft^3}$$

$$\dot{m} = \rho Q$$

$$Q = \frac{\dot{m}}{\rho} = \frac{100\frac{lb_m}{min}}{\left(62.4\frac{lb_m}{ft^3}\right)\left(\frac{1ft^3}{7.48gal}\right)} = 12gpm$$

Calculate the Water Horsepower delivered by the pump.

$$whp = \frac{Qh}{3960}$$

$$whp = \frac{(12)(400)}{3960} = 1.21hp$$

Use the pump and motor efficiencies to calculate the input power to the motor. Convert units to KW.

$$P_{[KW]} = \frac{whp}{\eta_m \eta_p} = \frac{(1.21hp)\left(0.7457\frac{KW}{hp}\right)}{(0.7)(0.9)} = 1.44KW$$

Select the equation in the table Power for Different Motor Phases for single-phase motors to determine the current. Assume the power factor is unity. Write and check all units.

$$P_{[KW]} = IV(pf)$$

$$I_{[amps]} = \frac{P_{[KW]}\left(\frac{1000W}{KW}\right)}{V(pf)} = \frac{(1.44KW)\left(\frac{1000W}{KW}\right)}{(240V)(1)} = 6A$$

Answer D

47.61 Olive oil has a dynamic viscosity of $40cP$ and a specific gravity of 0.92. What is the kinematic viscosity?

A. $4.3 \times 10^{-5} \frac{ft^2}{s}$

B. $4.7 \times 10^{-4} \frac{ft^2}{s}$

C. $2.0 \times 10^{-3} \frac{ft^2}{s}$

D. $1.7 \frac{ft^2}{s}$

Use the Specific Gravity to determine the density of the oil.

$$SG = \frac{\rho_{oil}}{\rho_{water}}$$

$$\rho_{oil} = SG \cdot \rho_{water} = (0.92)\left(62.4 \frac{lb_m}{ft^3}\right) = 57.4 \frac{lb_m}{ft^3}$$

Use the relation between Kinematic Viscosity and Absolute Viscosity i.e. 'Dynamic Viscosity'. Use Measurement Relationships for required unit conversioins to align with the answer choices.

$$\nu = \frac{\mu}{\rho}$$

$$\nu = \frac{(40cP)\left(2.412 \frac{lb_m}{hr \cdot ft \cdot cP}\right)\left(\frac{1hr}{3600s}\right)}{57.4 \frac{lb_m}{ft^3}} = 4.7 \times 10^{-4} \frac{ft^2}{s}$$

Answer B

47.62 $900gpm$ of a fluid flows through $500ft$ of a $8in$ pipe. The Reynolds number is $80,000$ and the relative roughness is 0.0003. What is the total pressure drop?

A. $2.5ft$

B. $3.5ft$

C. $5.8ft$

D. $8.2ft$

The pressure drop is calculated with the Darcy-Weisbach Equation.

$$h_f = \frac{fLv^2}{2Dg}$$

The Reynolds number and relative roughness are given. Use the Moody diagram to obtain the friction factor.

$$Re = 80,000$$

$$\frac{\epsilon}{D} = 0.0003$$

$$f = f\left(Re, \frac{\epsilon}{D}\right) \approx 0.021$$

Use the Steel Pipe Friction Tables to obtain the velocity and exact diameter based on the gpm and nominal pipe size.

$$v = 5.77\frac{ft}{s}$$

$$D = 7.981in$$

Substitute into the Darcy Equation and solve. Keep the final result with units of ft.

$$h_f = \frac{(0.021)\,(500ft)\left(5.77\frac{ft}{s}\right)^2}{2\left(\frac{7.981in}{12\frac{in}{ft}}\right)\left(32.2\frac{ft}{s^2}\right)} = 8.2ft$$

Answer D

47.63 $50°F$ water enters a steam boiler with a capacity 200 boiler horsepower. The boiler has an operating pressure of $10psig$. What is the required flow rate of feedwater at maximum capacity?

