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TUTORIAL

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HEAT TRANSFER

Course No: M01-301 - Course Credit: 1 PDH

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LEARNING OBJECTIVES

1. To understand the difference between heat, temperature and work
2. To familiarize with heat transfer terminology
3. To understand the Second Law of Thermodynamics
4. To learn about the three modes of heat transfer
5. To perform heat transfer calculations

HEAT TRANSFER TERMINOLOGY

Heat and Temperature:

- Temperature is a measure of the amount of energy possessed by the molecules of a substance. It is a relative measure of how hot or cold a substance is and can be used to predict the direction of heat transfer.
- The common scales for measuring temperature are the Fahrenheit, Rankine, Celsius, and Kelvin.
- Heat is energy in transit. The transfer of energy as heat occurs at the molecular level as a result of a temperature difference.
- Heat is capable of being transmitted through solids and fluids by conduction, through fluids by convection, and through empty space by radiation.
- Common units for measuring heat are the British Thermal Unit (Btu) in the English system of units and the calorie in the SI system.

HEAT TRANSFER TERMINOLOGY (CONT'D)

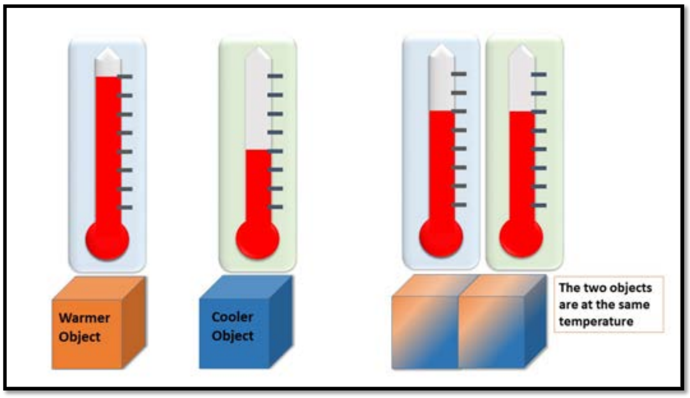


Figure 1: Temperature and Heat

HEAT TRANSFER TERMINOLOGY (CONT'D)

Heat and Work:

- Work is the transfer of energy resulting from a force acting through a distance, while heat is energy transferred as the result of a temperature difference.
- Neither heat nor work are thermodynamic properties of a system.
- Heat can be transferred into or out of a system and work can be done on or by a system, but a system cannot contain or store either heat or work.
- Heat into a system and work out of a system are considered positive quantities.
- When a temperature difference exists across a boundary, the Second Law of Thermodynamics indicates the natural flow of energy is from the hotter body to the colder body.

HEAT TRANSFER TERMINOLOGY (CONT'D)

- The Second Law of Thermodynamics, described by Max Planck in 1903, states that:

  "It is impossible to construct an engine that will work in a complete cycle and produce no other effect except the raising of a weight and the cooling of a reservoir."
- The second law denies the possibility of ever completely converting into work all the heat supplied to a system operating in a cycle.
- If you draw heat from a reservoir to raise a weight, lowering the weight will not generate enough heat to return the reservoir to its original temperature, and eventually the cycle will stop.
- If two blocks of metal at different temperatures are thermally insulated from their surroundings and are brought into contact with each other, the heat will flow from the hotter to the colder.
- The two blocks will reach the same temperature, and heat transfer will cease. Some energy has been transferred from one block to another.

HEAT TRANSFER TERMINOLOGY (CONT'D)

Modes of Transferring Heat:

There are three basic modes of heat transfer:

- Conduction, involves the transfer of heat by the interactions of atoms or molecules of a material through which the heat is being transferred.
- Convection, involves the transfer of heat by the mixing and motion of macroscopic portions of a fluid.
- Radiation, or radiant heat transfer, involves the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.

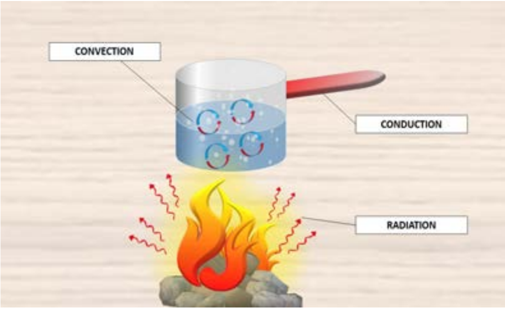


Figure 2: Modes of Heat Transfer

HEAT TRANSFER TERMINOLOGY (CONT'D)

Heat Flux:

- The rate of heat transfer is commonly expressed in Btu/hr, and is often represented by the symbol $\dot{Q}$.
- The heat transfer rate per unit area, or heat flux, is commonly denoted by $\dot{Q}''$, and has units of Btu/hr-ft^2.
- The heat flux is determined by using the following formula:

$$\dot{Q}'' = \frac{\dot{Q}}{A} \qquad (1)$$

Thermal Conductivity:

- The heat transfer characteristics of a solid material are measured by a property called the thermal conductivity (k), expressed in Btu/hr-ft-°F.
- It is a measure of a substance's ability to transfer heat through a solid by conduction.
- The thermal conductivity of most liquids and solids varies with temperature. For vapors, it depends upon pressure.

HEAT TRANSFER TERMINOLOGY (CONT'D)

Log Mean Temperature Difference:

- The inlet and outlet temperatures are commonly specified based on the fluid in the tubes.
- The temperature change across the heat exchanger from the entrance to the exit is not linear.
- The log mean temperature difference (LMTD or ΔT_{lm}) represents a precise temperature change between two fluids across the heat exchanger.
- It can be determined using the following equation:

$$\Delta T l_m = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \qquad (2)$$

ΔT_2: The larger temperature difference between the two fluid streams at either the entrance or the exit to the heat exchanger.

ΔT_1: The smaller temperature difference between the two fluid streams at either the entrance or the exit to the heat exchanger.

