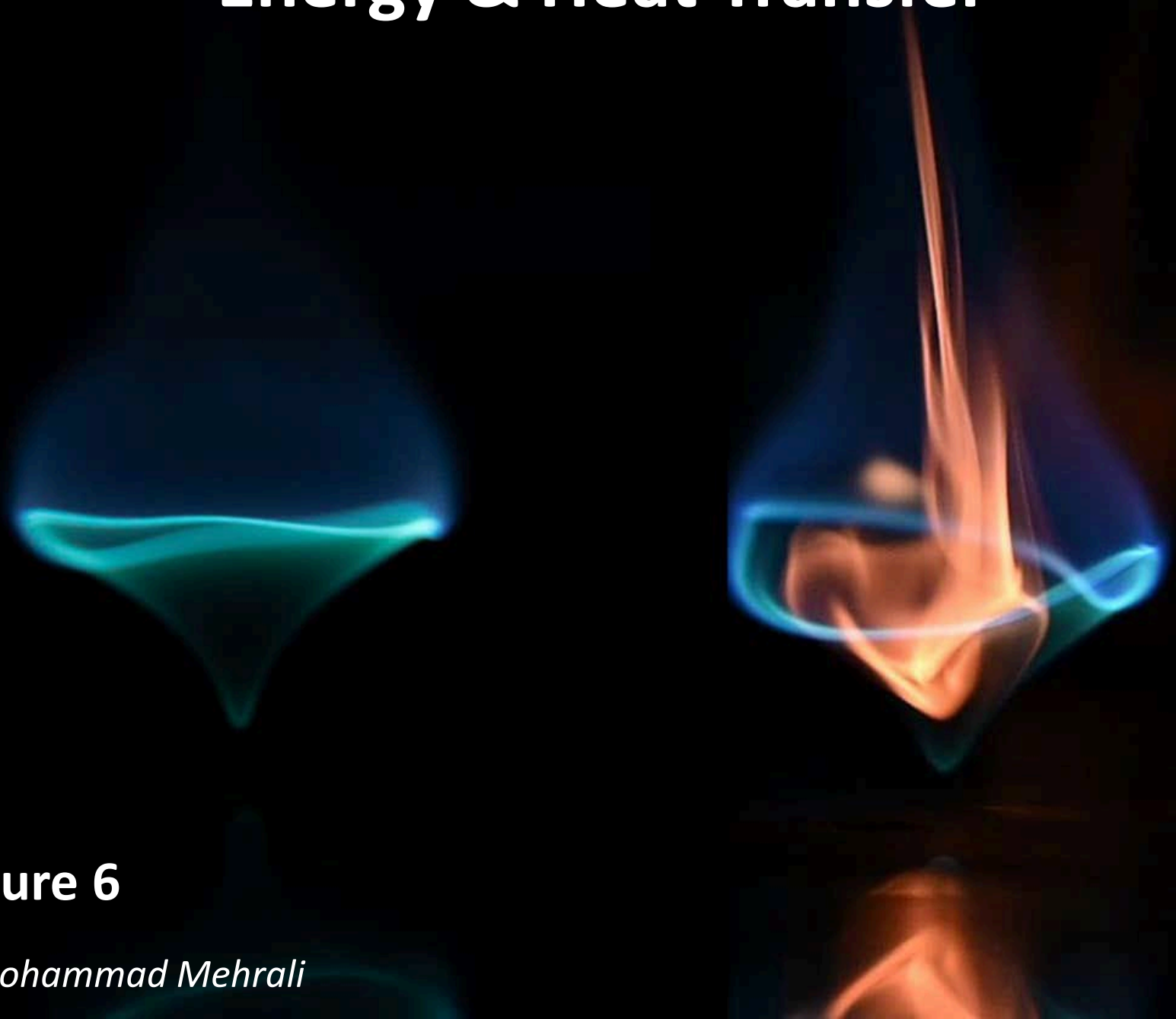


# Energy & Heat Transfer

## Lecture 6

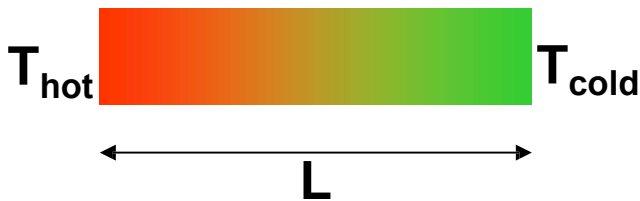
*By: Mohammad Mehrali*



# Recap of last lectures

## Heat Transfer Modes

### Conduction



- Fourier Law

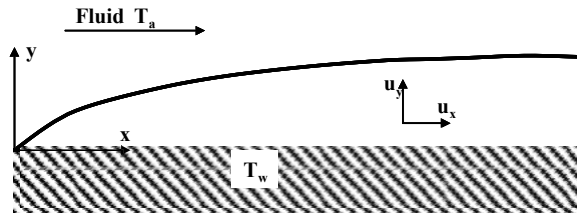
$$\dot{Q} = -kA \frac{\Delta T}{\Delta x} [W]$$

Thermal  
Conductivity  
[W/m.K]

Material properties

Cross-  
Sectional  
Area [m<sup>2</sup>]

### Convection



- Newton's law of cooling

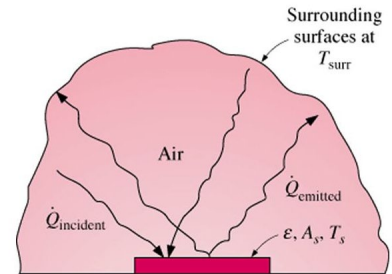
$$\dot{Q} = hA(T_w - T_a) [W]$$

Convective Heat  
Transfer Coefficient  
[W/m<sup>2</sup>K]

Flow dependent

- Natural Convection
- Forced Convection

### Radiation



- Stefan-Boltzmann law

$$\dot{Q} = \varepsilon \sigma A (T_s^4 - T_\infty^4) [W]$$

Emissivity

Stefan-Boltzmann  
constant

$$\sigma = 5.670 \times 10^{-8} \frac{W}{m^2 K^4}$$

# LEARNING OBJECTIVES LECTURE 6

- Problem Solving Approach
- Energy Balance
- Surface Energy Balance
- Combined Heat Transfer Examples

