Chapter 2:

Heat Transfer via Convection
Without a change in phase
(no evaporation of fluid; no condensation)

On distinguant 3 modes de convection :

- **Convection naturelle** : due aux différences de densité.

  Exemple :

  - L’air chaud qui monte près d’un radiateur.
  - L’eau qui circule dans une casserole chauffée par le bas.

- **Convection forcée** : Provoquée par une **action extérieure mécanique** (ventilateur, pompe, agitateur).

  Exemple :

- Le refroidissement d’un processeur par un ventilateur.
- L’eau qui circule dans un circuit de chauffage grâce à une pompe.
- **Convection mixte**

  Résulte de la combinaison de la **convection naturelle** et de la **convection forcée**.

- Exemple :

  - La ventilation dans une pièce chauffée : l’air circule à la fois à cause du ventilateur (forcé) et des différences de température (naturel).

Les flux d’air autour d’un véhicule chauffé par le soleil et en mouvement.

2.1 Introduction

In the previous chapter, the phenomenon of convection was considered solely as a boundary condition in conduction problems. Sometimes, convection itself is a heat transfer mode independent of conduction. In industrial processes, convection plays a crucial role as it allows heat transfer between a solid surface and a fluid, as well as between fluids themselves. Heat transfer by convection is governed by Newton’s law, which is used to calculate the heat flux transferred by convection. The convection heat transfer coefficient is an essential parameter to determine; it depends not only on fluid properties but also on the geometry of the surface and the conditions in which the fluid is found, such as its velocity. The layer of fluid separating it from the solid surface also plays an important role in the heat transfer by convection.

2.2 Definition and mechanisms of convection

Convection is defined as the mode of heat transfer between a solid surface and a fluid (liquid or gas) at different temperatures. Therefore, it is a heat transfer accompanied by fluid motion.

In convection, heat transfer at the solid surface occurs only by conduction. However, in the parts of the fluid surrounding the surface, two phenomena happen simultaneously: conduction and mass diffusion due to molecular and macroscopic movement. This movement enhances the heat flux transferred; the greater the velocity, the more significant the heat transfer. The mechanism of heat transfer by convection can be summarized as follows: the fluid in contact with the solid surface receives heat from it by conduction, and then transmits it to the rest of the fluid not in direct contact with the surface by diffusion, thanks to fluid motion.

At the solid surface, heat flux is thus calculated by Fourier's law because it is conduction:

$$\phi = -\lambda S \frac{dT}{dx} \qquad (2.1)$$

In the other part of the fluid, farther from the surface, the determination of the heat flux exchanged by convection between the plate and the fluid is given by Newton's cooling law:

$$\phi = hS(T_p - T_\infty) \qquad Si \quad T_p > T_\infty \qquad (2.2)$$

$$\phi = hS(T_\infty - T_p) \qquad Si \quad T_\infty > T_p$$

The main problem to solve before calculating the heat flux is to determine the coefficient **h**, which depends on several parameters. The convection coefficient can be calculated by equating the heat flux at the contact with the solid surface:

$$-\lambda S \frac{\partial T}{\partial y} = hS\left(T_p - T_\infty\right) \Rightarrow h = \frac{-\lambda S \frac{\partial T}{\partial y}}{T_p - T_\infty} \qquad (2.3)$$

The convection coefficient h depends on several factors:

- Geometry of the solid (or plate)
- Surface condition of the solid (smooth or rough)
- Physical nature of materials
- Physical properties of the fluid
- Fluid velocity
- Temperature difference

Convection modes and corresponding **h** values:

Mode de convection		h
Convection naturelle	Gaz	2 - 25
	Liquide	50 - 100
Convection forcée	Gaz	25 - 250
	Liquide	50 - 20 000
Convection avec changement de phase	Ébullition ou condensation	2500 – 100 000

- In <u>natural convection</u>, **h** depends on two dimensionless numbers, **Gr and Pr**:

h = f(Gr, Pr)

Where **Gr** is the Grashof number and **Pr** is the Prandtl number.

