

Heat Exchangers

Chapter 2:

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

1st year Master

Chemical Engineering & Pharmaceutical Engineering

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:

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

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:

$$\phi = hS(T_p - T_\infty) \quad \text{Si} \quad T_p > T_\infty \quad (2.2)$$

$$\phi = hS(T_\infty - T_p) \quad \text{Si} \quad T_\infty > T_p$$

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:

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

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 forced convection, **h** depends on **Re** and **Pr**:

$$\mathbf{h} = \mathbf{f}(\mathbf{Re}, \mathbf{Pr})$$

Pr is the Prandtl number.

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

$$\mathbf{Nu} = \frac{h.L}{\lambda_f} \quad ; \quad \mathbf{Pr} = \frac{c_{pf} \cdot \mu_f}{\lambda_f}$$

K_f, τ_{pf}, μ_f : *fluids properties*

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

$$\mathbf{h} = \mathbf{f}(\mathbf{Gr}, \mathbf{Pr})$$

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

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

Interpretation of numbers without convection-specific dimensions

Table 2.1 gives the expression and significance of these dimensionless numbers.

Nombre	Expression	Interprétation
Nusselt	$Nu = \frac{hL}{\lambda}$	Gradient de la température à la surface. Permet de calculer le coefficient de convection
Reynolds	$Re = \frac{VL}{\nu}$	Compare les forces d'inertie aux forces de viscosité. Convection forcée
Prandtl	$Pr = \frac{c_p \mu}{\lambda} = \frac{\nu}{\alpha}$	Compare le transfert de chaleur par les forces visqueuses au transfert par conduction.
Grashof	$Gr = \frac{\beta \times \Delta T \times L^3 \times \rho^2 \times g}{\mu^2}$ $= \frac{g\beta(T_p - T_\infty)L^3}{\nu^2}$	Compare les forces de gravité aux forces de viscosité. Convection libre.
Rayleigh	$Ra = Gr \times Pr$ $= \frac{g \times \beta \times \Delta T \times L^3 \times \rho^2 \times c_p}{\lambda \times \mu}$	Convection libre.
Peclet	$Pe = Pr \times Re = \frac{\rho c_p VL \Delta T}{\lambda \Delta T}$	Compare la capacité calorifique du fluide à la conductivité axiale.

c_p : la [capacité thermique massique](#) à pression constante (en $\text{J kg}^{-1} \text{K}^{-1}$)

Main influencing factors:

- **Reynolds number (Re):** expresses ratio of inertial to viscous forces; determines whether flow is laminar or turbulent
- **Prandtl number (Pr):** relates the diffusion of momentum to thermal diffusion
- **Nusselt number (Nu):** relates convective transfer to conductive transfer and is used to calculate h by: $h = \frac{\lambda \cdot Nu}{L}$

where λ is the thermal conductivity and **L** the characteristic length

Type de convection	Milieu	h (W/m ² ·K)
Convection naturelle	Air	5 – 25 <small>solidworks</small>
Convection forcée	Air	20 – 300 <small>solidworks</small>
Convection forcée	Eau	100 – 50 000 <small>energetique.uae</small>
Convection naturelle	Liquides	100 – 1000 <small>energetique.uae</small>

- ❖ The value of h varies greatly according to fluid type and flow regime: turbulence and fluid thermal conductivity greatly increase heat transfer.

- 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 δ_t , 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