HEAT TRANSFER TERMINOLOGY (CONT'D)

Convective Heat Transfer Coefficient:

- The convective heat transfer coefficient (h), defines, in part, the heat transfer due to convection, and is measured in units of Btu/hr-ft^2-^{o}F.
- Also referred to as a film coefficient, it represents the thermal resistance of a relatively stagnant layer of fluid between a heat transfer surface and the fluid medium.

Bulk Temperature:

- The bulk temperature (T_b), varies according to the details of the situation.
- For flow adjacent to a hot or cold surface, T_b is the temperature of the fluid that is "far" from the surface.
- For boiling or condensation, T_b is equal to the saturation temperature.

HEAT TRANSFER TERMINOLOGY (CONT'D)

Overall Heat Transfer Coefficient:

- The overall heat transfer coefficient (U_0), expressed in (Btu/hr-ft^2-^{o}F), combines the heat transfer coefficient of the two heat exchanger fluids, and the thermal conductivity of the heat exchanger tubes.
- The total rate of heat transfer, the overall cross-sectional area for heat transfer, and the overall temperature difference, can be related using the overall heat transfer coefficient through the following equation:

$$\dot{Q} = U_0 A_0 \Delta T_0 \qquad (3)$$

Where,

$\dot{Q}$: the rate heat of transfer (Btu/hr)

U_o: the overall heat transfer coefficient (Btu/hr-ft^2-^{o}F)

A_o: the overall cross-sectional area for heat transfer (ft^2)

ΔT_o: the overall temperature difference (^{o}F)

SUMMARY OF HEAT TRANSFER TERMINOLOGY

- Heat is energy transferred as a result of a temperature difference.
- Temperature is a measure of the amount of molecular energy contained in a substance.
- Work is a transfer of energy resulting from a force acting through a distance.
- Conduction involves the transfer of heat by the interactions of atoms or molecules of a material through which the heat is being transferred.
- Convection involves the transfer of heat by the mixing and motion of macroscopic portions of a fluid.
- Radiation, or radiant heat transfer, involves the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.

SUMMARY OF HEAT TRANSFER TERMINOLOGY (CONT'D)

- The Second Law of Thermodynamics implies that heat will not transfer from a colder to a hotter body without some external source of energy.
- Heat flux is the rate of heat transfer per unit area.
- Thermal conductivity is a measure of a substance's ability to transfer heat through itself.
- Log mean temperature difference is the ΔT that most accurately represents the ΔT for a heat exchanger.
- The bulk temperature is the temperature of the fluid that best represents the majority of the fluid which is not physically connected to the heat transfer site.
- The local heat transfer coefficient represents a measure of the ability to transfer heat through a stagnant film layer.
- The overall heat transfer coefficient is the measure of the ability of a heat exchanger to transfer heat from one fluid to another.

CONDUCTION HEAT TRANSFER

- Conduction involves the transfer of heat by the interaction between adjacent molecules of a material.
- Heat transfer by conduction is dependent upon the driving "force" of temperature difference and the resistance to heat transfer.
- The resistance to heat transfer is dependent upon the nature and dimensions of the heat transfer medium.
- Heat transfer problems involve the temperature difference, the geometry, and the physical properties of the object being studied.
- In conduction heat transfer problems, the object being studied is usually a solid.
- The geometry, physical properties, and temperature difference of an object, correlate with the rate of heat transfer through the object.

Fourier's Law of Conduction:

The law, in its equation form, is usually used in its rectangular or cylindrical form (pipes and cylinders), both of which are presented below:

- Rectangular $\dot{Q} = k\ A\ \left(\frac{\Delta T}{\Delta x}\right)$ (4)
- Cylindrical $\dot{Q} = k\ A\ \left(\frac{\Delta T}{\Delta r}\right)$ (5)

Where,

$\dot{Q}$: rate of heat transfer (Btu/hr)

A: cross-sectional area of heat transfer (ft^2)

Δx: thickness of slab (ft)

Δr: thickness of cylindrical wall (ft)

ΔT: temperature difference (°F)

k: thermal conductivity of slab (Btu/ft-hr-°F)

Example 1: Conduction Through a Slab

1,000 Btu/hr is conducted through a section of insulating material that measures 1 ft^2 in cross-sectional area. The thickness is 1 in. and the thermal conductivity is 0.12 Btu/hr-ft-°F. Compute the temperature difference across the material.

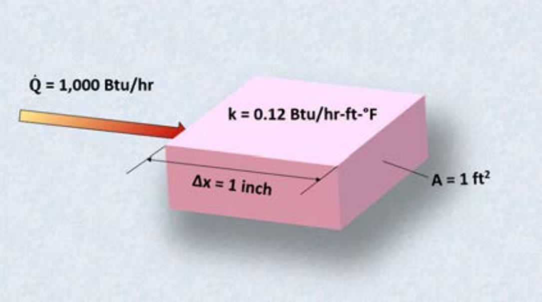


Figure 3: Conduction Through a Slab

Example 1: Solution

Rearrange Equation (4) and solve for ΔT.

$$\Delta T = \dot{Q}\left(\frac{\Delta X}{kA}\right) = \frac{\left(1{,}000\ \frac{Btu}{hr}\right)\left(\frac{1}{12}ft\right)}{(0.12\ \frac{Btu}{hr-ft-°\mathrm{F}})(1\ ft^2)}$$

$$\boldsymbol{\Delta T = 694}°\mathrm{F}$$

Example 2: Heat Transfer Through a Concrete Floor

A concrete floor with a conductivity of 0.8 Btu/hr-ft-°F measures 30 ft by 40 ft with a thickness of 4 inches. The floor has a surface temperature of 70°F and the temperature beneath it is 60°F. What is the heat flux and the heat transfer rate through the floor?

