# THERMODYNAMICS AND HEAT TRANSFER

- Heat transfer is always occurs from the higher-temperature to the lower-temperature of an object.
- Heat transfer stops when the two mediums reach the same temperature.
- Heat can be transferred in three different modes:

***conduction*, *convection*, *radiation.***

Example of heat transfer equipment are heat exchangers, boilers, condensers, radiators, heaters, furnaces, refrigerators, and solar collectors are designed primarily on the basis of heat transfer analysis.

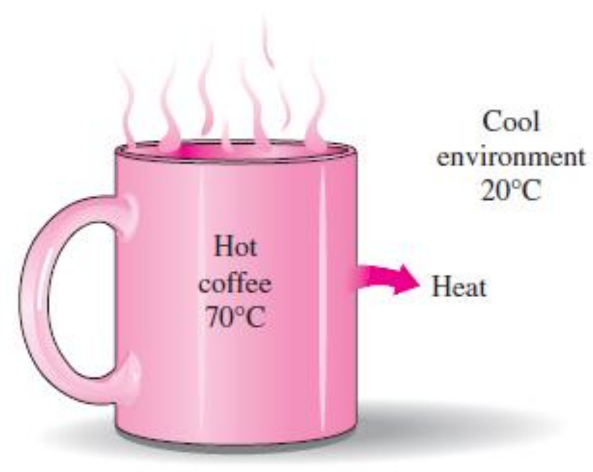


**FIGURE 1–2**
Heat flows in the direction of decreasing temperature.

# HEAT AND OTHER FORMS OF ENERGY

- Energy can exist in numerous forms such as:
  - ✓ thermal,
  - ✓ mechanical,
  - ✓ kinetic,
  - ✓ potential,
  - ✓ electrical,
  - ✓ magnetic,
  - ✓ chemical, and
  - ✓ nuclear.

- Their sum constitutes the **total energy** $E$ (or $e$ on a unit mass basis) of a system.
- The sum of all microscopic forms of energy is called the **internal energy** of a system.

- **Internal energy:** May be viewed as the sum of the kinetic and potential energies of the molecules. The velocity and activity of the molecules are proportional to the temperature.
- **Sensible heat:** The kinetic energy of the molecules.
- **Latent heat:** The internal energy associated with the phase of a system. The internal energy that cause the changes of object phase.
- **Chemical (bond) energy:** The internal energy associated with the atomic bonds in a molecule.
- **Nuclear energy:** The internal energy associated with the bonds within the nucleus of the atom itself.

What is the difference between thermal energy and heat?

Thermal energy refers to
within a system that is re
temperature. Heat is the
A whole branch of physic
deals with how heat is tra
different systems and ho
process (see the 1st law

# Internal Energy and Enthalpy

- In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties *u* (internal energy) and *Pv* (flow energy or flow work).
- The combination is defined as **enthalpy** ($h = u + Pv$).
- Enthalpy is a measure of the total energy of a thermodynamic system

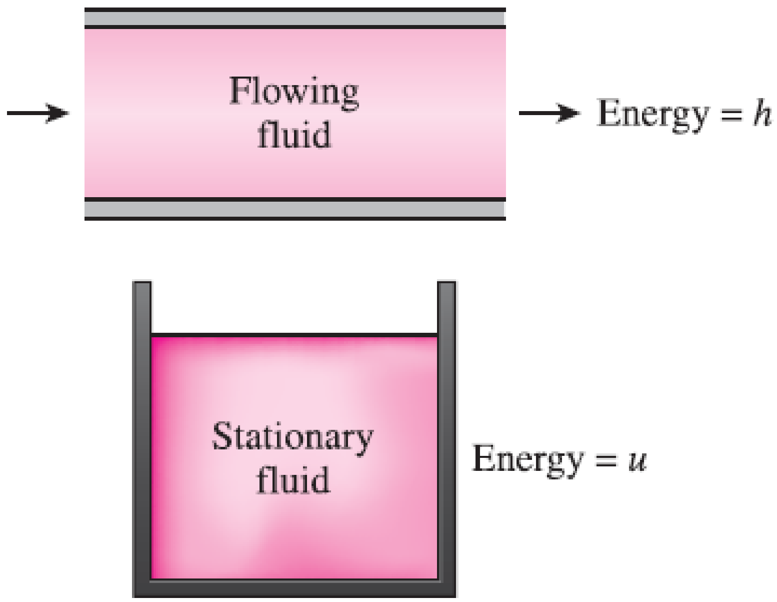


**FIGURE 1–8**
The *internal energy u* represents the microscopic energy of a nonflowing fluid, whereas *enthalpy h* represents the microscopic energy of a flowing fluid.

