CHAPTER 6

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Concept-Study Guide Problems

6.139E

Liquid water at 60 F flows out of a nozzle straight up 40 ft. What is nozzle $V_{\text{exit}}$?

Energy Eq.6.13: $h_{\text{exit}} + \frac{1}{2} V_{\text{exit}}^2 + gH_{\text{exit}} = h_2 + \frac{1}{2} V_2^2 + gH_2$

If the water can flow 40 ft up it has specific potential energy of $gH_2$ which must equal the specific kinetic energy out of the nozzle $V_{\text{exit}}^2/2$. The water does not change P or T so h is the same.

$$V_{\text{exit}}^2/2 = g(H_2 - H_{\text{exit}}) = gH \Rightarrow$$

$$V_{\text{exit}} = \sqrt{2gH} = \sqrt{2 \times 32.174 \times 40 \text{ ft}^2/\text{s}^2} = 50.7 \text{ ft/s}$$
R-134a at 90 F, 125 psia is throttled so it becomes cold at 10 F. What is exit P?

State 1 is slightly compressed liquid so

Table F.5.1: \( h = h_f = 105.34 \text{ Btu/lbm} \)

At the lower temperature it becomes two-phase since the throttle flow has constant \( h \) and at 10 F: \( h_g = 168.06 \text{ Btu/lbm} \)

\[
P = P_{\text{sat}} = 26.8 \text{ psia}
\]
In a boiler you vaporize some liquid water at 103 psia flowing at 3 ft/s. What is the velocity of the saturated vapor at 103 psia if the pipe size is the same? Can the flow then be constant P?

The continuity equation with average values is written

\[ \dot{m}_i = \dot{m}_e = \dot{m} = \rho AV = A\dot{V}/\dot{V} = A\dot{V}_i/\dot{V}_e = A\dot{V}_e/\dot{V}_e \]

From Table F.7.2 at 103 psia we get

\[ v_f = 0.01776 \text{ ft}^3/\text{kg}; \quad v_g = 4.3115 \text{ ft}^3/\text{kg} \]

\[ \dot{V}_e = \dot{V}_i v_e/\dot{V}_i = 3 \frac{4.3115}{0.01776} = 728 \text{ ft/s} \]

To accelerate the flow up to that speed you need a large force ( \( \Delta P A \) ) so a large pressure drop is needed.
Air at 60 ft/s, 480 R, 11 psia with 10 lbm/s flows into a jet engine and it flows out at 1500 ft/s, 1440 R, 11 psia. What is the change (power) in flow of kinetic energy?

\[
\dot{m} \Delta KE = \dot{m} \frac{1}{2} (V_e^2 - V_i^2)
\]

\[
= 10 \text{ lbm/s} \times \frac{1}{2} (1500^2 - 60^2) \left(\text{ft/s}\right)^2 \frac{1}{32.174} \left(\text{lbf/lbm-ft/s}^2\right)
\]

\[
= 349 \times 10^2 \text{ lbf-ft/s} = 448.6 \text{ Btu/s}
\]
An initially empty cylinder is filled with air from 70 F, 15 psia until it is full. Assuming no heat transfer is the final temperature larger, equal to or smaller than 70 F? Does the final T depends on the size of the cylinder?

This is a transient problem with no heat transfer and no work. The balance equations for the tank as C.V. become

**Continuity Eq.:** \( m_2 - 0 = m_i \)

**Energy Eq.:** \( m_2 u_2 - 0 = m_i h_i + Q - W = m_i h_i + 0 - 0 \)

Final state: \( u_2 = h_i \) & \( P_2 = P_i \)

\( T_2 > T_i \) and it does not depend on \( V \)
Air at 95 F, 16 lbf/in.\(^2\), flows in a 4 in. \(\times\) 6 in. rectangular duct in a heating system. The volumetric flow rate is 30 cfm (ft\(^3\)/min). What is the velocity of the air flowing in the duct?

Solution:
Assume a constant velocity across the duct area with

\[
A = 4 \times 6 \times \frac{1}{144} = 0.167 \text{ ft}^2
\]

and the volumetric flow rate from Eq.6.3,

\[
\dot{V} = \dot{m}v = AV
\]

\[
\frac{\dot{V}}{A} = \frac{30}{60 \times 0.167} = 3.0 \text{ ft/s}
\]

Ideal gas so note:

\[
\left(\text{note ideal gas: } v = \frac{RT}{P} = \frac{53.34 \times 554.7}{16 \times 144} = 12.842 \text{ ft}^3/\text{lbm}\right)
\]

\[
\dot{m} = \frac{\dot{V}}{v} = \frac{30}{60 \times 12.842} = 0.0389 \text{ lbm/s}
\]
A hot air home heating system takes 500 ft³/min (cfm) air at 14.7 psia, 65 F into a furnace and heats it to 130 F and delivers the flow to a square duct 0.5 ft by 0.5 ft at 15 psia. What is the velocity in the duct?

Solution:

The inflow is given by \( \dot{m}_i \).

Continuity Eq.: \( \dot{m}_i = \dot{V}_i / v_i = \dot{m}_e = A_e V_e / v_e \)

Ideal gas: \( v_i = \frac{RT_i}{P_i} = \frac{53.34 \times 525}{14.7 \times 144} = 13.23 \text{ ft}^3/\text{lbm} \)

\( v_e = \frac{RT_e}{P_e} = \frac{53.34 \times (130 + 460)}{15 \times 144} = 14.57 \text{ ft}^3/\text{lbm} \)

\( \dot{m}_i = \dot{V}_i / v_i = 500 / (60 \times 13.23) = 0.63 \text{ lbm/s} \)

\( V_e = \dot{m} v_e / A_e = \frac{0.63 \times 14.57}{0.5 \times 0.5} \text{ ft}^3/\text{s} = 36.7 \text{ ft/s} \)
Saturated vapor R-134a leaves the evaporator in a heat pump at 50 F, with a steady mass flow rate of 0.2 lbm/s. What is the smallest diameter tubing that can be used at this location if the velocity of the refrigerant is not to exceed 20 ft/s?

