Thermodynamics: An Engineering Approach
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CHAPTER 5
MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES

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Objectives

- Develop the conservation of mass principle
- Apply the conservation of mass principle to various systems including steady- and unsteady-flow control volumes
- Apply the first law of thermodynamics as the statement of the conservation of energy principle to control volumes
- Identify the energy carried by a fluid stream crossing a control surface as the sum of internal energy, flow work, kinetic energy, and potential energy of the fluid and to relate the combination of the internal energy and the flow work to the property enthalpy
- Solve energy balance problems for common steady-flow devices such as nozzles, compressors, turbines, throttling valves, mixers, heaters, and heat exchangers
- Apply the energy balance to general unsteady-flow processes with particular emphasis on the uniform-flow process as the model for charging and discharging processes

CONSERVATION OF MASS

- **Conservation of mass**: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process
- ***Closed systems***: The mass of the system remains constant during a process
- ***Control volumes***: Mass can cross the boundaries, and so we must keep track of the amount of mass *entering* and *leaving* the control volume

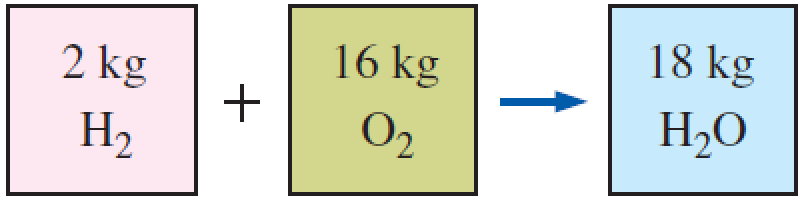


FIGURE 5–1
Mass is conserved even during chemical reactions.

MASS & ENERGY EQUIVALENCE

- Mass m and energy E can be converted to each other according to:

$$E = mc^2$$

- where c is the speed of light in a vacuum, which is $c = 2.9979 \times 10^8$ m/s.
- When1 kg to liquid water is formed from oxygen and hydrogen at normal atmospheric conditions the amount of energy released (converted from chemical to thermal) is: 15.8 MJ, which is equivalent to a mass of 1.76×10^{-10} kg
- The equivalent mass change due to this energy conversion is negligible in most engineering problems
- In nuclear reactions, the mass equivalence of the amount of energy interacted is a significant fraction of the total mass involved

Mass Flow Rates

$$\delta \dot{m} = \rho V_n \, dA_c$$

$$\dot{m} = \int_{A_c} \delta \dot{m} = \int_{A_c} \rho V_n \, dA_c$$

$$V_{\text{avg}} = \frac{1}{A_c} \int_{A_c} V_n \, dA_c$$

definition of average velocity

$$\dot{m} = \rho V_{\text{avg}} A_c \qquad (\text{kg/s})$$

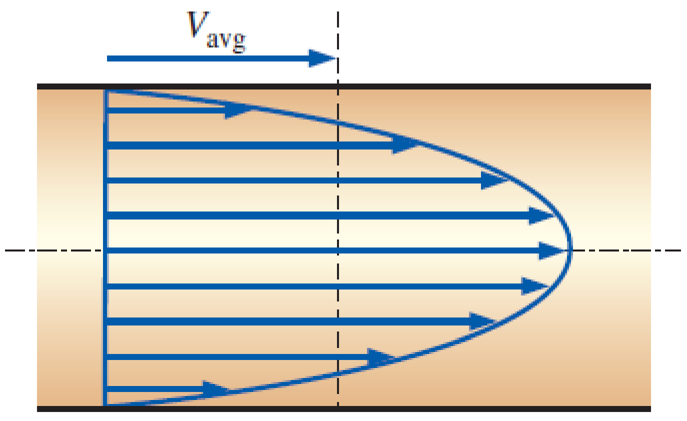


FIGURE 5–3
The average velocity V_{avg} is defined as the average speed through a cross section.

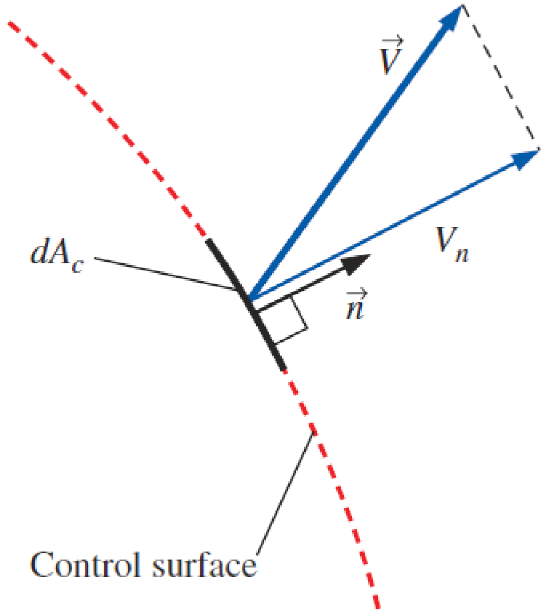


FIGURE 5–2
The normal velocity V_n for a surface is the component of velocity perpendicular to the surface.

Volume Flow Rates

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$ Mass flow rate

$$\dot{m} = \int_{A_c} \delta \dot{m} = \int_{A_c} \rho V_n \, dA_c$$

$$\dot{m} = \rho V_{\text{avg}} A_c \qquad (\text{kg/s})$$

Volume flow rate

$$\dot{V} = \int_{A_c} V_n \, dA_c = V_{\text{avg}} A_c = V A_c \qquad (\text{m}^3/\text{s})$$

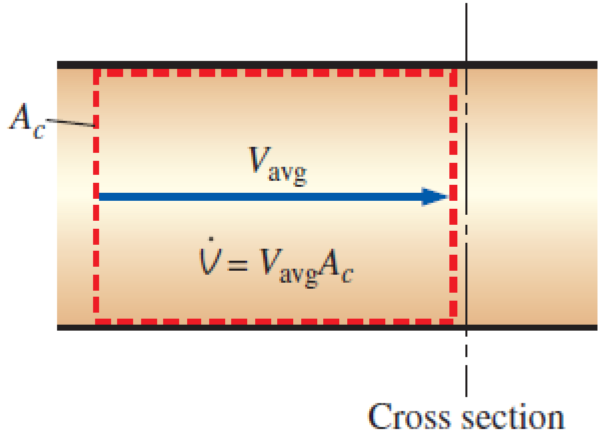


FIGURE 5–4
The volume flow rate is the volume of fluid flowing through a cross section per unit time.

Conservation of Mass Principle

$$\begin{pmatrix}\text{Total mass entering} \\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving} \\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change of mass} \\ \text{within the CV during } \Delta t\end{pmatrix}$$

The conservation of mass principle for a control volume: The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{CV}} \qquad (\text{kg})$$

$$\dot{m}_{\text{in}} - \dot{m}_{\text{out}} = dm_{\text{CV}}/dt \qquad (\text{kg/s})$$

These equations are often referred to as the **mass balance** and are *applicable to any control volume undergoing any kind of process*

$$\begin{pmatrix}\text{Total mass entering}\\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving}\\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change of mass}\\ \text{within the CV during } \Delta t\end{pmatrix}$$

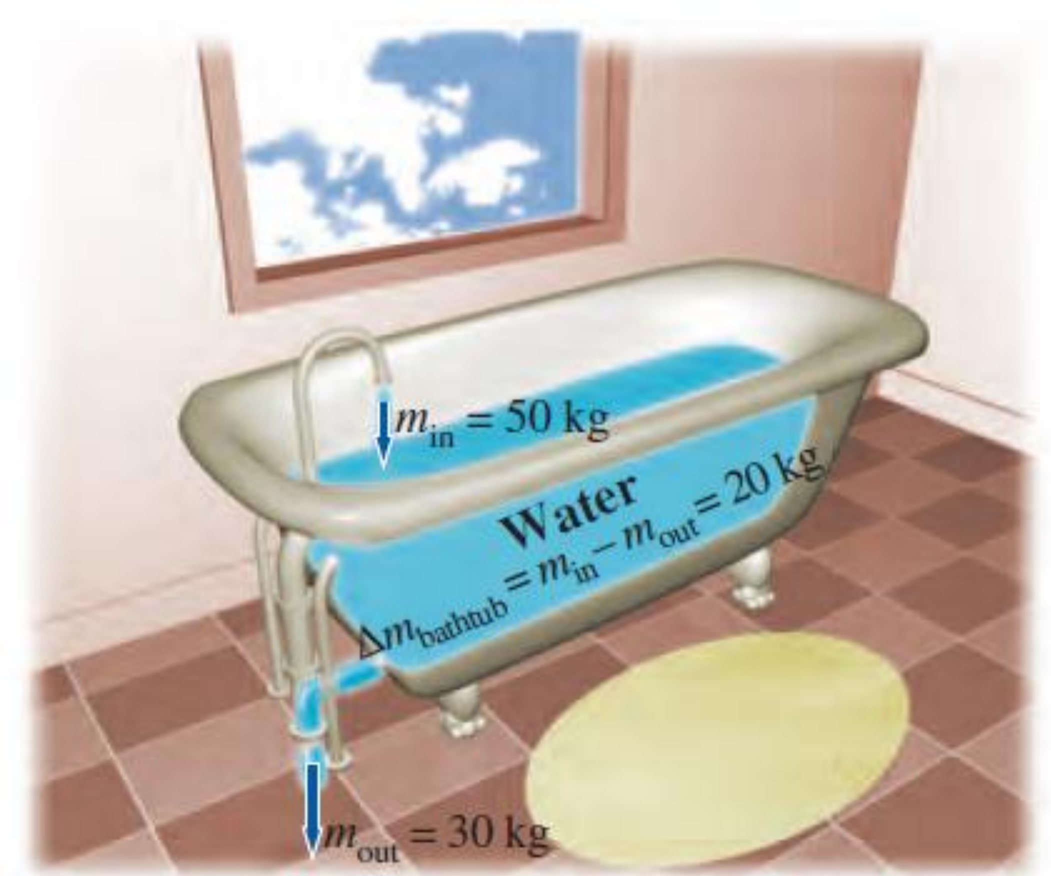


FIGURE 5–5

Conservation of mass principle for an ordinary bathtub.

$$\dot{m}_{in} - \dot{m}_{out} = dm_{CV}/dt \qquad (kg/s)$$

Total mass within the CV: $m_{CV} = \int_{CV} \rho \, dV$

Rate of change of mass within the CV: $\dfrac{dm_{CV}}{dt} = \dfrac{d}{dt}\int_{CV} \rho \, dV$

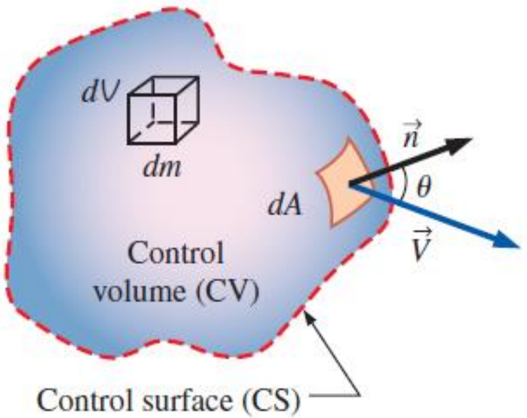


FIGURE 5–6
The differential control volume dV and the differential control surface dA used in the derivation of the conservation of mass relation.

Normal component of velocity: $V_n = V\cos\theta = \vec{V}\cdot\vec{n}$

$\vec{n}$ is the unit normal vector pointing **outwards**

Differential mass flow rate: $\delta\dot{m} = \rho V_n \, dA = \rho(V\cos\theta)\, dA = \rho(\vec{V}\cdot\vec{n})\, dA$

Net mass flow rate: going **out** of the CV $\dot{m}_{net} = \int_{CS} \delta\dot{m} = \int_{CS} \rho V_n \, dA = \int_{CS} \rho(\vec{V}\cdot\vec{n})\, dA$

$$\dot{m}_{net} = \dot{m}_{out} - \dot{m}_{in}$$

General conservation of mass: $\dfrac{d}{dt}\int_{CV} \rho \, dV + \int_{CS} \rho(\vec{V}\cdot\vec{n})\, dA = 0$

General conservation of mass: $$\frac{d}{dt}\int_{\mathrm{CV}} \rho \, dV + \int_{\mathrm{CS}} \rho(\vec{V}\cdot\vec{n})\, dA = 0$$

The time rate of change of mass within the control volume plus the net mass flow rate going out through the control surface is equal to zero

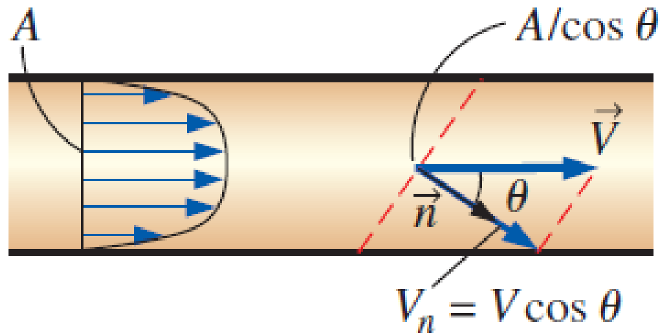
The equation is also valid for moving or deforming control volumes provided that the absolute velocity $\vec{V}$ is replaced by the relative velocity $\vec{V}_r$, which is the fluid velocity relative to the control surface

Splitting the surface integral into outgoing flow streams (positive) and incoming flow streams (negative)

$$\frac{d}{dt}\int_{\mathrm{CV}} \rho \, dV + \sum_{\mathrm{out}} \rho \left| V_n \right| dA - +\sum_{\mathrm{in}} \rho \left| V_n \right| dA = 0$$

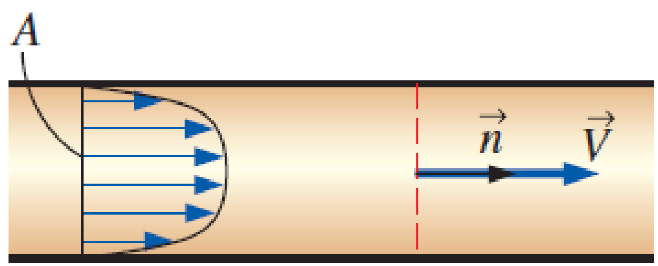
$$\frac{d}{dt}\int_{\mathrm{CV}} \rho \, d\forall = \sum_{\mathrm{in}} \dot{m} - \sum_{\mathrm{out}} \dot{m} \quad \text{or} \quad \frac{dm_{\mathrm{CV}}}{dt} = \sum_{\mathrm{in}} \dot{m} - \sum_{\mathrm{out}} \dot{m}$$

General conservation of mass in rate form



$$\dot{m} = \rho(V\cos\theta)(A/\cos\theta) = \rho VA$$

(a) Control surface *at an angle* to the flow



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

(b) Control surface *normal* to the flow

FIGURE 5–7

A control surface should always be selected *normal to the flow* at all locations where it crosses the fluid flow to avoid complications, even though the result is the same.

Mass Balance for Steady-Flow Processes

During a steady-flow process, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant)

Then the conservation of mass principle requires that the total amount of mass entering a control volume equal the total amount of mass leaving it

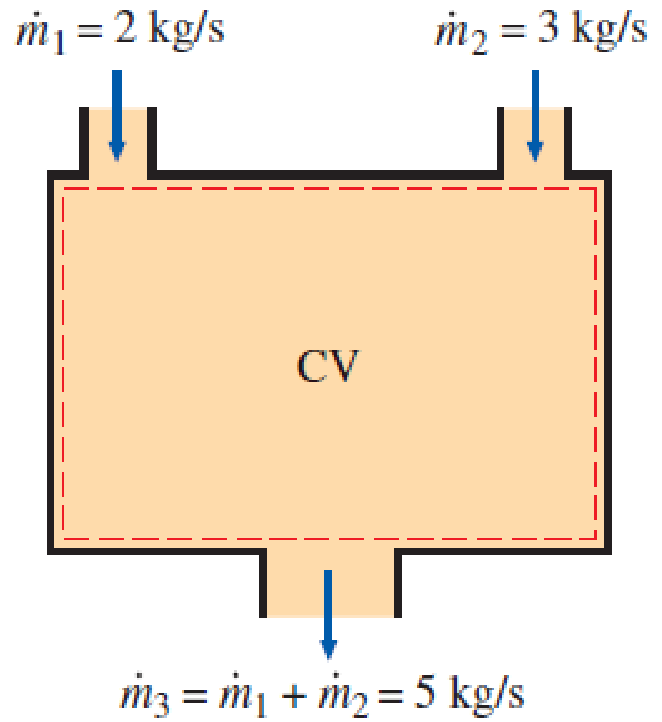


FIGURE 5–8
Conservation of mass principle for a two-inlet–one-outlet steady-flow system.