# Specific Heats of Gases, Liquids, and Solids

- **Specific heat:** *The energy required to raise the temperature of a unit mass of a substance/element by one degree.*
- Two kinds of specific heats:
  - ✓ specific heat at constant volume $c_v$
  - ✓ specific heat at constant pressure $c_p$
- The specific heats of a substance, depend on temperature and pressure.
- At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.
- PV=mRT @ Pv=RT @ P=ρRT (Ideal Gas)

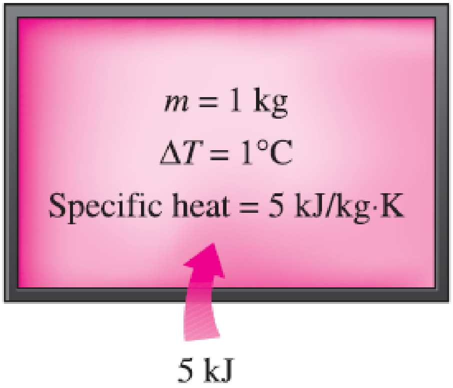


**FIGURE 1–9**
Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

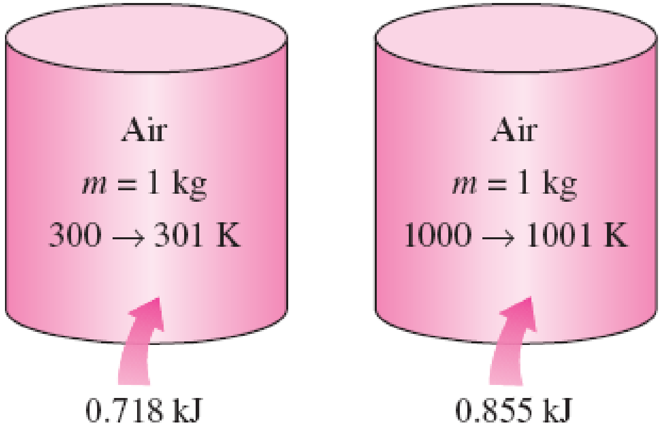


**FIGURE 1–10**
The specific heat of a substance changes with temperature.

$$1\ \text{kJ/kg}\cdot{}^\circ\text{C} \equiv 1\ \text{J/g}\cdot{}^\circ\text{C} \equiv 1\ \text{kJ/kg}\cdot\text{K} \equiv 1\ \text{J/g}\cdot\text{K}$$

Unit for specific heat

$$du = c_v\,dT \qquad \text{and} \qquad dh = c_p\,dT$$

$$\Delta u = c_{v,\,\text{avg}}\Delta T \qquad \text{and} \qquad \Delta h = c_{p,\,\text{avg}}\Delta T \qquad (\text{J/g})$$

Differential changes in internal energy and enthalpy

$$\Delta U = mc_{v,\,\text{avg}}\Delta T \qquad \text{and} \qquad \Delta H = mc_{p,\,\text{avg}}\Delta T \qquad (\text{J})$$

- **Incompressible substance:** A substance whose specific volume (or density) does not change with temperature or pressure.
- Therefore $c_v$ and $c_p$ value are same (=$c$) for incompressible substances.
- The specific heats of incompressible substances depend on temperature only.

$$\Delta U = mc_{\text{avg}}\Delta T \qquad (\text{J})$$

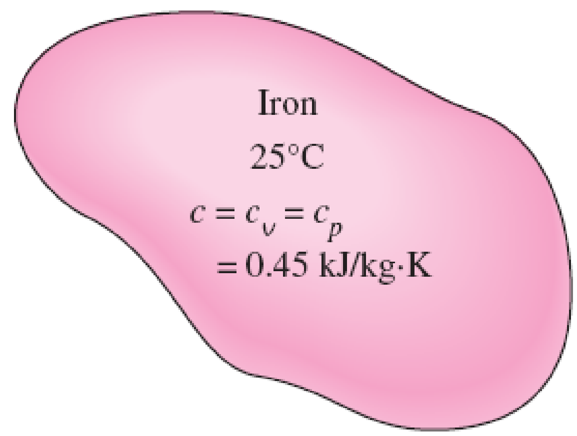


**FIGURE 1–11**
The $c_v$ and $c_p$ values of incompressible substances are identical and are denoted by $c$.

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What is the difference between incompressible substance and compressible substance?