Solution:

Mass flow rate Eq.6.3: \( \dot{m} = \dot{V}/v = AV/v \)

Exit state Table F.10.1: (T = 50 F, x =1) \( \Rightarrow \) \( v = v_g = 0.792 \text{ ft}^3/\text{lbm} \)

The minimum area is associated with the maximum velocity for given \( \dot{m} \)

\[
A_{\text{MIN}} = \frac{\dot{m}v_g}{V_{\text{MAX}}} = \frac{0.2 \text{ lbm/s} \times 0.792 \text{ ft}^3/\text{lbm}}{20 \text{ ft/s}} = 0.00792 \text{ ft}^2 = \frac{\pi}{4} D_{\text{MIN}}^2
\]

\[D_{\text{MIN}} = 0.1004 \text{ ft} = 1.205 \text{ in}\]
Single Flow Devices

6.147E

A pump takes 40 F liquid water from a river at 14 lbf/in.\(^2\) and pumps it up to an irrigation canal 60 ft higher than the river surface. All pipes have diameter of 4 in. and the flow rate is 35 lbm/s. Assume the pump exit pressure is just enough to carry a water column of the 60 ft height with 15 lbf/in.\(^2\) at the top. Find the flow work into and out of the pump and the kinetic energy in the flow.

Solution:

Flow work \(\dot{m}P_v;\)

Table F.7.1 \(v_i = v_f = 0.01602 \text{ ft}^3/\text{lbm}\)

\[P_e = P_o + \frac{Hg}{v}\]

\[= \left[15 + \frac{60 \times 32.174}{32.174 \times 0.01602 \times 144}\right] \text{ lbf/in}^2\]

\[= (15 + 26) \text{ lbf/in}^2 = 41 \text{ lbf/in}^2\]

\[\dot{W}_{\text{flow, i}} = \dot{m}P_v = 35 \times 14 \times 0.01602 \times 144/778 = 1.453 \text{ Btu/s}\]

\[V_i = V_e = \frac{\dot{m}v}{(\frac{\pi}{4} D^2)} = 35 \times 0.01602 \times 144/(\frac{\pi}{4} 4^2) = 6.425 \text{ ft/s}\]

\[\text{KE}_i = \frac{1}{2}V_i^2 = \text{KE}_e = \frac{1}{2}V_e^2 = \frac{1}{2}(6.425)^2 \text{ ft}^2/\text{s}^2 = 20.64 \text{ ft}^2/\text{s}^2\]

\[= 20.64/(32.174 \times 778) = 0.000825 \text{ Btu/lbm}\]

\[\dot{W}_{\text{flow, e}} = \dot{m}P_e v_e = 35 \times 41 \times 0.01602 \times 144/778 = 4.255 \text{ Btu/s}\]
In a jet engine a flow of air at 1800 R, 30 psia and 90 ft/s enters a nozzle where the air exits at 1500 R, 13 psia, as shown in Fig. P.6.33. What is the exit velocity assuming no heat loss?

Solution:
C.V. nozzle. No work, no heat transfer
Continuity \( \dot{m}_i = \dot{m}_e = \dot{m} \)
Energy: \( \dot{m} (h_i + \frac{1}{2} V_i^2) = \dot{m} (h_e + \frac{1}{2} V_e^2) \)
Due to high T take \( h \) from table F.5

\[
\frac{1}{2} V_e^2 = \frac{1}{2} V_i^2 + h_i - h_e
\]
\[
= \frac{90^2}{2 \times 32.174 \times 778} + 449.79 - 369.28
\]
\[
= 0.16 + 80.51 = 80.67 \text{ Btu/lbm}
\]

\[ V_e = (2 \times 32.174 \times 778 \times 80.67)^{1/2} \]
\[ = 2010 \text{ ft/s} \]
Nitrogen gas flows into a convergent nozzle at 30 lbf/in.², 600 R and very low velocity. It flows out of the nozzle at 15 lbf/in.², 500 R. If the nozzle is insulated find the exit velocity.

Solution:
C.V. Nozzle steady state one inlet and exit flow, insulated so it is adiabatic.

\[
\begin{align*}
V_2^2 & = 2 \left( h_1 - h_2 \right) \approx 2 C_{PN_2} \left( T_1 - T_2 \right) = 2 \times 0.249 \times (600 - 500) \\
& = 24.9 \text{ Btu/lbm} \\
V_2^2 & = 2 \times 24.9 \times 778 \times 32.174 \text{ ft}^2/\text{s}^2 = 1246562 \text{ ft}^2/\text{s}^2 \\
V_2 & = 1116 \text{ ft/s}
\end{align*}
\]
A diffuser shown in Fig. P6.36 has air entering at 14.7 lbf/in.², 540 R, with a velocity of 600 ft/s. The inlet cross-sectional area of the diffuser is 0.2 in.². At the exit, the area is 1.75 in.², and the exit velocity is 60 ft/s. Determine the exit pressure and temperature of the air.