# PROBLEM SOLVING APPROACH

**Step 1: Problem Statement**

**Step 2: Schematic**

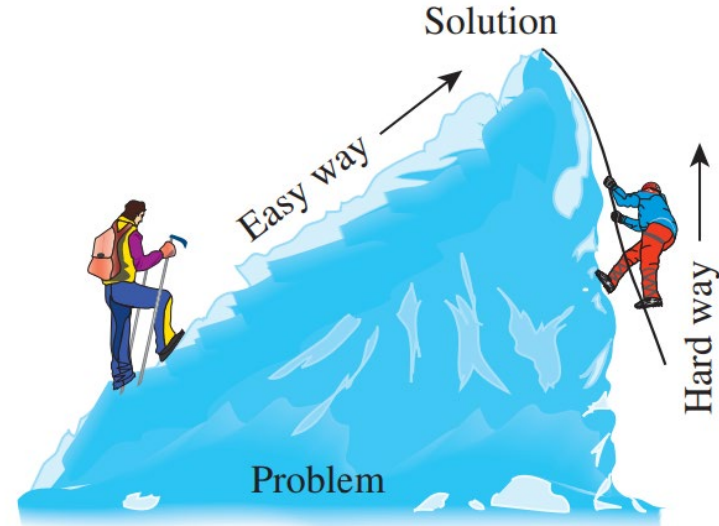
**Step 3: Assumptions**

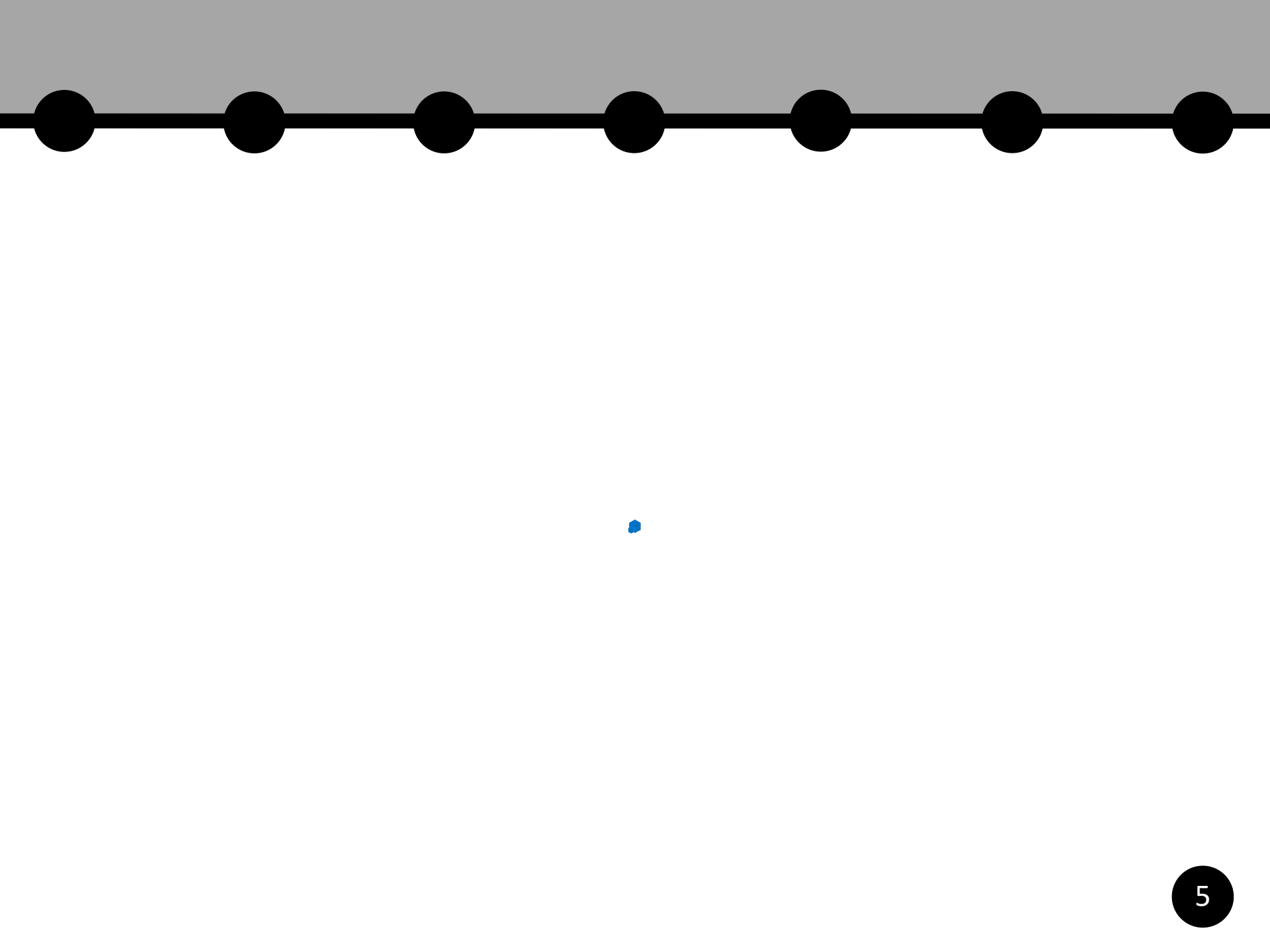
**Step 4: Physical Laws**

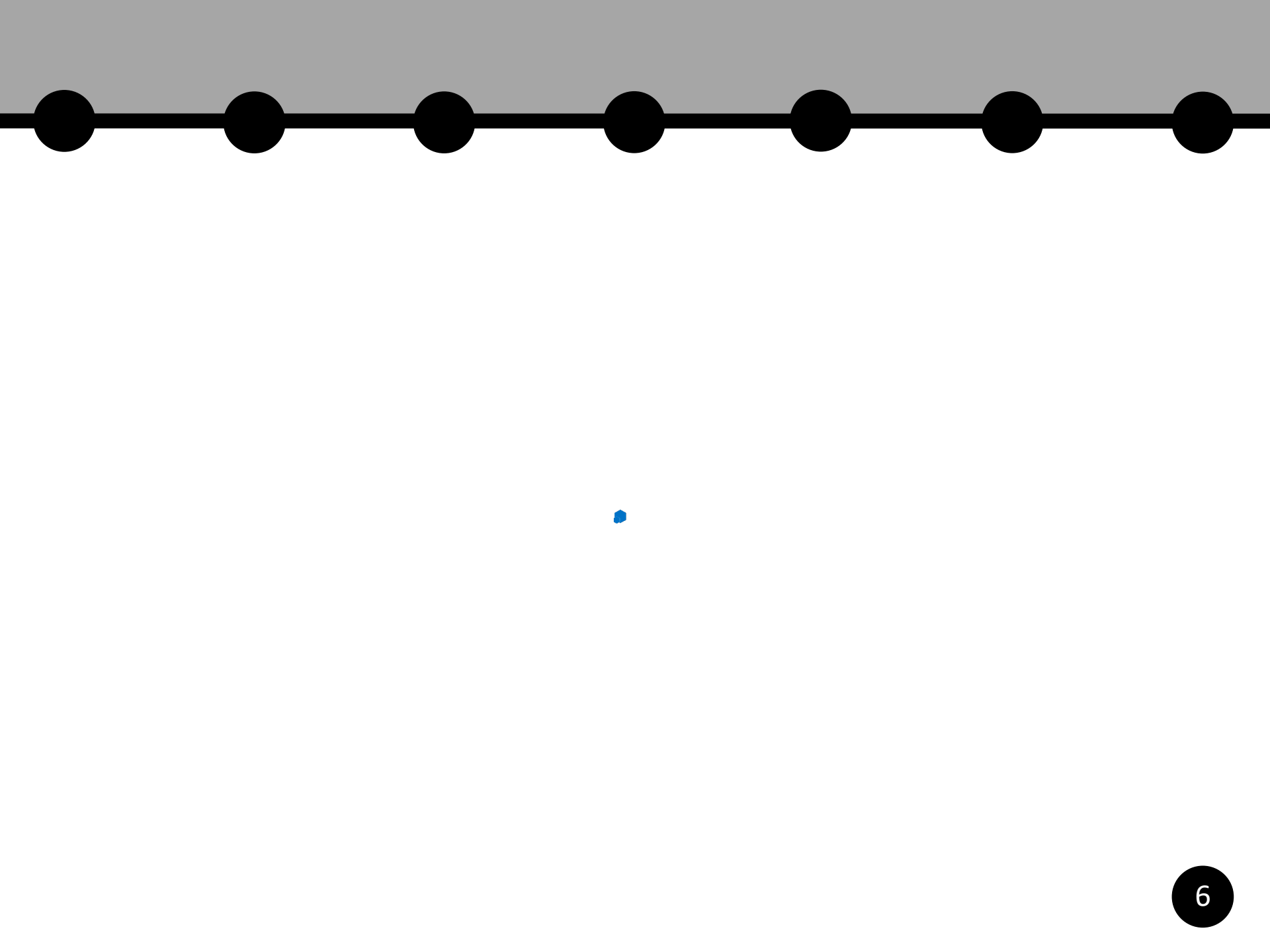
**Step 5: Properties**

**Step 6: Calculations**

**Step 7: Reasoning, Verification, and Discussion**







# LEARNING OBJECTIVES LECTURE 6



- Problem Solving Approach
- Energy Balance
- Surface Energy Balance
- Combined Heat Transfer Examples

# ENERGY BALANCE

## First Law of Thermodynamics

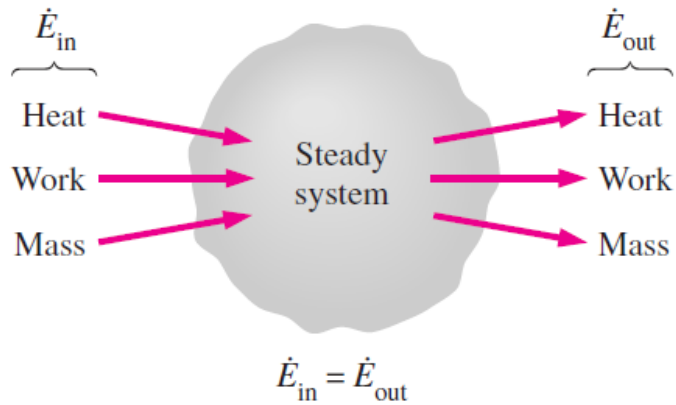
$$\left( \begin{array}{c} \text{Total energy} \\ \text{entering the} \\ \text{system} \end{array} \right) - \left( \begin{array}{c} \text{Total energy} \\ \text{leaving the} \\ \text{system} \end{array} \right) = \left( \begin{array}{c} \text{Change in the} \\ \text{total energy of} \\ \text{the system} \end{array} \right)$$

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

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



# ENERGY BALANCE



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

In heat transfer analysis, we are usually interested only in the forms of energy that can be transferred as a result of a temperature difference, that is, heat or thermal energy.