Mass Balance for Steady-Flow Processes

For *steady-flow processes*, we are interested in the amount of mass flowing per unit time, that is, *the mass flow rate*

$$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m} \qquad (\text{kg/s})$$

Multiple inlets and exits

$$\dot{m}_1 = \dot{m}_2 \quad \rightarrow \quad \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

Single inlet and exit

Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet)

Special Case: Incompressible Flow

The conservation of mass relations can be simplified even further when the fluid is incompressible (usually the case for liquids)

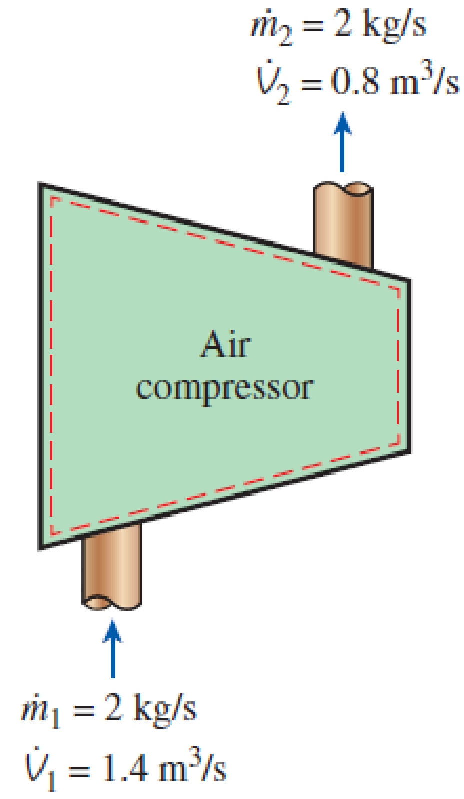


FIGURE 5–9
During a steady-flow process, volume flow rates are not necessarily conserved although mass flow rates are.

$$\sum_{\text{in}} \dot{V} = \sum_{\text{out}} \dot{V} \qquad (\text{m}^3/\text{s})$$

Steady, incompressible

$$\dot{V}_1 = \dot{V}_2 \rightarrow V_1 A_1 = V_2 A_2$$

Steady, incompressible flow (single stream)

For steady flow of liquids, the volume flow rates, as well as the mass flow rates, remain constant since liquids are essentially incompressible (constant density) substances

FLOW WORK AND THE ENERGY OF A FLOWING FLUID

Flow work, or flow energy: The work (or energy) required to push the mass into or out of the control volume. This work is necessary for maintaining a continuous flow through a control volume.

$$F = PA$$

$$W_{\text{flow}} = FL = PAL = PV \qquad (\text{kJ})$$

$$w_{\text{flow}} = Pv \qquad (\text{kJ/kg})$$

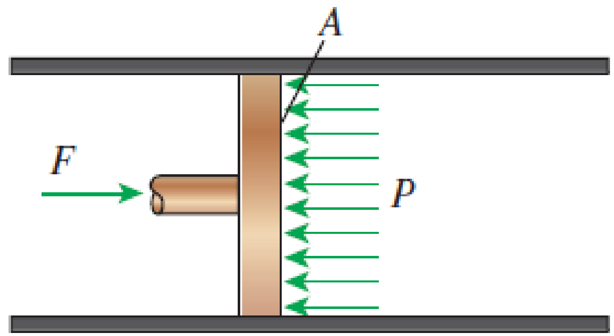


FIGURE 5–13
In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.

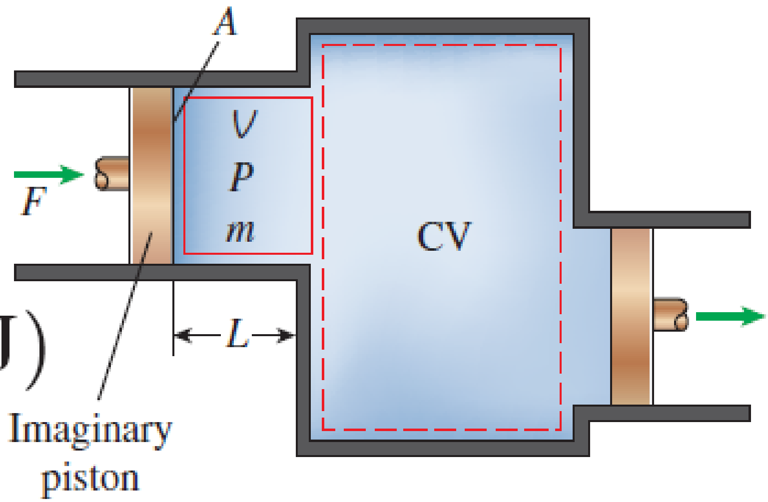


FIGURE 5–12
Schematic for flow work.

FLOW WORK

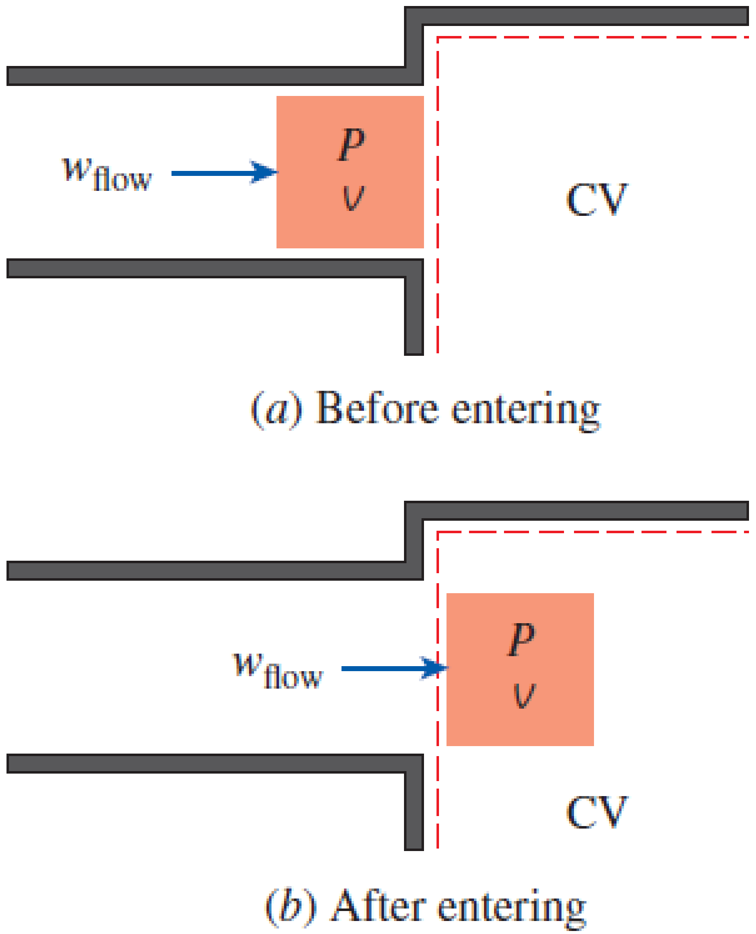


FIGURE 5–14
Flow work is the energy needed to push a fluid into or out of a control volume, and it is equal to Pv.

Total Energy of a Flowing Fluid

$$e = u + \text{ke} + \text{pe} = u + \frac{V^2}{2} + gz \qquad (\text{kJ/kg})$$

non-flowing fluid

$$\theta = \overbrace{P\text{v}}^{\text{Flow work or flow energy}} + e = P\text{v} + (u + \text{ke} + \text{pe})$$

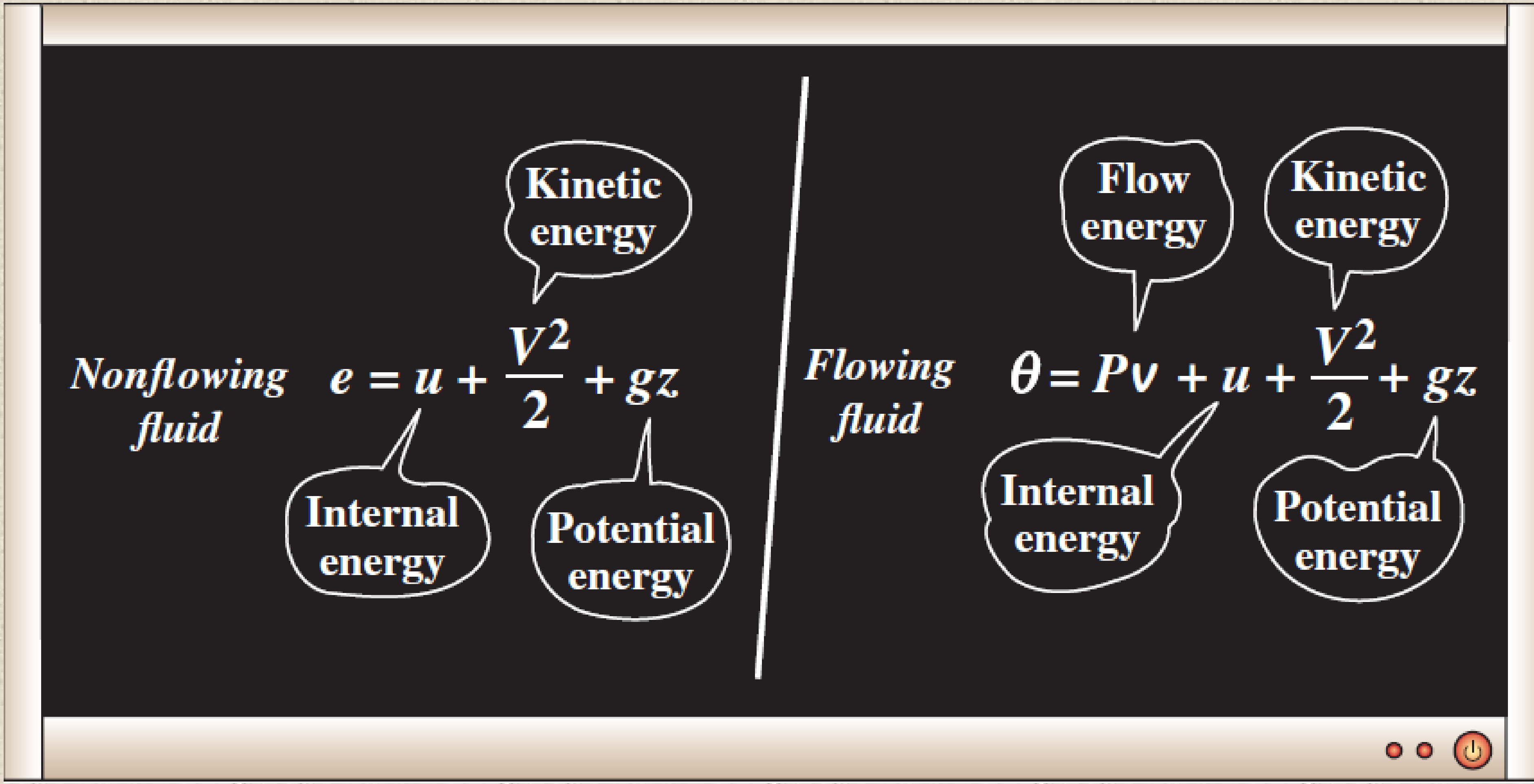
$$h = u + Pv$$

$$\theta = h + \text{ke} + \text{pe} = h + \frac{V^2}{2} + gz \qquad (\text{kJ/kg})$$

flowing fluid

The flow work or flow energy is automatically taken care of by enthalpy. In fact, **this is the main reason for defining the property enthalpy**.

Total Energy of a Flowing Fluid



Energy Transport by Mass

Amount of energy transport: $$E_{\text{mass}} = m\theta = m\left(h + \frac{V^2}{2} + gz\right) \qquad \text{(kJ)}$$

Rate of energy transport: $$\dot{E}_{\text{mass}} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right) \qquad \text{(kW)}$$

When the kinetic and potential energies of a fluid stream are negligible

$$E_{\text{mass}} = mh \qquad \dot{E}_{\text{mass}} = \dot{m}h$$

When the properties of the mass at each inlet or exit change with time as well as over the cross section

$$E_{\text{in,mass}} = \int_{m_i} \theta_i \, \delta m_i = \int_{m_i} \left(h_i + \frac{V_i^2}{2} + gz_i\right) \delta m_i$$

Energy Transport by Mass

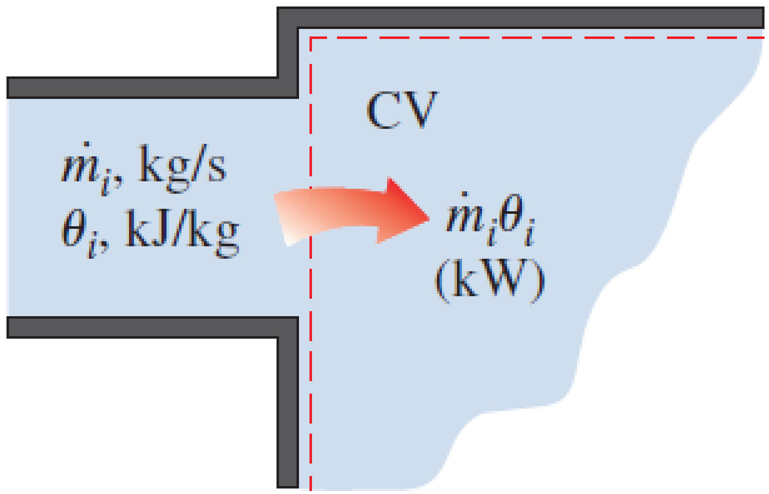


FIGURE 5–16

The product $\dot{m}_i\theta_i$ is the energy transported into control volume by mass per unit time.

ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS

Steady-flow process: *A process during which a fluid flows through a control volume steadily*

During a steady-flow process, no intensive or extensive properties change with time at any location within the control volume

Also, the heat and work interactions between a steady-flow system and its surroundings do not change with time

FIGURE 5–18
Many engineering systems such as power plants operate under steady conditions.

ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS

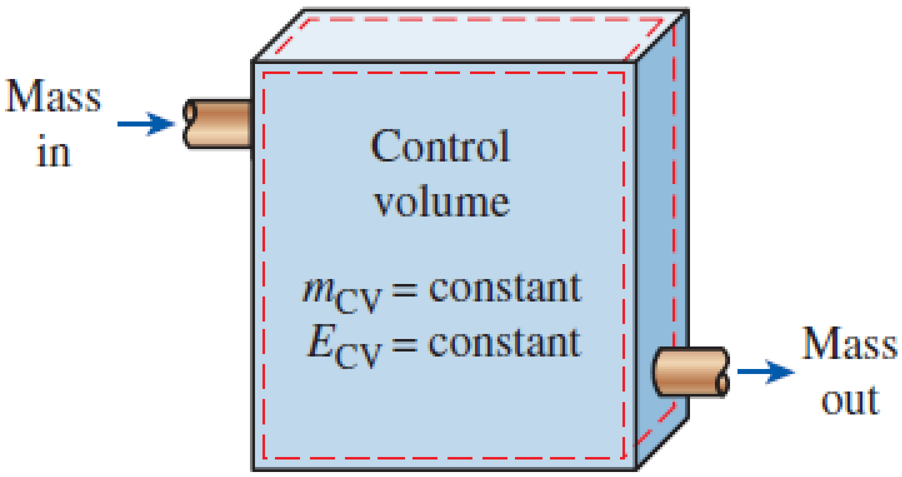


FIGURE 5–19

Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

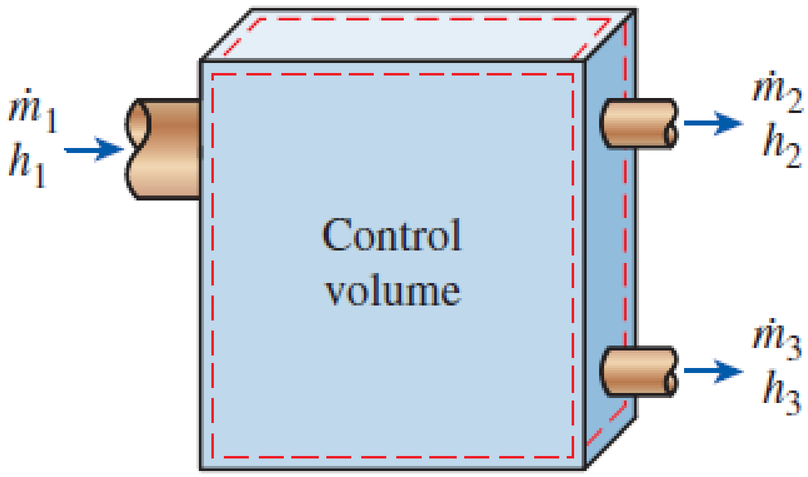


FIGURE 5–20

Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).