A. $12gpm$

B. $180gpm$

C. $290gpm$

D. $700gpm$

The feedwater must first be heated sensibly from its initial temperature, $T_1 = 50°F$, to the boiling point. Use the table Properties of Saturated Water and Steam (Pressure) to obtain the saturation temperature i.e. boiling point of water at the operating pressure. Also obtain the latent heat of vaporization, h_{fg}, from the same line in the steam table.

$$P = 10psig + 14.7psi \approx 25psia$$

$$T_{sat} = 240°F$$

$$h_{fg} = 952\frac{Btu}{lb}$$

Use Measurement Relationships to convert the heating capacity of the boiler from *boiler hp* to $\frac{Btu}{hr}$.

$$\dot{Q}_{total} = (200 boiler\, hp)\left(33,470 \frac{Btu}{hr \cdot boiler\, hp}\right) = 6,694,000 \frac{Btu}{hr}$$

Express the total heating as the sum of the sensible heating of water to the boiling point and the latent heat of vaporization. Factor out and solve for the mass flow rate. Convert to the volume flow rate in *gpm*.

$$\dot{Q}_{total} = \dot{Q}_S + \dot{Q}_L = \dot{m} c_p \Delta T + \dot{m} \Delta h$$

$$\dot{Q}_{total} = \dot{m} c_p (T_{sat} - T_1) + \dot{m} h_{fg} = \dot{m}\left[c_p (T_{sat} - T_1) + h_{fg}\right]$$

$$\dot{m} = \frac{\dot{Q}_{total}}{c_p (T_{sat} - T_1) + h_{fg}}$$

$$\dot{m} = \frac{6,694,000 \frac{Btu}{hr}}{\left(1 \frac{Btu}{lb \cdot {}^\circ F}\right)(240^\circ F - 50^\circ F) + 952 \frac{Btu}{lb}} = 5861.6 \frac{lb}{hr}$$

$$Q = \left(5861.6 \frac{lb}{hr}\right)\left(\frac{1 gal}{8.34 lb}\right)\left(\frac{1 hr}{60 min}\right) = 11.7 gpm$$

Answer A

47.64 A centrifugal pump rotating at $3600 rpm$ delivers $150 gpm$ of water against $50 ft$ of head. The pump efficiency is 78% and the motor efficiency is 88%. What is the annual cost to run the pump Monday-Friday 6am-6pm at an average electricity rate of $0.12/kWh?

A. $600

B. $680

C. $770

D. $1080

Calculate the Water Horsepower delivered by the pump. To use the formula below, the volume flow rate, Q, must be in *gpm* and the head, h, must be in ft. The standard density of water is embedded in the formula, so it is important to apply this formula only when dealing with water.

$$whp = \frac{Q \Delta h}{3960} = \frac{(150)(50)}{3960} = 1.893 hp$$

The input power to the motor driving the pump must account for both the pump efficiency and the motor efficiency, and be converted to KW.

$$\dot{W} = \frac{whp}{\eta_m \eta_p} = \frac{1.893 hp}{(0.78)(0.88)}\left(\frac{0.7457 KW}{1 hp}\right) = 2.057 KW$$

Determine the number of annual run hours based on hours per day and days per week for one year.

$$\left(\frac{12hr}{day}\right)\left(\frac{5days}{wk}\right)(52wks) = 3120hrs$$

Calculate the annual running cost based on demand, annual run hours, and the cost of electricity.

$$Cost = (2.057KW)(3120hrs)\left(\frac{\$0.12}{kWhr}\right) = \$770$$

Answer C

47.65 A continuously running $460V$ 3-phase motor draws $23A$. The motor has a power factor of 0.91 and an efficiency of 88% and drives a centrifugal pump with an efficiency of 77%. The pump supplies $300gpm$ of water against $200ft$ of head. To save energy and avoid cost, operators determine that the pump may be turned off for $8hours$ per day with no impact to the operation and no change to the operating parameters while in use. Electricity costs $\$0.15/kWh$ for consumption and $\$15/KW$ for peak demand. What are the expected annual savings for this initiative?

A. $5400

B. $6200

C. $7100

D. $7300

There will be no changes in the demand charge because the operating parameters are the same when the pump is in use. In other words, the maximum power draw is unchanged. Only the reduced electrical consumption will drive savings.