Solution:

Continuity Eq.6.3: \( \dot{m}_i = A_i V_i / v_i = \dot{m}_e = A_e V_e / v_e \),

Energy Eq.(per unit mass flow)6.13: \( h_i + \frac{1}{2} V_i^2 = h_e + \frac{1}{2} V_e^2 \)

\( h_e - h_i = (1/2) \times (600^2 - 60^2)/(32.174 \times 778) = 7.119 \text{ Btu/lbm} \)

\( T_e = T_i + (h_e - h_i)/C_p = 540 + 7.119/0.24 = 569.7 \text{ R} \)

Now use the continuity equation and the ideal gas law

\[ v_e = v_i \left( \frac{A_e V_e}{A_i V_i} \right) = \left( \frac{RT_i}{P_i} \right) \left( \frac{A_e V_e}{A_i V_i} \right) = \frac{R T_e}{P_e} \]

\[ P_e = P_i \left( \frac{T_e}{T_i} \right) \left( \frac{A_i V_i}{A_e V_e} \right) = 14.7 \left( \frac{569.7}{540} \right) \left( \frac{0.2 \times 600}{1.75 \times 60} \right) = 17.72 \text{ lbf/in.}^2 \]
6.151E

Helium is throttled from 175 lbf/in.², 70 F, to a pressure of 15 lbf/in.². The diameter of the exit pipe is so much larger than the inlet pipe that the inlet and exit velocities are equal. Find the exit temperature of the helium and the ratio of the pipe diameters.

C.V. Throttle. Steady state,

Process with: \( q = w = 0 \); and \( V_i = V_e, \ Z_i = Z_e \)

Energy Eq.6.13: \( h_i = h_e \), Ideal gas => \( T_i = T_e = 75 \) F

\[
\dot{m} = \frac{AV}{RT/P}
\]

But \( \dot{m}, V, T \) are constant => \( P_iA_i = P_eA_e \)

\[
\Rightarrow \frac{D_e}{D_i} = \left( \frac{P_i}{P_e} \right)^{1/2} = \left( \frac{175}{15} \right)^{1/2} = 3.416
\]
Water flowing in a line at 60 lbf/in.\(^2\), saturated vapor, is taken out through a valve to 14.7 lbf/in.\(^2\). What is the temperature as it leaves the valve assuming no changes in kinetic energy and no heat transfer?

C.V. Valve. Steady state, single inlet and exit flow

Continuity Eq.: \( \dot{m}_1 = \dot{m}_2 \)

Energy Eq.6.12: \( \dot{m}_1 h_1 + \dot{Q} = \dot{m}_2 h_2 + \dot{W} \)

Process: Throttling

Small surface area: \( \dot{Q} = 0 \);

No shaft: \( \dot{W} = 0 \)

Table F.7.1 \( h_2 = h_1 = 1178 \text{ btu/lbm} \) \( \Rightarrow T_2 = 254.6 \text{ F} \)
A small, high-speed turbine operating on compressed air produces a power output of 0.1 hp. The inlet state is 60 lbf/in.$^2$, 120 F, and the exit state is 14.7 lbf/in.$^2$, −20 F. Assuming the velocities to be low and the process to be adiabatic, find the required mass flow rate of air through the turbine.

Solution:

C.V. Turbine, no heat transfer, no ΔKE, no ΔPE

Energy Eq.6.13: $h_{in} = h_{ex} + w_T$

Ideal gas so use constant specific heat from Table A.5

$$w_T = h_{in} - h_{ex} \equiv C_p(T_{in} - T_{ex})$$

$$= 0.24(120 - (-20)) = 33.6 \text{ Btu/lbm}$$

$$\dot{W} = \dot{m}w_T \quad \Rightarrow$$

$$\dot{m} = \frac{\dot{W}}{w_T} = \frac{0.1 \times 550}{778 \times 33.6} = 0.0021 \text{ lbm/s} = 7.57 \text{ lbm/h}$$

The dentist’s drill has a small air flow and is not really adiabatic.
Hoover Dam across the Colorado River dams up Lake Mead 600 ft higher than the river downstream, as shown in Fig. P6.51. The electric generators driven by water-powered turbines deliver $1.2 \times 10^6$ Btu/s. If the water is 65 F, find the minimum amount of water running through the turbines.

Solution:

C.V.: H$_2$O pipe + turbines,

Continuity: $\dot{m}_{in} = \dot{m}_{ex};$

Energy Eq.6.13: $(h + V^2/2 + gz)_{in} = (h + V^2/2 + gz)_{ex} + w_T$

Water states: $h_{in} \cong h_{ex} ; \quad v_{in} \cong v_{ex}$

Now the specific turbine work becomes

$$w_T = g(z_{in} - z_{ex}) = (32.174/32.174) \times 600/778 = 0.771 \text{ Btu/lbm}$$

$$\dot{m} = \dot{W}_T/w_T = 1.2 \times 10^6/0.771 = 1.556 \times 10^6 \text{ lbm/s}$$

$$\dot{V} = \dot{mv} = 1.556 \times 10^6 \times 0.016043 = \textbf{24 963 ft}^3/\text{s}$$
A small expander (a turbine with heat transfer) has 0.1 lbm/s helium entering at 160 psia, 1000 R and it leaves at 40 psia, 540 R. The power output on the shaft is measured to 55 Btu/s. Find the rate of heat transfer neglecting kinetic energies.

Solution:

C.V. Expander. Steady operation

Continuity Eq.: \( \dot{m}_i = \dot{m}_e = \dot{m} \)

Energy Eq.: \( \dot{m} h_i + \dot{Q} = \dot{m} h_e + \dot{W} \)

\[ \dot{Q} = \dot{m} (h_e-h_i) + \dot{W} \]

Use heat capacity from Table F.4: \( C_{p\text{He}} = 1.24 \text{ Btu/lbm R} \)

\[ \dot{Q} = \dot{m} C_{p\text{He}} (T_e-T_i) + \dot{W} \]

\[ = 0.1 \text{ lbm/s} \times 1.24 \text{ Btu/lbm R} \times (540 - 1000) \text{ R} + 55 \text{ btu/s} \]

\[ = -57.04 + 55 = -2.0 \text{ Btu/s} \]
An exhaust fan in a building should be able to move 5 lbm/s air at 14.4 psia, 68 F through a 1.25 ft diameter vent hole. How high a velocity must it generate and how much power is required to do that?

Solution:

C.V. Fan and vent hole. Steady state with uniform velocity out.