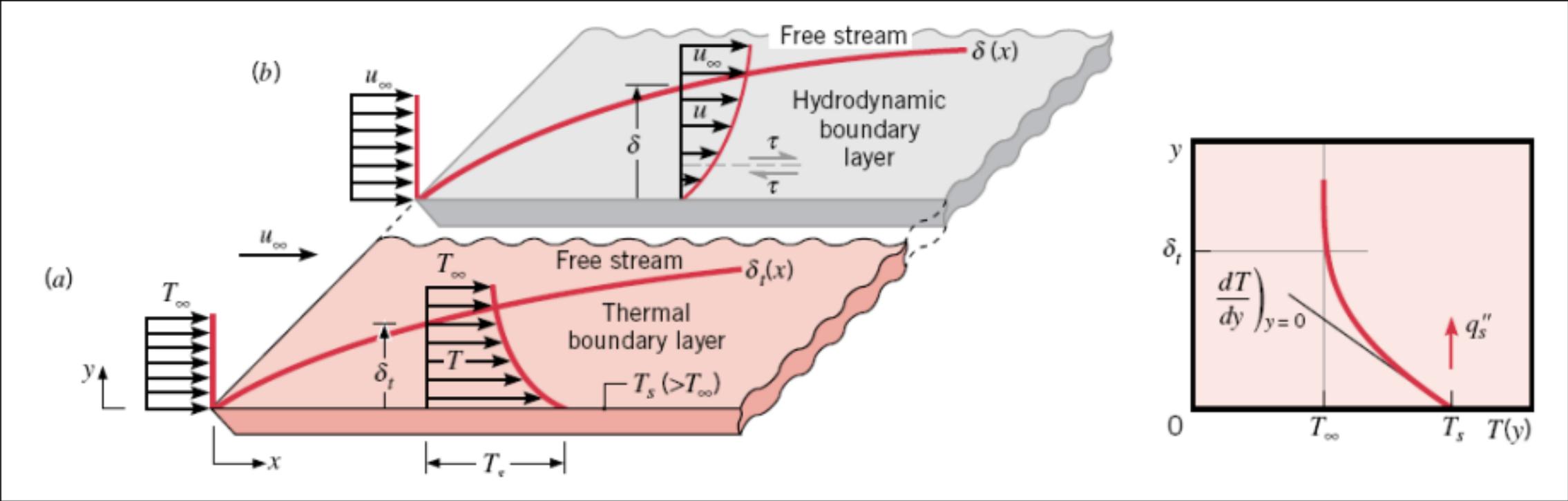


Fig.2 .1 Hydrodynamic and thermal boundary layers [1].

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 10^5 to 3×10^6 . For cylinders, it is typically equal to **2300**. It characterizes the transition from laminar to turbulent flow, that is:

if $Re < Re_c$, the flow is laminar

if $Re > Re_c$, the flow is turbulent.

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

$Re_c = 5 \times 10^5$ for flat plates

$Re_c = 2300$ 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

2.5- Steps for Selecting a Correlation in Calculating the Convection Coefficient

In all cases of convection, selecting the correlation that allows calculation of the convection coefficient h involves the following steps:

- Identify the geometry of the solid surface by determining whether the flow is internal or external, or whether it occurs on a flat plate or a cylinder.
- Calculate the specific or reference temperature T_{ref} , which is used to find the fluid properties such as viscosity and thermal conductivity in tables.
- For external isothermal flows:

$$T_{ref} = T_p = T_\infty \quad (2.12)$$

- For external flows with heat transfer:

$$T_{ref} = \frac{T_p + T_\infty}{2} \quad (2.13)$$

- For internal isothermal flows:

$$T_{ref} = T_p \quad (2.14)$$

- For internal flows with heat transfer: the reference temperature is equal to T_p for calculating the local Nusselt number, and equal to equation (2.13) for calculating the average Nusselt number.
- Calculate the Reynolds number: to determine whether the flow regime is laminar or turbulent.
- Decide whether to use a local or average convection coefficient: the local coefficient is used to determine the heat flux density at a specific point on the surface, while the average coefficient is used to calculate the heat transfer over the entire surface.
- Select the appropriate correlation to calculate the convection coefficient h .

2.6- Practical Correlations for Calculating the Thermal Convection Coefficient

The correlation used to calculate the Nusselt number to obtain the value of the convection coefficient h depends on the geometry and the type of flow. Each case has its own specific expression. The local Nusselt number at location x is denoted by Nu_x , while the overall Nusselt number is denoted by \overline{Nu} . $\overline{Nu} = 2 Nu$

2.6.1- Correlations for flow through flat plates

In all these cases :

$$\bar{Nu} = 2Nu_L$$

- **Laminar Regime**

These values are valid for $0.6 < Pr < 50$:

- The local Nusselt number is:

$$Nu_x = 0.332 Re_x^{0.5} Pr^{0.33} \quad (2.16)$$

The global Nusselt number is:

$$\bar{Nu} = 2Nu_L = 0.664 Re_L^{0.5} Pr^{0.33} \quad (2.17)$$

For liquid metals and silicones where $Pr < 0.05$ or $Pr > 50$ and $Re > 100$, the local Nusselt number is:

$$Nu_x = \frac{0.3387 Re_x^{0.5} Pr^{0.33}}{[1 + (0.0468/Pr)^{0.67}]^{0.25}} \quad (2.18)$$

- **Constant heat flux**

-For $0.6 < Pr < 50$, the local Nusselt number is:

$$Nu_x = 0.453 Re_x^{0.5} Pr^{0.333} \quad (2.19)$$

This correlation is widely accepted for laminar flow over a flat plate with a constant surface heat flux.