Calculate the input power demand to run the motor using the fourth formula on the right side of the table under Power for Different Motor Phases. There is no need to work backwards from water horsepower and apply the pump and motor efficiencies since the current, voltage, and power factor are all given.

$$P_{KW} = \frac{\sqrt{3}IV(pf)}{1000} = \frac{\sqrt{3}(23)(460)(0.91)}{1000} = 16.67KW$$

Multiply the electrical demand by time and the unit rate for electricy to determine the annual savings.

$$Savings = (16.67KW)\left(\frac{8hr}{day}\right)(365days)\left(\frac{\$0.15}{kWh}\right) = \$7304$$

Answer D

47.66 Decane ($C_{10}H_{22}$) undergoes complete, stoichiometric combustion in air. What is the mass fraction of carbon dioxide in the product gas?

A. 13%

B. 19%

C. 49%

D. 69%

Decane is not listed in the table Combustion Reactions of Common Fuel Constituents. Therefore, it is necessary to write the balanced reaction. Since the combustion is stoichiometric, there is no excess air. Start by writing the products and reactants using arbitrary constant coefficients. For the reactants, there are 3.77 nitrogen molecules per oxygen molecule in air. The products are carbon dioxide, water vapor, and nitrogen. Nitrogen does not participate in the reaction.

$$C_{10}H_{22} + x\left(O_2 + 3.77N_2\right) \rightarrow aCO_2 + bH_2O + cN_2$$

Balance the carbon.

$$a = 10$$

Balance the hydrogen.

$$22 = 2b \rightarrow b = 11$$

Balance the oxygen.

$$2x = 2a + b = 2\left(10\right) + 11 = 31$$

$$x = \frac{31}{2} = 15.5$$

Balance the nitrogen.

$$2c = 2\left(3.77\right)x = 2\left(3.77\right)\left(15.5\right) = 116.87$$

$$c = \frac{116.87}{2} = 58.435$$

Re-write the product side of the reaction with all known coeffients.

$$Reactants \rightarrow 10CO_2 + 11H_2O + 58.435N_2$$

Determine the Mass Fraction of carbon dioxide in the product gas. Use the Periodic Table to look up atomic weights as required. The mass of each constiuent is the product of the number of moles and the molecular weight.

$$y_{CO_2} = \frac{m_{CO_2}}{\sum m_i} = \frac{m_{CO_2}}{m_{CO_2} + m_{H_2O} + m_{N_2}}$$

$$y_{CO_2} = \frac{(10)[12+2(16)]}{(10)[12+2(16)]+11[2(1)+16]+58.435[2(14)]} = 0.19 = 19\%$$

Answer B

47.67 A $1500cfm$ two-pipe fan coil unit with electric reheat maintains a room at $74°F$ and 50% relative humidity. The supply air from the unit is $58°F$. The cooling coil discharge condition is $48°F$ db / $46°F$ wb. There is $1°F$ of temperature rise across the fan. Neglecting losses, how much power is required to run the reheat coil?

A. $4300W$

B. $4700W$

C. $5200W$

D. $5700W$

The electric reheat coil provides sensible heating only. Use the sensible heating rule of thumb for air.

$$\dot{Q}_{htg} = 1.08cfm\Delta T$$

The volume flow rate is given. Air enters the heating coil after leaving the cooling coil at a dry bulb temperature of $48°F$. Since the fan adds $1°F$ of temperature rise to achieve the $58°F$ supply air temperaure from the unit, the air leaving the reheat coil and entering the fan is $57°F$. Solve for the reheat load, and convert units to W.

$$\dot{Q}_{htg} = 1.08(1500)(57-48) = 14,580\frac{Btu}{hr}\left(\frac{1W}{3.412\frac{Btu}{hr}}\right) = 4273W$$

Answer A

47.68 A pump located $10ft$ above an open water tank at sea level transports $80gpm$ of $80°F$ water. The head loss in the suction piping is $15ft$. The net positive suction head required is $4ft$. What is the net positive suction head available?

A. $8ft$

B. $18ft$

C. $28ft$

D. $38ft$

Net Positive Suction Head Available is a function of the physical layout of the pump, piping, and source. The Net Positive Suction Head Required is determined from the manufacturer's specifications and has no bearing on the NPSHA. The criterion for avoiding cavitation is that $NPSH_A > NPSH_R$. Since this problem only requires calculating NPSHA, the NPSHR is extra information.