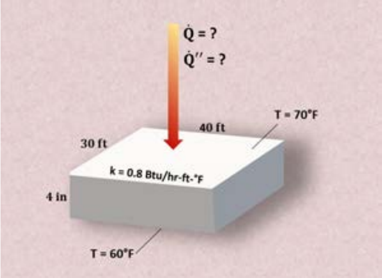


Figure 4: Heat Transfer Through a Concrete Floor

CONDUCTION HEAT TRANSFER (CONT'D)

Example 2: Solution

Using Equations (1) and (4):

$$\dot{Q}'' = \frac{\dot{Q}}{A} = k\left(\frac{\Delta T}{\Delta X}\right) = \left(0.8\ \frac{Btu}{hr-ft-°\mathrm{F}}\right)\left(\frac{10°\mathrm{F}}{0.333\ ft}\right)$$

$$\boldsymbol{\dot{Q}'' = 24\ \frac{Btu}{hr-ft^2}}$$

$$\dot{Q} = \dot{Q}''A = \left(24\ \frac{Btu}{hr-ft^2}\right)(1{,}200\ ft^2)$$

$$\boldsymbol{\dot{Q} = 28{,}800\ \frac{Btu}{hr}}$$

CONDUCTION HEAT TRANSFER (CONT'D)

Equivalent Resistance Method:

- Heat Transfer can be compared to current flow in electrical circuits
- The heat transfer rate may be considered as a current flow.
- The combination of thermal conductivity, thickness of material, and area as a resistance to this flow.
- The temperature difference is the potential or driving function for the heat flow, resulting in the Fourier equation being written in a form similar to Ohm's Law of Electrical Circuit Theory.
- The thermal resistance term ∆x/k is written as a resistance term where the resistance is the reciprocal of the thermal conductivity divided by the thickness of the material.

CONDUCTION HEAT TRANSFER (CONT'D)

The "electrical" Fourier equation may be written as follows:

$$\dot{Q}'' = \frac{\Delta T}{R_{th}} \qquad (6)$$

Where,

$\dot{Q}''$: Heat Flux (Btu/hr-ft^2)
ΔT: Temperature Difference (°F)
R_{th}: Thermal Resistance (Δx/k) (hr-ft^2-°F/Btu)

CONDUCTION HEAT TRANSFER (CONT'D)

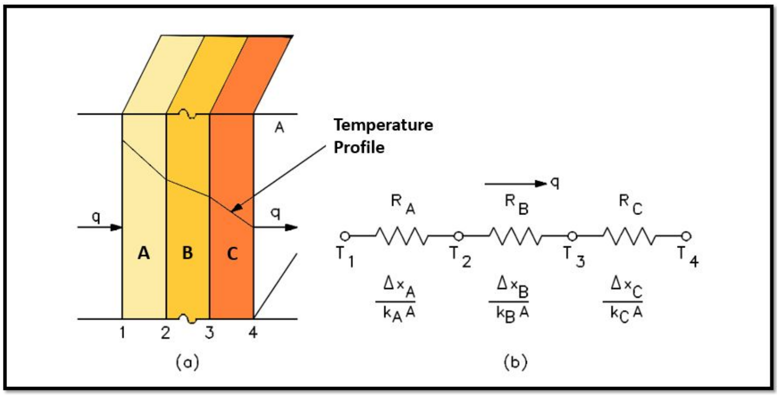


Figure 5: Equivalent Resistance

(*Source: DOE Fundamentals Handbook, “Thermodynamics, Heat Transfer and Fluid Flow”, Vol.2.)*

Example 3: Electrical Analogy

A composite protective wall is formed of a 1 in. copper plate, a 1/8 in. layer of insulation board, and a 2 in. layer of fiberglass.

The thermal conductivities of the materials in units of Btu/hr-ft-°F are as follows: k_{Cu} = 240, k_{ins} = 0.048, and k_{fib} = 0.022.

The overall temperature difference across the wall is 500°F.

Calculate the thermal resistance of each layer of the wall and the heat transfer rate per unit area (heat flux) through the composite structure.

Example 3: Solution

- $R_{Cu} = \frac{\Delta x Cu}{k_{Cu}} = \frac{\left(1 \text{ in.} \frac{1\text{ft}}{12\ in.}\right)}{240\,\frac{Btu}{hr-ft-\text{°F}}} = 0.000347\ \frac{hr-ft^2-\text{°F}}{Btu}$
- $R_{ins} = \frac{\Delta x_{ins}}{k_{ins}} = \frac{\left(0.125 \text{ in.} \frac{1\text{ft}}{12\ in.}\right)}{0.048\,\frac{Btu}{hr-ft-\text{°F}}} = 0.217\ \frac{hr-ft^2-\text{°F}}{Btu}$
- $R_{fib} = \frac{\Delta x_{fib}}{k_{fib}} = \frac{\left(2 \text{ in.} \frac{1\text{ft}}{12\ in.}\right)}{0.022\frac{Btu}{hr-ft-\text{°F}}} = 7.5758\ \frac{hr-ft^2-\text{°F}}{Btu}$
- $\dot{Q}'' = \frac{\dot{Q}}{A} = \frac{(T_i - To)}{R_{CU} + Rins + Rfib} = \frac{500\ \text{°F}}{(0.000347 + 0.2170 + 7.5758)\,\frac{hr-\ ft^2-\text{°F}}{Btu}} = 64.2\,\frac{Btu}{hr-ft^2}$

CONDUCTION HEAT TRANSFER (CONT’D)

Conduction: Cylindrical Coordinates

- The surface area (A) for transferring heat through the pipe is directly proportional to the radius (r) of the pipe and the length (L) of the pipe.

$$A = 2\pi r L$$

- As the radius increases from the inner wall to the outer wall, the heat transfer area increases.
- It is necessary to define a log mean cross-sectional area (A_{lm}).