-For $Pr < 0.05$ or $Pr > 50$, the local Nusselt number is:

$$Nu_x = \frac{0.453 Re_x^{0.5} Pr^{0.333}}{[1+(0.0207/Pr)^{0.67}]^{0.25}} \quad (2.20)$$

Example 2.6

In an industrial process, water at 30°C flows over a plate with dimensions 1m x 1m maintained at 10°C with a free stream velocity of 0.3 m/s. Calculate the required heat flux to ensure the cooling of this plate.

Solution

This is a thermal convection problem. The heat flux is given by Newton's law:

$$\phi = \bar{h}S(T_p - T_\infty)$$

where $T_p = 10^\circ\text{C}$, $T_\infty = 30^\circ\text{C}$. The convection coefficient h must be determined.

Start by establishing the flow regime by calculating the Reynolds number:

$$Re = \frac{VL}{\nu}$$

The properties of the fluid must be known. To do this, the reference temperature is calculated:

$$T_{ref} = \frac{T_p + T_\infty}{2} = \frac{10 + 30}{2} = 20^\circ\text{C}$$

According to table B-3, at this temperature:

$$\rho = 1000.52 \text{ kg/m}^3, \quad c_p = 4.1818 \text{ J/(kg K)}, \quad \nu = 1.06 \times 10^{-6} \text{ m}^2/\text{s}, \quad \lambda = 0.597 \text{ W/(m K)}, \quad \alpha = 1.430 \times 10^{-7} \text{ m}^2/\text{s}$$

$$Re = \frac{VL}{\nu} = \frac{0,3 \times 1}{1,006 \times 10^{-6}} = 2,98 \times 10^5 < 5 \times 10^5$$

Therefore, the flow regime is laminar.

The Prandtl number is calculated as:

$$Pr = \frac{c_p \mu}{\lambda} = \frac{\nu}{\alpha} = \frac{1.006 \times 10^{-6}}{1.430 \times 10^{-7}} = 7.03$$

For flow over a flat plate in the laminar regime with $0.6 < Pr < 50$:

$$\bar{Nu} = 2Nu_L = 0.664 Re_L^{0.5} Pr^{0.33} = 0.664 \times (2.98 \times 10^5)^{0.5} \times 7.03^{0.33} = 1038.97 \approx 1039$$

Since:

$$\bar{Nu} = \frac{hL}{\lambda} \Rightarrow h = \frac{\lambda \bar{Nu}}{L} = \frac{0.597 \times 1039}{1} = 620.283 \text{ W}/(m^2 K)$$

The heat flux required for cooling the plate is:

$$\phi = 620.283 \times 1 \times 1 \times (30 - 10) = 12405.66 \text{ W} = 12.4056 \text{ kW}$$

Example 2.7

Air at -10°C flows over a plate 3.1 m long maintained at 10°C with a free-stream velocity of 80 m/s.

1. Determine the abscissa x from which the flow becomes turbulent.
2. Calculate the local convection coefficient at that location, considering the flow to be turbulent.

Solution

1. The flow becomes turbulent when: $Re_x > 5 \cdot 10^5$. Thus: $Re_c = 5 \cdot 10^5$.

$Re_x = \frac{Vx}{\nu} \Rightarrow x = \frac{Re_x \times \nu}{V}$ The abscissa at which the flow becomes turbulent therefore corresponds to:

$x = \frac{Re_c \times \nu}{V}$ To determine the kinematic viscosity, we compute the reference temperature:

$T_{\text{ref}} = \frac{T_p + T_{\infty}}{2} = \frac{10 + (-10)}{2} = 0^{\circ}\text{C}$ We interpolate the viscosity values between 250 K and 300 K from table B-4:

$$\Rightarrow \nu(273.15) = \frac{\nu(300) - \nu(250)}{300 - 250} (273.15 - 250) + \nu(250)$$

$$\nu(273.15) = \frac{15.69 - 11.31}{300 - 250} \times 10^{-6} (273.15 - 250) + 11.31 \times 10^{-6} = 13.34 \times 10^{-6} \text{ m}^2/\text{s}$$

Therefore:

$$x = \frac{5 \times 10^5 \times 13.34 \times 10^{-6}}{80} = 0.0833 \text{ m}$$

This length is smaller than L , hence turbulence exists along the plate.

