PART A :

Heat transfer

Chapter 4 :

Convective heat transfer

Introduction

It involves the transfer of heat between a surface and a fluid (liquid or gas) in motion. Convection heat transfer can occur in both natural (free or buoyancy-driven) and forced (externally induced) modes.

1. **First of all :** Convection is one of the three primary modes of heat transfer, alongside conduction and radiation.
2. **What examine convective heat transfer?**
   - Convective heat transfer examine the transfer of heat between a surface and a fluid (liquid or gas) in motion.
3. **What types of convective heat transfer?**
   - Convection heat transfer can occur in both **natural** (free or buoyancy-driven) and **forced** (externally induced) modes.

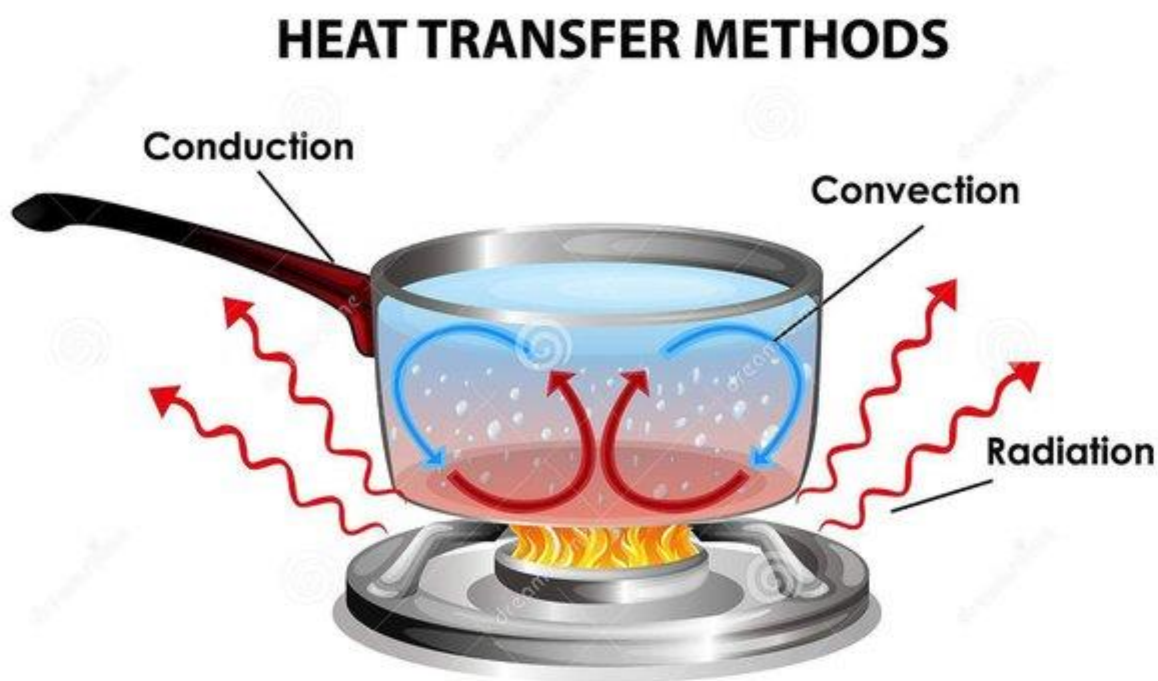
IV - 1.Definitions

i. Natural Convection

Definition: Natural convection is driven by density differences in a fluid due to temperature variations. As a fluid near a heated surface becomes warmer, it tends to rise, creating a flow. Conversely, cooler fluid descends.

Mechanism: When a fluid is heated, it expands, becomes less dense, and rises, creating a natural circulation pattern. This rising and falling motion establishes a convective heat transfer process.

Example: Boiling water on a stovetop is a common example of natural convection, where the warmer water near the bottom rises, and cooler water descends in a continuous cycle.