Continuity Eq.: \( \dot{m} = \text{constant} = \rho A \dot{V} = A \dot{V} / \nu = A \dot{V} P / RT \)

Ideal gas: \( P v = RT \), and area is \( A = \frac{\pi}{4} D^2 \)

Now the velocity is found

\[
\dot{V} = \frac{\dot{m} RT}{\left( \frac{\pi}{4} D^2 P \right)} = \frac{5 \times 53.34 \times (459.7 + 68)}{\frac{\pi}{4} \times 1.25^2 \times 14.4 \times 144} = 55.3 \text{ ft/s}
\]

The kinetic energy out is

\[
\frac{1}{2} \dot{V}_2^2 = \frac{1}{2} \times 55.3^2 / 32.174 = 47.52 \text{ lbf-ft/lbm}
\]

which is provided by the work (only two terms in energy equation that does not cancel, we assume \( V_1 = 0 \))

\[
\dot{W}_{in} = m \frac{1}{2} \dot{V}_2^2 = 5 \times 47.52 = 237.6 \text{ lbf-ft/s} = 0.305 \text{ Btu/s}
\]
In a steam generator, compressed liquid water at 1500 lbf/in.\(^2\), 100 F, enters a 1-in. diameter tube at the rate of 5 ft\(^3\)/min. Steam at 1250 lbf/in.\(^2\), 750 F exits the tube. Find the rate of heat transfer to the water.

Solution:

C.V. Steam generator. Steady state single inlet and exit flow.

Constant diameter tube: \[ A_i = A_e = \frac{\pi}{4} \left( \frac{1}{12} \right)^2 = 0.00545 \text{ ft}^2 \]

Table B.1.4 \[ \dot{m} = \frac{\dot{V}_i}{v_i} = 5 \times 60/0.016058 = 18682 \text{ lbm/h} \]

\[ V_i = \frac{\dot{V}_i}{A_i} = 5/(0.00545 \times 60) = 15.3 \text{ ft/s} \]

Exit state properties from Table B.1.3

\[ V_e = V_i \times \frac{v_e}{v_i} = 15.3 \times 0.503/0.016058 = 479.3 \text{ ft/s} \]

The energy equation Eq.6.12 is solved for the heat transfer as

\[ \dot{Q} = \dot{m} \left[ (h_e - h_i) + \left( \frac{V_e^2 - V_i^2}{2} \right) \right] \]

\[ = 18682 \left[ 1342.4 - 71.99 + \frac{479.3^2 - 15.3^2}{2 \times 32.174 \times 778} \right] = 2.382 \times 10^7 \text{ Btu/h} \]
Carbon dioxide gas enters a steady-state, steady-flow heater at 45 lbf/in.² 60 F, and exits at 40 lbf/in.², 1800 F. It is shown in Fig. P6.63 here changes in kinetic and potential energies are negligible. Calculate the required heat transfer per lbm of carbon dioxide flowing through the heater.

Solution:
C.V. Heater Steady state single inlet and exit flow.

Energy Eq.6.13: \( q + h_i = h_e \)

\[
q = h_e - h_i = \frac{20470.8 - (-143.4)}{44.01} = 468.4 \text{ Btu/lbm}
\]

(Use \( C_p \) then \( q \approx 0.203(1800 - 60) = 353.2 \text{ Btu/lbm} \))

Too large \( \Delta T, T_{ave} \) to use \( C_p \) at room temperature.
A flow of liquid glycerine flows around an engine, cooling it as it absorbs energy. The glycerine enters the engine at 140 F and receives 13 hp of heat transfer. What is the required mass flow rate if the glycerine should come out at a maximum 200 F?

Solution:
C.V. Liquid flow (glycerine is the coolant), steady flow. no work.
Energy Eq.: \( \dot{m} \dot{h}_i + Q = \dot{m} \dot{h}_e \)
\[
\dot{m} = \frac{Q}{(h_e - h_i)} = \frac{\dot{Q}}{C_{gly} (T_e - T_i)}
\]
From table F.3: \( C_{gly} = 0.58 \text{ Btu/lbm R} \)
\[
\dot{m} = \frac{13 \text{ hp} \times (2544.4/3600) \text{ btu/s-hp}}{0.58 \text{ btu/lbm-R} (200 - 140) \text{ R}} = 0.264 \text{ lbm/s}
\]
A small water pump is used in an irrigation system. The pump takes water in from a river at 50 F, 1 atm at a rate of 10 lbm/s. The exit line enters a pipe that goes up to an elevation 60 ft above the pump and river, where the water runs into an open channel. Assume the process is adiabatic and that the water stays at 50 F. Find the required pump work.

Solution:
C.V. pump + pipe. Steady state, 1 inlet, 1 exit flow. Assume same velocity in and out, no heat transfer.

Continuity Eq.: \( m_{in} = m_{ex} = \dot{m} \)

Energy Eq.6.12:
\[
\dot{m}(h_{in} + \frac{1}{2}V_{in}^2 + g z_{in}) = \dot{m}(h_{ex} + \frac{1}{2}V_{ex}^2 + g z_{ex}) + \dot{W}
\]

States: \( h_{in} = h_{ex} \) same (T, P)

\[
\dot{W} = \dot{m}g(z_{in} - z_{ex}) = 10 \text{ lbm/s} \times \frac{32.174 \text{ ft/s}^2}{32.174 \text{ lbm ft/s}^2 /\text{lbf}} \times (-60) \text{ ft}
\]

\[
= -600 \text{ lbf-ft/s} = -0.771 \text{ Btu/s}
\]

I.E. 0.771 Btu/s required input
Multiple Flow Devices

6.161E

A steam turbine receives water at 2000 lbf/in.², 1200 F at a rate of 200 lbm/s as shown in Fig. P6.78. In the middle section 40 lbm/s is withdrawn at 300 lbf/in.², 650 F and the rest exits the turbine at 10 lbf/in.², 95% quality. Assuming no heat transfer and no changes in kinetic energy, find the total turbine work.