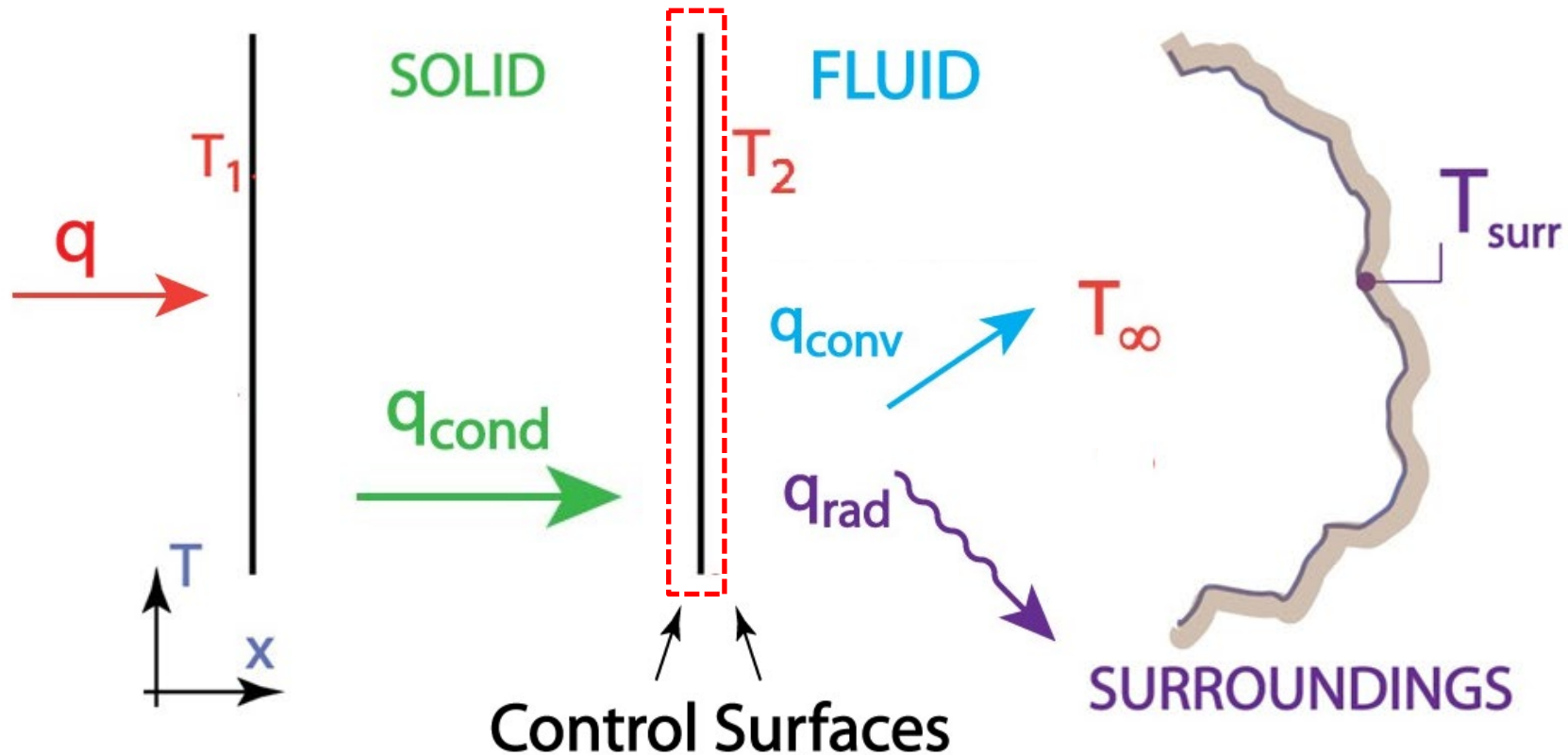
$$\underbrace{Q_{in} - Q_{out}}_{\text{Net heat transfer}} + \underbrace{E_{gen}}_{\text{Heat generation}} = \underbrace{\Delta E_{\text{thermal, system}}}_{\text{Change in thermal energy of the system}}$$

# LEARNING OBJECTIVES LECTURE 6



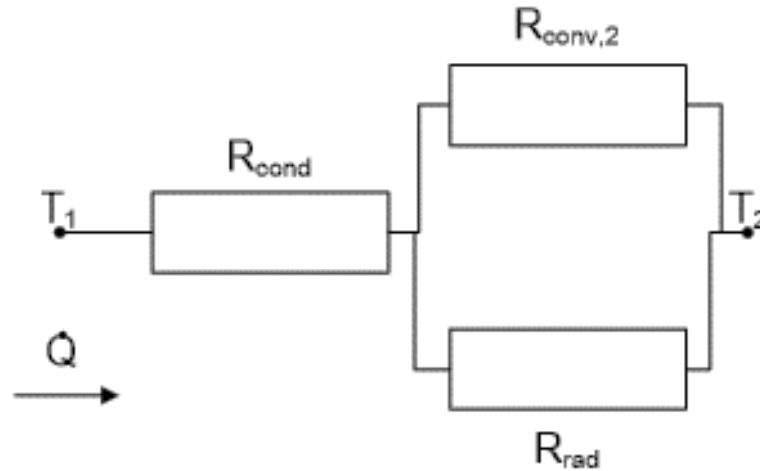
- Problem Solving Approach
- Energy Balance
- Surface Energy Balance
- Combined Heat Transfer Examples

# SURFACE ENERGY BALANCE



# SURFACE ENERGY BALANCE

$$\dot{q}_{cond} = \dot{q}_{conv} + \dot{q}_{rad}$$



$$\Rightarrow \dot{Q} = h_{tot} A \Delta T \quad \text{with} \quad h_{tot} = h_{conv} + h_{rad}$$

$$h_{rad} = \varepsilon \cdot \sigma \cdot (T_s^2 + T_\infty^2) \cdot (T_s + T_\infty)$$



# LEARNING OBJECTIVES LECTURE 6



- Problem Solving Approach
- Energy Balance
- Surface Energy Balance
- Combined Heat Transfer Examples

# STEP BY STEP PLAN

## Conduction:

1. Schematic (Steady state)
2. Negligible heat losses (insulation, adiabatic,...)
3. Geometry (flat plate, cylinder,...)
4. Arrangement of the layers
5. Resistance network
6. Calculation of resistances
7. Calculation of overall resistance
8. Calculation of heat flow
9. Calculation of temperatures for different layers