Mass balance for a steady-flow process

$$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m} \qquad (\text{kg/s})$$

Mass balance

$$\dot{m}_1 = \dot{m}_2$$

Single inlet and exit

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

Single inlet and exit

V is the average flow velocity in the flow direction and A is the cross-sectional area normal to flow direction

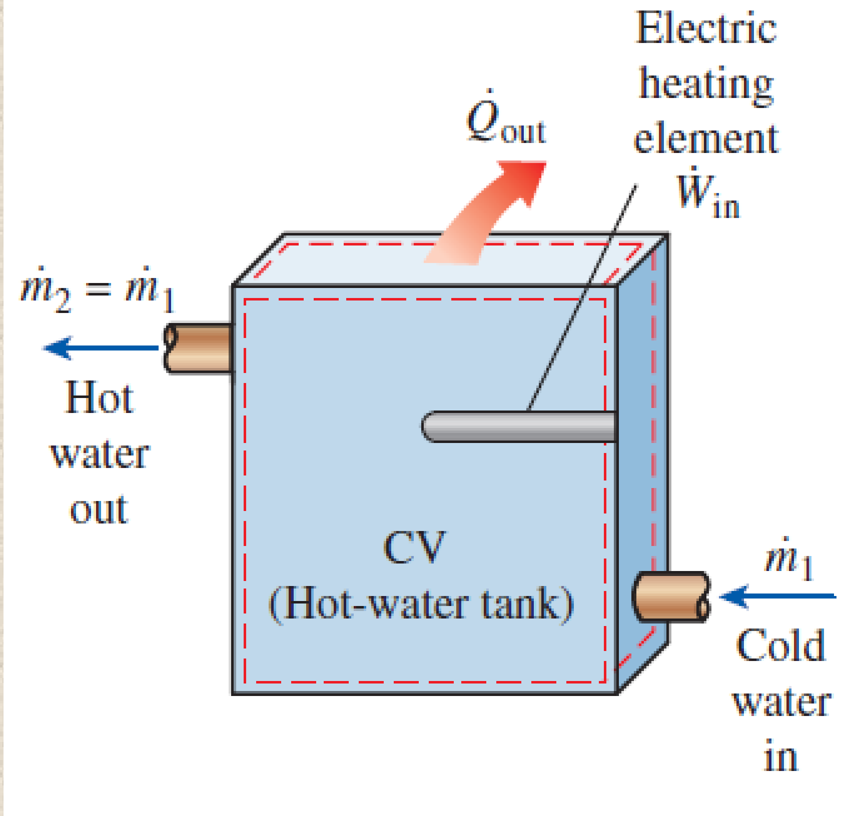


FIGURE 5–21
A water heater in steady operation.

Energy balance for a steady-flow process

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt \overset{\nearrow 0 \text{ (steady)}}{}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} = 0$$

$$\underbrace{\dot{E}_{\text{in}}}_{\substack{\text{Rate of net energy transfer in} \\ \text{by heat, work, and mass}}} = \underbrace{\dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer out} \\ \text{by heat, work, and mass}}} \qquad \text{(kW)}$$

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \dot{m}\theta = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \dot{m}\theta$$

Energy balance

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}} = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}}$$

Energy balance relations with sign conventions

(i.e., heat input and work output are positive)

$$\dot{Q} - \dot{W} = \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}} - \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}}$$

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

$$q - w = h_2 - h_1 + \underbrace{\frac{V_2^2 - V_1^2}{2}}_{\Delta \text{ke}} + \underbrace{g(z_2 - z_1)}_{\Delta \text{pe}}$$

$$q - w = h_2 - h_1$$

when kinetic and potential energy changes are negligible

$$q = \dot{Q}/\dot{m} \qquad w = \dot{W}/\dot{m}$$

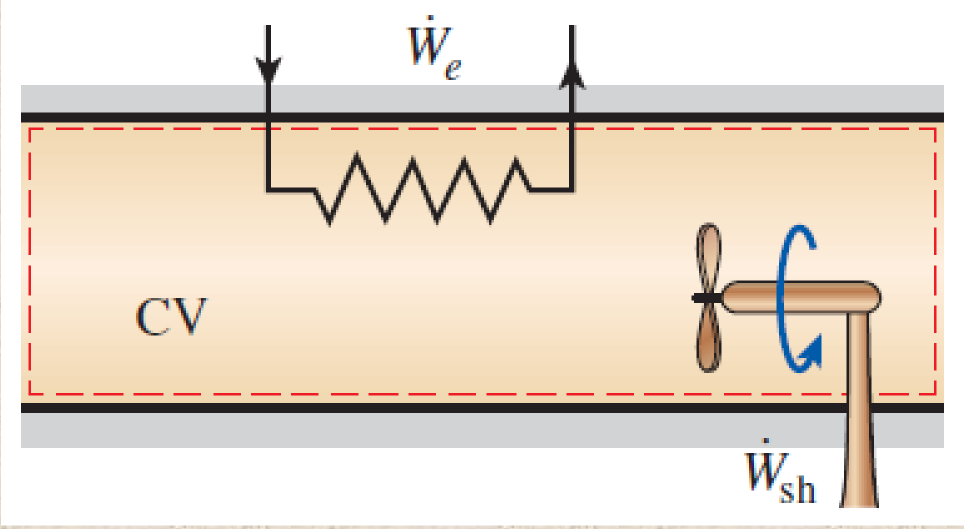
Change in Kinetic Energy

$$\underbrace{\frac{V_2^2 - V_1^2}{2}}_{\Delta \text{ke}}$$

V_1 m/s	V_2 m/s	Δke kJ/kg
0	45	1
50	67	1
100	110	1
200	205	1
500	502	1

At very high velocities, even small changes in velocities can cause significant changes in the kinetic energy of the fluid.

Work forms for a simple compressible open system

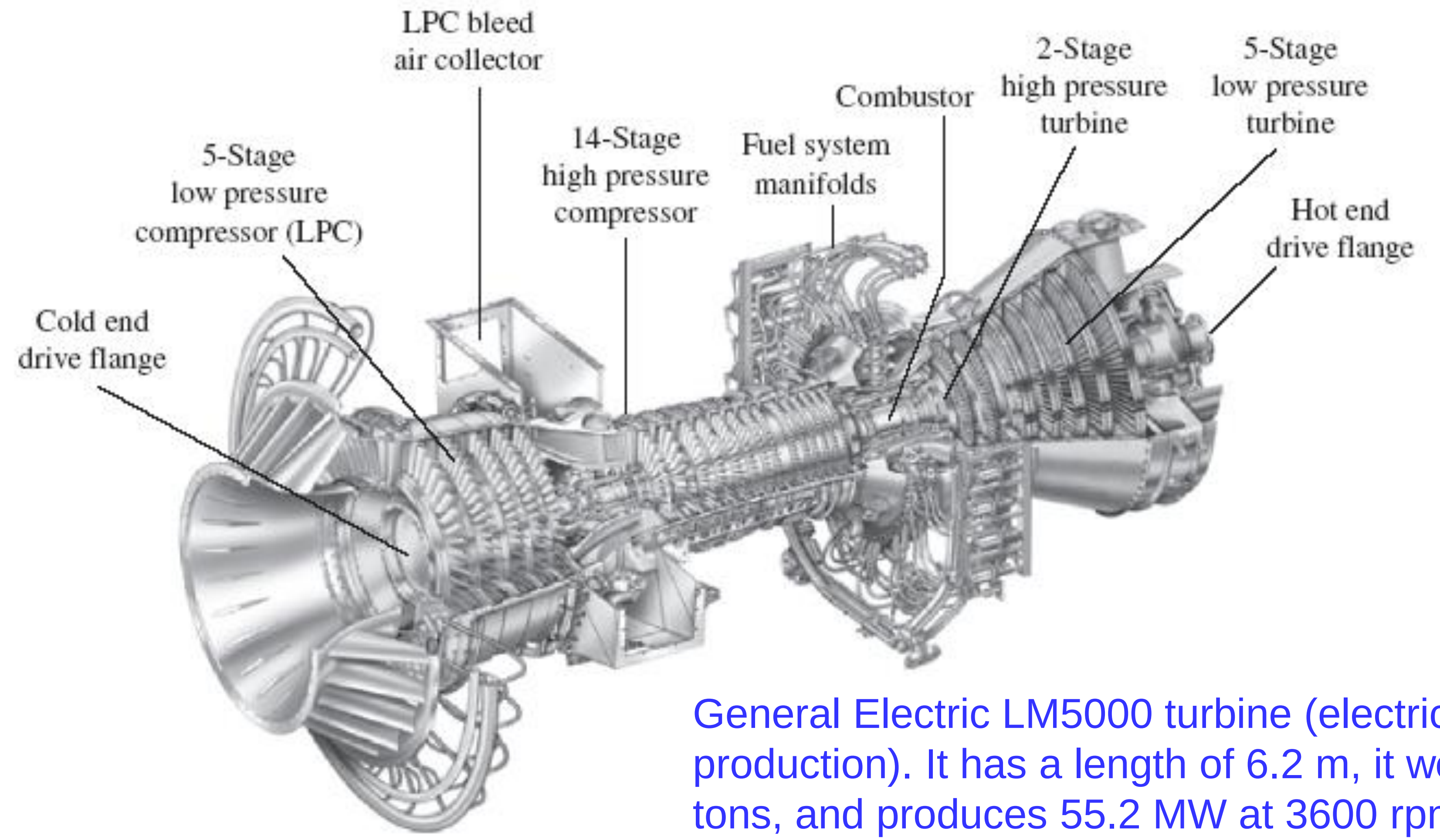


For **steady-flow** devices, the control volume is constant; thus there is no boundary work involved

Under **steady** operation, shaft work and electrical work are the only forms of work a simple compressible system may involve (note: we have subsumed the flow work in the enthalpy)

SOME STEADY-FLOW ENGINEERING DEVICES

Many engineering devices operate essentially under the same conditions for long periods of time. The components of a steam power plant (turbines, compressors, heat exchangers, and pumps), for example, operate nonstop for months before the system is shut down for maintenance. Therefore, these devices can be conveniently analyzed as steady-flow devices.



General Electric LM5000 turbine (electricity production). It has a length of 6.2 m, it weighs 12.5 tons, and produces 55.2 MW at 3600 rpm

Nozzles and Diffusers

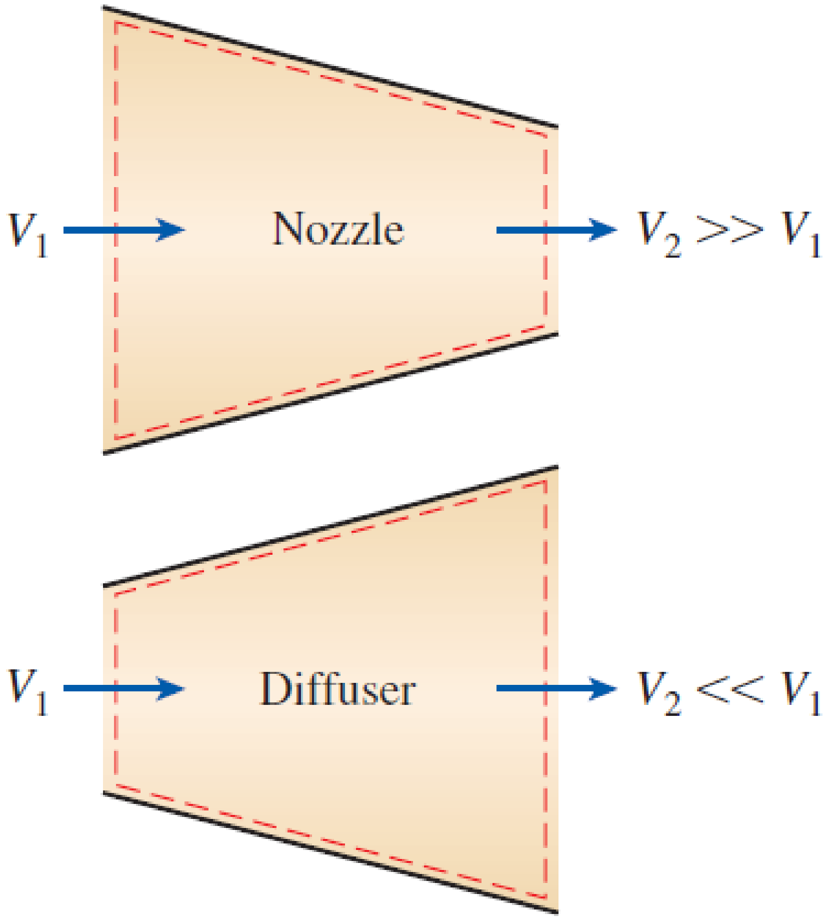


FIGURE 5–26
Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses
- A **nozzle** is a device that *increases the velocity of a fluid* at the expense of pressure
- A **diffuser** is a device that *increases the pressure of a fluid* by slowing it down
- The cross-sectional area of a **nozzle** decreases in the flow direction for subsonic flows and increases for supersonic flows. The reverse is true for **diffusers**.