C.V. Turbine Steady state, 1 inlet and 2 exit flows.

Continuity Eq.6.9: \( \dot{m}_1 = \dot{m}_2 + \dot{m}_3 \); \( \Rightarrow \dot{m}_3 = \dot{m}_1 - \dot{m}_2 = 160 \text{ lbm/s} \)

Energy Eq.6.10: \( \dot{m}_1 h_1 = \dot{W}_T + \dot{m}_2 h_2 + \dot{m}_3 h_3 \)

Table F.7.2 \( h_1 = 1598.6 \text{ Btu/lbm}, \)
\( h_2 = 1341.6 \text{ Btu/lbm} \)

Table F.7.1 \( h_3 = h_f + x_3 h_{fg} = 161.2 + 0.95 \times 982.1 = 1094.2 \text{ Btu/lbm} \)

From the energy equation, Eq.6.10

\( \dot{W}_T = \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 = 200 \times 1598.6 - 40 \times 1341.6 - 160 \times 1094.2 \)

\( = 9.1 \times 10^4 \text{ Btu/s} \)
A condenser, as the heat exchanger shown in Fig. P6.84, brings 1 lbm/s water flow at 1 lbf/in.\(^2\) from 500 F to saturated liquid at 1 lbf/in.\(^2\). The cooling is done by lake water at 70 F that returns to the lake at 90 F. For an insulated condenser, find the flow rate of cooling water.

Solution:

C.V. Heat exchanger

Energy Eq.6.10: \[ m_{\text{cool}} h_{70} + m_{\text{H}_2\text{O}} h_{500} = m_{\text{cool}} h_{90} + m_{\text{H}_2\text{O}} h_{f,1} \]

Table F.7.1: \( h_{70} = 38.09 \text{ Btu/lbm} \), \( h_{90} = 58.07 \text{ Btu/lbm} \), \( h_{f,1} = 69.74 \text{ Btu/lbm} \)

Table F.7.2: \( h_{500,1} = 1288.5 \text{ btu/lbm} \)

\[
\dot{m}_{\text{cool}} = \dot{m}_{\text{H}_2\text{O}} \frac{h_{500} - h_{f,1}}{h_{90} - h_{70}} = 1 \times \frac{1288.5 - 69.74}{58.07 - 38.09} = 61 \text{ lbm/s}
\]
A heat exchanger is used to cool an air flow from 1400 to 680 R, both states at 150 lbf/in.². The coolant is a water flow at 60 F, 15 lbf/in.² and it is shown in Fig. P6.86. If the water leaves as saturated vapor, find the ratio of the flow rates \( \frac{m_{\text{H}_2\text{O}}}{m_{\text{air}}} \).

**Solution:**

C.V. Heat exchanger, steady flow 1 inlet and 1 exit for air and water each. The two flows exchange energy with no heat transfer to/from the outside.

Continuity Eqs.: Each line has a constant flow rate through it.

Energy Eq.6.10: \( m_{\text{air}}h_{1} + m_{\text{H}_2\text{O}}h_{3} = m_{\text{air}}h_{2} + m_{\text{H}_2\text{O}}h_{4} \)

Process: Each line has a constant pressure.

Table F.5: \( h_{1} = 343.016 \) Btu/lbm, \( h_{2} = 162.86 \) Btu/lbm

Table F.7: \( h_{3} = 28.08 \) Btu/lbm, \( h_{4} = 1150.9 \) Btu/lbm (at 15 psia)

\[
\frac{m_{\text{H}_2\text{O}}}{m_{\text{air}}} = \frac{h_{1} - h_{2}}{h_{4} - h_{3}} = \frac{343.016 - 162.86}{1150.9 - 28.08} = 0.1604
\]
An automotive radiator has glycerine at 200 F enter and return at 130 F as shown in Fig. P6.88. Air flows in at 68 F and leaves at 77 F. If the radiator should transfer 33 hp what is the mass flow rate of the glycerine and what is the volume flow rate of air in at 15 psia?

Solution:

If we take a control volume around the whole radiator then there is no external heat transfer - it is all between the glycerin and the air. So we take a control volume around each flow separately.

Heat transfer: \( \dot{Q} = 33 \text{ hp} = 33 \times 2544.4 / 3600 = 23.324 \text{ Btu/s} \)

Glycerine: \( \dot{m}_i + (-\dot{Q}) = \dot{m}_e \)

Table F.3: \( \dot{m}_{\text{gly}} = \frac{-\dot{Q}}{h_e - h_i} = \frac{-23.324}{0.58(130 - 200)} = 0.574 \text{ lbm/s} \)

Air

\( \dot{m}_i + \dot{Q} = \dot{m}_e \)

Table F.4: \( \dot{m}_{\text{air}} = \frac{\dot{Q}}{h_e - h_i} = \frac{23.324}{0.24(77 - 68)} = 8.835 \text{ lbm/s} \)

\( \dot{V} = \dot{m}_i \cdot v_i = \frac{RT_i}{P_i} = \frac{53.34 \times 527.7}{15 \times 144} = 13.03 \text{ ft}^3/\text{lbm} \)

\( \dot{V}_{\text{air}} = \dot{m}_i \cdot v_i = 8.835 \times 13.03 = 115 \text{ ft}^3/\text{s} \)
An insulated mixing chamber receives 4 lbm/s R-134a at 150 lbf/in.², 220 F in a line with low velocity. Another line with R-134a as saturated liquid 130 F flows through a valve to the mixing chamber at 150 lbf/in.² after the valve. The exit flow is saturated vapor at 150 lbf/in.² flowing at 60 ft/s. Find the mass flow rate for the second line.

Solution:
C.V. Mixing chamber. Steady state, 2 inlets and 1 exit flow.

Insulated \( q = 0 \), No shaft or boundary motion \( w = 0 \).