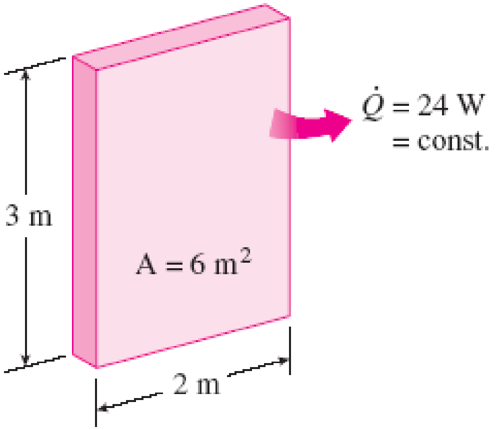
# Energy Transfer

- Energy can be transferred by two mechanisms: ***heat transfer*** $Q$ and ***work W***.
- **Heat transfer rate:** The amount of heat transferred per unit time. (unit J/s or W)
- **Heat flux:** The rate of heat transfer ***per unit area*** normal to the direction of heat transfer.

$$Q = \int_0^{\Delta t} \dot{Q}\,dt \qquad \text{(J)}$$

when $\dot{Q}$ is constant:

$$Q = \dot{Q}\,\Delta t \qquad \text{(J)}$$




$$\dot{q} = \frac{\dot{Q}}{A} = \frac{24\text{ W}}{6\text{ m}^2} = 4\text{ W/m}^2$$

**FIGURE 1–13**
Heat flux is heat transfer *per unit time* and *per unit area*, and is equal to $\dot{q} = \dot{Q}/A$ when $\dot{Q}$ is uniform over the area $A$.

$$\dot{q} = \frac{\dot{Q}}{A} \qquad (\text{W/m}^2)$$

## *EXAMPLE 1–1* Heating of a Copper Ball

A 10-cm-diameter copper ball is to be heated from 100°C to an average temperature of 150°C in 30 minutes (Fig. 1–14). Taking the average density and specific heat of copper in this temperature range to be $\rho$ = 8950 kg/m$^3$ and $c_p$ = 0.395 kJ/kg·°C, respectively, determine (*a*) the total amount of heat transfer to the copper ball, (*b*) the average rate of heat transfer to the ball, and (*c*) the average heat flux.

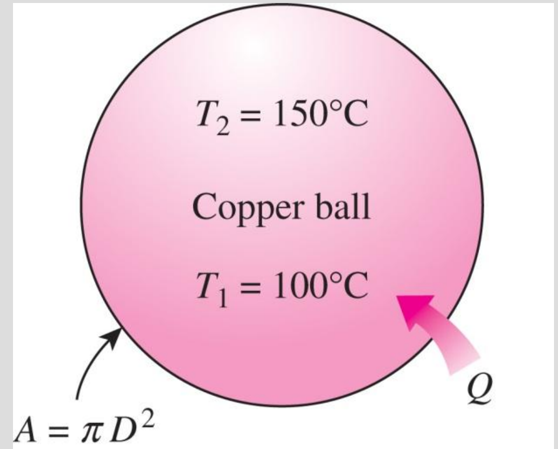



**FIGURE 1–14**
Schematic for Example 1–1.

**SOLUTION** The copper ball is to be heated from 100°C to 150°C. The total heat transfer, the average rate of heat transfer, and the average heat flux are to be determined.

***Assumptions*** Constant properties can be used for copper at the average temperature.

***Properties*** The average density and specific heat of copper are given to be $\rho$ = 8950 kg/m$^3$ and $c_p$ = 0.395 kJ/kg·°C.