Energy balance for a nozzle or diffuser (steady flow process):

$$\dot{Q} - \dot{W} = \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}} - \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}}$$

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt^{\nearrow 0\ (\text{steady})}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

if heat transfer is negligible

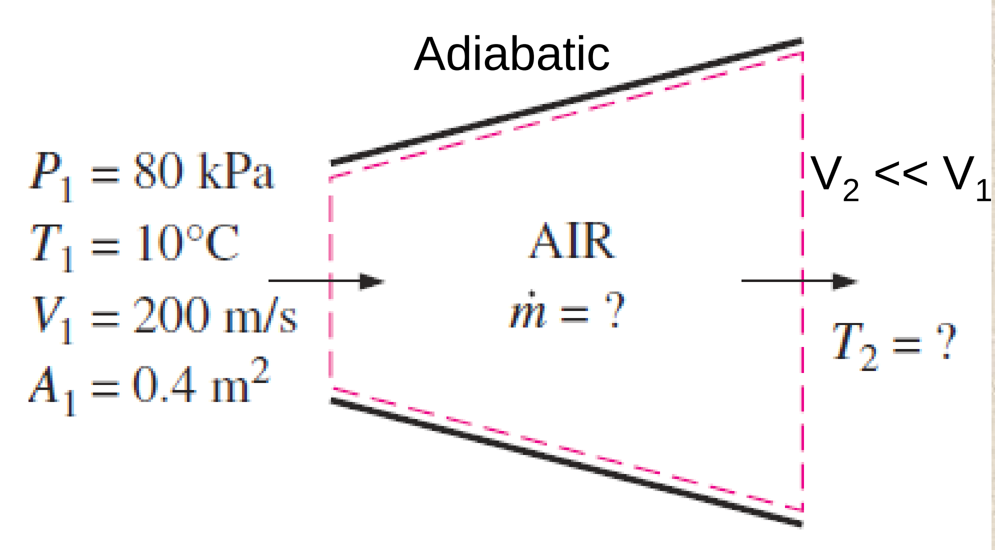
$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$$

(since $\dot{Q} \cong 0$, $\dot{W} = 0$, and $\Delta\text{pe} \cong 0$)

if no work interaction

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

Example: Deceleration of Air in a Diffuser



<u>Assumptions:</u>

- Steady flow process: $\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$
- Potential energy change is zero: $\Delta pe = 0$
- Heat transfer is negligible
- No work interaction

- Air is an ideal gas: (low pressure $P_{R1} = P_1/P_{CR} = 0.02$, high temperature $T_{R1} = T_1/T_{CR} = 2.14$ ($P_{CR} = 3.77$ MPa, $T_{CR} = 132.5$ K: Table A-1)

FIGURE 5–27
The diffuser of a jet engine discussed

Example: Deceleration of Air in a Diffuser

- Mass balance:
  - ✓ Only one inlet and one outlet thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$

$$v_1 = \frac{RT_1}{P_1} = 1.015\, m^3/kg$$

Ideal gas equation

$$\dot{m} = \frac{1}{v_1} V_1 A_1 = 78.8\, kg/s$$

note: V_1 is used for velocity and not volume

- Energy balance:

$V_2 << V_1$

$$h_2 = h_1 - \frac{\cancel{V_2^2} - V_1^2}{2}$$

$$(\text{since } \dot{Q} \cong 0,\ \dot{W} = 0, \text{ and } \Delta\text{pe} \cong 0)$$

$$h_1 = h_{@\,283\text{ K}} = 283.14 \text{ kJ/kg}$$

(Table A-17)

$$h_2 = 303.14\, kJ/kg$$

$$T_2 = 303\, K$$

(Table A-17)

Linear interpolation can be used to obtain the intermediate values

TABLE A–17

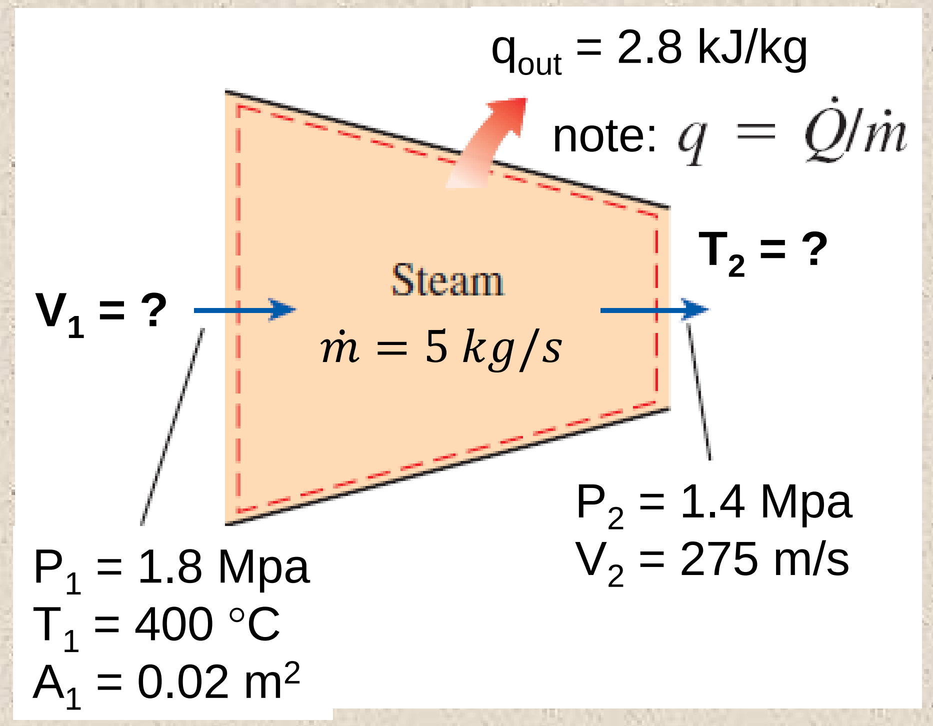
Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg·K
200	199.97	0.3363	142.56	1707.0	1.29559
210	209.97	0.3987	149.69	1512.0	1.34444
220	219.97	0.4690	156.82	1346.0	1.39105
230	230.02	0.5477	164.00	1205.0	1.43557
240	240.02	0.6355	171.13	1084.0	1.47824
250	250.05	0.7329	178.28	979.0	1.51917
260	260.09	0.8405	185.45	887.8	1.55848
270	270.11	0.9590	192.60	808.0	1.59634
280	280.13	1.0889	199.75	738.0	1.63279
285	285.14	1.1584	203.33	706.1	1.65055
290	290.16	1.2311	206.91	676.1	1.66802
295	295.17	1.3068	210.49	647.9	1.68515
298	298.18	1.3543	212.64	631.9	1.69528
300	300.19	1.3860	214.07	621.2	1.70203
305	305.22	1.4686	217.67	596.0	1.71865
310	310.24	1.5546	221.25	572.3	1.73498
315	315.27	1.6442	224.85	549.8	1.75106
320	320.29	1.7375	228.42	528.6	1.76690
325	325.31	1.8345	232.02	508.4	1.78249
330	330.34	1.9352	235.61	489.4	1.79783

T_1 = 283 K

T_2 = 303 K

Example: Acceleration of Steam in a Nozzle (Non-Adiabatic)



Assumptions:

- Steady flow process: $\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$
- Potential energy change is zero: $\Delta pe = 0$
- No work interaction

✓ Use property tables

✓ Note that heat transfer is present

Example: Acceleration of Steam in a Nozzle (Non-Adiabatic)

$$\left.\begin{array}{l} P_1 = 1.8\ MPa \\ T_1 = 400\ °C \end{array}\right\} \begin{array}{l} v_1 = 0.16849\ m^3/kg \\ h_1 = 3251.6\ kJ/kg \end{array}$$

$$\dot{m} = \frac{1}{v_1} V_1 A_1$$

note: V_1 is used for velocity and not volume

$$\dot{m} = 5\ kg/s$$

$$A_1 = 0.02\ m^2$$

$$V_1 = 42.1\ m/s$$

TABLE A–6

Superheated water

	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 1.80 MPa (207.11°C)			
Sat.	0.11037	2597.3	2795.9	6.3775
225	0.11678	2637.0	2847.2	6.4825
250	0.12502	2686.7	2911.7	6.6088
300	0.14025	2777.4	3029.9	6.8246
350	0.15460	2863.6	3141.9	7.0120
400	0.16849	2948.3	3251.6	7.1814
500	0.19551	3118.5	3470.4	7.4845
600	0.22200	3292.7	3692.3	7.7543
700	0.24822	3472.6	3919.4	8.0005
800	0.27426	3658.8	4152.4	8.2284
900	0.30020	3851.5	4391.9	8.4417
1000	0.32606	4050.7	4637.6	8.6427
1100	0.35188	4256.2	4889.6	8.8331
1200	0.37766	4467.6	5147.3	9.0143
1300	0.40341	4684.5	5410.6	9.1872

Example: Acceleration of Steam in a Nozzle (Non-Adiabatic)

Energy balance:

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0\ (\text{steady})}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{Q}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) \quad (\text{since } \dot{W} = 0, \text{ and } \Delta\text{pe} \cong 0)$$

$$h_2 = h_1 - q_{out} - \frac{V_2^2 - V_1^2}{2}$$

$$q_{out} = 2.8\ kJ/kg$$

$$Note:\ \dot{Q}_{out} = \dot{m}q_{out}$$

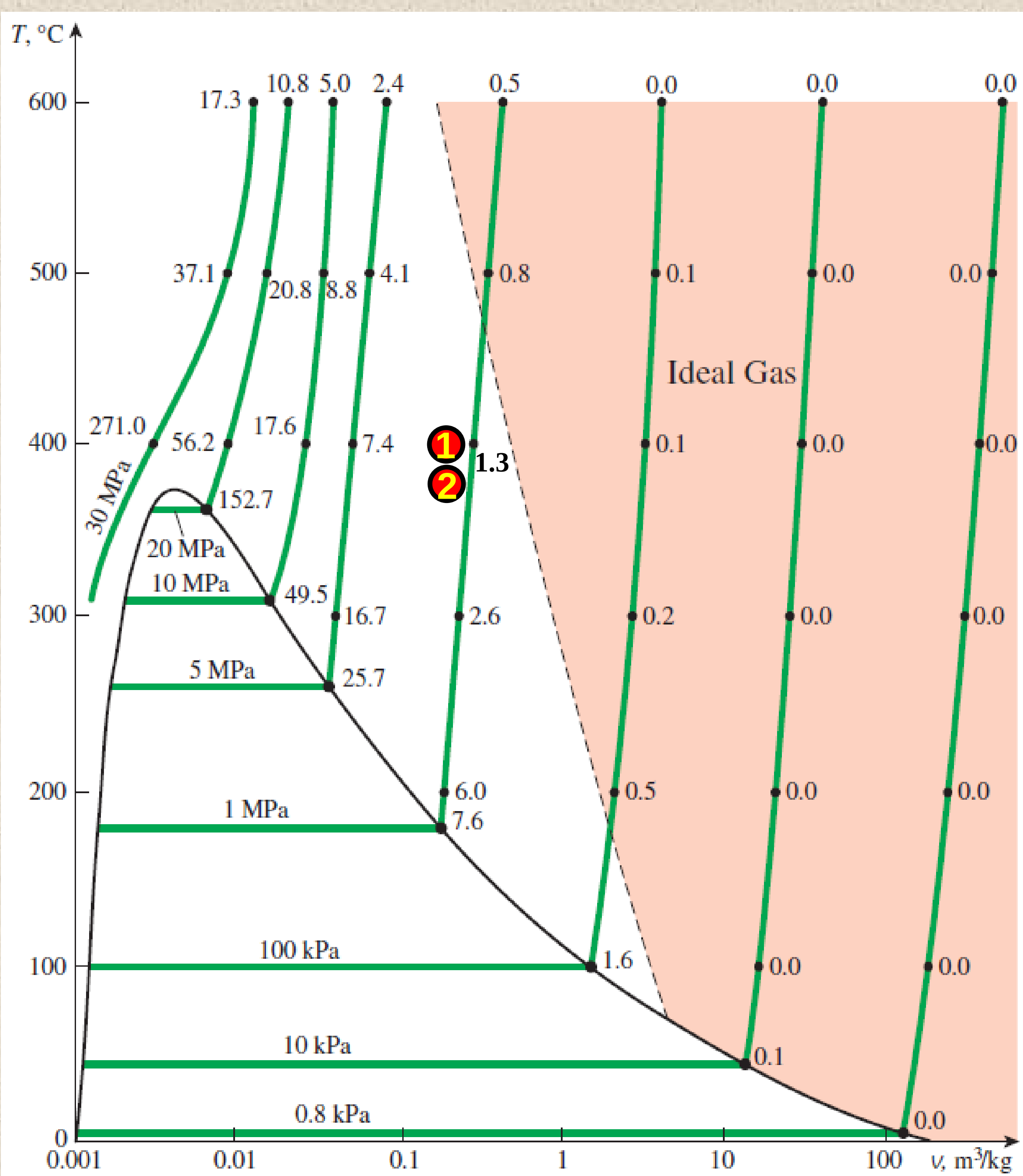
$$h_2 = 3211.9\ kJ/kg$$

$$P_2 = 1.4\ MPa$$

$$T_2 = 378.6\ °C$$

TABLE A–6

	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 1.40 MPa (195.04°C)			
Sat.	0.14078	2591.8	2788.9	6.4675
225	0.14303	2602.7	2803.0	6.4975
250	0.16356	2698.9	2927.9	6.7488
300	0.18233	2785.7	3040.9	6.9553
350	0.20029	2869.7	3150.1	7.1379
400	0.21782	2953.1	3258.1	7.3046
500	0.25216	3121.8	3474.8	7.6047
600	0.28597	3295.1	3695.5	7.8730



Also try this problem by assuming steam as an ideal gas: (low pressure $P_{R1} = P_1/P_{CR} = 0.08$, low temperature $T_{R1} = T_1/T_{CR} = 1.04$ ($P_{CR} = 22.06$ MPa, $T_{CR} = 647.1$ K: Table A-1)

Percentage of error ($[|v_{table} - v_{ideal}|/v_{table}] \times 100$) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

Turbines and Compressors

Turbine drives the electric generator In steam, gas, or hydroelectric power plants

As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft. As a result, the shaft rotates, and the turbine produces work.

Compressors, as well as **pumps** and **fans**, are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft.

A ***fan*** increases the pressure of a gas slightly and is mainly used to mobilize a gas

A ***compressor*** is capable of compressing the gas to very high pressures

Pumps work very much like compressors except that they handle liquids instead of gases

Turbines and Compressors

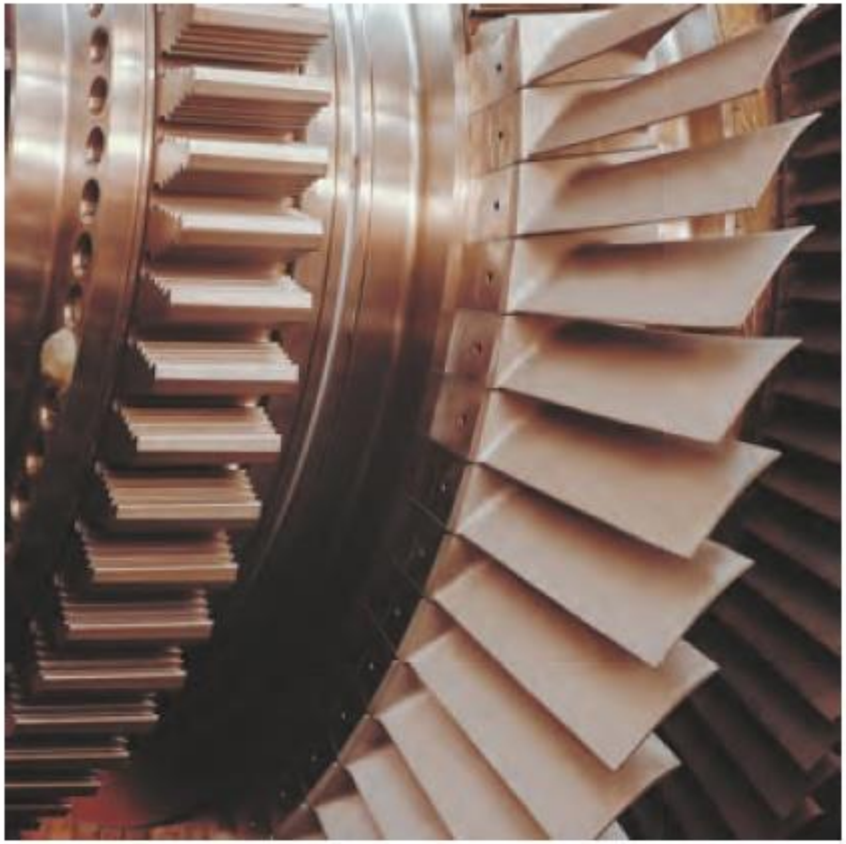


FIGURE 5–29
Turbine blades attached to the turbine shaft.