## Radiation:

1. Schematic (Steady state)
2. Negligible Radiations
3. Surrounding Temperature
4. Calculation of heat flow

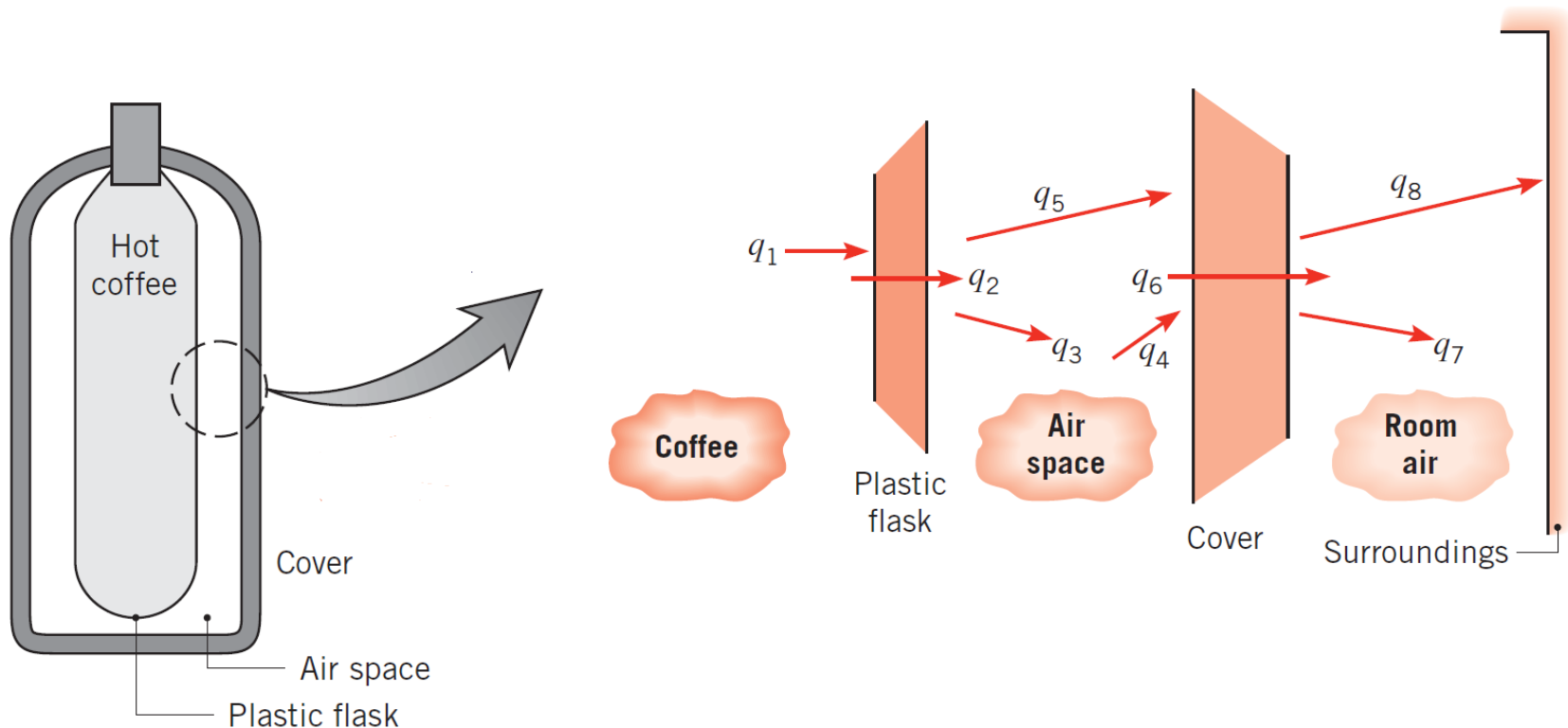
## Convection:

1. Schematic
2. Force of natural convection?
3. Geometry
4. Finding the film temperature
5. Finding ingredients from Table
6. Calculation of dimensionless numbers
7. Calculation of characteristic length
8. Finding correlations from tables to calculate Nu
9. Calculation of  $h$
10. Calculation of heat flow

# EXAMPLE (1)

**Known:** Hot coffee is separated from its cooler surroundings by a plastic flask, an air space, and a plastic cover.

**Find:** Relevant heat transfer processes.





# EXAMPLE (1)

Pathways for energy transfer from the coffee are as follows:

$q_1$ : free convection from the coffee to the flask.

$q_2$ : conduction through the flask.

$q_3$ : free convection from the flask to the air.

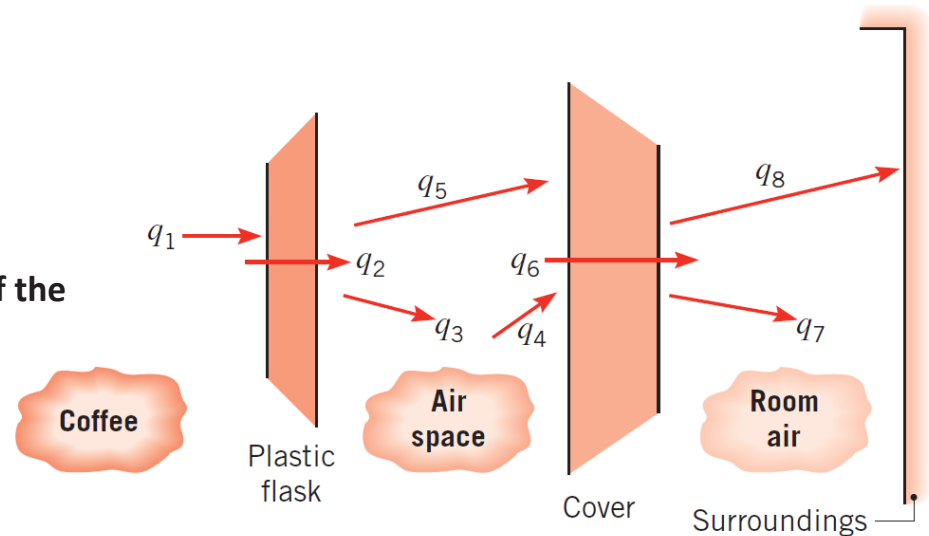
$q_4$ : free convection from the air to the cover.

