

Heat Exchangers

Chapter 1:

Review of Heat Transfer Laws

1st year Master

Chemical Engineering & Pharmaceutical Engineering

2025 - 2026

1- Review of Heat Transfer Laws

Heat transfer is a branch of thermal sciences that studies the mechanisms of energy exchange ("heat flux") caused by a temperature difference. Heat transfer refers to the exchange of thermal energy between two systems, or between two parts of the same system, due to a temperature difference. It continues until thermal equilibrium is reached (uniform temperature throughout).

The human body provides a perfect and relevant illustration (through metabolism and heat exchanges with the air by conduction, convection, and radiation). However, these phenomena are also found in most natural and technological processes in our environment (such as an iron, cooking with an oven, water heater, television, heating systems, computer, radiator, automobile, etc.).

* (Fer à repasser, cuisinier (le four) chauffe eau, T.V , chauvage, ordinateur, radiateur, automobile.....).

◆ Exemples concrets de transfert thermique

1. Conduction

- **Iron:** the metallic soleplate heats up through an electric resistance, then transmits the heat directly to the fabric.
- **Cook using a pan on the stove:** the heat propagates through the metal of the pan by conduction.

2. Convection

- **Water heater:** hot water rises and cold water sinks → circulation by natural convection.
- **Household radiator:** the air in contact with the radiator warms up and rises → natural convection that heats the room.
- **Automobile (engine cooling):** the coolant circulates thanks to a pump → forced convection.

3. Radiation

- **Electric oven:** heating elements emit infrared radiation that cooks the food.
- **Television / computer:** electronic components heat up and emit thermal radiation (infrared).
- **Radiant panel heating:** direct heat transfer by infrared radiation.

The amount of heat transferred per unit of time through a surface corresponds to a **heat flux (Φ)**,

$$dQ = \phi dt \quad Q_2 - Q_1 = \Delta Q = \int_{t_1}^{t_2} \phi \Delta t$$

The variation of heat during a time interval is: $\Delta t = t_2 - t_1$

A **heat flux** is defined as the quantity of heat transferred through a surface S per unit of time: $\Phi = \frac{dQ}{dt} \left(\frac{J}{s} \right) (W)$

□ Heat transfers are based on the laws of thermodynamics:

1st Law of Thermodynamics (Conservation of Energy):

This law expresses the conservation of energy: energy can not be created or destroyed, it can only be transformed from one form to another.

The quantity of heat transmitted per unit of time and per unit area of the isothermal surface is called the **heat flux density**:

$$\varphi = \frac{1}{S} \frac{dQ}{dt} \quad (W/m^2)$$

- **For a closed system:** $\Delta U = Q - W$

The variation of internal energy ΔU is equal to the heat received Q minus the work performed W

- Q : heat received by the system (J)
- W : work performed by the system (J)
- ΔU : variation of the system's internal energy (J)

👉 **Interpretation:** the internal energy of a closed system **increases** if the system receives heat or if work is done on it.

For an Open System (Energy Balance)

For an open system (where mass can enter or leave), the **1st law of thermodynamics** is written in its general form:

$$\frac{dE_{syst}}{dt} = \dot{Q} - \dot{W} + \sum \dot{m}_{entrée} h_{entrée} - \sum \dot{m}_{sortie} h_{sortie}$$

where:

- $\dot{Q}$ = heat exchanged per unit of time (W)
- $\dot{W}$ = work exchanged per unit of time (W)
- $\dot{m}$ = mass flow rate (kg/s)
- h = specific enthalpy (J/kg)

➤ In this case, it is necessary to take into account the energy transfers associated with mass flows (enthalpy).

2nd Law of Thermodynamics

Heat transfers are governed by the **second law of thermodynamics**, which specifies the natural direction of heat exchange: heat flows spontaneously from a region at higher temperature to a region at lower temperature.

“The 2nd law states that heat cannot spontaneously flow from a colder body to a hotter body.”

This process is **irreversible** and is accompanied by an **increase in the total entropy (S)** of the system under consideration and its surroundings.

In real processes (which are always irreversible): $dS \geq \frac{\delta Q}{T}$

- Equality $\left(dS = \frac{\delta Q}{T}\right)$ holds **only for reversible transformations**.
- The inequality expresses that any real transformation is accompanied by an entropy production.

Entropy **S** is a state function introduced by **Clausius** to formulate the **Second Law of Thermodynamics**.

👉 **This means that entropy measures the “*quality*” of thermal energy: the higher the temperature at which heat is exchanged, the more “useful” (noble) this energy is, and the greater its potential to be converted into work.**

For a **reversible transformation**:

where:
$$dS = \frac{\delta Q_{rev}}{T}$$

- dS = infinitesimal change in entropy (J/K),
- δQ_{rev} = heat exchanged in a reversible process (J),
- T = absolute temperature at which the heat transfer takes place (K).

To **reverse this transfer** (for example, to transfer heat from a cold body to a hot body), it is necessary to supply **external work** — this is the operating principle of **refrigeration machines** and **heat pumps**.

There are several forms of energy:

Thermal energy ; Mechanical energy ; Kinetic energy (E_c) ; Potential energy (E_p) ; Electrical energy ; Chemical energy ;
Nuclear energy.