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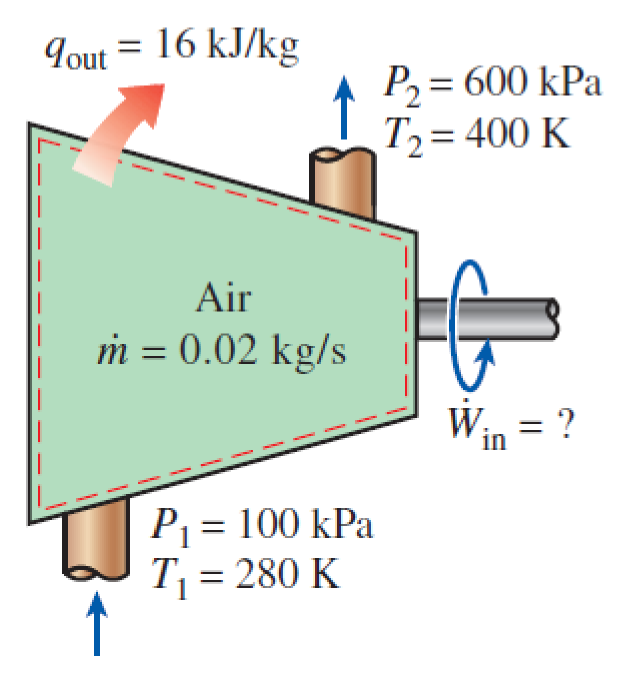
Compressing Air by a Compressor

<u>Assumptions:</u>

- Steady flow process: $\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$
- Potential energy change is zero: $\Delta pe = 0$
- Assume air as an ideal gas
- Note that both heat and work interactions are involved



$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}}^{\nearrow 0 \text{ (steady)}} = 0$$

$$h_1 = h_{@\ 280\ \mathrm{K}} = 280.13 \text{ kJ/kg}$$

$$h_2 = h_{@\ 400\ \mathrm{K}} = 400.98 \text{ kJ/kg}$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2 \qquad (\text{since } \Delta \mathrm{ke} = \Delta \mathrm{pe} \cong 0)$$

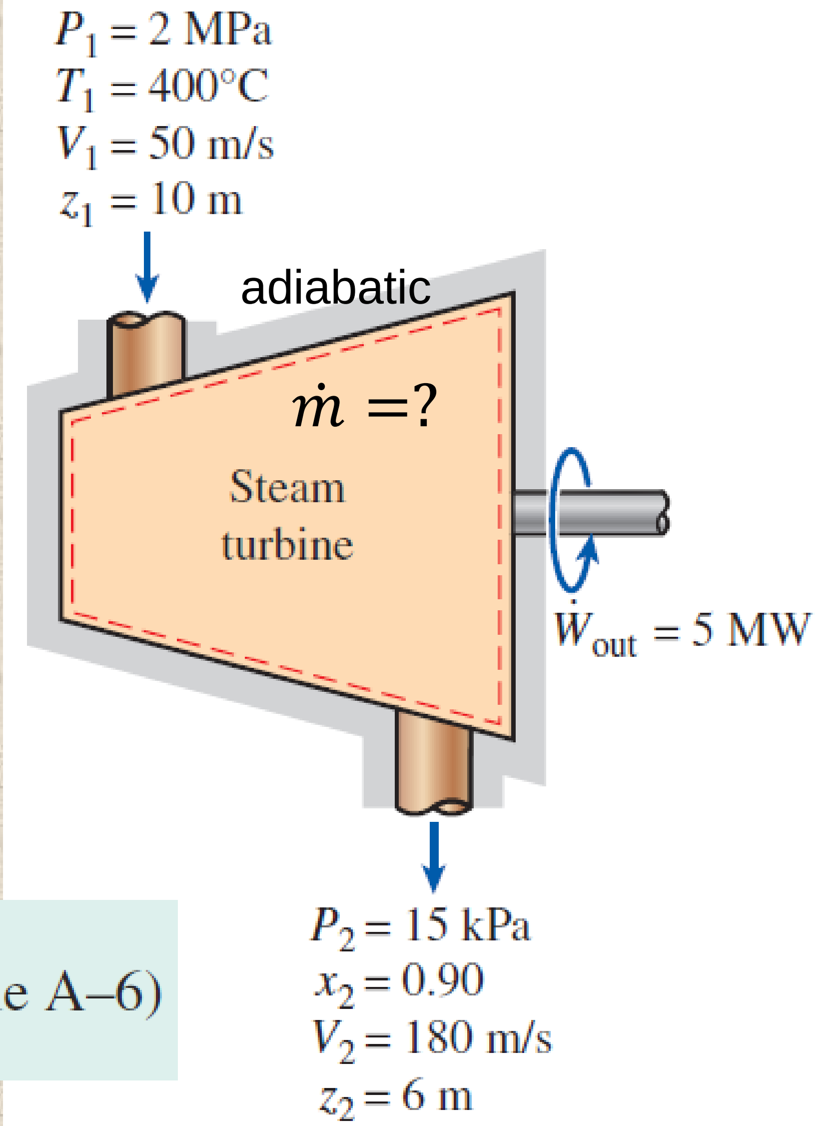
$$\dot{W}_{in} = \dot{m}q_{out} + \dot{m}(h_2 - h_1)$$

$$\dot{W}_{in} = \mathbf{2.74\ kW}$$

Example: Power Generation by a Steam Turbine

Assumptions:

- Steady flow process: $\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$
- Potential energy change is zero: $\Delta pe = 0$
- Use property tables for steam
- Note that work interaction is involved



$$\left.\begin{aligned} P_1 &= 2 \text{ MPa} \\ T_1 &= 400°\text{C} \end{aligned}\right\} \quad h_1 = 3248.4 \text{ kJ/kg} \qquad \text{(Table A–6)}$$

$$h_2 = h_f + x_2 h_{fg} = [225.94 + (0.9)(2372.3)] \text{ kJ/kg} = 2361.01 \text{ kJ/kg}$$

(Table A-5)

Example: Power Generation by a Steam Turbine

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) \quad (\text{since } \dot{Q} = 0)$$

$$w_{out} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] = -(\Delta h + \Delta \mathrm{ke} + \Delta \mathrm{pe})$$

$$w_{out} = \mathbf{872.48\ kJ/kg}$$

$$\dot{m} = \frac{\dot{W}_{out}}{w_{out}} = \frac{5000\ \text{kJ/s}}{872.48\ \text{kJ/kg}} = \mathbf{5.73\ kg/s}$$

Throttling valves

Throttling valves are *any kind of flow-restricting devices* that cause a significant pressure drop in the fluid.

What is the difference between a turbine and a throttling valve?

In throttling value work interaction is absent

The pressure drop in the fluid is often accompanied by a *large drop in temperature*, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.

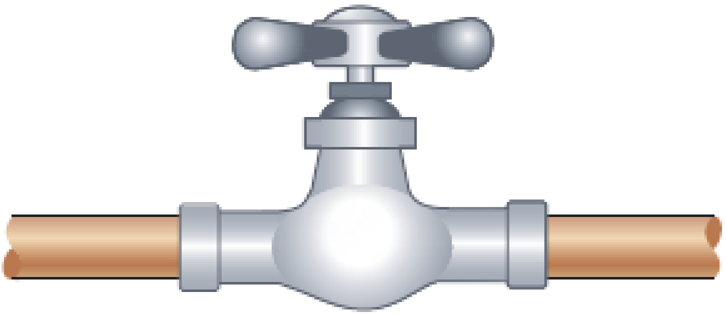
Energy balance

$$h_2 \cong h_1$$

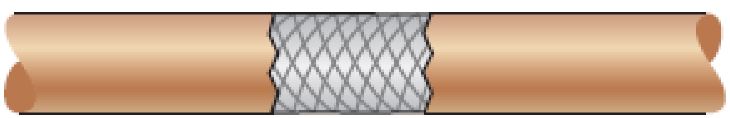
$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

$$\text{Internal energy} + \text{Flow energy} = \text{Constant}$$

Throttling valves



(*a*) An adjustable valve



(*b*) A porous plug

(*c*) A capillary tube

FIGURE 5–32
Throttling valves are devices that cause large pressure drops in the fluid.

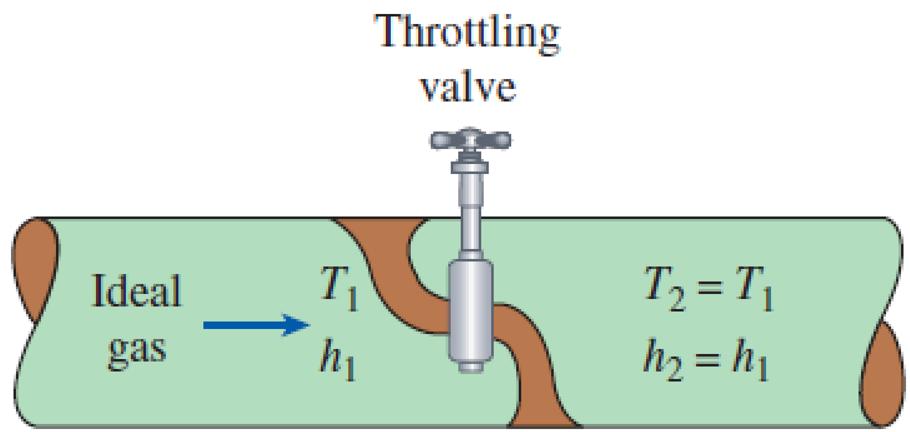


FIGURE 5–33
The temperature of an ideal gas does not change during a throttling (h = constant) process since $h = h(T)$.

Example: Expansion of Refrigerant-134a in a Refrigerator

Assumptions:

- Heat transfer from the tube is negligible
- Kinetic energy change of the refrigerant is negligible

Energy Balance:

$$h_2 \cong h_1 \qquad \text{(kJ/kg)}$$

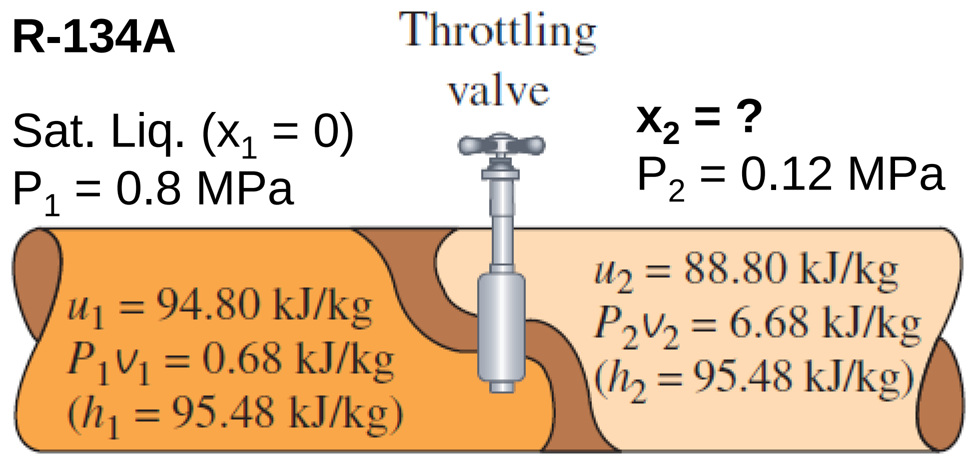


FIGURE 5–34
During a throttling process, the enthalpy (flow energy + internal energy) of a fluid remains constant. But internal and flow energies may be converted to each other.

Example: Expansion of Refrigerant-134a in a Refrigerator

At inlet: $\left.\begin{array}{l} P_1 = 0.8 \text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} T_1 = T_{\text{sat @ 0.8 MPa}} = 31.31^\circ\text{C} \\ h_1 = h_{f\,@\,0.8\text{ MPa}} = 95.48 \text{ kJ/kg} \end{array}$ (Table A–12)

At exit: $\begin{array}{l} P_2 = 0.12 \text{ MPa} \\ (h_2 = h_1) \end{array} \longrightarrow \begin{array}{l} h_f = 22.47 \text{ kJ/kg} \quad T_{\text{sat}} = -22.32^\circ\text{C} \\ h_g = 236.99 \text{ kJ/kg} \end{array}$

Obviously $h_f < h_2 < h_g$; thus, the refrigerant exists as a saturated mixture at the exit state. The quality at this state is

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{95.48 - 22.47}{236.99 - 22.47} = \mathbf{0.340}$$

Since the exit state is a saturated mixture at 0.12 MPa, the exit temperature must be the saturation temperature at this pressure, which is -22.32°C. Then the temperature change for this process becomes

$$\Delta T = T_2 - T_1 = (-22.32 - 31.31)^\circ\text{C} = \mathbf{-53.63^\circ C}$$

TABLE A–12

Saturated refrigerant-134a—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.01633	0.94812	0.96445
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.03264	0.92783	0.96047
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.04707	0.91009	0.95716
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.06003	0.89431	0.95434
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.07182	0.88008	0.95191
120	−22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99	0.09269	0.85520	0.94789
140	−18.77	0.0007381	0.14020	26.96	192.60	219.56	27.06	212.13	239.19	0.11080	0.83387	0.94467
160	−15.60	0.0007435	0.12355	31.06	190.31	221.37	31.18	209.96	241.14	0.12686	0.81517	0.94202
180	−12.73	0.0007485	0.11049	34.81	188.20	223.01	34.94	207.95	242.90	0.14131	0.79848	0.93979
200	−10.09	0.0007532	0.099951	38.26	186.25	224.51	38.41	206.09	244.50	0.15449	0.78339	0.93788
240	−5.38	0.0007618	0.083983	44.46	182.71	227.17	44.64	202.68	247.32	0.17786	0.75689	0.93475
280	−1.25	0.0007697	0.072434	49.95	179.54	229.49	50.16	199.61	249.77	0.19822	0.73406	0.93228
320	2.46	0.0007771	0.063681	54.90	176.65	231.55	55.14	196.78	251.93	0.21631	0.71395	0.93026
360	5.82	0.0007840	0.056809	59.42	173.99	233.41	59.70	194.15	253.86	0.23265	0.69591	0.92856
400	8.91	0.0007905	0.051266	63.61	171.49	235.10	63.92	191.68	255.61	0.24757	0.67954	0.92711
450	12.46	0.0007983	0.045677	68.44	168.58	237.03	68.80	188.78	257.58	0.26462	0.66093	0.92555
500	15.71	0.0008058	0.041168	72.92	165.86	238.77	73.32	186.04	259.36	0.28021	0.64399	0.92420
550	18.73	0.0008129	0.037452	77.09	163.29	240.38	77.54	183.44	260.98	0.29460	0.62842	0.92302
600	21.55	0.0008198	0.034335	81.01	160.84	241.86	81.50	180.95	262.46	0.30799	0.61398	0.92196
650	24.20	0.0008265	0.031680	84.72	158.51	243.23	85.26	178.56	263.82	0.32052	0.60048	0.92100
700	26.69	0.0008331	0.029392	88.24	156.27	244.51	88.82	176.26	265.08	0.33232	0.58780	0.92012
750	29.06	0.0008395	0.027398	91.59	154.11	245.70	92.22	174.03	266.25	0.34348	0.57582	0.91930
800	31.31	0.0008457	0.025645	94.80	152.02	246.82	95.48	171.86	267.34	0.35408	0.56445	0.91853
850	33.45	0.0008519	0.024091	97.88	150.00	247.88	98.61	169.75	268.36	0.36417	0.55362	0.91779
900	35.51	0.0008580	0.022703	100.84	148.03	248.88	101.62	167.69	269.31	0.37383	0.54326	0.91709
950	37.48	0.0008640	0.021456	103.70	146.11	249.82	104.52	165.68	270.20	0.38307	0.53333	0.91641
1000	39.37	0.0008700	0.020329	106.47	144.24	250.71	107.34	163.70	271.04	0.39196	0.52378	0.91574

Mixing chambers

- In engineering applications, the section where the mixing process takes place is commonly referred to as a **mixing chamber**
- The mixing chamber does not have to be a distinct "chamber." An ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams.

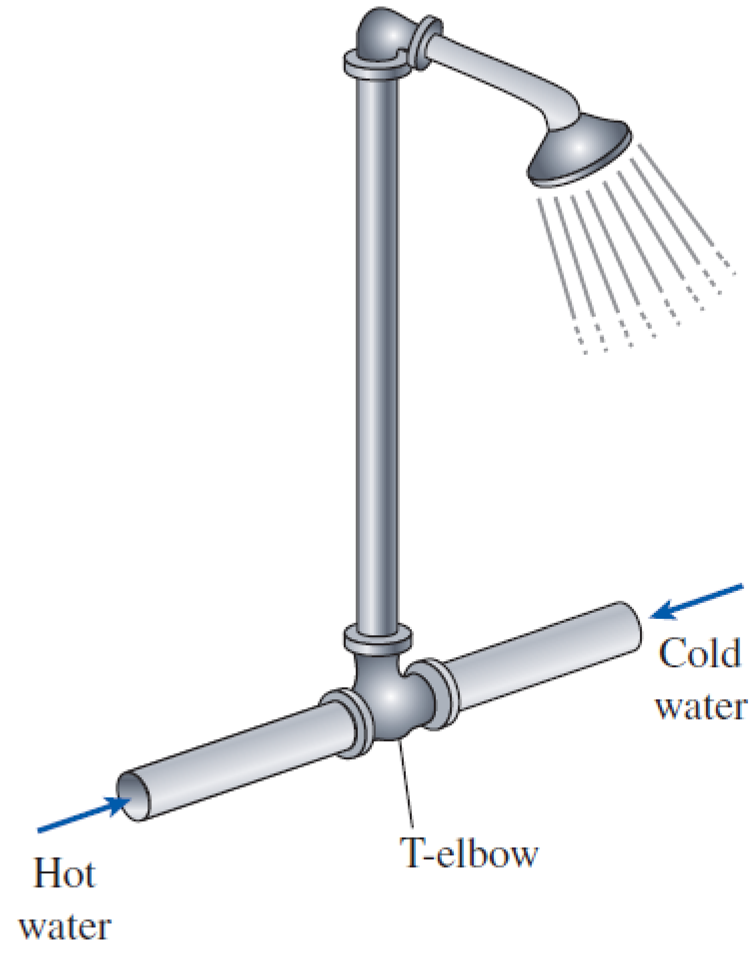


FIGURE 5–35
The T-elbow of an ordinary shower serves as the mixing chamber for the hot- and the cold-water streams.