$q_5$ : net radiation exchange between the outer surface of the flask and the inner surface of the cover.

$q_6$ : conduction through the cover.

$q_7$ : free convection from the cover to the room air.

$q_8$ : net radiation exchange between the outer surface of the cover and the surroundings.



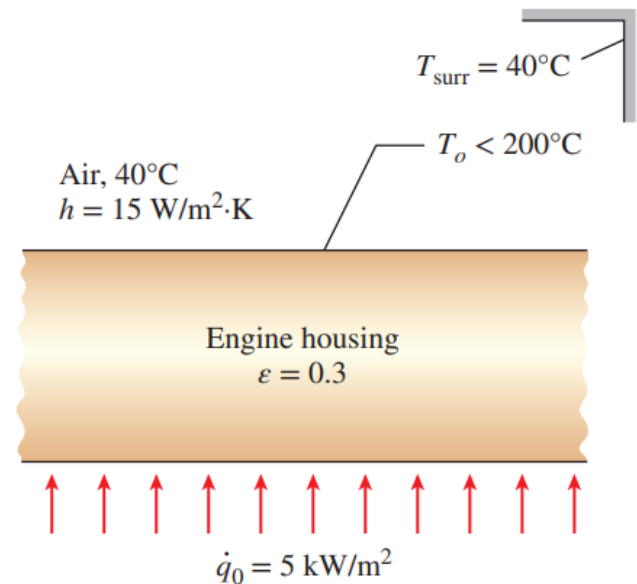
## Resistance Network ????

**Comments:** Design improvements are associated with

- (1) use of aluminized (low emissivity) surfaces for the flask and cover to reduce net radiation
- (2) evacuating the air space or using a filler material to retard free convection.

# EXAMPLE (2)

Oil leakage and spillage on hot engine surfaces can create fire hazards. Some engine oils have an autoignition temperature above  $250^{\circ}\text{C}$ . When oil leakage comes in contact with a hot engine surface that has a higher temperature than its autoignition temperature, the oil can ignite spontaneously. Consider the outer surface of an engine situated in a place where there is a possibility of being in contact with oil leakage. The engine surface has an emissivity of 0.3, and when it is in operation, its inner surface is subjected to  $5\text{ kW/m}^2$  of heat flux. The engine is in an environment where the ambient air and surrounding temperature is  $40^{\circ}\text{C}$ , while the convection heat transfer coefficient is  $15\text{ W/m}^2\cdot\text{K}$ . To prevent a fire hazard, the temperature of the engine surface should be kept below  $200^{\circ}\text{C}$ . Determine whether oil on the engine surface is at a risk of autoignition. If there is a risk of autoignition, discuss a possible prevention measure that can be implemented.



# EXAMPLE (2)

## Assumptions:

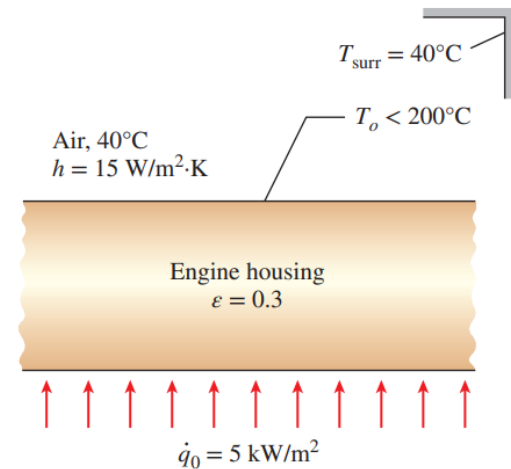
- 1 -Steady operating conditions exist.
- 2 -The surrounding surfaces are at the same temperature as the ambient air.
- 3- Heat conduction through the engine housing is one-dimensional.
- 4 -The engine inner surface is subjected to uniform heat flux.

## Properties :

- Emissivity of the engine surface is given as  $\varepsilon = 0.3$ .

## Analysis :

When in operation, the inner surface of the engine is subjected to a uniform heat flux, which is equal to the sum of heat fluxes transferred by convection and radiation on the outer surface.



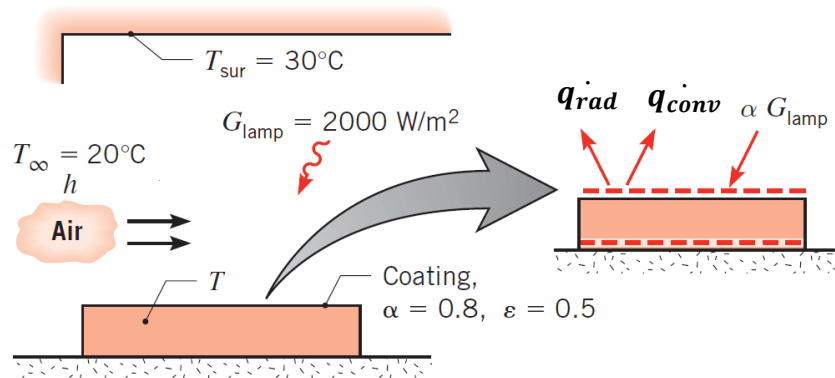
$$\dot{q}_0 = h(T_o - T_\infty) + \varepsilon\sigma(T_o^4 - T_{\text{surr}}^4)$$

# EXAMPLE (3)

The coating on a plate is cured by exposure to an infrared lamp providing a uniform irradiation of  $2000 \text{ W/m}^2$ . It absorbs 80% of the infrared irradiation and has an emissivity of 0.50. It is also exposed to an airflow and large surroundings for which temperatures are  $20^\circ \text{ C}$  and  $30^\circ \text{ C}$ , respectively.

1. If the convection coefficient between the plate and the ambient air is  $15 \text{ W/m}^2 \cdot \text{K}$ , what is the cure temperature of the plate?
2. The final characteristics of the coating, including wear and durability, are known to depend on the temperature at which curing occurs. An airflow system is able to control the air velocity, and hence the convection coefficient, on the cured surface . What value of  $h$  would provide a cure temperature of  $50^\circ \text{ C}$ ?