Sketch and label the system. Work through each term in the NPSHA formula.

$$NPSH_A = h_p + h_z - h_{vpa} - h_f$$

The first term, h_p, is the atmospheric pressure. Use the conversion factor rule of thumb for water to convert from psi to ft.

$$h_p = (14.7psia)\left(2.31\frac{ft}{psi}\right) \approx 34ft$$

The second term, h_z, is the elevation term and is taken as negative becasue the pump is *above* the water source, thereby *reducing* the head available at the pump inlet. Sometimes the operator before this term is written as "plus or minus" $\pm$ to reflect this arrangement. It is fine to regard the value as positive as long as in the final step it is subtracted.

$$h_z = -10ft$$

The third term, h_{vpa}, is the vapor pressure and is a function of the temperature of the water. The vapor pressure is always subtracted. The higher the water temperature, the higher the vapor pressure, and the harder it will be to avoid cavitation. Use the Properties of Saturated Water and Steam (Temperature) table to look up the saturation pressure at $T = 80°F$. Use the conversion factor rule of thumb for water to convert from psi to ft.

$$T = 80°F$$

$$P_{sat} = 0.51psia\left(2.31\frac{ft}{psi}\right) = 1.178ft$$

The fourth term, h_f, is always subtracted since losses reduce the available head. The value for h_f was given.

$$h_f = 15ft$$

Calculate the NPSHA.

$$NPSH_A = 34ft - 10ft - 1.178ft - 15ft = 7.8ft$$

Answer A

47.69 Refrigerant R-410a is compressed isentropically from a saturated condition at $20psia$ to a pressure of $190psia$. What is the change in temperature during the compression process?

A. $11°F$

B. $63°F$

C. $76°F$

D. $174°F$

Sketch the compression process on a Pressure-Enthalpy diagram. Use the table for Refrigerant 410A to obtain the saturation temperature corresponding to the compressor inlet pressure, P_1. Note the table provides two temperatures, 'Bubble' and 'Dew'. Typically the values are close in magnitude and selection is of little consequence. For simplicity, use the 'Dew' temperature since this value corresponds to when the last drop of refrigerant evaporates, which should be complete prior to entering the compressor.

$$P_1 = 20psia \ (saturated)$$

$$T_1 = -49.2°F$$

Using the chart Pressure Versus Enthalpy Curves for Refrigerant 410A, draw a horizontal line across the chart for the high pressure condition, $P_2 = 190psia$. To locate the line properly, check the table for the corresponding saturation temperature which is approximately $T_3 \approx 61.6°F$. The goal is to find T_2, however, knowing T_3 will help draw the horizontal line contain the condensing process from $2 \rightarrow 3$ in the correct location on the chart. The vertical axis uses log scale so using pressure alone can be challenging. It is also essential to recognize that in the superheated region, the temperature is no longer constant along a horizontal line.

Next, draw a line of constant entropy starting from State 1 and making best effort to remain parallel with local constant entropy lines on the chart, which tend to travel north-northeast to south-southwest, but are not perfectly linear. Find the interesection of this constant entropy line from $1 \rightarrow 2$ and the horizontal line containing States 2 & 3. The interesection represents State 2. Read the temperature by following the constant temperature lines which waterfall down and to the right. Be willing to accept reduced precision when using a graphical approach.

$$T_2 \approx 125°F$$

Calculate the change in temperature between State 2 and State 1.

$$T_2 - T_1 = 125°F - (-49.2°F) = 174.2°F$$

Answer D

47.70 **$20\frac{lb_m}{min}$ of $50°F$ air at atmostpheric pressure enters an air compressor and exits at $350°F$. What is the power required to drive the compressor?**

A. $34hp$

B. $40hp$

C. $114hp$

D. $142hp$

Consider the air entering the Compressor as State 1 and the air exiting the compressor as State 2. Since there is not enough information about State 2 to fully define it, assume the air behaves as an Ideal Gas with Constant Specific Heats. Solve for the compressor power and convert units to hp.

$$\dot{W}_{comp} = \dot{m}c_p\left(T_e - T_i\right)$$

$$\dot{W}_{comp} = \left(20\frac{lb}{min}\right)\left(0.24\frac{Btu}{lb \cdot °F}\right)(350°F - 50°F) = 1440\frac{Btu}{min}$$

$$\dot{W}_{comp} = 1440\frac{Btu}{min}\left(\frac{60min}{1hr}\right)\left(\frac{1KW}{3412\frac{Btu}{hr}}\right)\left(\frac{1hp}{0.7457KW}\right) = 34hp$$

