Heat Transfer

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Module 1: Heat Transfer Terminology

Learning Objectives

By the end of this section, you will be able to:

- **Distinguish** between the physical properties of temperature and the transitional nature of heat and work.
- **Identify** the three fundamental modes of heat transfer and their governing physical mechanisms.
- **Define** critical engineering parameters including heat flux, thermal conductivity, and the log mean temperature difference used in heat exchanger analysis.

Executive Summary: Heat transfer is the study of energy in transit due to temperature gradients. Success in thermal design requires a rigorous distinction between stored molecular energy (temperature) and transitional energy (heat/work), governed by the Second Law of Thermodynamics which dictates the direction of spontaneous energy flow.

Heat and Temperature

In describing heat transfer problems, students often make the mistake of interchangeably using the terms **heat** and **temperature**. Actually, there is a distinct difference between the two.

Temperature (T) 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 symbol for temperature is **T**. The common scales for measuring temperature are the Fahrenheit, Rankine, Celsius, and Kelvin temperature scales.

Heat (Q) 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. The symbol for heat is **Q**. Common units for measuring heat are the British Thermal Unit (Btu) in the English system of units and the calorie in the SI system (International System of Units).

Heat and Work

Distinction should also be made between the energy terms heat and work. Both represent energy in transition.

- **Work** is the transfer of energy resulting from a force acting through a distance.
- **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.

⚠️ **Safety Constraint:** Heat into a system and work out of a system are considered positive quantities.

The Second Law of Thermodynamics

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. The Second Law of Thermodynamics denies the possibility of ever completely converting into work all the heat supplied to a system operating in a cycle. 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 says that 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. Eventually the two blocks will reach the same temperature, and heat transfer will cease. Energy has not been lost, but instead some energy has been transferred from one block to another.

Modes of Transferring Heat

Heat is always transferred when a temperature difference exists between two bodies. 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.

The three modes of heat transfer will be discussed in greater detail in the subsequent chapters of this module.

Heat Flux

The rate at which heat is transferred is represented by the symbol **Q-dot**. Common units for heat transfer rate is Btu/hr. Sometimes it is important to determine the heat transfer rate per unit area, or **heat flux**, which has the symbol **Q"**. Units for heat flux are Btu/hr-ft2. The heat flux can be determined by dividing the heat transfer rate by the area through which the heat is being transferred.

Equation 2-1:

$$\dot{Q} = \frac{Q}{A}$$

Where:

- **Q̇** = heat transfer rate (Btu/hr)
- **Q** = heat flux (Btu/hr-ft2)
- **A** = area (ft2)

Thermal Conductivity

The heat transfer characteristics of a solid material are measured by a property called the **thermal conductivity (k)** measured 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.

Log Mean Temperature Difference

In heat exchanger applications, the inlet and outlet temperatures are commonly specified based on the fluid in the tubes. The temperature change that takes place across the heat exchanger from the entrance to the exit is not linear. A precise temperature change between two fluids across the heat exchanger is best represented by the **log mean temperature difference (LMTD or ΔT_{lm})**, defined in Equation 2-2.

Equation 2-2:

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$$

Where:

- **ΔTlm** = Log mean temperature difference (°F)
- **ΔT2** = the larger temperature difference between the two fluid streams at either the entrance or the exit to the heat exchanger
- **ΔT1** = the smaller temperature difference between the two fluid streams at either the entrance or the exit to the heat exchanger

Convective Heat Transfer Coefficient

The **convective heat transfer coefficient (h)**, defines, in part, the heat transfers due to convection. The convective heat transfer coefficient is sometimes referred to as a **film coefficient** and represents the thermal resistance of a relatively stagnant layer of fluid between a heat transfer surface and the fluid medium. Common units used to measure the convective heat transfer coefficient are Btu/hr - ft2 - °F.

Overall Heat Transfer Coefficient

In the case of combined heat transfer, it is common practice to relate the total rate of heat transfer (Q-dot), the overall cross-sectional area for heat transfer (Ao), and the overall temperature difference (DTo) using the **overall heat transfer coefficient (Uo)**. The overall heat transfer coefficient combines the heat transfer coefficient of the two heat exchanger fluids and the thermal conductivity of the heat exchanger tubes. Uo is specific to the heat exchanger and the fluids that are used in the heat exchanger.

Equation 2-3:

$$\dot{Q} = U_o A_o \Delta T_o$$

Where:

- **Q̇** = the rate heat of transfer (Btu/hr)
- **Uo** = the overall heat transfer coefficient (Btu/hr - ft2 - °F)
- **Ao** = the overall cross-sectional area for heat transfer (ft2)
- **ΔTo** = the overall temperature difference (°F)

Bulk Temperature

The fluid temperature (Tb), referred to as the **bulk temperature**, varies according to the details of the situation. For flow adjacent to a hot or cold surface, Tb is the temperature of the fluid that is "far" from the surface, for instance, the center of the flow channel. For boiling or condensation, Tb is equal to the **saturation temperature**.

🧮 **Calculation Note:** When selecting a bulk temperature for non-phase-change flow, ensure you are using the temperature at the centerline of the channel or a representative average of the flow stream away from the boundary layer.

Checkpoint Quiz

1. **Which of the following is defined as energy in transition specifically resulting from a force acting through a distance?**
   a) Heat
   b) Work
   c) Temperature
   d) Heat Flux

Answer: (b). Heat is driven by temperature differences, while work is driven by force through a distance.

2. **In a heat exchanger, the temperature profile from entrance to exit is typically:**
   a) Linear
   b) Constant
   c) Non-linear
   d) Parabolic

Answer: (c). This is why the Log Mean Temperature Difference (LMTD) is used for accurate calculations.

3. Which mode of heat transfer involves the mixing and motion of macroscopic portions of a fluid?

a) Conduction
b) Radiation
c) Convection
d) Adsorption

Answer: (c). Conduction relies on molecular interaction in solids, and radiation on electromagnetic waves.