**Schematic:**



# EXAMPLE (3)

## Assumptions:

1. Steady-state conditions.
2. Negligible heat loss from back surface of plate.
3. Plate is small object in large surroundings, and coating has an absorptivity of  $\alpha_{\text{sur}} = \varepsilon = 0.5$  with respect to irradiation from the surroundings.

## Analysis:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = 0 \quad \Longrightarrow \quad G \cdot \alpha_{\text{sur}} - \dot{q}_{\text{rad}} - \dot{q}_{\text{conv}} = 0$$

$$(\alpha G)_{\text{lamp}} - h(T - T_{\infty}) - \varepsilon \sigma (T^4 - T_{\text{sur}}^4) = 0$$

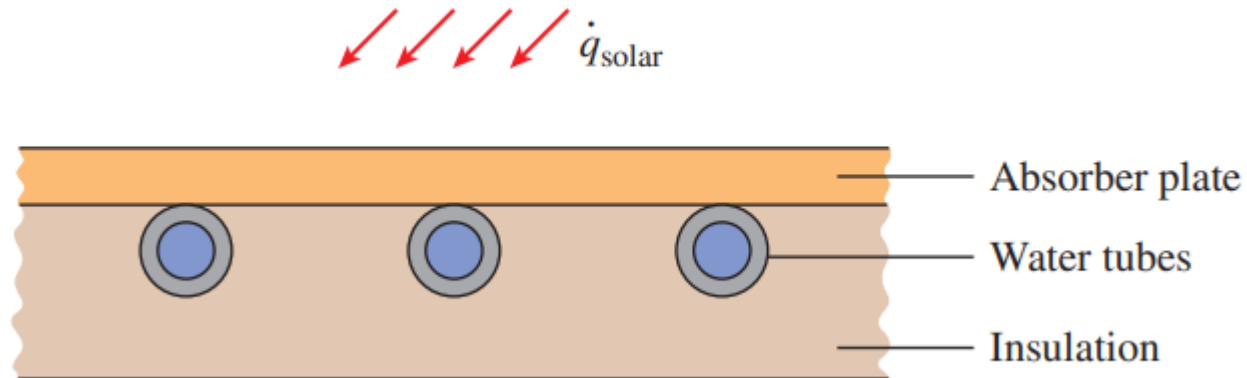
$$0.8 \times 2000 \text{ W/m}^2 - 15 \text{ W/m}^2 \cdot \text{K} (T - 293) \text{ K} - 0.5 \times 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4 (T^4 - 303^4) \text{ K}^4 = 0$$

and solving by trial-and-error, we obtain :

$$T = 377 \text{ K} = 104^{\circ} \text{ C} \quad h(T = 50^{\circ} \text{ C}) = 51.0 \text{ W/m}^2 \cdot \text{K}$$

## EXAMPLE (4)

A flat-plate solar collector is used to heat water by having water flow through tubes attached at the back of the thin solar absorber plate. The absorber plate has a surface area of  $2 \text{ m}^2$  with emissivity and absorptivity of 0.9. The surface temperature of the absorber is  $35^\circ \text{ C}$ , and solar radiation is incident on the absorber at  $500 \text{ W/m}^2$  with a surrounding temperature of  $0^\circ \text{ C}$ . The convection heat transfer coefficient at the absorber surface is  $5 \text{ W/m}^2 \cdot \text{K}$ , while the ambient temperature is  $25^\circ \text{ C}$ . Net heat absorbed by the solar collector heats the water from an inlet temperature ( $T_{\text{in}}$ ) to an outlet temperature ( $T_{\text{out}}$ ). If the water flow rate is  $5 \text{ g/s}$  with a specific heat of  $4.2 \text{ kJ/kg} \cdot \text{K}$ , determine the temperature rise of the water.

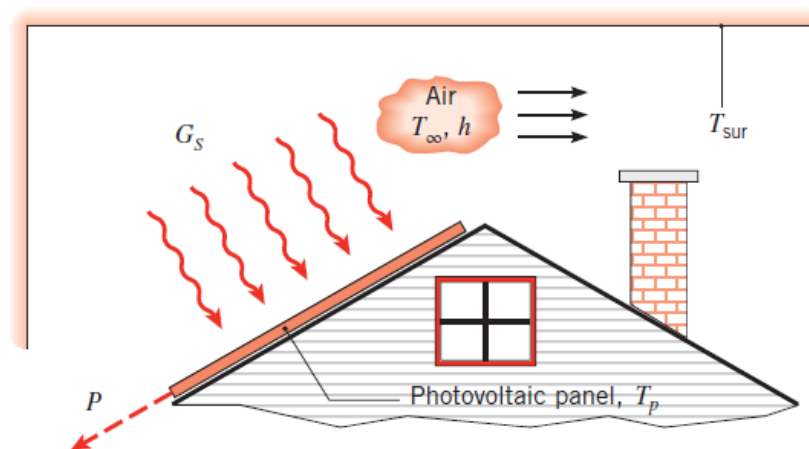


# EXAMPLE (5)

A photovoltaic panel of dimension  $2 \text{ m} \times 4 \text{ m}$  is installed on the roof of a home. The panel is irradiated with a solar flux of  $G_S = 700 \text{ W/m}^2$ , oriented normal to the top panel surface. The absorptivity of the panel to the solar irradiation is  $\alpha_s = 0.83$ , and the efficiency of conversion of the absorbed flux to electrical power is  $\eta = P/\alpha_s G_S A = 0.553 - 0.001 \text{ K}^{-1} T_p$ , where  $T_p$  is the panel temperature expressed in kelvins and  $A$  is the solar panel area. The panel emissivity is  $\epsilon = 0.90$ .