- The conservation of mass principle for a mixing chamber requires that the sum of the incoming mass flow rates equal the mass flow rate of the outgoing mixture

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

- The conservation of energy equation is analogous to the conservation of mass equation

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt^{\nearrow 0 \text{ (steady)}}}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

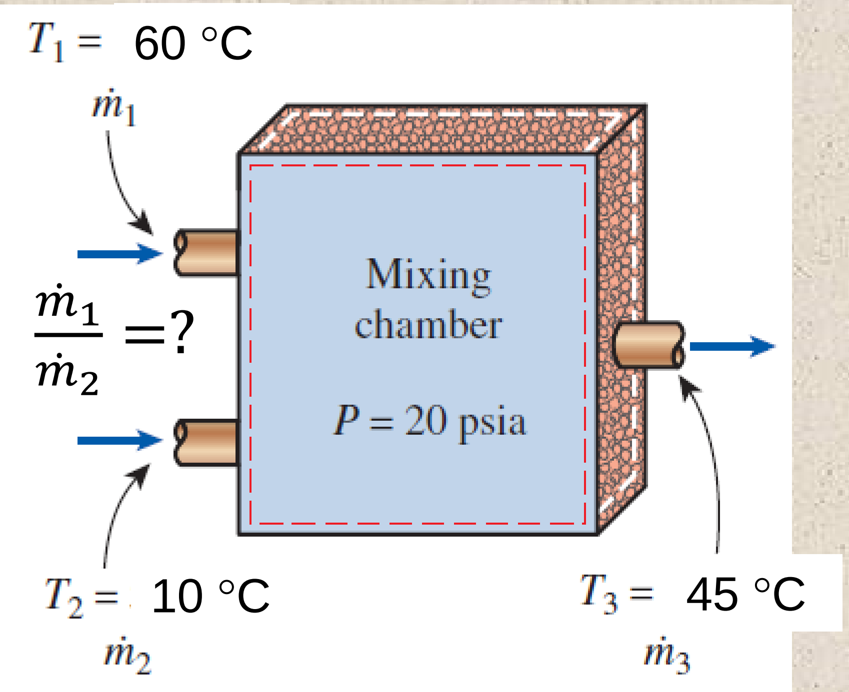
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (\text{since } \dot{Q} \cong 0, \dot{W} = 0, \text{ke} \cong \text{pe} \cong 0)$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3$$

Example: Mixing of Hot and Cold Waters in a Shower

Assumptions:

- Steady flow process: $\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$
- Kinetic and potential energies are negligible: ke = pe $\cong 0$
- Heat losses from the system are negligible
- There is no work interaction involved



$$h_1 \cong h_{f@60°C} = 251.18\ kJ/kg$$

$$h_2 \cong h_{f@10°C} = 42.02\ kJ/kg$$

$$h_3 \cong h_{f@45°C} = 188.44\ kJ/kg$$

Mass Balance:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3$$

$$\frac{\dot{m}_1}{\dot{m}_2} = \frac{h_3 - h_2}{h_1 - h_3} = 2.33$$

Heat exchangers

- **Heat exchangers** are devices where two moving fluid streams exchange heat without mixing
- Heat exchangers are widely used in various industries, and they come in various designs

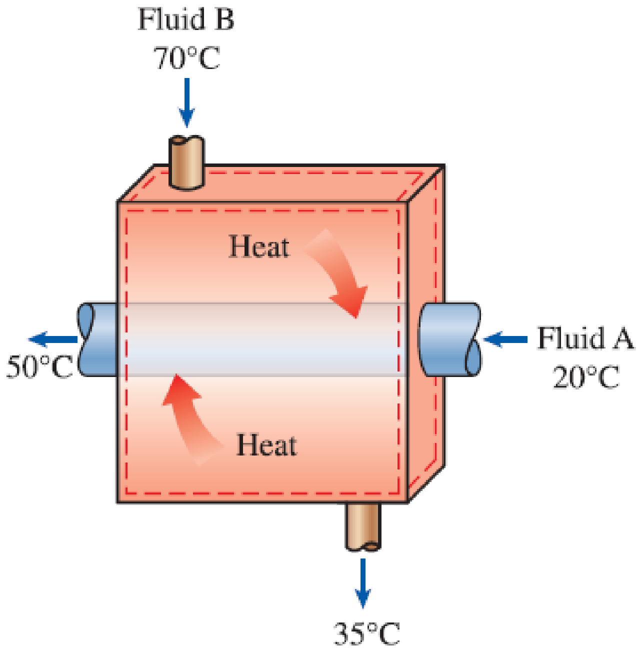
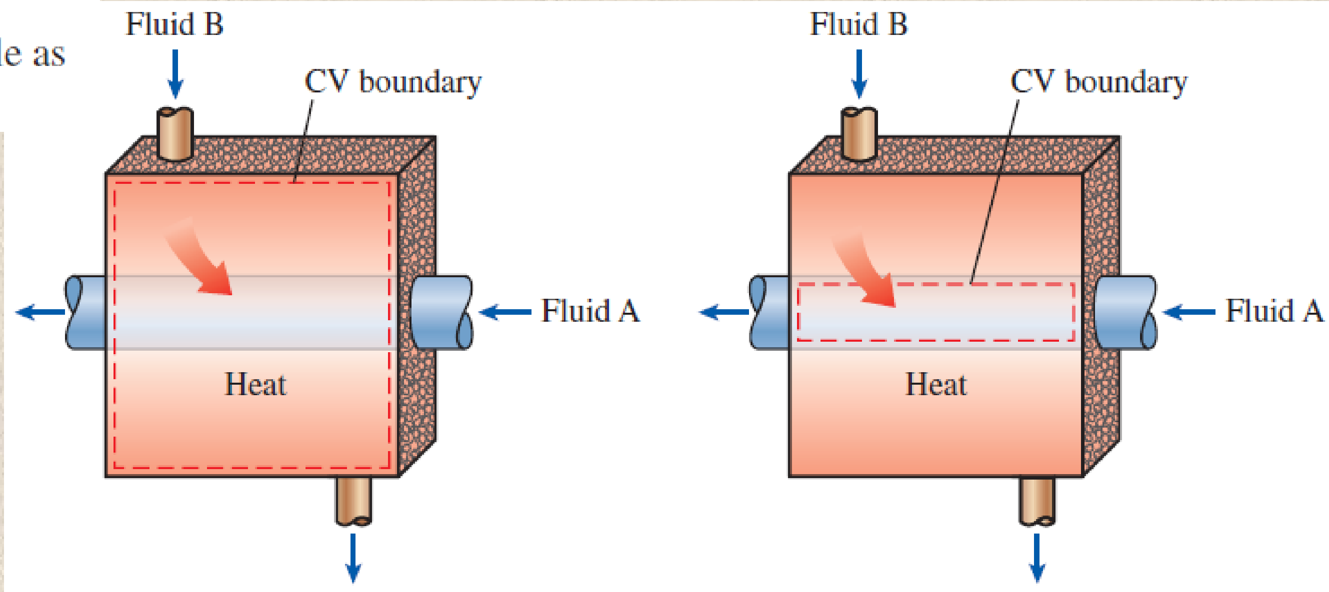


FIGURE 5–38
A heat exchanger can be as simple as two concentric pipes.

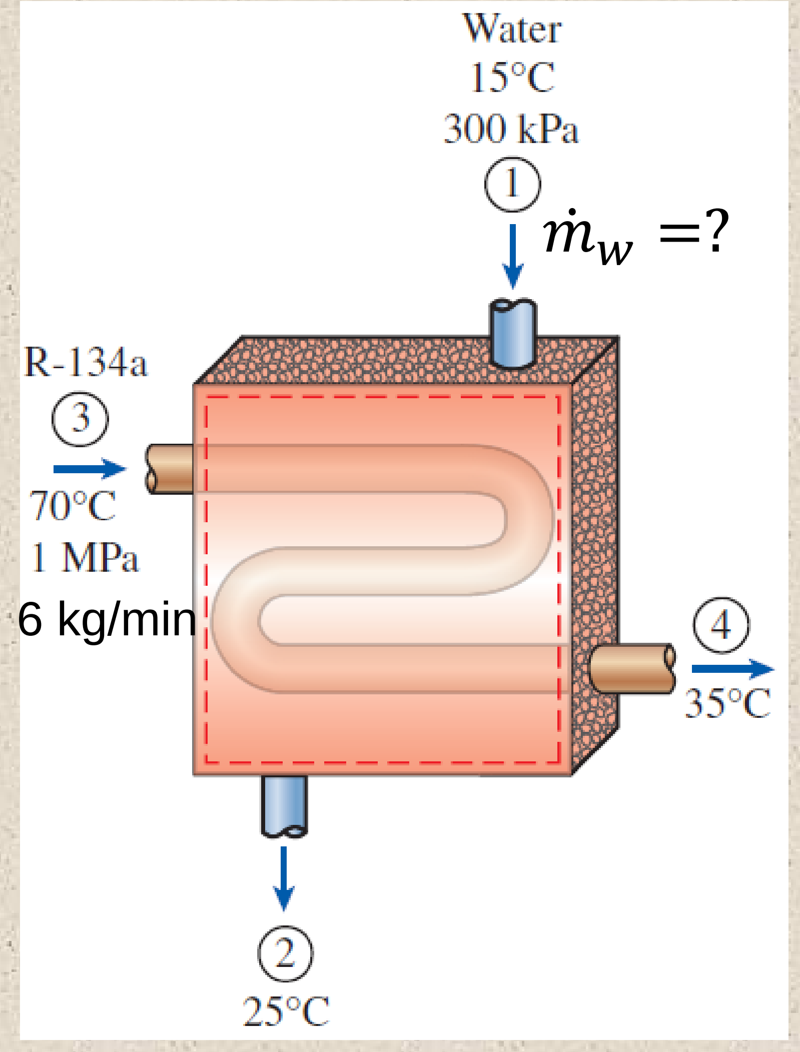


(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

(*b*) System: Fluid A ($Q_{CV} \neq 0$)

The heat transfer associated with a heat exchanger may be zero or nonzero depending on how the control volume is selected

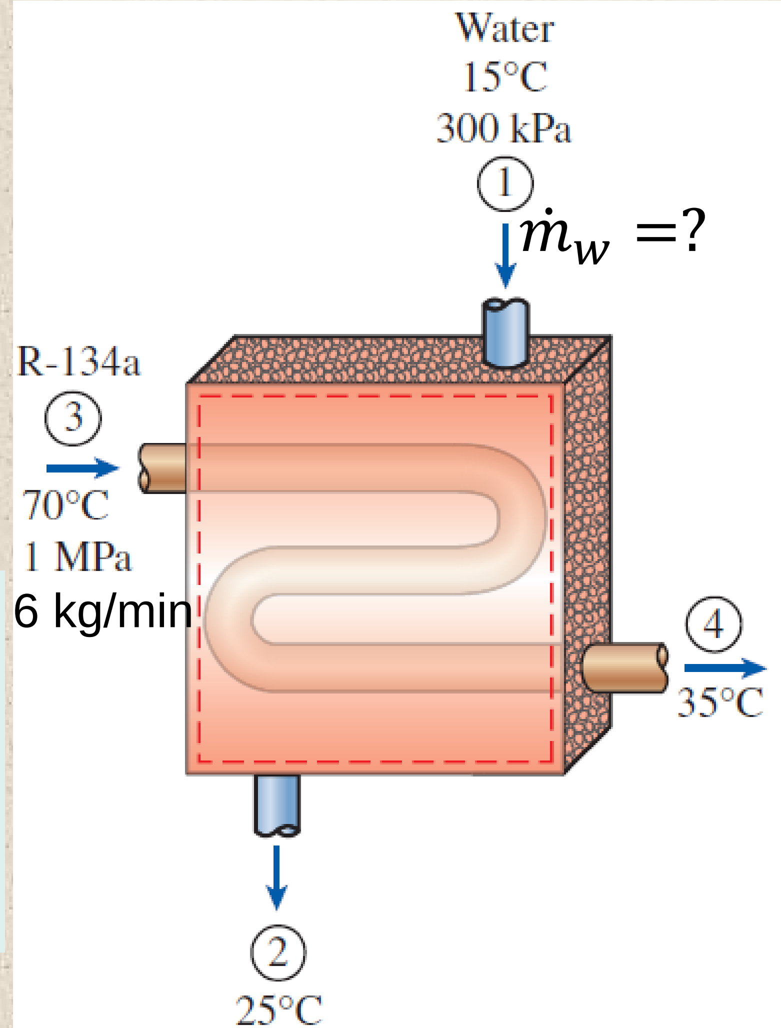
Example: Cooling of Refrigerant-134a by Water



Assumptions:

- Steady flow process: $\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$
- Kinetic and potential energies are negligible: ke = pe $\cong 0$
- Heat losses from the system are negligible
- There is no work interaction involved

Example: Cooling of Refrigerant-134a by Water



Mass Balance:

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Energy Balance:

Energy balance:

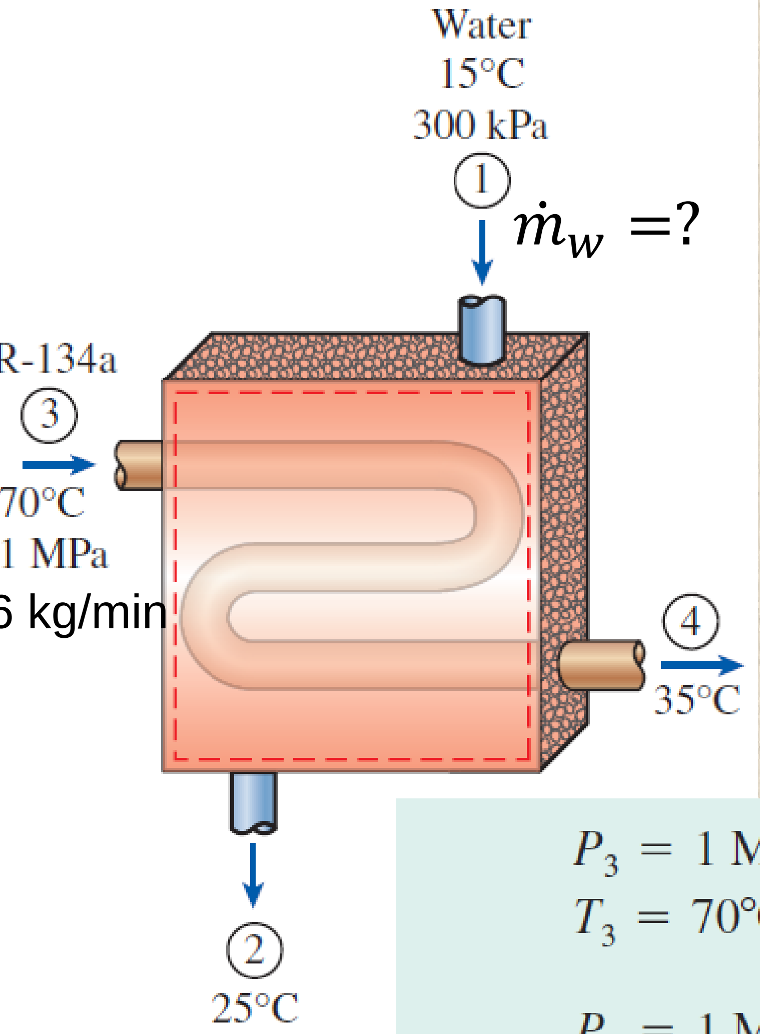
$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}}^{\nearrow 0 \text{ (steady)}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0,\ \text{ke} \cong \text{pe} \cong 0)$$

$$\dot{m}_w(h_1 - h_2) = \dot{m}_R(h_4 - h_3)$$

Example: Cooling of Refrigerant-134a by Water



$$h_1 \cong h_{f\,@\,15^\circ C} = 62.982 \text{ kJ/kg}$$

(Table A–4)

$$h_2 \cong h_{f\,@\,25^\circ C} = 104.83 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1 \text{ MPa} \\ T_3 = 70^\circ\text{C} \end{array}\right\} \quad h_3 = 303.87 \text{ kJ/kg} \qquad \text{(Table A–13)}$$

$$\left.\begin{array}{l} P_4 = 1 \text{ MPa} \\ T_4 = 35^\circ\text{C} \end{array}\right\} \quad h_4 \cong h_{f\,@\,35^\circ\text{C}} = 100.88 \text{ kJ/kg} \qquad \text{(Table A–11)}$$