Continuity Eq.6.9: \( \dot{m}_1 + \dot{m}_2 = \dot{m}_3 \);

Energy Eq.6.10: \( \dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 (h_3 + \frac{1}{2} V_3^2) \)

\[ \dot{m}_2 (h_2 - h_3 - \frac{1}{2} V_3^2) = \dot{m}_1 (h_3 + \frac{1}{2} V_3^2 - h_1) \]

State 1: Table F.10.1: 150 psia, 220 F, \( h_1 = 209.63 \) Btu/lbm
State 2: Table F.10.1: \( x = 0 \), 130 F, \( h_2 = 119.88 \) Btu/lbm
State 3: Table F.10.2: \( x = 1 \), 150 psia, \( h_3 = 180.61 \) Btu/lbm

\[ \frac{1}{2} V_3^2 = \frac{1}{2} \times 60^2 / (32.174 \times 778) = 0.072 \text{ Btu/lbm} \]

\[ \dot{m}_2 = \dot{m}_1 (h_3 + \frac{1}{2} V_3^2 - h_1) / (h_2 - h_3 - \frac{1}{2} V_3^2) \]

\[ = 4 (180.61 + 0.072 - 209.63) / (119.88 - 180.61 - 0.072) = 1.904 \text{ lbm/s} \]

Notice how kinetic energy was insignificant.
An air compressor takes in air at 14 lbf/in.², 60 F and delivers it at 140 lbf/in.², 1080 R to a constant-pressure cooler, which it exits at 560 R. Find the specific compressor work and the specific heat transfer.

Solution
- C.V. air compressor  \( q = 0 \)
- Continuity Eq.:  \( m_2 = m_1 \)
- Energy Eq.6.13:  \( h_1 + w_c = h_2 \)

![Diagram of air compressor and cooler](image)

Table F.5:
- \( w_c \) in = \( h_2 - h_1 \) = 261.1 - 124.3 = **136.8 Btu/lbm**
- C.V. cooler  \( w = 0 \)
- Continuity Eq.:  \( m_3 = m_1 \)
- Energy Eq.6.13:  \( h_2 = q_{out} + h_3 \)

\[ q_{out} = h_2 - h_3 = 261.1 - 133.98 = **127.12 Btu/lbm** \]
The following data are for a simple steam power plant as shown in Fig. P6.99.

<table>
<thead>
<tr>
<th>State</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>P psia</td>
<td>900</td>
<td>890</td>
<td>860</td>
<td>830</td>
<td>800</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>T °F</td>
<td>115</td>
<td>350</td>
<td>920</td>
<td>900</td>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>h Btu/lbm</td>
<td>-</td>
<td>85.3</td>
<td>323</td>
<td>1468</td>
<td>1456</td>
<td>1029</td>
<td>78</td>
</tr>
</tbody>
</table>

State 6 has \( x_6 = 0.92 \), and velocity of 600 ft/s. The rate of steam flow is 200 000 lbm/h, with 400 hp input to the pump. Piping diameters are 8 in. from steam generator to the turbine and 3 in. from the condenser to the steam generator. Determine the power output of the turbine and the heat transfer rate in the condenser.

Turbine: \( A_5 = \pi D_5^2 / 4 = 0.349 \text{ ft}^2 \), \( v_5 = 0.964 \text{ ft}^3/\text{lbm} \)

\[ V_5 = \dot{m}v_5 / A_5 = \frac{200,000 \times 0.964}{3600 \times 0.349} = 153 \text{ ft/s} \]

\[ w = (h_5 + 0.5V_5^2) - (h_6 + 0.5V_6^2) = 1456 - 1029 - \frac{600^2 - 153^2}{2 \times 25,037} \]

\[ w = 420.2 \text{ Btu/lbm} \]

Recall the conversion 1 Btu/lbm = 25 037 ft²/s², 1 hp = 2544 Btu/h

\[ \dot{W}_{TURB} = \frac{420.2 \times 200,000}{2544} = 33,000 \text{ hp} \]
For the same steam power plant as shown in Fig. P6.99 and Problem 6.167E determine the rate of heat transfer in the economizer which is a low temperature heat exchanger and the steam generator. Determine also the flow rate of cooling water through the condenser, if the cooling water increases from 55 to 75 °F in the condenser.

Condenser: \( A_7 = \pi D_7^2/4 = 0.0491 \text{ ft}^2, \quad v_7 = 0.01617 \text{ ft}^3/\text{lbm} \)

\[ V_7 = \frac{\dot{m}v_7}{A_7} = \frac{200000 \times 0.01617}{3600 \times 0.0491} = 18 \text{ ft/s} \]

\[ q = 78.02 - 1028.7 + \frac{18^2 - 600^2}{2 \times 25 \times 37} = -957.9 \text{ Btu/lbm} \]

\[ \dot{Q}_{\text{COND}} = 200000 \times (-957.9) = -1.916 \times 10^8 \text{ Btu/h} \]

Economizer \( V_3 \approx V_2 \) since liquid \( v \) is constant: \( v_3 \approx v_2 \) and \( A_3 = A_2 \).

\[ q = h_3 - h_2 = 323.0 - 85.3 = 237.7 \text{ Btu/lbm} \]

\[ \dot{Q}_{\text{ECON}} = 200000 \times (237.7) = 4.75 \times 10^7 \text{ Btu/h} \]