Turbulence exists in the plate.

2. The local Nusselt number is: $Nu_x = 0.0296 Re_x^{0.8} Pr^{0.33}$

We interpolate from Table B-4 to find the Prandtl number at 0°C:

$$Pr(273.15) = \frac{0.708 - 0.722}{300 - 250} \times (273.15 - 250) + 0.722 = 0.715$$

$$Nu_x = 0.0296 (5 \times 10^5)^{0.8} \times 0.715^{0.33} = 960.26$$

$h_x = \frac{\lambda Nu_x}{x}$; We calculate λ by interpolation:

$$\lambda(273.15) = \frac{0.02624 - 0.02227}{300 - 250} \times (273.15 - 250) + 0.02227 = 0.02411 \text{ W/mK}$$

$$h_x = \frac{0.02411 \times 960.26}{0.0833} = 277.93 \text{ W/m}^2\text{K}$$

2.8.3 Correlations for Flow Around a Cylinder

The flow around a cylinder generates streamlines as shown in figure 2.2.

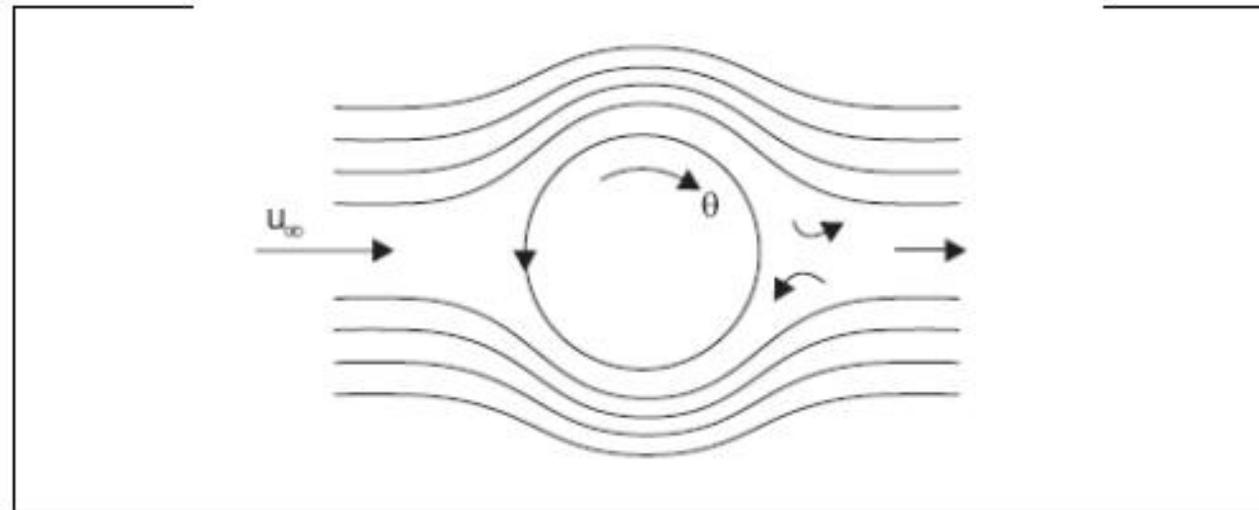


Fig. 2.2 Flow across a cylinder

There are several correlations for this type of flow. One of the simplest is the following, which is valid for liquids for $2 \times 10^4 < Re < 4 \times 10^5$ and $Pr > 0.2$:

$$Nu_D = 0.3 + \frac{0.62Re_D^{0.5} Pr^{0.33}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{0.67}\right]^{0.25}} \left[1 + \left(\frac{Re_D}{282000}\right)^{0.5}\right] \quad (2.24)$$

For liquid metals:

$$Nu_D = [0.8237 - \ln(Pr_D^{0.5})]^{-1} \quad (2.25)$$

2.8.4 Correlations for Flow Around a Sphere

For $0.71 < Pr < 380$ and $3.5 < Re < 7.6 \times 10^4$, the following correlation is applicable:

$$Nu_D = 2 + (0.4Re^{0.5} + 0.06Re^{0.67})Pr^{0.4} \left(\frac{\mu}{\mu_\infty}\right)^{0.25} \quad (2.26)$$

2.8.5 Correlations for Internal Flow in Tubes

Laminar Regime

The laminar regime in tubes is determined by $Re < 2300$.