The **internal energy** of a system corresponds to the sum of the microscopic energies (kinetic and potential) of the particles that make it up: translation, rotation, vibration, intermolecular interactions, as well as electronic and nuclear energies.

👉 It is therefore associated with **molecular motion** and **particle interactions**.

1 – Modes of Heat Transfer

There are three fundamental modes:

1. **Conduction**

2. **Convection**

Radiation

➤ These three modes can act simultaneously in most real situations.

Conduction

Definition

Conduction is the transfer of heat **within a material medium** (solid, liquid, or stationary gas) without macroscopic movement of matter.

👉 It is caused by **collisions between particles** (atoms, molecules, free electrons). Heat is transmitted only through **microscopic interactions** between neighboring particles.

- **In metals:**

conduction is mainly due to the movement of **free electrons**, which efficiently transport kinetic energy.

- **In fluids (stationary gases or liquids):**

heat transfer is related to **molecular collisions** caused by thermal agitation.

In a **moving fluid**, heat is transferred both by:

- **conduction** (microscopic exchanges between particles),
- and **convection** (macroscopic transport due to the motion of the fluid).

Loi de Fourier :

Fourier's Law (heat conduction)

- **Total heat flux:** $\Phi = -\lambda A \frac{dT}{dx}$
- **Heat flux density:** $\varphi = -\lambda \frac{dT}{dx}$

where:

- λ : thermal conductivity of the material (W/m·K)
- A : surface area crossed by the flux (m²)
- dT/dx : temperature gradient (temperature variation with respect to distance).

👉 **Interpretation:** heat always flows in the opposite direction to the temperature gradient (from the hot region to the cold region).

2. Convection

Definition

Convection is a mode of heat transfer that occurs in moving fluids (liquids or gases) when a **temperature gradient** is present

Fluid motion can be:

- **natural (free convection):** caused by density differences resulting from temperature variations (buoyancy effect),
- **forced convection:** generated by mechanical action, such as a pump, a fan, or mechanical stirring.

Summary:

- **No fluid motion** → heat transfer occurs only by **conduction**.
- **Fluid motion + temperature gradient** → heat transfer occurs by **convection** (which always includes a microscopic conduction contribution).

Convection combines:

- Conduction in the thin boundary layer of the fluid in contact with the surface.
- The movement of the fluid, which renews this boundary layer.

We distinguish three modes of convection:

- **Natural convection:** caused by density differences.

Example:

- Hot air rising near a radiator.
- Water circulating in a pan heated from below.

- **Forced convection:** produced by an external mechanical action (fan, pump, stirrer).

Example:

- Cooling of a processor by a fan.
- Water circulating in a heating circuit thanks to a pump.

- **Mixed convection:** results from the combination of natural and forced convection.

Example:

- Ventilation in a heated room: the air circulates both due to the fan (forced) and due to temperature differences (natural).
- Air flows around a vehicle heated by the sun and in motion.

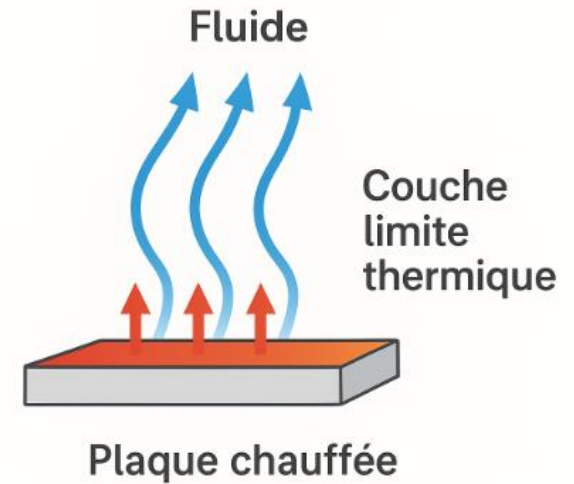
Newton's Law of Cooling

The determination of the heat flux exchanged by convection between the plate and the fluid is given by **Newton's law of cooling**:

Total heat flux: $\phi = h A(T_s - T_f)$

where:

- h : convection heat transfer coefficient (W/m².K),
- A : exchange surface area.
- T_s : surface temperature.
- T_f : fluid temperature.



3. Radiation

Definition

Thermal radiation is a mode of heat transfer that corresponds to the emission and absorption of energy in the form of electromagnetic waves by the surfaces of bodies. Unlike conduction and convection, it does not require any material medium and can propagate in a vacuum, but also through certain gases or partially transparent solids.

Fundamental Laws

Stefan–Boltzmann Law (blackbody): $E = \sigma T^4$

The total radiant power emitted per unit area of a blackbody is proportional to the fourth power of its absolute temperature T .

$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ is the Stefan–Boltzmann constant.

Real body (emissivity ϵ): $E = \epsilon \sigma T^4$

- For real surfaces, the emissivity factor ϵ (**with** $0 \leq \epsilon \leq 1$) accounts for the deviation from ideal blackbody behavior.

🏆 Wien's Law

The wavelength λ_{max} at which the emission is maximum is inversely proportional to the absolute temperature **T**.

$$\lambda_{\text{max}} = \frac{b}{T}$$

b=2.898×10⁻³ m.K is Wien's constant.