Answer A

47.71 **What is the wet bulb temperature of $150°F$ sea level air with 50% relative humidity?**

A. $123°F$

B. $126°F$

C. $135°F$

D. $138°F$

Use the high temperature Psychrometric Chart. Identify the state point which is fully defined since the temperature and relative humidity are both given.

$$T = 150°F$$

$$\phi = 50\%$$

Read the wet bulb temperature from the light gray diagnonal lines that run from west-northwest to east-southeast on the chart. Note the wet bulb temperature and enthalpy are not perfectly parallel at high temperature. Special care should be taken to avoid inadverently reporting the enthalpy value rather than the wet bulb temperature, as $120°F\,wb$ and $120\frac{Btu}{lb}$ are close together, and the constant enthalpy lines are heavier and easier to read.

The light gray lines of constant wet bulb temperature are $2°F$ apart. By visual inspection, the state point in consideration is between $125°F\,wb$ and $126°F\,wb$.

Answer B

47.72 A 460-V three phase AC motor rated for $60hp$ operates with an efficiency of 93% and a power factor of 0.85. How much current will the motor draw?

A. $60A$

B. $66A$

C. $71A$

D. $123A$

Use the first three-phase equation in the table Power for Different Motor Phases, where the power rating is given in horsepower. Voltage, power factor, and efficiency are all given. Calculate the current.

$$I_{[amps]} = \frac{P_{[hp]}(746)}{\sqrt{3}V\eta(pf)}$$

$$I_{[amps]} = \frac{(60)(746)}{\sqrt{3}(460)(0.93)(0.85)} = 71A$$

Answer C

47.73 Steam enters a turbine at a pressure of $1000psia$ and a temperature of $800°F$ and exits at a pressure of $90psia$ and a temperature of $400°F$. What is the efficiency?

A. 52%

B. 67%

C. 72%

D. 89%

Consider the entering steam as State 1 and the exit steam as State 2. Both states are fully defined and superheated. Use the properties of Superheated Steam tables to look up the enthalpy and entropy for State 1, and the *actual* enthalpy for State 2.

$$P_1 = 1000psia$$

$$T_1 = 800°F$$

$$h_1 = 1389\frac{Btu}{lb}$$

$$s_1 = 1.567\frac{Btu}{lb \cdot °R}$$

$$P_2 = 90psia$$

$$T_2 = 400°F$$

$$h_2^{'} = 1229.3\frac{Btu}{lb}$$

If the expanstion process was isentropic, i.e. 100% efficient, the entropy at State 2 would be equal to the entropy at State 1. Use the properties of Saturated Water and Steam table to obtain the enthalpy and entropy values at $P_2 = 90psia$ and determine the quality at State 2 for isentropic expansion.

$$s_2 = s_1 = 1.567\frac{Btu}{lb \cdot {}^{\circ}R}$$

$$\chi_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{1.567\frac{Btu}{lb \cdot {}^{\circ}R} - 0.4643\frac{Btu}{lb \cdot {}^{\circ}R}}{1.1474\frac{Btu}{lb \cdot {}^{\circ}R}} = 0.961$$

Use the quality to find the *ideal* enthalpy at State 2.

$$h_2 = h_f + \chi_2 h_{fg} = 290.76\frac{Btu}{lb} + (0.961)\left(894.9\frac{Btu}{lb}\right) = 1150.7\frac{Btu}{lb}$$

The efficiency is the *actual* change in enthalpy compared with the *ideal* difference in enthalpy for an isentropic process across the same pressure range. Calculate the efficiency.

$$\eta = \frac{h_1 - h_2^{'}}{h_1 - h_2}$$

$$\eta = \frac{1389\frac{Btu}{lb} - 1229.3\frac{Btu}{lb}}{1389\frac{Btu}{lb} - 1150.7\frac{Btu}{lb}} = 0.67$$

Answer B

47.74 A R-134a refrigeration cycle has a cooling capacity of 30 tons. Refrigerant enters the compressor at $20°F$ saturated and is discharged at $110psia$. There is no subcooling. What is the mass flow rate of refrigerant through the cycle?