***Analysis*** (*a*) The amount of heat transferred to the copper ball is simply the change in its internal energy, and is determined from

$$\text{Energy transfer to the system} = \text{Energy increase of the system}$$
$$Q = \Delta U = mc_{\text{avg}}(T_2 - T_1)$$

where

$$m = \rho V = \frac{\pi}{6}\rho D^3 = \frac{\pi}{6}(8950\text{ kg/m}^3)(0.1\text{ m})^3 = 4.686\text{ kg}$$

Substituting,

$$Q = (4.686\text{ kg})(0.395\text{ kJ/kg·°C})(150 - 100)\text{°C} = \mathbf{92.6\ kJ}$$

Therefore, 92.6 kJ of heat needs to be transferred to the copper ball to heat it from 100°C to 150°C.

(*b*) The rate of heat transfer normally changes during a process with time. However, we can determine the *average* rate of heat transfer by dividing the total amount of heat transfer by the time interval. Therefore,

$$\dot{Q}_{\text{avg}} = \frac{Q}{\Delta t} = \frac{92.6 \text{ kJ}}{1800 \text{ s}} = 0.0514 \text{ kJ/s} = \mathbf{51.4 \text{ W}}$$

(*c*) Heat flux is defined as the heat transfer per unit time per unit area, or the rate of heat transfer per unit area. Therefore, the average heat flux in this case is

$$\dot{q}_{\text{avg}} = \frac{\dot{Q}_{\text{avg}}}{A} = \frac{\dot{Q}_{\text{avg}}}{\pi D^2} = \frac{51.4 \text{ W}}{\pi (0.1 \text{ m})^2} = \mathbf{1636 \text{ W/m}^2}$$

***Discussion*** Note that heat flux may vary with location on a surface. The value calculated above is the *average* heat flux over the entire surface of the ball.

# THE FIRST LAW OF THERMODYNAMICS

The **first law of thermodynamics** (**conservation of energy principle**) states that *energy can neither be created nor destroyed during a process; it can only change forms.*

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the}\\ \text{system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the}\\ \text{system}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total energy of}\\ \text{the system}\end{pmatrix}$$

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

The **energy balance** in normal form

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

The **energy balance** in the rate form

*Steady, rate form:* $$\underbrace{\dot{E}_{in}}_{\substack{\text{Rate of net energy transfer in} \\ \text{by heat, work, and mass}}} = \underbrace{\dot{E}_{out}}_{\substack{\text{Rate of net energy transfer out} \\ \text{by heat, work, and mass}}}$$

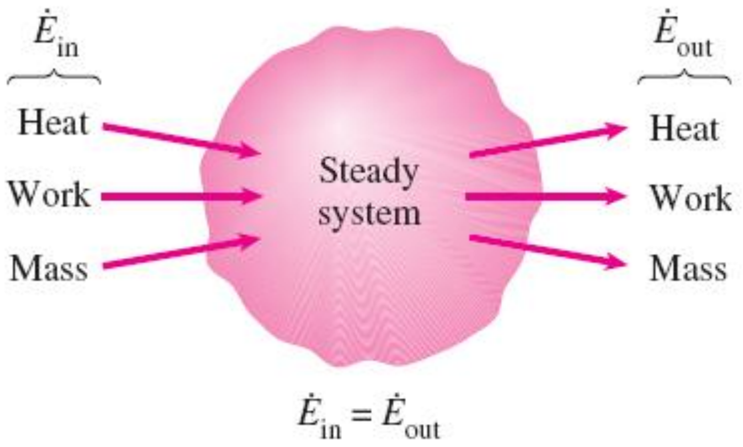



**FIGURE 1–15**

In steady operation, the rate of energy transfer to a system is equal to the rate of energy transfer from the system.

In heat transfer problems, it is convenient to write a **heat balance** as below

$$\underbrace{Q_{in} - Q_{out}}_{\substack{\text{Net heat} \\ \text{transfer}}} + \underbrace{E_{gen}}_{\substack{\text{Heat} \\ \text{generation}}} = \underbrace{\Delta E_{thermal,\ system}}_{\substack{\text{Change in thermal} \\ \text{energy of the system}}} \qquad \text{(J)}$$

and all the conversion of nuclear, chemical, mechanical and electrical energies into thermal energy called as *heat generation.*

What is the difference between steady systems and unsteady system?

# Energy Balance for
# Closed Systems *(Fixed Mass)*


**FIGURE 1–16**
In the absence of any work interactions, the change in the energy content of a closed system is equal to the net heat transfer.

A closed system consists of a *fixed mass.*

The total energy *E* is the internal energy *U.*

This is especially the case for stationary systems since no changes in the velocity or elevation during a process.