$$A_{lm} = \frac{A_{outer} - A_{inner}}{\ln\left(\frac{A_{outer}}{A_{inner}}\right)} \qquad (7)$$

- Substituting the expression $2\pi r L$ for the area in Equation (7):

$$A_{lm} = \frac{2\pi L\ (router - rinner)}{\ln\left(\frac{r_{outer}}{r_{inner}}\right)}$$

CONDUCTION HEAT TRANSFER (CONT’D)

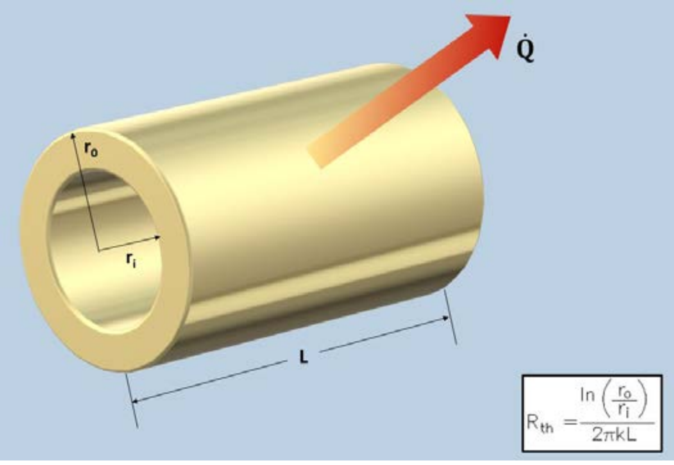


Figure 6: Cross-sectional Surface Area of a Cylindrical Pipe

CONDUCTION HEAT TRANSFER (CONT'D)

- The expression of log mean area can be inserted into Equation 5, allowing us to calculate the heat transfer rate for cylindrical geometries.

$$\dot{Q} = k\ Alm\left(\frac{\Delta T}{\Delta r}\right) = k\left(\frac{2\pi L\ (r_o - ri)}{\ln\left(\frac{r_o}{r_i}\right)}\right)\left(\frac{T_o - T_i}{r_o - ri}\right)$$

$$\dot{Q} = \frac{2\pi k L(\Delta T)}{\ln\left(\frac{r_o}{r_i}\right)} \qquad (8)$$

Where,

L: length of pipe (ft)

r_i: inside pipe radius (ft)

r_o: outside pipe radius (ft)

CONDUCTION HEAT TRANSFER (CONT'D)

Example 4: Heat Transfer Through a Pipe

A stainless steel pipe with a length of 35 ft has an inner diameter of 0.92 ft and an outer diameter of 1.08 ft.

The temperature of the inner surface of the pipe is 122°F and the temperature of the outer surface is 118°F.

The thermal conductivity of the stainless steel is 108 Btu/hr-ft-°F.

Calculate the heat transfer rate through the pipe, and the heat flux at the outer surface of the pipe.

CONDUCTION HEAT TRANSFER (CONT'D)

Example 4: Solution

Using Equations (8) and (1):

$$\dot{Q} = \frac{2\pi\, k\, L\, (T_h - Tc)}{\ln\left(\frac{r_o}{r_i}\right)} = \frac{6.28\left(108\,\frac{Btu}{hr - ft - °F}\right)(35\,ft)(122°F - \ 118°F)}{\ln\left(\frac{0.54\,ft}{0.46\,ft}\right)}$$

$$\boldsymbol{\dot{Q} = 5.92 \text{ x } 10^5\, \frac{Btu}{hr}}$$

$$\dot{Q}'' = \frac{\dot{Q}}{2\pi roL} = \frac{5.92 \text{ x } 10^5\, \frac{Btu}{hr}}{2\ (3.14)\ (0.54\,ft)\ (35\,ft)}$$

$$\boldsymbol{\dot{Q}'' = 4{,}985\, \frac{Btu}{hr - ft^2}}$$

CONDUCTION HEAT TRANSFER (CONT'D)

Example 5: Inner Surface Temperature of a Pipe

A 10 ft length of pipe with an inner radius of 1 in. and an outer radius of 1.25 in., has an outer surface temperature of 250°F.

The heat transfer rate is 30,000 Btu/hr.

Assume k = 25 Btu/hr-ft-°F.

Find the interior surface temperature.

CONDUCTION HEAT TRANSFER (CONT'D)

Example 5: Solution

Using Equation 8, solve for T_h:

$$\dot{Q} = \frac{2\pi k L (T_h - Tc)}{\ln\left(\frac{r_o}{r_i}\right)}$$

$$T_h = \frac{\dot{Q}\ \ln\left(\frac{r_o}{r_i}\right)}{2\pi k L} + Tc = \frac{\left(30{,}000\,\frac{Btu}{hr}\right)\left(ln\,\frac{1.25}{1}\right)}{2\ (3.14)\left(25\,\frac{Btu}{hr - ft - {}^\circ\mathrm{F}}\right)(10\ ft)} + 250^\circ\mathrm{F}$$

$$\boldsymbol{T_h = 254}\ {}^\circ\mathrm{F}$$

CONDUCTION HEAT TRANSFER (CONT'D)

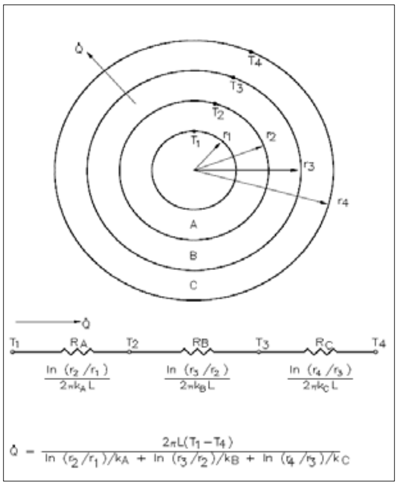


Figure 7: Composite Cylindrical Layers

(*Source: DOE Fundamentals Handbook, "Thermodynamics, Heat Transfer and Fluid Flow", Vol.2.)*

Example 6: Pipe Insulation

A thick-walled nuclear coolant pipe (k_s = 12.5 Btu/hr-ft-°F) with 10 in. inside diameter (ID) and 12 in. outside diameter (OD) is covered with a 3 in. layer of insulation (k_{ins} = 0.14 Btu/hr-ft-°F). If the inside wall temperature of the pipe is maintained at 550°F and the outside temperature is 100°F, calculate the heat loss per foot of length.