Generator: \( A_4 = \pi D_4^2/4 = 0.349 \text{ ft}^2, \quad v_4 = 0.9595 \text{ ft}^3/\text{lbm} \)

\[ V_4 = \frac{\dot{m}v_4}{A_4} = \frac{200000 \times 0.9595}{3600 \times 0.349} = 151 \text{ ft/s} \]

\[ A_3 = \pi D_3^2/4 = 0.349 \text{ ft}^2, \quad v_3 = 0.0491 \text{ ft}^3/\text{lbm} \]

\[ V_3 = \frac{\dot{m}v_3}{A_3} = \frac{200000 \times 0.0491}{3600 \times 0.0491} = 20 \text{ ft/s} \]

\[ q = 1467.8 - 323.0 + \frac{151^2 - 20^2}{2 \times 25 \times 37} = 1145.2 \text{ Btu/lbm} \]

\[ \dot{Q}_{\text{GEN}} = 200000 \times (1145.2) = 2.291 \times 10^8 \text{ Btu/h} \]
A proposal is made to use a geothermal supply of hot water to operate a steam turbine, as shown in Fig. P6.105. The high pressure water at 200 lbf/in.\(^2\), 350 F, is throttled into a flash evaporator chamber, which forms liquid and vapor at a lower pressure of 60 lbf/in.\(^2\). The liquid is discarded while the saturated vapor feeds the turbine and exits at 1 lbf/in.\(^2\), 90% quality. If the turbine should produce 1000 hp, find the required mass flow rate of hot geothermal water in pound-mass per hour.

Solution:

Separation of phases in flash-evaporator constant \(h\) in the valve flow so

Table F.7.3: \(h_1 = 321.8 \text{ Btu/lbm}\)

\[h_1 = 321.8 = 262.25 + x \times 915.8\]

\[\Rightarrow \quad x = 0.06503 = \frac{\dot{m}_2}{\dot{m}_1}\]

Table F.7.2: \(h_2 = 1178.0 \text{ Btu/lbm};\)

Table F.7.1: \(h_3 = 69.74 + 0.9 \times 1036 = 1002.1 \text{ Btu/lbm}\)

\[\dot{W} = \dot{m}_2(h_2 - h_3) \quad \Rightarrow \quad \dot{m}_2 = \frac{1000 \times 2545}{1178.0 - 1002.1} = 14472 \text{ lbm/h}\]

\[\Rightarrow \dot{m}_1 = 222539 \text{ lbm/h}\]

Notice conversion \(1 \text{ hp} = 2445 \text{ Btu/h}\) from Table A.1
Transient Processes

6.170E

A 1-ft³ tank, shown in Fig. P6.111, that is initially evacuated is connected by a valve to an air supply line flowing air at 70°F, 120 lbf/in.². The valve is opened, and air flows into the tank until the pressure reaches 90 lbf/in.². Determine the final temperature and mass inside the tank, assuming the process is adiabatic. Develop an expression for the relation between the line temperature and the final temperature using constant specific heats.

Solution:

C.V. Tank:
Continuity Eq.6.15: \( m_2 = m_i \)
Energy Eq.6.16: \( m_2u_2 = m_ih_i \)
Table F.5: \( u_2 = h_i = 126.78 \text{ Btu/lbm} \)

\[ \Rightarrow T_2 = 740 \text{ R} \]

\[ m_2 = \frac{p_2V}{RT_2} = \frac{90 \times 144 \times 1}{53.34 \times 740} = 0.3283 \text{ lbm} \]

Assuming constant specific heat,
\[ h_i = u_i + RT_i = u_2, \quad RT_i = u_2 - u_i = C_{V_0}(T_2 - T_i) \]

\[ C_{V_0}T_2 = (C_{V_0} + R)T_i = C_{P_0}T_i, \quad T_2 = \left( \frac{C_{P_0}}{C_{V_0}} \right) T_i = kT_i \]

For \( T_i = 529.7 \text{ R} \) & constant \( C_{P_0}, \quad T_2 = 1.40 \times 529.7 = 741.6 \text{ R} \)
6.171E

Helium in a steel tank is at 40 psia, 540 R with a volume of 4 ft³. It is used to fill a balloon. When the tank pressure drops to 24 psia the flow of helium stops by itself. If all the helium still is at 540 R how big a balloon did I get? Assume the pressure in the balloon varies linearly with volume from 14.7 psia (V = 0) to the final 24 psia. How much heat transfer did take place?

Solution:
Take a C.V. of all the helium.
This is a control mass, the tank mass changes density and pressure.

Energy Eq.: \[ U_2 - U_1 = Q_2 - W_2 \]
Process Eq.: \[ P = P_0 + CV \]
State 1: \[ P_1, T_1, V_1 \]
State 2: \[ P_2, T_2, V_2 = ? \]

Ideal gas:
\[ P_2 V_2 = mRT_2 = mRT_1 = P_1 V_1 \]
\[ V_2 = V_1 \left( \frac{P_1}{P_2} \right) = 4 \times \left( \frac{40}{24} \right) = 6.6667 \text{ ft}^3 \]
\[ V_{bal} = V_2 - V_1 = 6.6667 - 4 = 2.6667 \text{ ft}^3 \]

\[ W_2 = \int P \, dV = \text{AREA} = \frac{1}{2} \left( P_1 + P_2 \right) \left( V_2 - V_1 \right) \]
\[ = \frac{1}{2} \left( 40 + 24 \right) \times 2.6667 \times 144 = 12288 \text{ lbf-ft} = 15.791 \text{ Btu} \]
\[ U_2 - U_1 = Q_2 - W_2 = m \left( u_2 - u_1 \right) = mC_v \left( T_2 - T_1 \right) = 0 \]
so \[ Q_2 = W_2 = 15.79 \text{ Btu} \]

Remark: The process is transient, but you only see the flow mass if you select the tank or the balloon as a control volume. That analysis leads to more terms that must be eliminated between the tank control volume and the balloon control volume.
A 20-ft³ tank contains ammonia at 20 lbf/in.², 80 F. The tank is attached to a line flowing ammonia at 180 lbf/in.², 140 F. The valve is opened, and mass flows in until the tank is half full of liquid, by volume at 80 F. Calculate the heat transferred from the tank during this process.