Substituting, we find

$$\dot{m}_w(62.982 - 104.83) \text{ kJ/kg} = (6 \text{ kg/min})[(100.88 - 303.87) \text{ kJ/kg}]$$

$$\dot{m}_w = \mathbf{29.1 \text{ kg/min}}$$

Example: Cooling of Refrigerant-134a by Water

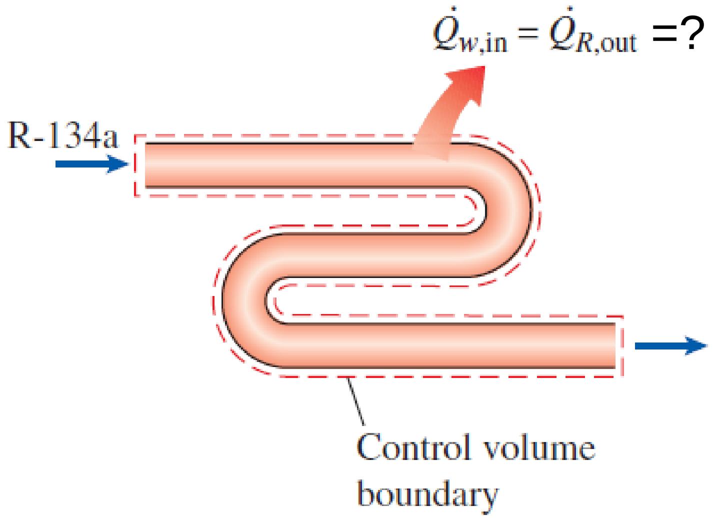


FIGURE 5–41
In a heat exchanger, the heat transfer depends on the choice of the control volume.

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt^{\nearrow 0\ (\text{steady})}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc., energies}}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{Q}_{w,\text{ in}} + \dot{m}_w h_1 = \dot{m}_w h_2$$

$$\dot{Q}_{w,\text{in}} = \dot{m}_w(h_2 - h_1) = (29.1\ \text{kg/min})[(104.83 - 62.982)\ \text{kJ/kg}]$$
$$= \mathbf{1218\ kJ/min}$$

Pipe and duct flow

- The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications

- Flow through a pipe or a duct usually satisfies the steady-flow conditions

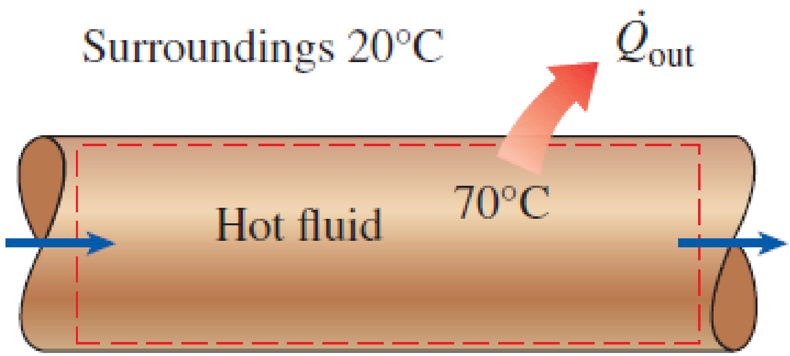


FIGURE 5–42
Heat losses from a hot fluid flowing through an uninsulated pipe or duct to the cooler environment may be very significant.

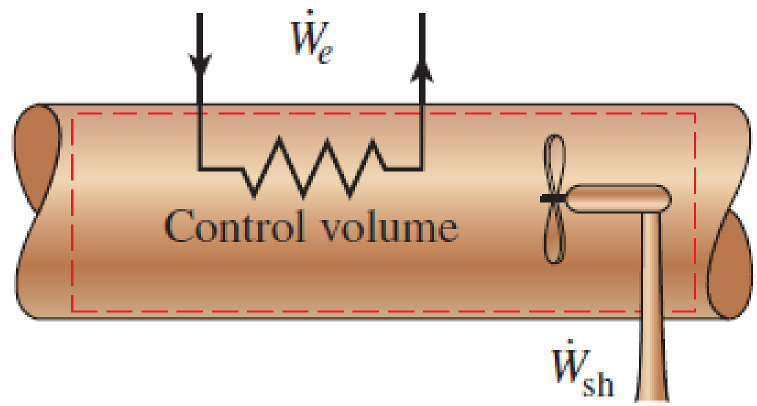
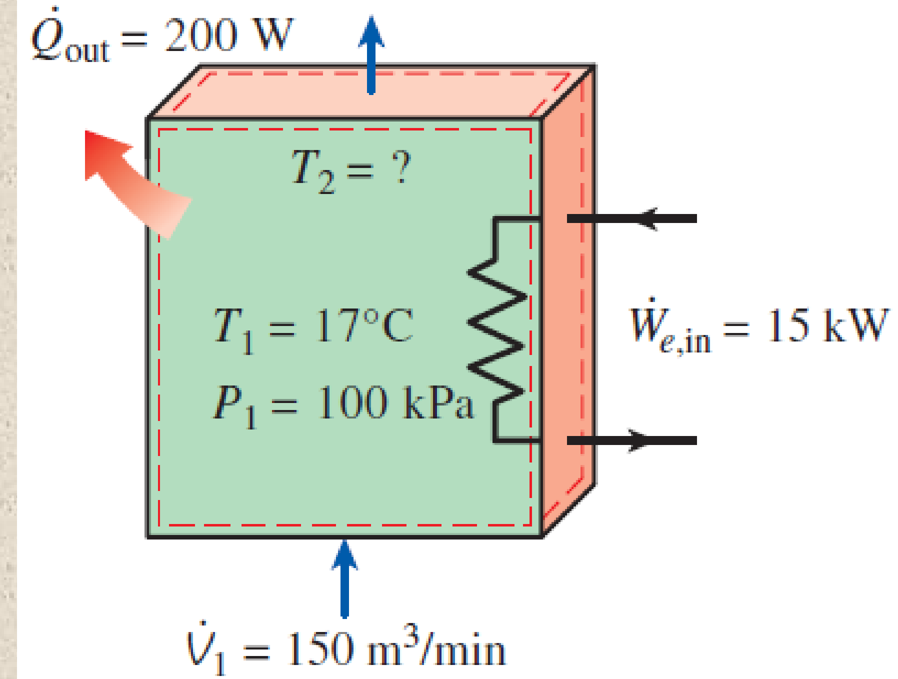


FIGURE 5–43
Pipe or duct flow may involve more than one form of work at the same time.

Electric Heating of Air in a House

<u>Assumptions:</u>

- Steady flow process: $\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$
- Air is an ideal gas (high temperature and low pressure relative to its critical point)
- Kinetic and potential energies changes are negligible: $\Delta ke = \Delta pe \cong 0$
- Constant specific heats at room temperature can be used for air



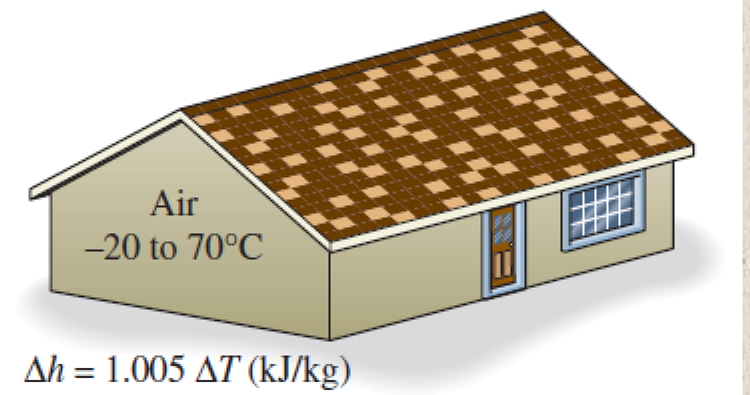


FIGURE 5–45
The error involved in $\Delta h = c_p\,\Delta T$, where $c_p = 1.005$ kJ/kg·°C, is less than 0.5 percent for air in the temperature range −20 to 70°C.

Electric Heating of Air in a House

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} \overset{0 \text{ (steady)}}{} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

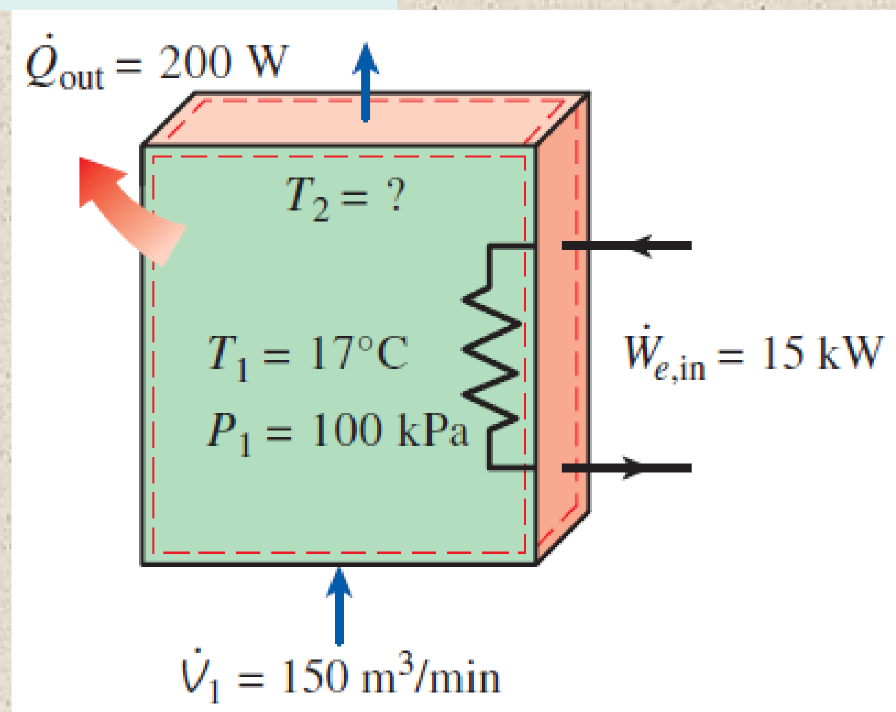
$$\dot{W}_{e,in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0)$$

$$\dot{W}_{e,in} - \dot{Q}_{out} = \dot{m}c_p(T_2 - T_1)$$

$$v_1 = \frac{RT_1}{P_1} = 0.832 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1} = 3.0 \text{ kg/s}$$

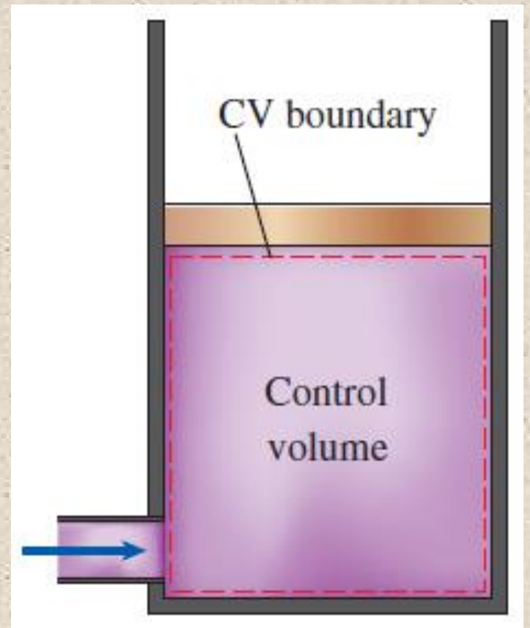
$$T_2 = \mathbf{21.9°C}$$



ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES

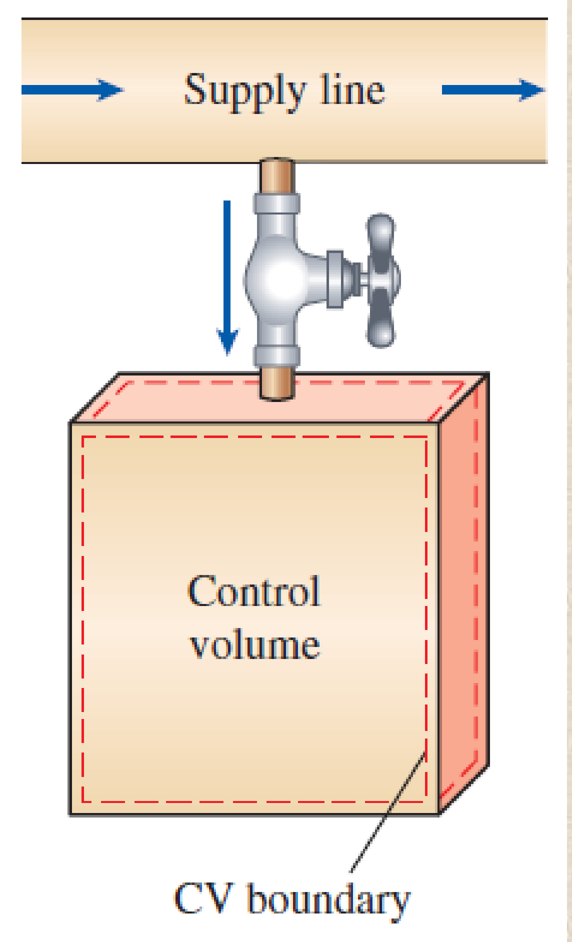
- Many processes of interest, involve *changes* within the control volume with time. Such processes are called *unsteady-flow,* or *transient-flow,* processes
- Most unsteady-flow processes can be represented reasonably well by the *uniform-flow process*

The shape and size of a control volume may change during an unsteady-flow process



ENERGY ANALYSIS OF UNSTEADY-FLOW PROCESSES

- **Uniform-flow process:** The fluid flow at any inlet or exit is uniform and steady, and thus the fluid properties do not change with time or position over the cross section of an inlet or exit. If they do, they are averaged and treated as constants for the entire process



Charging of a rigid tank from a supply line is an unsteady-flow process since it involves changes within the control volume