A. $91\frac{lb}{min}$

B. $95\frac{lb}{min}$

C. $104\frac{lb}{min}$

D. $110\frac{lb}{min}$

Draw a typical refrigeration cycle on a Pressure-Enthalpy diagram. Consider the entering compressor condition as State 1, the compressor exit condition as State 2, the condenser exit as State 3, and the evaporator entering condition as State 4. The cooling capacity corresponds to the heat absorbed by the exaporator, $\dot{Q}_{evap}$, which depends on the difference in enthalpy between State 1 and State 4, $h_1 - h_4$.

Start by analyzing State 1. The temperature is given and the refrigerant is known to be a saturated vapor. Use the Refrigerant 134a table to look up the enthalpy, h_1.

$$T_1 = 20°F\ (saturated\,vapor)$$

$$h_1 = 106.056\frac{Btu}{lb}$$

Next analyize State 3, after the condenser prior to expansion. The pressure is given and there is no sub-cooling. Therefore, the refrigerant is a saturated liquid. Use the table again to obtain the enthalpy at State 3. It is not necessary to gain additional precision by interpolating in this case.

$$P_3 = 110psia\,(saturated\,liquid)$$

$$h_3 \approx 39.9\frac{Btu}{lb}$$

Since the expansion process from State 3 to State 4 for is isenthalpic, the enthalpy at State 4 may also be specified.

$$h_4 = h_3 = 39.9\frac{Btu}{lb}$$

Express the heat absorbed by the evaporator as the product of the mass flow rate of refrigerant, $\dot{m}_R$, and the change in enthalpy through the evaporator.

$$\dot{Q}_{evap} = \dot{m}_R\,(h_1 - h_4)$$

Rearrange for the mass flow rate, $\dot{m}_R$, substitute, and solve.

$$\dot{m}_R = \frac{\dot{Q}_{evap}}{h_1 - h_4} = \frac{(30tons)\left(12,000\frac{Btu}{hr\cdot ton}\right)\left(\frac{1hr}{60min}\right)}{\left(106.056\frac{Btu}{lb} - 39.9\frac{Btu}{lb}\right)} = 90.7\frac{lb}{min}$$

Answer A

47.75 A room is maintained at $74°F$ and 50% relative humidity by supplying $8000cfm$ of $60°F$ supply air. The room has a sensible heat load of $150,000\frac{Btu}{hr}$ and a sensible heat ratio of 0.75. $1000cfm$ of air is exhausted from the space and a corresponding volume of outside air at $92°F$ db / $74°F$ wb is introduced. What is the wet bulb temperature of the supply air?

A. $50°F$

B. $53°F$

C. $55°F$

D. $58°F$

Sketch the system and label with given information. Apply the Sensible Heat Ratio to determine the total heat load in the room.

$$SHR = \frac{\dot{Q}_s}{\dot{Q}_t}$$

$$\dot{Q}_t = \frac{\dot{Q}_s}{SHR} = \frac{150,000\frac{Btu}{hr}}{0.75} = 200,000\frac{Btu}{hr}$$

Determine the enthalpy of the room/return condition using the Psychrometric Chart.

$$T_{room} = 74°F\,db\,/\,50\%\,RH$$

$$h_{room} = 27.56\frac{Btu}{lb}$$

Draw a system boundary around the room and the supply/return air only. Ignore the exhaust air, outside air, and mixing prior to the cooling coil. Use the total cooling rule of thumb for air to determine the enthalpy of the supply air, which depends on the total heat load in the room as previously calculated, the enthalpy of the room/return condition, and the supply airflow.

$$\dot{Q}_t = 4.5cfm\Delta h = 4.5cfm\left(h_{room} - h_{supply}\right)$$

$$h_{supply} = h_{room} - \frac{\dot{Q}_t}{4.5cfm} = 27.56 - \frac{200,000}{(4.5)\,(8000)} = 22\frac{Btu}{lb}$$

Use the Psychrometric Chart again to determine the supply wet-bulb temperature corresponding to the enthalpy.

$$T_{supply,wb} = f\left(h_{supply}\right) \approx 53°F$$

Answer B

47.76 An expansion tank consists of an air bladder which is filled to a pressure of $10psig$ which sits atop a column of water $4ft$ high. The tank has a single opening at the bottom of the tank. What is the pressure at the opening?