Solution:

C.V. Tank. Transient process as flow comes in.

\[
\begin{align*}
    m_1 &= V/v_1 = 20/16.765 = 1.193 \text{ lbm} \\
    m_{f2} &= V_{f2}/v_{f2} = 10/0.026677 = 374.855 \text{ lbm,} \\
    m_{g2} &= V_{g2}/v_{g2} = 10/1.9531 = 5.120 \text{ lbm} \\
    m_2 &= m_{f2} + m_{g2} = 379.975 \text{ lbm} \quad => \quad x_2 = m_{g2}/m_2 = 0.013475 \\
    \text{Table F.8.1,} \quad u_2 &= 130.9 + 0.013475 \times 443.4 = 136.9 \text{ Btu/lbm} \\
    u_1 &= 595.0 \text{ Btu/lbm,} \quad h_i = 667.0 \text{ Btu/lbm} \\
    \text{Continuity Eq.:} \quad m_i = m_2 - m_1 = 378.782 \text{ lbm} \quad , \\
    \text{Energy eq.:} \quad QCV + m_ih_i = m_2u_2 - m_1u_1 \\
\end{align*}
\]

\[
\begin{align*}
    QCV &= 379.975 \times 136.9 - 1.193 \times 595.0 - 378.782 \times 667.0 \\
    &= \mathbf{-201\,339 \text{ Btu}} \\
\end{align*}
\]
An initially empty bottle, $V = 10$ ft$^3$, is filled with water from a line at 120 lbf/in.$^2$, 500 F. Assume no heat transfer and that the bottle is closed when the pressure reaches line pressure. Find the final temperature and mass in the bottle.

Solution;
C.V. Bottle, transient process with no heat transfer or work.

Continuity Eq.6.15: $m_2 - m_1 = m_{in}$;

Energy Eq.6.16: $m_2 u_2 - m_1 u_1 = -m_{in} h_{in}$

State 1: $m_1 = 0$ => $m_2 = m_{in}$ and $u_2 = h_{in}$

State 2: $P_2 = P_{line}$, Table F.7 $u_2 = h_{in} = 1277.1$ Btu/lbm

$\Rightarrow T_2 \approx 764$ F, $v_2 = 6.0105$ ft$^3$/lbm

$m_2 = V/v_2 = 10/6.0105 = 1.664$ lbm
A nitrogen line, 540 R, and 75 lbf/in\(^2\), is connected to a turbine that exhausts to a closed initially empty tank of 2000 ft\(^3\), as shown in Fig. P6.119. The turbine operates to a tank pressure of 75 lbf/in\(^2\), at which point the temperature is 450 R. Assuming the entire process is adiabatic, determine the turbine work.

C.V. turbine & tank ⇒ Transient problem

Conservation of mass: \(m_1 = m_2 = m\)

1\(^{st}\) Law: \(m_1h_1 = m_2u_2 + W_{CV}\); \(W_{CV} = m(h_i - u_2)\)

Inlet state: \(P_1 = 75 \text{ lbf/in}^2, \ T_i = 540 \text{ R}\)

Final state 2: \(P_2 = 75 \text{ lbf/in}^2, \ T_2 = 450 \text{ R}\)

\(v_2 = \frac{RT_2}{P_2} = \frac{55.15 \times 450}{75 \times 144} = 2.298 \text{ ft}^3/\text{lbm}\)

\(m_2 = \frac{V}{v_2} = \frac{2000}{2.298} = 870.32 \text{ lbm}\)

\(h_i - u_2 = u_i + \frac{RT_i}{v_2} - u_2 = \frac{RT_i}{v_2} + C_v (T_i - T_2)\)

\(= \frac{55.15}{778.17} \times 540 + 0.178 (540 - 450) = 38.27 + 16.02 = 54.29 \text{ Btu/lbm}\)

\(W_{CV} = 870.32 \times 54.29 = 47250 \text{ Btu}\)
Review Problem

6.175E

A mass-loaded piston/cylinder containing air is at 45 lbf/in.², 60 F with a volume of 9 ft³, while at the stops \( V = 36 \text{ ft}^3 \). An air line, 75 lbf/in.², 1100 R, is connected by a valve, as shown in Fig. P6.133. The valve is then opened until a final inside pressure of 60 lbf/in.² is reached, at which point \( T = 630 \text{ R} \). Find the air mass that enters, the work, and heat transfer.

Solution:

C.V. Cylinder volume.

Continuity Eq.6.15: \( m_2 - m_1 = m_{\text{in}} \)

Energy Eq.6.16: \( m_2u_2 - m_1u_1 = m_{\text{in}}h_{\text{line}} + 1Q_2 - 1W_2 \)

Process: \( P_1 \) is constant to stops, then constant \( V \) to state 2 at \( P_2 \)

State 1: \( P_1, T_1 \)

\[
m_1 = \frac{P_1V}{RT_1} = \frac{45 \times 9 \times 144}{53.34 \times 519.7} = 2.104 \text{ lbm}
\]

Open to: \( P_2 = 60 \text{ lbf/in}^2 \)

Table F.5:

\[
h_i = 266.13 \text{ btu/lbm} \\
u_1 = 88.68 \text{ Btu/lbm} \\
u_2 = 107.62 \text{ Btu/lbm}
\]

\( P = P_1 \) until \( V = V_{\text{stop}} \) then constant \( V \)

\[
1W_2 = \int PdV = P_1(V_{\text{stop}} - V_1) = 45 \times (36 - 9)\frac{144}{778} = 224.9 \text{ Btu}
\]

\[
m_2 = P_2V_2/RT_2 = 60 \times 36 \times 144/(53.34 \times 630) = 9.256 \text{ lbm}
\]

\[
1Q_2 = m_2u_2 - m_1u_1 - m_{\text{in}}h_i + 1W_2 \\
= 9.256 \times 107.62 - 2.104 \times 88.68 - 7.152 \times 266.13 + 224.9 \\
= -868.9 \text{ Btu}
\]