For circular tubes with a uniform surface and under laminar regime with constant flux, the Nusselt number is constant:

$$Nu_D = 4.36 \quad (2.27)$$

In the case of circular tubes with constant surface temperature, the Nusselt number is also constant:

$$Nu_D = 3.66 \quad (2.28)$$

Turbulent regime

The most commonly used correlation for smooth tubes is the following:

$$Nu = 0.023 Re^{0.8} Pr^n \quad (2.29) \quad \text{where: } n = 0.3 \text{ for cooling and } n = 0.4 \text{ for heating.}$$

2.8.6 Correlations for Natural Convection

In natural convection, the Prandtl (Pr) and Grashof (Gr), thus Rayleigh (Ra), numbers are used in the correlations.

All the correlations have the following form:

$$Nu = C(Gr \times Pr)^n = C \times Ra^n \quad (2.30) \quad C \text{ and } n \text{ depend on the geometry of the surfaces.}$$

Vertical Plates

$$\bar{Nu}_L = 0.59 \times Ra_L^{0.25} \quad 10^4 \leq Ra_L \leq 10^9 \quad (2.31)$$

$$\bar{Nu}_L = 0.10 \times Ra_L^{0.33} \quad 10^9 \leq Ra_L \leq 10^{13} \quad (2.32)$$

A more general correlation can also be applied in all these cases, regardless of the Rayleigh number:

$$\bar{Nu}_L = \left\{ 0.825 + \frac{0.387 Ra_L^{0.16}}{[1 + (0.492/Pr)^{0.56}]^{0.3}} \right\}^2 \quad (2.33)$$

Horizontal Plates

For a hot surface with flow below or a cold surface with flow above (cases A and B in figure 2.3):

$$\bar{Nu}_L = 0.27 Ra_L^{0.25} \quad 10^5 \leq Ra_L \leq 10^{10} \quad (2.34)$$

For a hot surface with flow above or a cold surface with flow below (cases C and D in figure 2.3):

$$N\bar{u}_L = 0.54Ra_L^{0.25}10^4 \leq Ra_L \leq 10^7 \quad (2.35)$$

$$N\bar{u}_L = 0.15Ra_L^{0.33}10^7 \leq Ra_L \leq 10^{11} \quad (2.36)$$

Horizontal Cylinders and Spheres

For flow around horizontal cylinders:

$$N\bar{u}_D = \left\{0.60 + \frac{0.387Ra_D^{0.16}}{[1+(0.559/Pr)^{0.56}]^{0.3}}\right\}^2 Ra_D \leq 10^{12} \quad (2.37)$$

For flow around horizontal spheres:

$$N\bar{u}_D = 2 + \frac{0.589Ra_D^{0.25}}{[1 + (0.469/Pr)^{0.56}]^{0.44}} Ra_D \leq 10^{11}, Pr \geq 0.7 \quad (2.38)$$

ANNEXE

PROPRIETES DES LIQUIDES A L'ETAT DE SATURATION (SUITE)

t (°C)	ρ (kg/m ³)	c_p (J/kg·K)	ν (m ² /s)	k (W/m·K)	α (m ² /s)	Pr	β (K ⁻¹)
Water, H ₂ O							
0	1 002.28	4.2178×10^3	1.788×10^{-6}	0.552	1.308×10^{-7}	13.6	0.18×10^{-3}
20	1 000.52	4.1818	1.006	0.597	1.430	7.02	
40	994.59	4.1784	0.658	0.628	1.512	4.34	
60	985.46	4.1843	0.478	0.651	1.554	3.02	
80	974.08	4.1964	0.364	0.668	1.636	2.22	
100	960.63	4.2161	0.294	0.680	1.680	1.74	
120	945.25	4.250	0.247	0.685	1.708	1.446	
140	928.27	4.283	0.214	0.684	1.724	1.241	
160	909.69	4.342	0.190	0.680	1.729	1.099	
180	889.03	4.417	0.173	0.675	1.724	1.004	
200	866.76	4.505	0.160	0.665	1.706	0.937	
220	842.41	4.610	0.150	0.652	1.680	0.891	
240	815.66	4.756	0.143	0.635	1.639	0.871	
260	785.87	4.949	0.137	0.611	1.577	0.874	
280.6	752.55	5.208	0.135	0.580	1.481	0.910	
300	714.26	5.728	0.135	0.540	1.324	1.019	