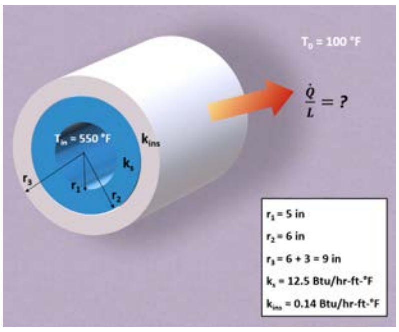


Figure 8: Pipe Insulation Problem

Example 6: Solution

Using the equation for composite cylindrical layers:

$$\frac{\dot{Q}}{L} = \frac{2\pi\,(T_{in} - To)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_s} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{ins}}} = \frac{2\pi\,(550°\mathrm{F} - 100°\mathrm{F})}{\frac{\ln\left(\frac{6\ in}{5\ in}\right)}{12.5\frac{Btu}{hr-ft-°\mathrm{F}}} + \frac{\ln\left(\frac{9\ in}{6\ in}\right)}{0.14\frac{Btu}{hr-ft-°\mathrm{F}}}}$$

$$\boldsymbol{\frac{\dot{Q}}{L} = 971\frac{Btu}{hr-ft}}$$

SUMMARY OF CONDUCTION HEAT TRANSFER

- Conduction heat transfer is the transfer of thermal energy by interactions between adjacent molecules of a material.
- Fourier’s Law of Conduction can be used to solve for rectangular and cylindrical coordinate problems.
- Heat flux ($\dot{Q}''$) is the heat transfer rate ($\dot{Q}$) divided by the area (A).
- Heat conductance problems can be solved using equivalent resistance formulas analogous to electrical circuit problems.

CONVECTION HEAT TRANSFER

- Convection is the transfer of heat by the motion and mixing of "macroscopic" portions of a fluid.
- Natural convection occurs when the motion and mixing is caused by density variations resulting from temperature differences within the fluid.
- Forced convection occurs when the motion and mixing is caused by an outside force, such as a pump.
- The transfer of heat from a hot water radiator to a room is an example of heat transfer by natural convection.
- The transfer of heat from the surface of a heat exchanger to the bulk of a fluid being pumped through the heat exchanger is an example of forced convection.
- Heat transfer by convection is more difficult to analyze than heat transfer by conduction.
- Convection varies from one situation to another (upon the fluid flow conditions), and it is frequently coupled with the mode of fluid flow.

CONVECTION HEAT TRANSFER (CONT'D)

- Convection heat transfer is treated empirically (by direct observation) because of the factors that affect the stagnant film thickness: Fluid velocity - Fluid viscosity - Heat flux - Surface roughness - Type of flow (single-phase/two-phase).
- Convection involves the transfer of heat between a surface at a given temperature (T_s) and fluid at a bulk temperature (T_b).
- Heat transfer by convection is determined using the following equation:

$$\dot{Q} = h\,A\,\Delta T \qquad (9)$$

- The convective heat transfer coefficient (h) is dependent upon the physical properties of the fluid and the physical situation.
- For laminar flow, the convective heat transfer coefficient is relatively low compared to turbulent flow, due to turbulent flow having a thinner stagnant fluid film layer on the heat transfer surface.

CONVECTION HEAT TRANSFER (CONT'D)

Example 7: Heat Transfer By Convection

A 22-foot uninsulated steam line crosses a room. The outer diameter of the steam line is 18 in. and the outer surface temperature is 280°F.

The convective heat transfer coefficient for the air is 18 Btu/hr-ft^2-°F.

Calculate the heat transfer rate from the pipe into the room if the room temperature is 72°F.

CONVECTION HEAT TRANSFER (CONT'D)

Example 7: Solution

Using Equation 9:

$$\dot{Q} = hA\Delta T = h(2\pi rl)\Delta T$$

$$\dot{Q} = \left(18 \frac{Btu}{hr - ft^2 - °\mathrm{F}}\right)\big(2(3.14)(0.75\ ft)(22\ ft)\big)(280°\mathrm{F} - 72°\mathrm{F})$$

$$\boldsymbol{\dot{Q} = 3.88 \text{ x } 10^5 \frac{Btu}{hr}}$$

CONVECTION HEAT TRANSFER (CONT'D)

- In many applications, the surface area of heat transfer normally given in the convection equation, varies as heat passes through the cylinder.
- The temperature difference between the inside and the outside of the pipe, as well as the temperature differences along the pipe, necessitates the use of some average temperature value.
- This average temperature difference is called the log mean temperature difference (LMTD).
- The definition of LMTD involves two important assumptions: (1) the fluid specific heats do not vary significantly with temperature; (2) the convection heat transfer coefficients are relatively constant throughout the heat exchanger.

CONVECTION HEAT TRANSFER (CONT'D)

Overall Heat Transfer Coefficient:

- Most heat transfer processes encountered in nuclear facilities involve a combination of both conduction and convection.
- For example, heat transfer in a steam generator involves convection from the bulk of the reactor coolant to the steam generator inner tube surface, conduction through the tube wall, and convection from the outer tube surface to the secondary side fluid.
- There is the convective heat transfer coefficient (h) for the fluid film inside the tubes, and a convective heat transfer coefficient for the fluid film outside the tubes.
- The thermal conductivity (k) and thickness (Δx) of the tube wall must also be accounted for.
- An additional term (U_o), called the overall heat transfer coefficient, must be used instead.