*Stationary closed system:*

$$E_{in} - E_{out} = \Delta U = mc_v \Delta T \qquad \text{(J)}$$

*Stationary closed system, no work:*

$$Q = mc_v \Delta T \qquad \text{(J)}$$

# Energy Balance for Steady-Flow Systems

However, many engineering devices (water heaters, car radiators, etc) involve mass flow in and out of a system, and are modeled as *control volumes.*

The term *steady* means *no change with time* at a specified location.

**Mass flow rate:** The amount of mass flowing through a cross section of a flow device per unit time.

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

**Volume flow rate:** The volume of a fluid flowing through a pipe or duct per unit time.

$$\dot{V} = V A_c = \frac{\dot{m}}{\rho} \qquad (\text{m}^3/\text{s})$$

When changes in kinetic and potential energy is negligible, there is no work interaction occurs thus the energy balance is:

$$\dot{Q} = \dot{m}\Delta h = \dot{m} c_p \Delta T \qquad \text{(kJ/s)}$$

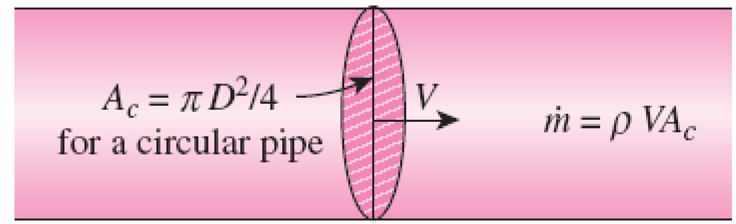



**FIGURE 1–17**
The mass flow rate of a fluid at a cross section is equal to the product of the fluid density, average fluid velocity, and the cross-sectional area.

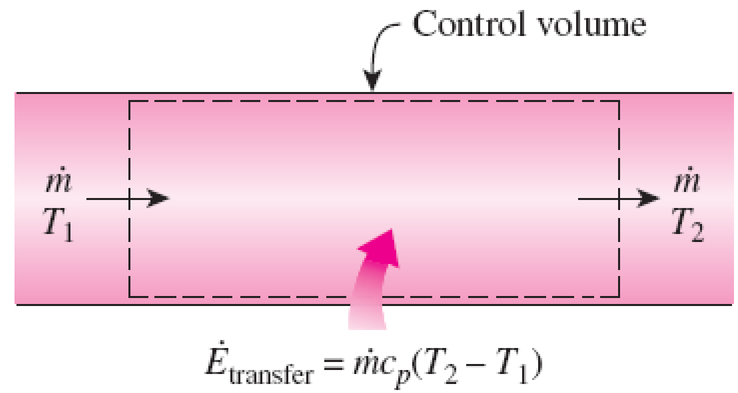



**FIGURE 1–18**
Under steady conditions, the net rate of energy transfer to a fluid in a control volume is equal to the rate of increase in the energy of the fluid stream flowing through the control volume.

# Surface Energy Balance

A surface contains no volume or mass, and thus no energy. Therefore, a surface can be viewed as a fictitious system whose energy content remains constant during a process.

*Surface energy balance:* $\dot{E}_{in} = \dot{E}_{out}$

This relation is valid for both steady and transient conditions, and the surface energy balance does not involve heat generation since a surface does not have a volume as shown in figure.

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

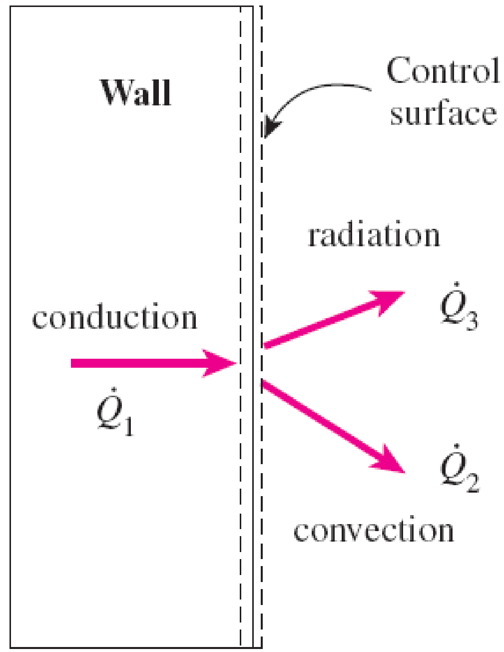



**FIGURE 1–19**
Energy interactions at the outer wall surface of a house.

When the directions of interactions are not known, all energy interactions can be assumed to be towards the surface, and the surface energy balance can be expressed as $\Sigma\, \dot{E}_{in} = 0$. Note that the interactions in opposite direction will end up having negative values, and balance this equation.