Nusselt number **Nu** also depends on **Gr and Pr**: **Nu = f(Gr, Pr)**

$$\boldsymbol{Nu = \cdots \dots \dots \dots \dots \dots \dots}$$

- In <u>forced convection</u>, **h** depends on Re and Pr:

h = f(Re, Pr)

Pr is the Prandtl number.

Nusselt number **Nu** also depends on **Re** and **Pr** : $\boldsymbol{Nu = f(Re, Pr)}$

$$\boldsymbol{Nu = \cdots \dots \dots \dots \dots \dots \dots}$$

The worker requested the physical meaning of each dimension number.

- The complexity of **h** arises from the influence of all previously cited characteristics. Their effect on h is predominant in a zone close to the solid surface called the boundary layer.

The boundary layer corresponds to the region near the solid surface where the fluid experiences viscosity effects: its velocity varies from zero (adhesion to the wall) to the free stream velocity.

Near the surface, heat transfer thus depends on the same phenomena as the transfer of momentum. In this zone, two sublayers are often distinguished:

- The hydrodynamic boundary layer, where the velocity gradient dominates
- The thermal boundary layer, where the temperature gradient dominates

When considering heat transfer within the boundary layer that forms along a solid surface in contact with a moving fluid, two main mechanisms are involved: conduction near the wall and convection further from the surface. The balance between these two phenomena explains the value of **h**.

1- Conduction zone (near the wall)

In the very first layer of fluid, right at the contact with the solid, fluid molecules are almost stationary compared to the surface (adhesion). Here, heat transfer occurs mainly by thermal conduction: energy is transmitted from molecule to molecule, from the hot or cold surface to the fluid. This zone is very thin but essential, as it's where the temperature gradient is highest.

2. Convection zone (farther from the wall)

As you move away from the wall, the fluid begins to move: heat transfer then becomes convective. Fluid movement carries the heat, transporting energy away from the wall.

- **Thickness of the boundary layer and temperature profile**

  The key problem in convection is determining the convection coefficient h. It’s necessary to know the surface geometry and fluid flow conditions, and to identify the fluid part in direct contact with the solid surface. This very thin part is directly affected by the solid’s temperature and is called the thermal boundary layer.

  The fluid is divided into two zones: boundary layer and free flow. The thermal boundary layer is defined as the zone in which the temperature drops from that of the wall to the following value: $T = 99\%\, T_\infty = 0.99\, T_\infty$

The thickness of the thermal boundary layer, usually denoted δt, represents the distance from the surface to the point where the fluid temperature approaches that of the undisturbed ("bulk") fluid. It equals the vertical distance between the wall and the zone where : $\frac{T_P - T}{T_p - T_\infty} = 0.99$

A temperature profile develops in this layer: it’s steep near the wall (dominant conduction) then more spread out farther away (dominant convection).