CONVECTION HEAT TRANSFER (CONT'D)

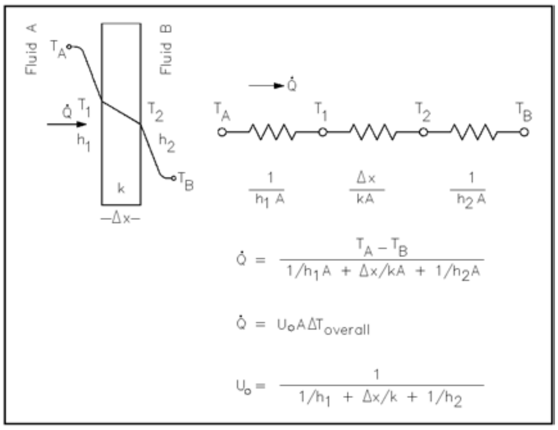


Figure 9: Overall Heat Transfer Coefficient

(*Source: DOE Fundamentals Handbook, "Thermodynamics, Heat Transfer and Fluid Flow", Vol.2.)*

CONVECTION HEAT TRANSFER (CONT'D)

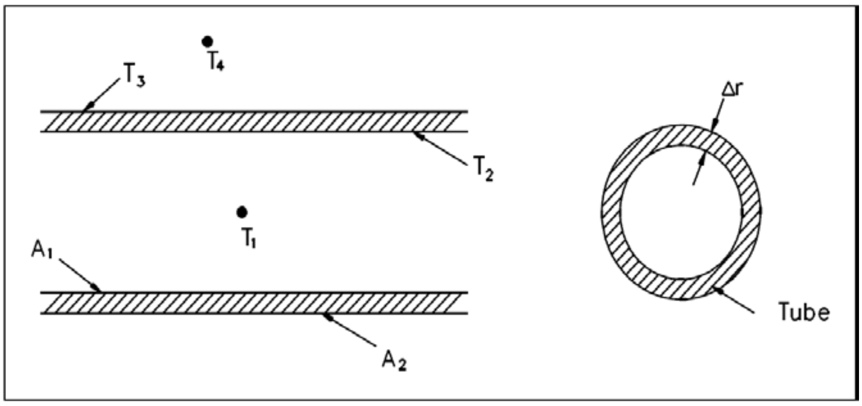


Figure 10: Combined Heat Transfer

(*Source: DOE Fundamentals Handbook, "Thermodynamics, Heat Transfer and Fluid Flow", Vol.2.)*

CONVECTION HEAT TRANSFER (CONT'D)

The three processes can be expressed using Equations 5 and 9:

$$\dot{Q} = h_1 A_1 (T_1 - T_2) = \frac{k}{\Delta r} Alm (T_2 - T_3) = h_2 A_2 (T_3 - T_4)$$

ΔT_o can be expressed as the sum of the ΔT of the three individual processes:

$$\Delta T_0 = (T_1 - T_2) + (T_2 - T_3) + (T_3 - T_4)$$

$$\Delta T_0 = \dot{Q}\left(\frac{1}{h_1 A_1} + \frac{\Delta r}{kA_{lm}} + \frac{1}{h_2 A_2}\right) = \frac{\dot{Q}}{A_0}\left(\frac{A_0}{h_1 A_1} + \frac{\Delta r A_0}{kA_{lm}} + \frac{A_0}{h_2 A_2}\right)$$

Solving for $\dot{Q}$ results in an equation in the form $\dot{Q} = U_0 A_0 \Delta T_0$, where:

$$\dot{Q} = \frac{1}{\left(\frac{A_0}{h_1 A_1} + \frac{\Delta r A_0}{kA_{lm}} + \frac{A_0}{h_2 A_2}\right)} A_0 \Delta T_0$$

$$U_0 = \frac{1}{\left(\frac{A_0}{h_1 A_1} + \frac{\Delta r A_0}{kA_{lm}} + \frac{A_0}{h_2 A_2}\right)} \qquad (10)$$

$$U_0 = \frac{1}{\left(\frac{1}{h_1} + \frac{\Delta r}{k} + \frac{1}{h_2}\right)} \qquad (11)$$

CONVECTION HEAT TRANSFER (CONT'D)

- The convection heat transfer process is strongly dependent upon the properties of the fluid being considered.
- the convective heat transfer coefficient (h), the overall coefficient (U_o), and the other fluid properties may vary substantially if the fluid experiences a large temperature change during its path.
- The temperature at which the properties are obtained must be an average value, rather than the inlet or outlet temperature value.
- For internal flow, the bulk or average value of temperature is obtained analytically through the use of conservation of energy.
- For external flow, an average film temperature is normally calculated, which is an average of the free stream temperature and the solid surface temperature.

CONVECTION HEAT TRANSFER (CONT'D)

Example 8: Bulk Temperature of the Environment

A flat wall is exposed to the environment. The wall is covered with a layer of insulation 1 in. thick whose thermal conductivity is 0.8 Btu/hr-ft-°F. The temperature of the wall on the inside of the insulation is 600°F.

The wall loses heat to the environment by convection on the surface of the insulation. The average value of the convection heat transfer coefficient on the insulation surface is 950 Btu/hr-ft^2-°F.

Calculate the bulk temperature of the environment (T_b) if the outer surface of the insulation does not exceed 105°F.