Determine the electrical power generated for

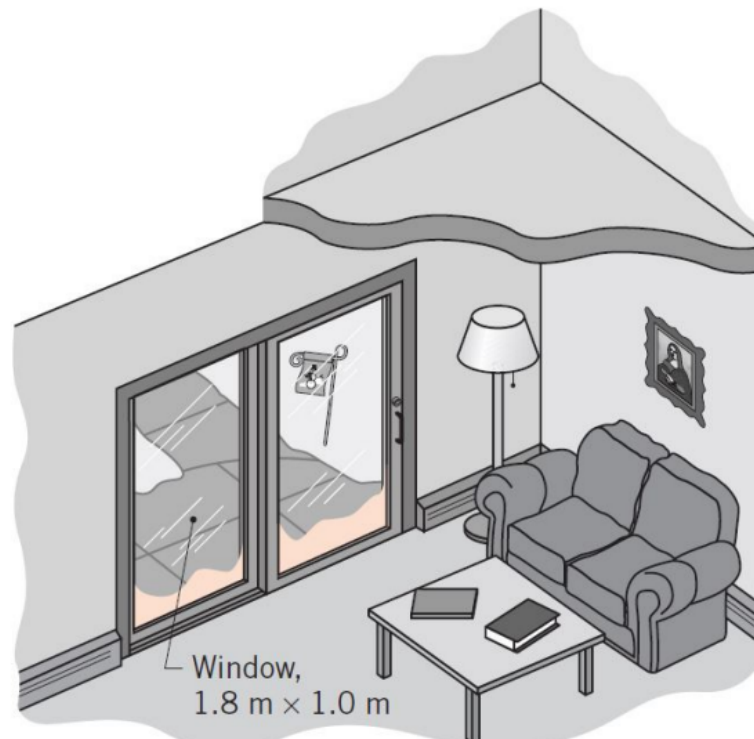
- (a) a still summer day, in which  $T_{\text{sur}} = T_{\infty} = 35^\circ \text{ C}$ ,  $h = 10 \text{ W/m}^2 \cdot \text{K}$
- (b) a breezy winter day, for which  $T_{\text{sur}} = T_{\infty} = -15^\circ \text{ C}$ ,  $h = 30 \text{ W/m}^2 \cdot \text{K}$ .



# EXAMPLE (6)

During a winter day, the window of a patio door with a height of 1.8 m and width of 1.0 m shows a frost line near its base. The room wall and air temperatures are 15 °C.

- Explain why the window would show a frost layer at the base rather than at the top.
- Estimate the heat loss through the window due to free convection and radiation. Assume the window has a uniform temperature of 0 °C and the emissivity of the glass surface is 0.94. If the room has electric baseboard heating, estimate the corresponding daily cost of the window heat loss for a utility rate of €0.18 per *kWh*.

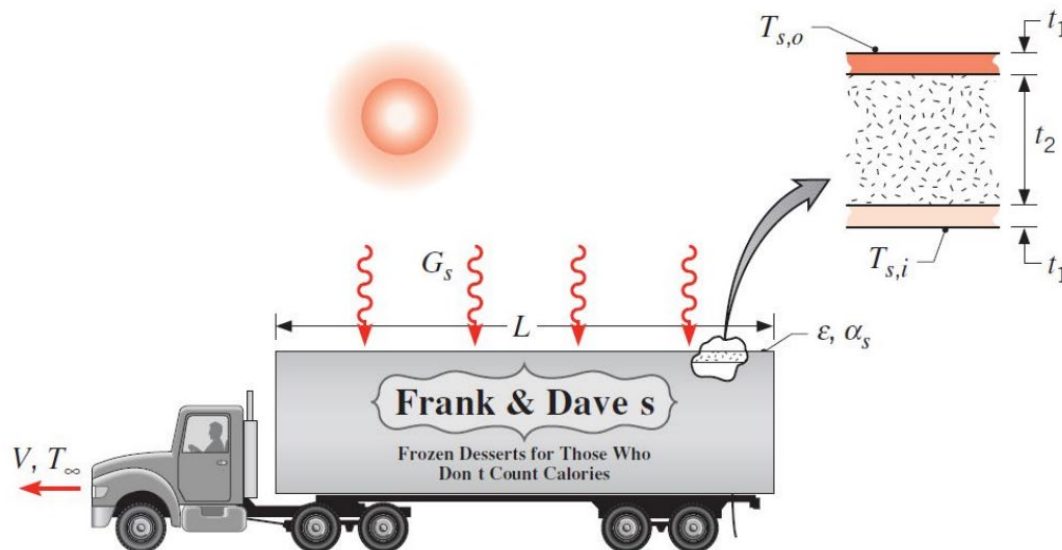




# EXAMPLE (7)

The roof of a refrigerated truck compartment is of composite construction, consisting of a layer of foamed urethane insulation ( $t_2 = 50.00 \text{ mm}$ ,  $k_i = 0.0260 \text{ W/m} \cdot \text{K}$ ) sandwiched between aluminum alloy panels ( $t_1 = 5.00 \text{ mm}$ ,  $k_p = 180.00 \text{ W/m} \cdot \text{K}$ ). The length and width of the roof are  $L = 10.00 \text{ m}$  and  $W = 3.50 \text{ m}$ , respectively, and the temperature of the inner surface is  $T_{s,i} = -10.00^\circ\text{C}$ . Consider conditions for which the truck is moving at a speed of  $V = 105.00 \text{ km/h}$ , the air temperature is  $T_\infty = 32.00^\circ\text{C}$ , and the solar irradiation is  $G_S = 750.00 \text{ W m}^{-2}$ . Turbulent flow may be assumed over the entire length of the roof. **Hint: you may assume that the irradiation from the sky is negligible. To solve the equilibrium equation, you can use that  $T_{s,o}^4 = T_{s,o}^2 * T_\infty^2$**

- a) For equivalent values of the solar absorptivity and the emissivity of the outer surface ( $\alpha_S = \varepsilon = 0.500$ ), estimate the average temperature  $T_{s,o}$  of the outer surface. What is the corresponding heat load imposed on the refrigeration system? The refrigeration has to compensate for this heat load to keep the system in equilibrium.



# Energy & heat transfer: Learning path



## HEATQUIZ

Tables

Practice  
Exam

Extra Practice  
Material