A. $12psia$

B. $26psia$

C. $29psia$

D. $34psia$

Consider the static pressure due to the air bladder and the height of the water column which exerts additional hydrostatic pressure on the point of interest. Neglect velocity pressure.

$$P = P_s + \gamma z$$

Since the answer choices are in *absolute* pressure, convert the bladder pressure from $psig$ to $psia$.

$$P_s = 10psig + 14.7psi = 24.7psia$$

For the water column, divide by the coversion factor rule of thumb for water, $2.31\frac{ft}{psi}$.

$$\frac{4ft}{2.31\frac{ft}{psi}} = 1.73psi$$

Solve for the total pressure.

$$P = 24.7psia + 1.73psi = 26.43psia$$

Answer B

47.77 How much air is required to burn $25lb$ of methane with 30% excess air?

A. $260lb$

B. $340lb$

C. $430lb$

D. $560lb$

Use the Combustion Reactions of Common Fuel Constituents table and consider the reaction and Stoichiometric Oxygen and Air Requirements for methane. Optionally, re-write the reaction including nitrogen on both sides to validate the stoichiometric air requirements provided in the table. Calculate the air-to-fuel ratio on a molar/volume basis as well as on a mass basis. Use the Periodic Table for atomic weights as needed. Alternatively, use the values provided directly in the table.

$$CH_4 + 2\left(O_2 + 3.77N_2\right) \rightarrow CO_2 + 2H_2O + 7.54N_2$$

$$\frac{N_{air}}{N_{fuel}} = \frac{2 + 2\left(3.77\right)}{1} = 9.54\frac{moles_{air}}{moles_{fuel}} = 9.54\frac{ft^3_{air}}{ft^3_{fuel}}$$

$$\frac{m_{air}}{m_{fuel}} = \frac{9.54\left(29\right)}{1\left(16\right)} = 17.29\frac{lb_{air}}{lb_{fuel}}$$

Calculate the mass of air based on the mass of fuel given, the air-to-fuel ratio, and the amount of excess air.

$$m_{air} = \left(25lb_{fuel}\right)\left(17.29\frac{lb_{air}}{lb_{fuel}}\right)\left(1.3\right) = 562lb_{air}$$

Answer D

47.78 During the process of condensing in a counterflow heat exchanger, the enthalpy of R-410A is reduced from $125\frac{Btu}{lb}$ to $42\frac{Btu}{lb}$. The cooling medium is water which enters at $50°F$ and exits at $75°F$. The surface area of the heat exchanger is $40ft^2$ and the overall coefficient of heat transfer is $10\frac{Btu}{hr\cdot ft^2\cdot °F}$. What is the mass flow rate of refrigerant being condensed?

A. $36\frac{lb}{hr}$

B. $41\frac{lb}{hr}$

C. $46\frac{lb}{hr}$

D. $51\frac{lb}{hr}$

Search for Heat Exchangers and use the formula for the rate of heat transfer in the condenser. Assume $F = 1$. The overall coeffient of heat transfer, U, is given. The area, A, is given.

$$\dot{Q} = UAF\Delta T_{lm}$$

To determine the Log Mean Temperature Difference, ΔT_{lm}, sketch the water cooled condenser and label the entering and exiting refrigerant and water temperatures. Use the Refrigerant 410A table and observe that for the condenser exit condition corresponding to State 3 of the refrigeration cycle, $h_3 = 42\frac{Btu}{lb}$,therefore $P_3 \approx 240psia$ and $T_3 \approx 77°F$. The temperature of the refrigerant throughout the condenser is approximately constant as it is undergoing a phase change at constant pressure.

$$77°F \longleftarrow 77°F$$

$$50°F \longrightarrow 75°F$$

Calculate the temperature differential on each physical side of the exchanger, arbitrarily labeling the sides A & B.

$$\Delta T_A = 77^\circ F - 50^\circ F = 27^\circ F$$

$$\Delta T_B = 77^\circ F - 75^\circ F = 2^\circ F$$

Calculate the Log Mean Temperature Difference, ΔT_{lm}. The formula below is consistent with the formula shown in the reference handbook, but may be easier to correctly apply once the temperature differentials are properly defined. Note that interchanging ΔT_A and ΔT_B leads to the same correct result!