Example 8: Solution

Find heat flux ($\dot{Q}''$) through the insulation:

$$\dot{Q}'' = \frac{\dot{Q}}{A} = k\left(\frac{\Delta T}{\Delta x}\right) = \left(0.8\frac{Btu}{hr - ft - °F}\right)\left(\frac{600°F - 105°F}{(1\ in)\left(\frac{1ft}{12\ in}\right)}\right) = 4{,}752\frac{Btu}{hr - ft^2}$$

Find the bulk temperature of the environment:

$$\dot{Q} = h\,A\,(Tins\ - Tb)$$

$$T_b = Tins\ - \frac{\dot{Q}''}{h} = 105°F\ - \frac{4{,}752\frac{Btu}{hr - ft^2}}{950\frac{Btu}{hr - ft^2 - °F}} = \mathbf{100}°F$$

SUMMARY OF CONVECTION HEAT TRANSFER

- Convection heat transfer is the transfer of thermal energy by the mixing and motion of a fluid or gas.
- Whether convection is natural or forced is determined by how the medium is placed into motion.
- When both convection and conduction heat transfer occurs, the overall heat transfer coefficient must be used to solve problems.
- The heat transfer equation for convection heat transfer is $\dot{Q} = h\,A\,\Delta T$.

RADIANT HEAT TRANSFER

- Radiant heat transfer involves the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.
- Mostly occurs in the infra-red region of the electromagnetic spectrum, although some of it is in the visible region.
- The term thermal radiation is frequently used to distinguish this form of electromagnetic radiation from other forms, such as radio waves, x-rays, or gamma rays.
- Radiant heat transfer does not need a medium to take place.
- Any material that has a temperature above absolute zero gives off some radiant energy.

RADIANT HEAT TRANSFER (CONT'D)

Black Body Radiation:

- A black body is a body that emits the maximum amount of heat for its absolute temperature.
- Radiant heat transfer rate from a black body to its surroundings can be expressed by the following equation:

$$\dot{Q} = \sigma A T^4 \qquad (12)$$

Where,

$\dot{Q}$: heat transfer rate (Btu/hr)

σ: Stefan-Boltzman constant (0.174 Btu/hr-ft^2-°R^4)

A: surface area (ft^2)

T: temperature (°R)

RADIANT HEAT TRANSFER (CONT'D)

- Two black bodies that radiate toward each other have a net heat flux between them.
- The net flow rate of heat between them is given by an adaptation of Equation 12:

$$\dot{Q} = \sigma\, A\, ({T_1}^4 - {T_2}^4)$$

Where,

A: surface area of the first body (ft^2)

T_1: temperature of the first body (°R)

T_2: temperature of the second body (°R)

- All bodies above absolute zero temperature radiate some heat. The sun and earth both radiate heat toward each other.
- Each body must be in direct line of sight of the other to receive radiation from it.
- Therefore, whenever the cool body is radiating heat to the hot body, the hot body must also be radiating heat to the cool body.
- The net flow of heat is from hot to cold, and the Second Law is still satisfied.

RADIANT HEAT TRANSFER (CONT'D)

Emissivity:

- Real objects radiate less heat than a black body and are called gray bodies.
- To take this into account, Equation 12 is modified to be of the following form:

$$\dot{Q} = \varepsilon \sigma A T^4$$

Where,

ε: emissivity of the gray body (dimensionless)

- Emissivity is simply a factor by which we multiply the black body heat transfer to take into account that the black body is the ideal case.
- Emissivity is a dimensionless number and has a maximum value of 1.0.

RADIANT HEAT TRANSFER (CONT'D)

Radiation Configuration Factor:

- The radiative heat transfer rate between two gray bodies can be calculated by the equation stated below:

$$\dot{Q} = fa\, fe\, \sigma\, A\, ({T_1}^4 - {T_2}^4)$$

Where,

f_a: the shape factor, depends on the spatial arrangement of the two objects (dimensionless)

f_e: the emissivity factor, depends on the emissivities of both objects (dimensionless)

- By combining fa and fe into the symbol f, we have the following equation:

$$\dot{Q} = f\, \sigma\, A\, ({T_1}^4 - {T_2}^4) \qquad (13)$$

- The symbol (f) is a dimensionless factor, sometimes called the radiation configuration factor, which takes into account the emissivity of both bodies and their relative geometry.

RADIANT HEAT TRANSFER (CONT'D)

Example 9: Radiant Heat Transfer

Calculate the radiant heat between the floor (15 ft x 15 ft) of a furnace and the roof, if the two are located 10 ft apart.

The floor and roof temperatures are 2000°F (2460°R) and 600°F (1060°R), respectively.

Assume that the floor and the roof have black surfaces.

Take $f_{1\text{-}2} = f_{2\text{-}1} = 0.31$

RADIANT HEAT TRANSFER (CONT'D)

Example 9: Solution

$A_1 = A_2 = (15 \text{ ft}) (15 \text{ ft}) = 225 \text{ ft}^2$

$T_1 = 2{,}460°R$

$T_2 = 1{,}060°R$

$$\dot{Q}_{12} = \sigma\, A\, f (T_1{}^4 - T_2{}^4)$$

$$\dot{Q}_{12} = \left(0.174 \frac{Btu}{hr - ft^2 - {}^oR^4}\right) (225\, ft^2)\, (0.31)\, [\, (2460^oR)^4\, - (1060^oR)4]$$

$$\boldsymbol{\dot{Q}_{12} = 4.29 \text{ x } 10^{14}\, Btu/hr}$$

SUMMARY OF RADIANT HEAT TRANSFER

- Black body radiation is the maximum amount of heat that can be transferred from an ideal object.
- Emissivity is a measure of the departure of a body from the ideal black body.
- Radiation configuration factor takes into account the emittance and relative geometry of the two objects.