## *EXAMPLE 1–2* **Cooling of Stainless Steel Sheets**

A heated continuous AISI 304 stainless steel sheet is being conveyed at a constant speed of 1 cm/s into a chamber to be cooled (Fig. 1–20). The stainless steel sheet is 5 mm thick and 2 m wide, and it enters and exits the chamber at 500 K and 300 K, respectively. Determine the rate of heat loss from the stainless steel sheet inside the chamber.

**SOLUTION** The rate of heat loss from a stainless steel sheet being conveyed inside a chamber is to be determined.

***Assumptions*** **1** Steady operating conditions exist. **2** The stainless steel sheet has constant properties. **3** Changes in potential and kinetic energy are negligible.

***Properties*** The constant pressure specific heat of AISI 304 stainless steel at the average temperature of $(500 + 300)/2 = 400$ K is 515 J/kg·K. The density of AISI 304 stainless steel is 7900 kg/m$^3$ (Table A–3).

***Analysis*** The mass of the stainless steel sheet being conveyed enters and exits the chamber at a rate of

$$\begin{aligned}\dot{m} &= \rho V w t \\ &= (7900\ \text{kg/m}^3)(0.01\ \text{m/s})(2\text{m})(0.005\text{m}) \\ &= 0.79\ \text{kg/s}\end{aligned}$$

The rate of heat loss from the stainless steel sheet in the chamber can be determined as

$$\begin{aligned}\dot{Q}_{\text{loss}} &= \dot{m} c_p (T_{\text{in}} - T_{\text{out}}) \\ &= (0.79\ \text{kg/s})(515\ \text{J/kg·K})(500 - 300)\text{K} = 81370\ \text{J/s} \\ &= \mathbf{81.4\ kW}\end{aligned}$$

***Discussion*** The stainless steel sheet being conveyed in and out of the chamber is treated as a control volume.

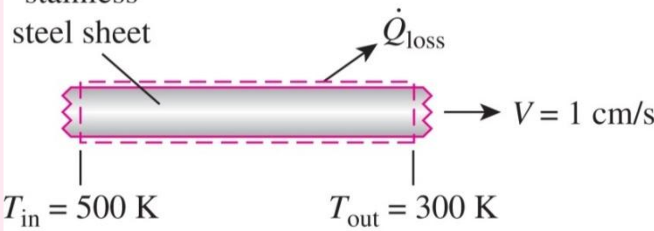
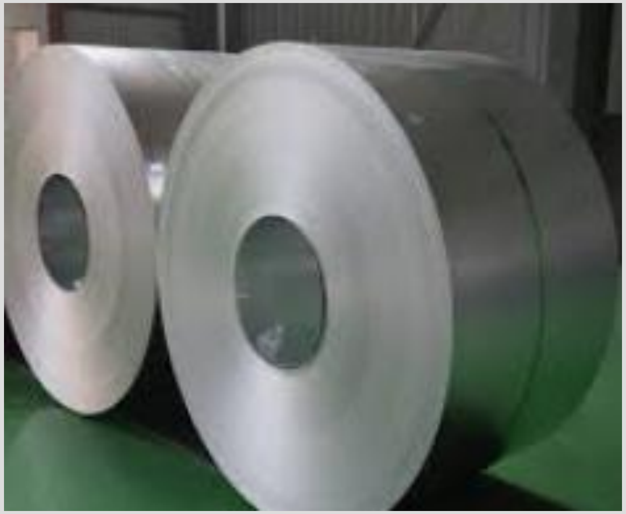



**FIGURE 1–20**
Schematic for Example 1–2.



# HEAT TRANSFER MECHANISMS-recap

- *Heat* is the form of energy that can be transferred from one system to another as a result of temperature difference.
- Heat can be transferred in three basic modes:
  - ✓ conduction
  - ✓ convection
  - ✓ radiation
- All modes of heat transfer require the existence of a temperature difference.