$$\Delta T_{lm} = \frac{\Delta T_A - \Delta T_B}{ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$$

$$\Delta T_{lm} = \frac{27^\circ F - 2^\circ F}{ln\left(\frac{27^\circ F}{2^\circ F}\right)} = 9.6^\circ F$$

Calculate the heat transfer through the heat exchanger.

$$\dot{Q} = UAF\Delta T_{lm} = \left(10\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}\right)\left(40ft^2\right)(1)\left(9.6^\circ F\right) = 3840\frac{Btu}{hr}$$

Equate the heat transfer through the heat exchanger to the quantity of heat given up by the refrigerant, which is a function of the unknown mass flow rate, $\dot{m}_r$, and the change in enthalpy, Δh, of the refrigerant as it flows through the condenser.

$$\dot{Q} = \dot{m}_r\left(h_2 - h_3\right)$$

$$\dot{m}_r = \frac{\dot{Q}}{\left(h_2 - h_3\right)} = \frac{3840\frac{Btu}{hr}}{\left(125\frac{Btu}{lb} - 42\frac{Btu}{lb}\right)} = 46.3\frac{lb}{hr}$$

Answer C

47.79 An apartment complex uses a central domestic hot water heating system to produce $1000gpm$ of $130°F$ hot water. 30% of the supply water is consumed by tenants, and 70% is recirculated. $55°F$ make up water is introduced to the return line to replenish the system. The supply and return piping experience $1,000,000\frac{Btu}{hr}$ and $600,000\frac{Btu}{hr}$ of losses, respectively. What is the temperature of the water entering the heating system?

A. $99°F$

B. $102°F$

C. $105°F$

D. $108°F$

Sketch the domestic heating system and label all given information. Start by analyizing the supply piping. The water leaving the central system starts at a known temperature and experiences a known quantity of heat loss for a fixed volume flow rate. Use the sensible heating/cooling rule of thumb for water to determine the temperature of the hot water at the time it branches off to serve the tenant demand. Consider this point in the system State 1.

$$\dot{Q}_{supply,loss} = 500gpm\Delta T$$

$$1 \times 10^6 = 500\,(1000)\,(130°F - T_1)$$

$$T_1 = 128°F$$

Next, analyze the return piping. The water being recirculated is only 70% of the original *gpm* since 30% was used to serve the load. The heat loss in the return piping is known, and the starting temperature is $T_1 = 128°F$. Use the same rule of thumb to solve for the temperature after the return piping before any make-up water has been mixed in. Consider this point in the system State 2.

$$\dot{Q}_{return,loss} = 500gpm\Delta T$$

$$6 \times 10^5 = 500\,(700)\,(128°F - T_2)$$

$$T_2 = 126.29°F$$

Lastly, perform a mixing calculation between the $700gpm$ of recirculated water and $300gpm$ of make-up water to determine the mixed water temperature prior to entering the heating system. Consider the mixed water condition as State 3.

$$T_3 = \frac{gpm_2 T_2 + gpm_{make-up} T_{make-up}}{gpm_{total}} = \frac{(700gpm)\,(126.29°F) + (300gpm)\,(55°F)}{1000gpm} = 104.9°F$$

Answer C

47.80 A hot water heating system is rated for $200,000\frac{Btu}{hr}$ at sea level. The system includes a fuel gas burner and a combustion intake fan. What would the heating capacity be if the system was installed at an elevation of $4000ft$ above sea level?

A. $173MBH$

B. $189MBH$

C. $200MBH$

D. $231MBH$

Since air is less dense at higher elevation, the fuel's heating value will be reduced at $4000ft$ as compared with sea level operation. The reduction in capacity is proportional to the reduction in air density. Use the Altitude Corrections for Air table to obtain the density factor for $4000ft$. Calculate the new capacity, and convert units to MBH.

$$\dot{Q}_{4000ft} = \dot{Q}_{0ft}\,(Density\,Factor)$$

$$\dot{Q}_{4000ft} = \left(200,000\frac{Btu}{hr}\right)(0.864)\left(\frac{1MBH}{1000\frac{Btu}{hr}}\right) = 172.8MBH$$

Answer A