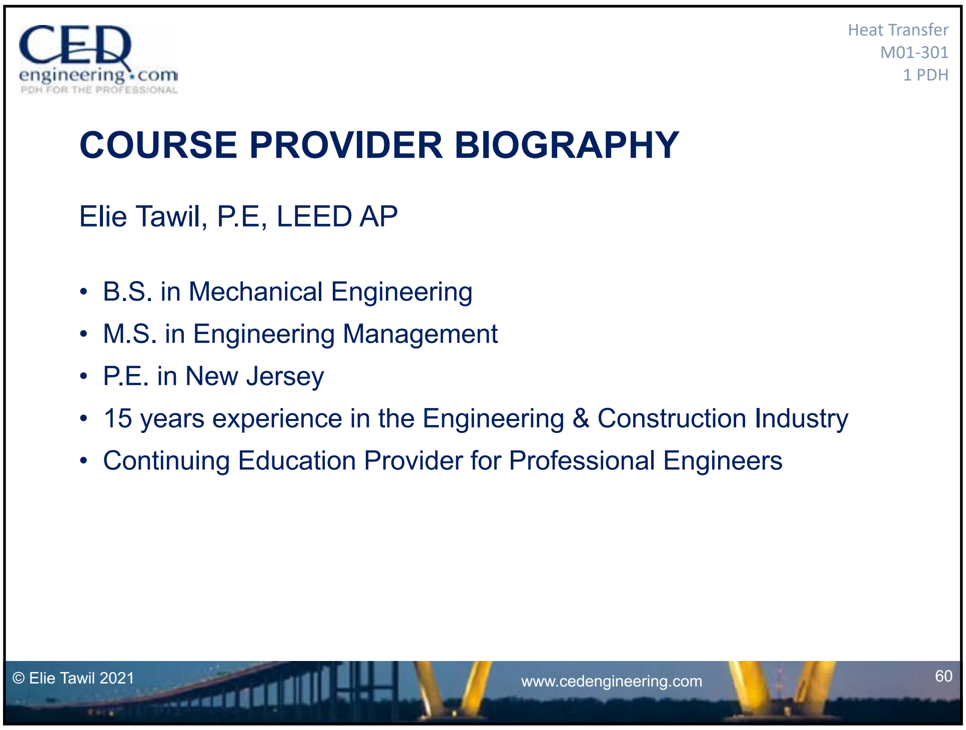
THANK YOU FOR LISTENING!

This concludes our presentation, and we hope that you enjoyed it.

For instructions on how to receive PDH credits, please continue till the end of the presentation.

REFERENCES

This interactive presentation was adapted from DOE Fundamentals Handbook, “Thermodynamics, Heat Transfer and Fluid Flow”, Vol.2., DOE-HDBK-1012/2-92.



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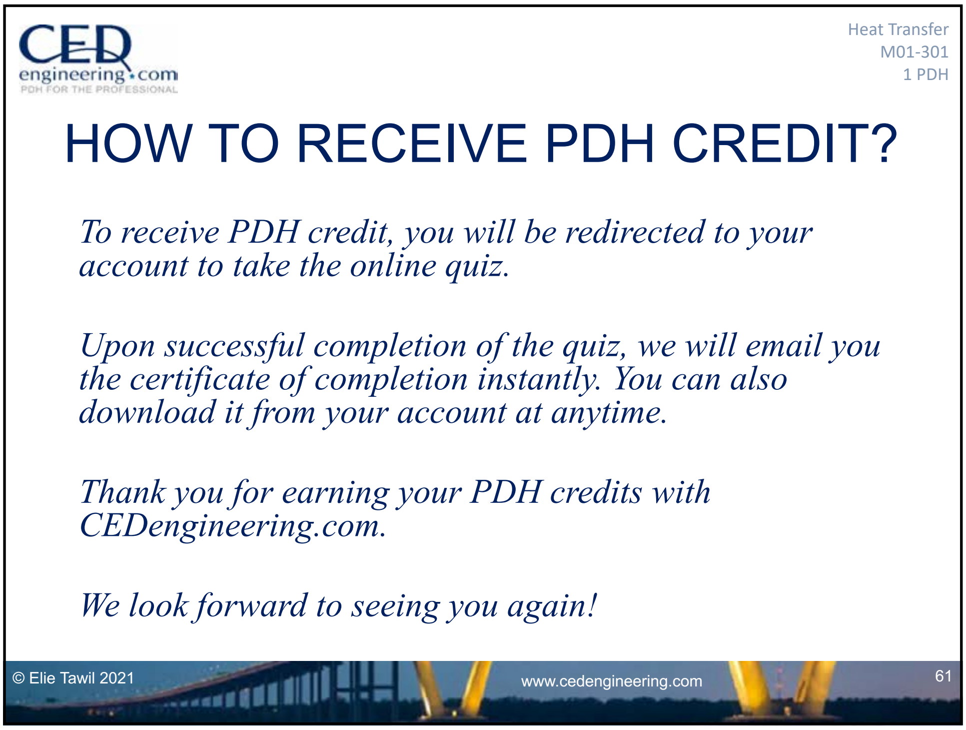

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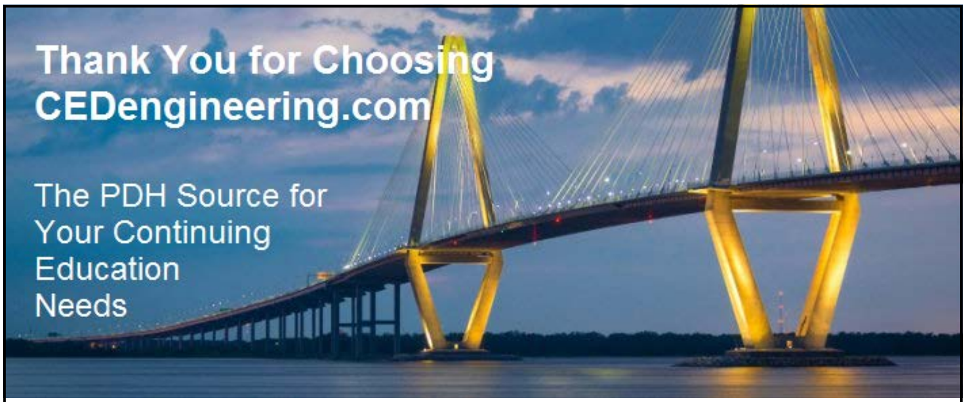

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