Ammonia, NH ₃							
-50	703.69	4.463×10^3	0.435×10^{-6}	0.547	1.742×10^{-7}	2.60	2.45×10^{-3}
-40	691.68	4.467	0.406	0.547	1.775	2.28	
-30	679.34	4.476	0.387	0.549	1.801	2.15	
-20	666.69	4.509	0.381	0.547	1.819	2.09	
-10	653.55	4.564	0.378	0.543	1.825	2.07	
0	640.10	4.635	0.373	0.540	1.819	2.05	
10	626.16	4.714	0.368	0.531	1.801	2.04	
20	611.75	4.798	0.359	0.521	1.775	2.02	
30	596.37	4.890	0.349	0.507	1.742	2.01	
40	580.99	4.999	0.340	0.493	1.701	2.00	
50	564.33	5.116	0.330	0.476	1.654	1.99	
Carbon dioxide, CO ₂							
-50	1 156.34	1.84×10^3	0.119×10^{-6}	0.0855	0.4021×10^{-7}	2.96	14.00×10^{-3}
-40	1 117.77	1.88	0.118	0.1011	0.4810	2.46	
-30	1 076.76	1.97	0.117	0.1116	0.5272	2.22	
-20	1 032.39	2.05	0.115	0.1151	0.5445	2.12	
-10	983.38	2.18	0.113	0.1099	0.5133	2.20	
0	926.99	2.47	0.108	0.1045	0.4578	2.38	
10	860.03	3.14	0.101	0.0971	0.3608	2.80	
20	772.57	5.0	0.091	0.0872	0.2219	4.10	
30	597.81	36.4	0.080	0.0703	0.0279	28.7	

t (°C)	ρ (kg/m ³)	c_p (J/kg·K)	ν (m ² /s)	k (W/m·K)	α (m ² /s)	Pr	β (K ⁻¹)
Sulfur dioxide, SO ₂							
-50	1 560.84	1.3595 × 10 ³	0.484 × 10 ⁻⁶	0.242	1.141 × 10 ⁻⁷	4.24	1.94 × 10 ⁻³
-40	1 536.81	1.3607	0.424	0.235	1.130	3.74	
-30	1 520.64	1.3616	0.371	0.230	1.117	3.31	
-20	1 488.60	1.3624	0.324	0.225	1.107	2.93	
-10	1 463.61	1.3628	0.288	0.218	1.097	2.62	
0	1 438.46	1.3636	0.257	0.211	1.081	2.38	
10	1 412.51	1.3645	0.232	0.204	1.066	2.18	
20	1 386.40	1.3653	0.210	0.199	1.050	2.00	
30	1 359.33	1.3662	0.190	0.192	1.035	1.83	
40	1 329.22	1.3674	0.173	0.185	1.019	1.70	
50	1 299.10	1.3683	0.162	0.177	0.999	1.61	
Methyl chloride, CH ₃ Cl							
-50	1 052.58	1.4759 × 10 ³	0.320 × 10 ⁻⁶	0.215	1.388 × 10 ⁻⁷	2.31	
-40	1 033.35	1.4826	0.318	0.209	1.368	2.32	
-30	1 016.53	1.4922	0.314	0.202	1.337	2.35	
-20	999.39	1.5043	0.309	0.196	1.301	2.38	
-10	981.45	1.5194	0.306	0.187	1.257	2.43	
0	962.39	1.5378	0.302	0.178	1.213	2.49	
10	942.36	1.5600	0.297	0.171	1.166	2.55	
20	923.31	1.5860	0.293	0.163	1.112	2.63	
30	903.12	1.6161	0.288	0.154	1.058	2.72	
40	883.10	1.6504	0.281	0.144	0.996	2.83	
50	861.15	1.6890	0.274	0.133	0.921	2.97	