Mass balance for unsteady flow processes

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}}$$

$$\Delta m_{\text{system}} = m_{\text{final}} - m_{\text{initial}}$$

$$m_i - m_e = (m_2 - m_1)_{\text{CV}}$$

i = inlet, e = exit, 1 = initial state, and 2 = final state

Energy balance

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$$

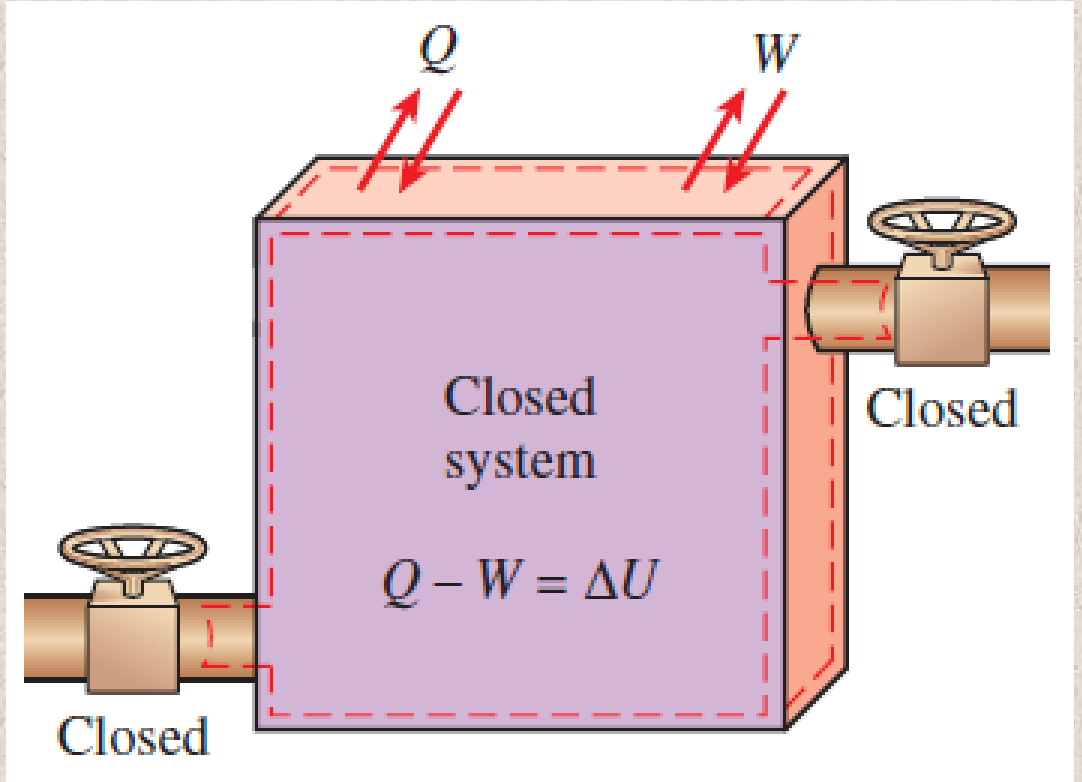
$$\left(Q_{\text{in}} + W_{\text{in}} + \sum_{\text{in}} m\theta\right) - \left(Q_{\text{out}} + W_{\text{out}} + \sum_{\text{out}} m\theta\right) = (m_2e_2 - m_1e_1)_{\text{system}}$$

$$\theta = h + \text{ke} + \text{pe} \qquad e = u + \text{ke} + \text{pe}$$

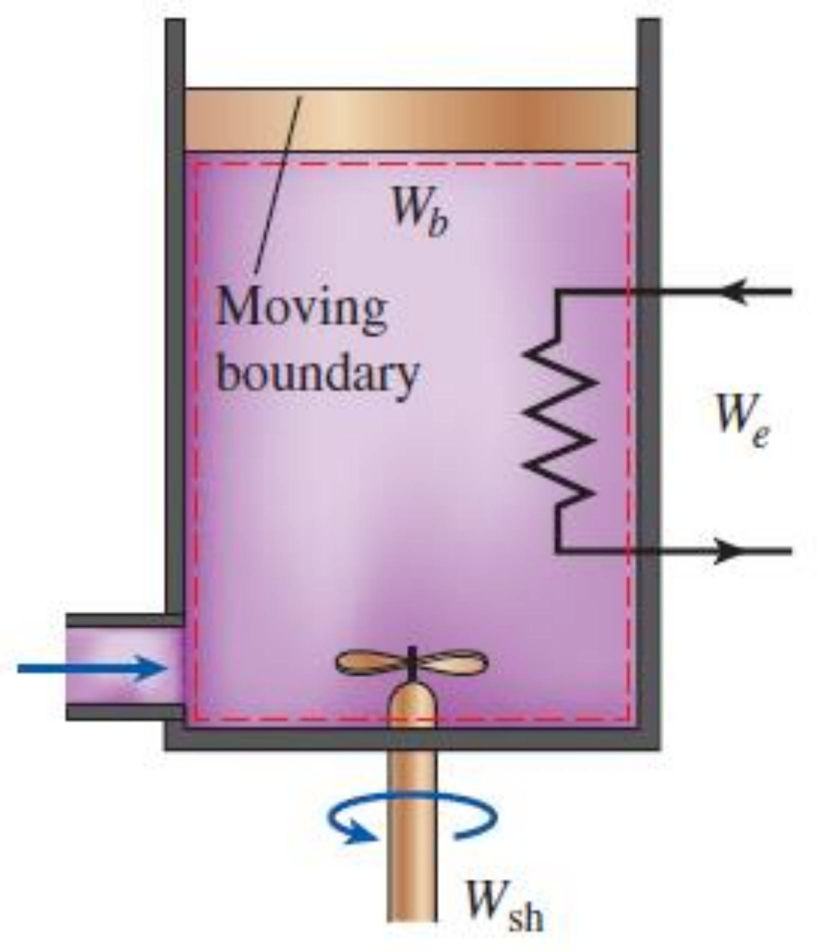
$$Q - W = \sum_{\text{out}} mh - \sum_{\text{in}} mh + (m_2u_2 - m_1u_1)_{\text{system}}$$

$$Q = Q_{\text{net,in}} = Q_{\text{in}} - Q_{\text{out}}$$

$$W = W_{\text{net,out}} = W_{\text{out}} - W_{\text{in}}$$

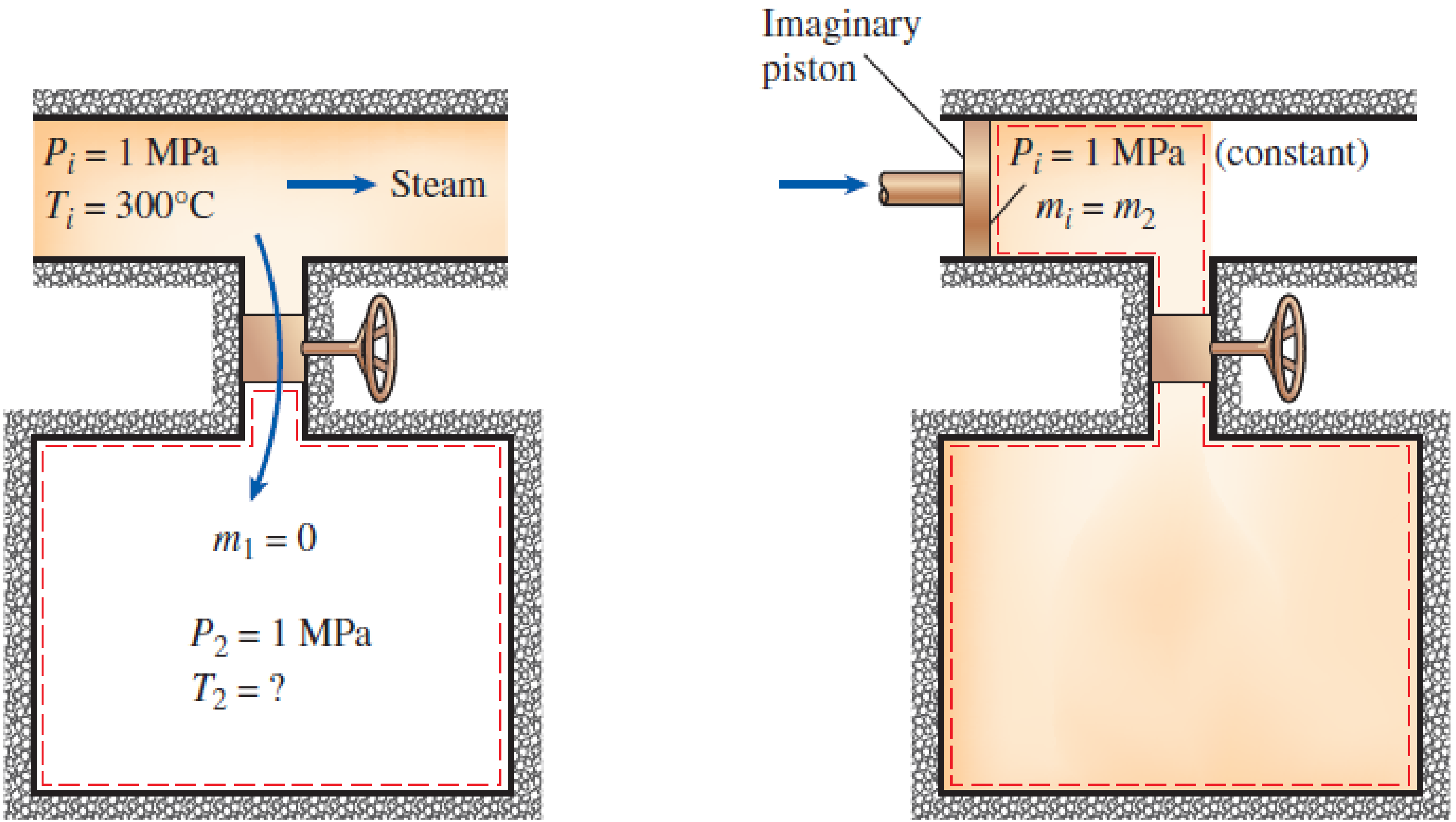


The energy equation of a uniform-flow system reduces to that of a closed system when all the inlets and exits are closed.



A uniform-flow system may involve electrical, shaft, and boundary work all at once.

Charging of a Rigid Tank by Steam



(*a*) Flow of steam into an evacuated tank

(*b*) The closed-system equivalence

Charging of a Rigid Tank by Steam

<u>Assumptions:</u>

- Analyze as a uniform flow process since the properties of steam entering the control volume remain constant
- Kinetic and potential energies of the streams are negligible: ke = pe $\cong$ 0
- Tank is stationary and thus its kinetic and potential energy changes are zero; i.e., $\Delta KE = \Delta PE = 0$ and $\Delta E_{system} = \Delta U_{system}$
- There are no boundary, electrical, or shaft work, interactions involved
- The tank is well insulated and thus there is no heat transfer

Mass balance: $m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \rightarrow m_i = m_2 - \cancelto{0}{m_1} = m_2$

Energy balance:

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

$$m_i h_i = m_2 u_2 \quad (\text{since } W = Q = 0, \text{ke} \cong \text{pe} \cong 0, m_1 = 0)$$

$$u_2 = h_i$$

That is, the final internal energy of the steam in the tank is equal to the enthalpy of the steam entering the tank. The enthalpy of the steam at the inlet state is

$$\left.\begin{array}{l} P_i = 1 \text{ MPa} \\ T_i = 300°\text{C} \end{array}\right\} h_i = 3051.6 \text{ kJ/kg} \quad (\text{Table A–6})$$

which is equal to u_2. Since we now know two properties at the final state, it is fixed and the temperature at this state is determined from the same table to be

$$\left.\begin{array}{l} P_2 = 1 \text{ MPa} \\ u_2 = 3051.6 \text{ kJ/kg} \end{array}\right\} T_2 = \mathbf{456.1°C}$$

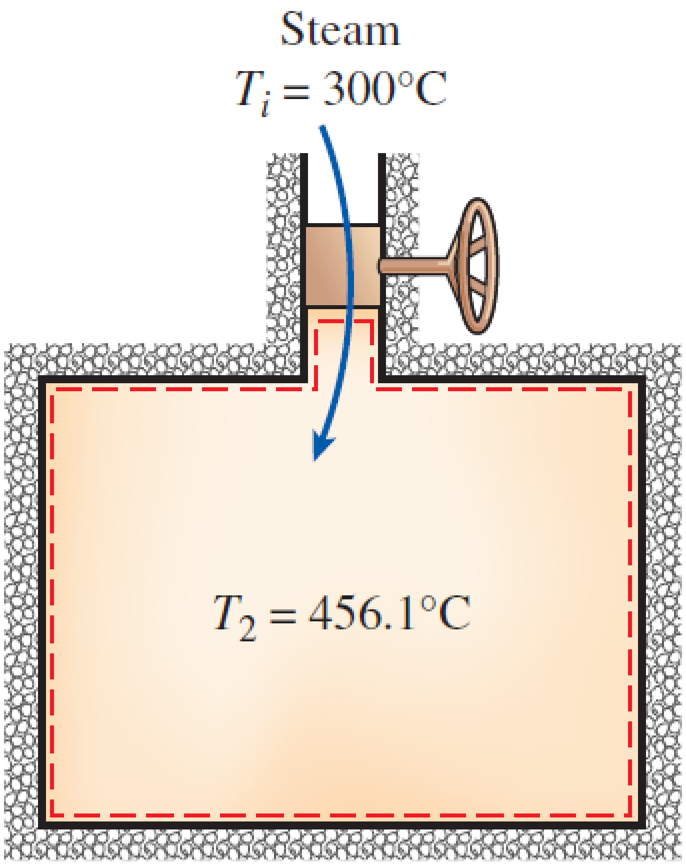


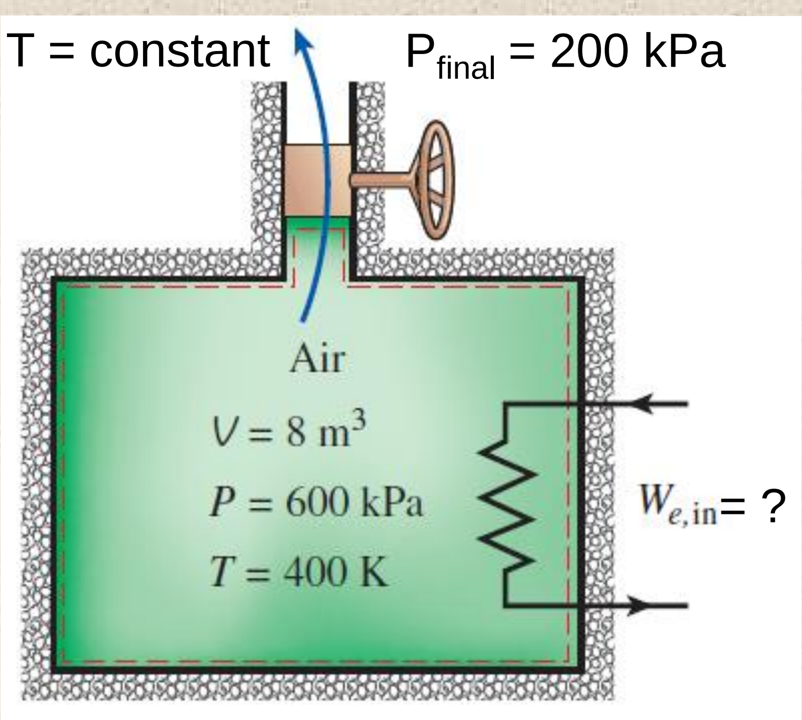
FIGURE 5–51

The temperature of steam rises from 300 to 456.1°C as it enters a tank as a result of flow energy being converted to internal energy.

Discharge of Heated Air at Constant Temperature

<u>Assumptions:</u>

- This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform flow process since the exit conditions remain constant
- Kinetic and potential energies are negligible
- The tank is insulated and thus heat transfer is negligible
- Air is an ideal gas with variable specific heats



Discharge of Heated Air at Constant Temperature

Mass balance: $m_{in} - m_{out} = \Delta m_{system} \rightarrow m_e = m_1 - m_2$

Energy balance: $\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$

$$W_{e,in} - m_e h_e = m_2 u_2 - m_1 u_1 \quad (\text{since } Q \cong \text{ke} \cong \text{pe} \cong 0)$$

$$m_1 = \frac{P_1 V_1}{RT_1} = 41.81 \text{ kg}$$

$$m_2 = \frac{P_2 V_2}{RT_2} = 13.94 \text{ kg}$$

$$m_e = m_1 - m_2 = 27.87 \text{ kg}$$

The enthalpy and internal energy of air at 400 K are $h_e = 400.98$ kJ/kg and $u_1 = u_2 = 286.16$ kJ/kg (Table A-17).

$$W_{e,in} = m_e h_e + m_2 u_2 - m_1 u_1 = 3200 \text{ kJ} = \mathbf{0.889 \text{ kWh}}$$

Summary

- Conservation of mass
  - ✓ Mass and volume flow rates
  - ✓ Mass balance for a steady-flow process
  - ✓ Mass balance for incompressible flow
- Flow work and the energy of a flowing fluid
  - ✓ Energy transport by mass
- Energy analysis of steady-flow systems
- Some steady-flow engineering devices
  - ✓ Nozzles and Diffusers
  - ✓ Turbines and Compressors
  - ✓ Throttling valves
  - ✓ Mixing chambers and Heat exchangers
  - ✓ Pipe and Duct flow
- Energy analysis of unsteady-flow processes