Figure 2.1 shows both the hydrodynamic and thermal boundary layers

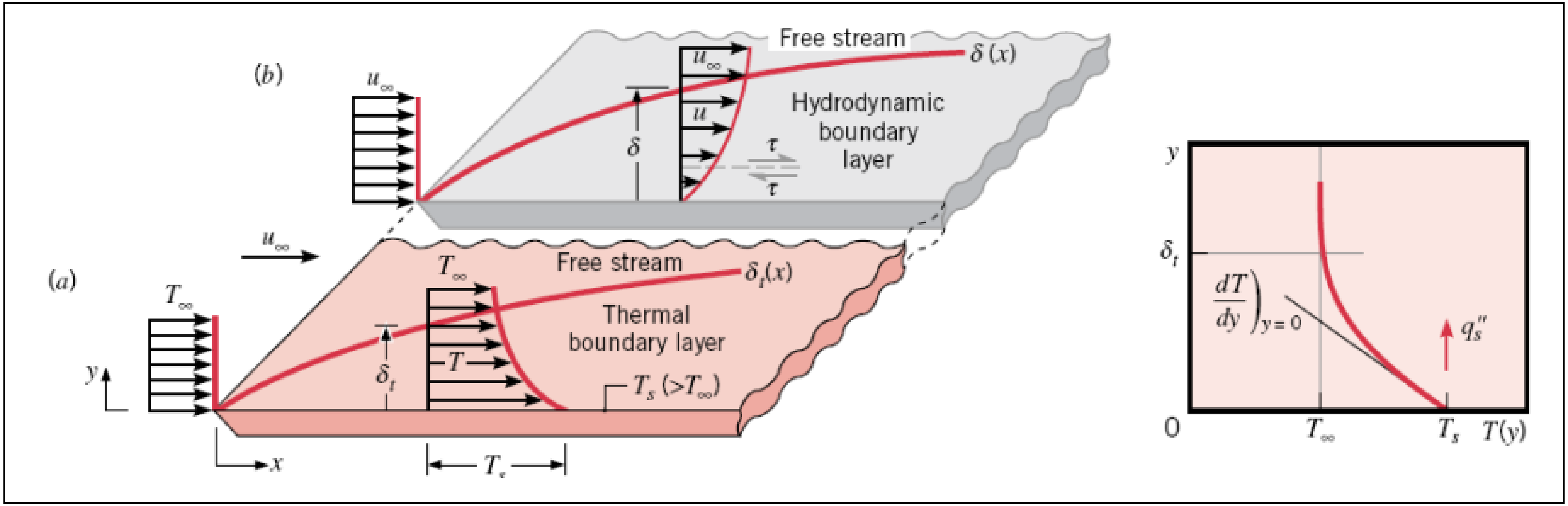

Fig.2 .1 Hydrodynamic and thermal boundary layers [1].

Hydrodynamic and thermal boundary layers ensure the transition between fluid and solid. The velocity of free flow and its laminar or turbulent regime are key factors for calculating h. The more turbulent the flow, the better the mixing and the more efficient the heat transfer.

Transition from laminar to turbulent regime can be known by calculating the critical Reynolds number. $Re = \frac{U_\infty x}{\nu}$

U_∞ is the free flow velocity away from the solid obstacle and ν is the kinematic viscosity In m^2/s : $\nu = \frac{\mu}{\rho}$;

μ : *est la viscosité dynamique.*

In the case of a flow in a cylindrical or spherical tube of diameter D, the Reynolds number is: $Re_c = \frac{U_\infty D}{\nu} = \frac{\rho U_\infty D}{\mu}$

The Reynolds number represents the ratio of inertial forces to viscous forces. The critical Reynolds number depends on the surface roughness and the level of turbulence of the free stream. It is generally on the order of $\mathbf{10^5}$ **to** $\mathbf{3 \times 10^6}$. For cylinders, it is typically equal to **2300**. It characterizes the transition from laminar to turbulent flow, that is:

if $\boldsymbol{Re} < \boldsymbol{Re_c}$, the flow is laminar

if $\boldsymbol{Re} > \boldsymbol{Re_c}$, the flow is turbulent.

In general, the representative value of the critical Reynolds number is:

$\boldsymbol{Re_c} = \mathbf{5x10^5}$ for flat plates

$\boldsymbol{Re_c} = \mathbf{2300}$ for cylinders and spheres

- The value of the convection coefficient **h** depends on the mode of transfer throughout the boundary layer:

- A thin boundary layer (steep temperature gradient and efficient conduction) leads to high **h**
- A thick boundary layer (shallow gradient) leads to low **h**

The transition from conduction near the wall to convection further away explains why h depends heavily on flow conditions (laminar or turbulent), fluid properties (viscosity, thermal conductivity, Prandtl number) and surface state.

Schematic summary:

- Near the surface: heat transferred by conduction in nearly stationary fluid
- Further away: heat transferred by convection — heat is carried by fluid movement
- Boundary layer thickness: defines the “frontier” where transfer becomes mainly convective

Studying this region (boundary layer) allows predicting thermal exchanges, optimizing cooling devices (fins, heat exchangers), and improving numerical convection simulations