Dichlorodifluoromethane (Freon), CCl ₂ F ₂							
-50	1 546.75	0.8750 × 10 ³	0.310 × 10 ⁻⁶	0.067	0.501 × 10 ⁻⁷	6.2	2.63 × 10 ⁻³
-40	1 518.71	0.8847	0.279	0.069	0.514	5.4	
-30	1 489.56	0.8956	0.253	0.069	0.526	4.8	
-20	1 460.57	0.9073	0.235	0.071	0.539	4.4	
-10	1 429.49	0.9203	0.221	0.073	0.550	4.0	
0	1 397.45	0.9345	0.214	0.073	0.557	3.8	
10	1 364.30	0.9496	0.203	0.073	0.560	3.6	
20	1 330.18	0.9659	0.198	0.073	0.560	3.5	
30	1 295.10	0.9835	0.194	0.071	0.560	3.5	
40	1 257.13	1.0019	0.191	0.069	0.555	3.5	
50	1 215.96	1.0216	0.190	0.067	0.545	3.5	
Eutectic calcium chloride solution, 29.9% CaCl ₂							
-50	1 319.76	2.608 × 10 ³	36.35 × 10 ⁻⁶	0.402	1.166 × 10 ⁻⁷	312	
-40	1 314.96	2.6356	24.97	0.415	1.200	208	
-30	1 310.15	2.6611	17.18	0.429	1.234	139	
-20	1 305.51	2.688	11.04	0.445	1.267	87.1	
-10	1 300.70	2.713	6.96	0.459	1.300	53.6	

t (°C)	ρ (kg/m ³)	c_p (J/kg·K)	ν (m ² /s)	k (W/m·K)	α (m ² /s)	Pr	β (K ⁻¹)
Eutectic calcium chloride solution, 29.9% CaCl ₂ (continued)							
0	1 296.06	2.738×10^3	4.39×10^{-6}	0.472	1.332×10^{-7}	33.0	
10	1 291.41	2.763	3.35	0.485	1.363	24.6	
20	1 286.61	2.788	2.72	0.498	1.394	19.6	
30	1 281.96	2.814	2.27	0.511	1.419	16.0	
40	1 277.16	2.839	1.92	0.523	1.445	13.3	
50	1 272.51	2.868	1.65	0.535	1.468	11.3	
Glycerin, C ₃ H ₅ (OH) ₃							
0	1 276.03	2.261×10^3	0.008 31	0.282	0.983×10^{-7}	84.7×10^3	
10	1 270.11	2.319	0.003 00	0.284	0.965	31.0	
20	1 264.02	2.386	0.001 18	0.286	0.947	12.5	0.50×10^{-3}
30	1 258.09	2.445	0.000 50	0.286	0.929	5.38	
40	1 252.01	2.512	0.000 22	0.286	0.914	2.45	
50	1 244.96	2.583	0.000 15	0.287	0.893	1.63	
Ethylene glycol, C ₂ H ₄ (OH) ₂							
0	1 130.75	2.294×10^3	57.53×10^{-6}	0.242	0.934×10^{-7}	615	
20	1 116.65	2.382	19.18	0.249	0.939	204	0.65×10^{-3}
40	1 101.43	2.474	8.69	0.256	0.939	93	
60	1 087.66	2.562	4.75	0.260	0.932	51	
80	1 077.56	2.650	2.98	0.261	0.921	32.4	
100	1 058.50	2.742	2.03	0.263	0.908	22.4	

Engine oil (unused)							
0	899.12	1.796×10^3	0.004 28	0.147	0.911×10^{-7}	47 100	0.70×10^{-3}
20	888.23	1.880	0.000 90	0.145	0.872	10 400	
40	876.05	1.964	0.000 24	0.144	0.834	2 870	
60	864.04	2.047	0.839×10^{-4}	0.140	0.800	1 050	
80	852.02	2.131	0.375	0.138	0.769	490	
100	840.01	2.219	0.203	0.137	0.738	276	
120	828.96	2.307	0.124	0.135	0.710	175	
140	816.94	2.395	0.080	0.133	0.686	116	
160	805.89	2.483	0.056	0.132	0.663	84	
Mercury, Hg							
0	13 628.22	0.1403×10^3	0.124×10^{-6}	8.20	42.99×10^{-7}	0.0288	1.82×10^{-4}
20	13 579.04	0.1394	0.114	8.69	46.06	0.0249	
50	13 505.84	0.1386	0.104	9.40	50.22	0.0207	
100	13 384.58	0.1373	0.0928	10.51	57.16	0.0162	
150	13 264.28	0.1365	0.0853	11.49	63.54	0.0134	
200	13 144.94	0.1570	0.0802	12.34	69.08	0.0116	
250	13 025.60	0.1357	0.0765	13.07	74.06	0.0103	
315.5	12 847	0.134	0.0673	14.02	81.5	0.0083	

T (K)	ρ (kg/m ³)	c_p (J/kg·K)	μ (kg/m·s)	ν (m ² /s)	k (W/m·K)	α (m ² /s)	Pr
Carbon dioxide							
220	2.4733	0.783×10^3	11.105×10^{-6}	4.490×10^{-6}	0.010 805	$0.059 20 \times 10^{-4}$	0.818
250	2.1657	0.804	12.590	5.813	0.012 884	0.074 01	0.793
300	1.7973	0.871	14.958	8.321	0.016 572	0.105 88	0.770
350	1.5362	0.900	17.205	11.19	0.020 47	0.148 08	0.755
400	1.3424	0.942	19.32	14.39	0.024 61	0.194 63	0.738
450	1.1918	0.980	21.34	17.90	0.028 97	0.248 13	0.721
500	1.0732	1.013	23.26	21.67	0.033 52	0.308 4	0.702
550	0.9739	1.047	25.08	25.74	0.038 21	0.375 0	0.685
600	0.8938	1.076	26.83	30.02	0.043 11	0.448 3	0.668
Carbon monoxide							
220	1.553 63	1.0429×10^3	13.832×10^{-6}	8.903×10^{-6}	0.019 06	$0.117 60 \times 10^{-4}$	0.758
250	0.841 0	1.0425	15.40	11.28	0.021 44	0.150 63	0.750
300	1.138 76	1.0421	17.843	15.67	0.025 25	0.212 80	0.737
350	0.974 25	1.0434	20.09	20.62	0.028 83	0.283 6	0.728
400	0.853 63	1.0484	22.19	25.99	0.032 26	0.360 5	0.722
450	0.758 48	1.0551	24.18	31.88	0.043 6	0.443 9	0.718
500	0.682 23	1.0635	26.06	38.19	0.038 63	0.532 4	0.718
550	0.620 24	1.0756	27.89	44.97	0.041 62	0.624 0	0.721
600	0.568 50	1.0877	29.60	52.06	0.044 46	0.719 0	0.724

Ammonia, NH ₃							
220	0.3828	2.198×10^3	7.255×10^{-6}	1.90×10^{-5}	0.0171	0.2054×10^{-4}	0.93
273	0.7929	2.177	9.353	1.18	0.0220	0.1308	0.90
323	0.6487	2.177	11.035	1.70	0.0270	0.1920	0.88
373	0.5590	2.236	12.886	2.30	0.0327	0.2619	0.87
423	0.4934	2.315	14.672	2.97	0.0391	0.3432	0.87
473	0.4405	2.395	16.49	3.74	0.0467	0.4421	0.84
Steam (H ₂ O vapor)							
380	0.5863	2.060×10^3	12.71×10^{-6}	2.16×10^{-5}	0.0246	0.2036×10^{-4}	1.060
400	0.5542	2.014	13.44	2.42	0.0261	0.2338	1.040
450	0.4902	1.980	15.25	3.11	0.0299	0.307	1.010
500	0.4405	1.985	17.04	3.86	0.0339	0.387	0.996
550	0.4005	1.997	18.84	4.70	0.0379	0.475	0.991
600	0.3652	2.026	20.67	5.66	0.0422	0.573	0.986
650	0.3380	2.056	22.47	6.64	0.0464	0.666	0.995
700	0.3140	2.085	24.26	7.72	0.0505	0.772	1.000
750	0.2931	2.119	26.04	8.88	0.0549	0.883	1.005
800	0.2739	2.152	27.86	10.20	0.0592	1.001	1.010
850	0.2579	2.186	29.69	11.52	0.0637	1.130	1.019