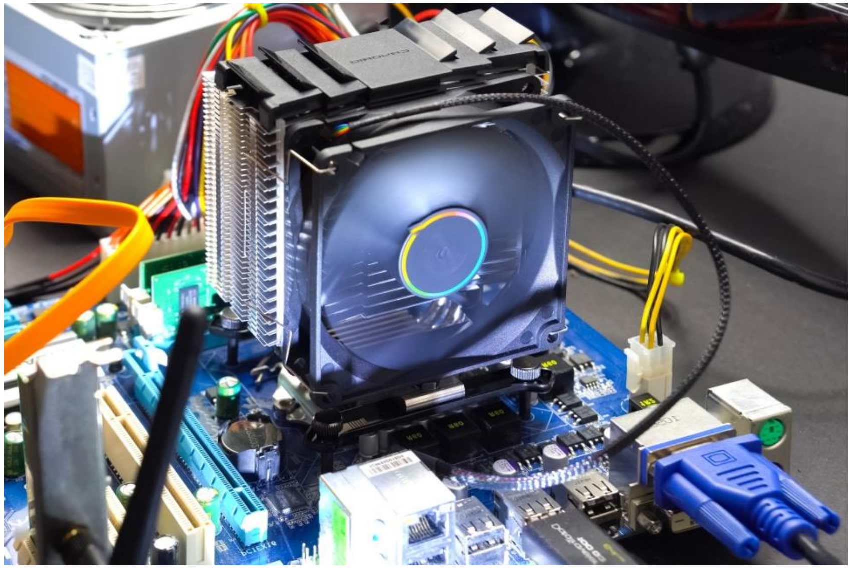


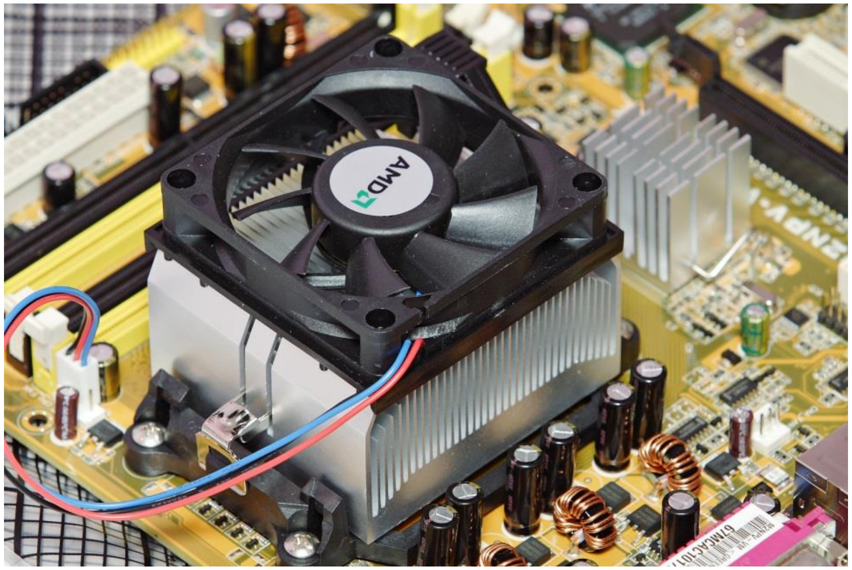
ii. Forced Convection

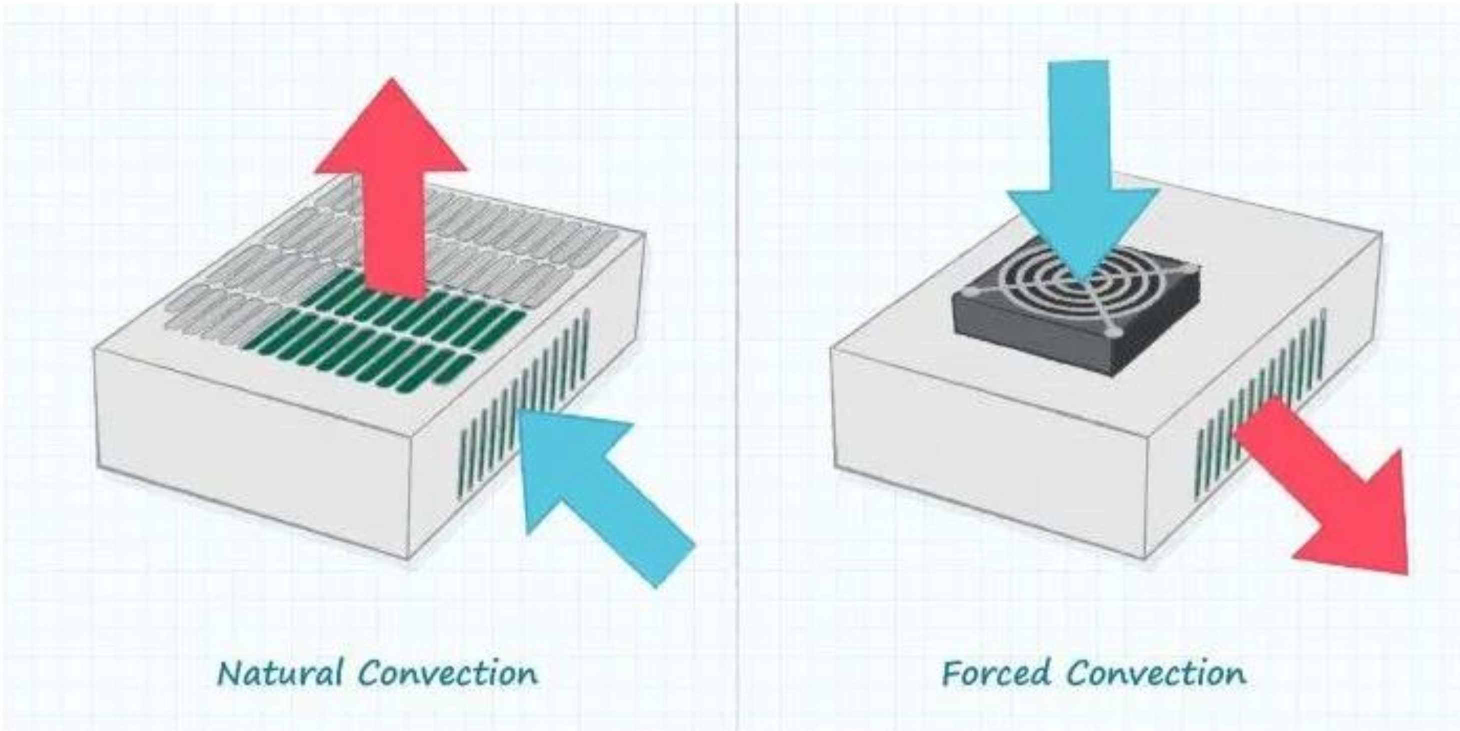
Definition: Forced convection occurs when an external force, such as a pump or a fan, induces fluid motion over a surface. This enhances heat transfer compared to natural convection.

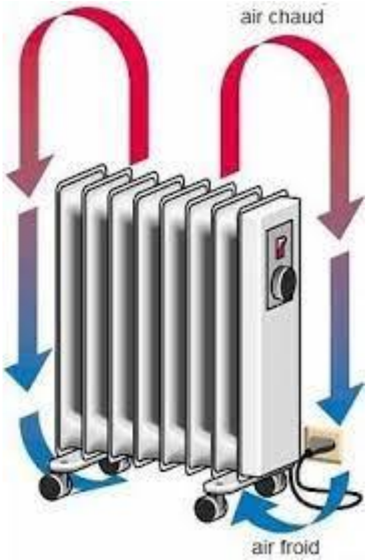
Mechanism: The motion of the fluid is driven by an external source, such as a fan, pump, or any mechanical means. This increased fluid motion leads to higher convective heat transfer rates.

Example: Cooling a computer's central processing unit (CPU) with a fan is an example of forced convection. The fan forces air to flow over the surface of the CPU, enhancing heat dissipation.






Natural Convection
Forced Convection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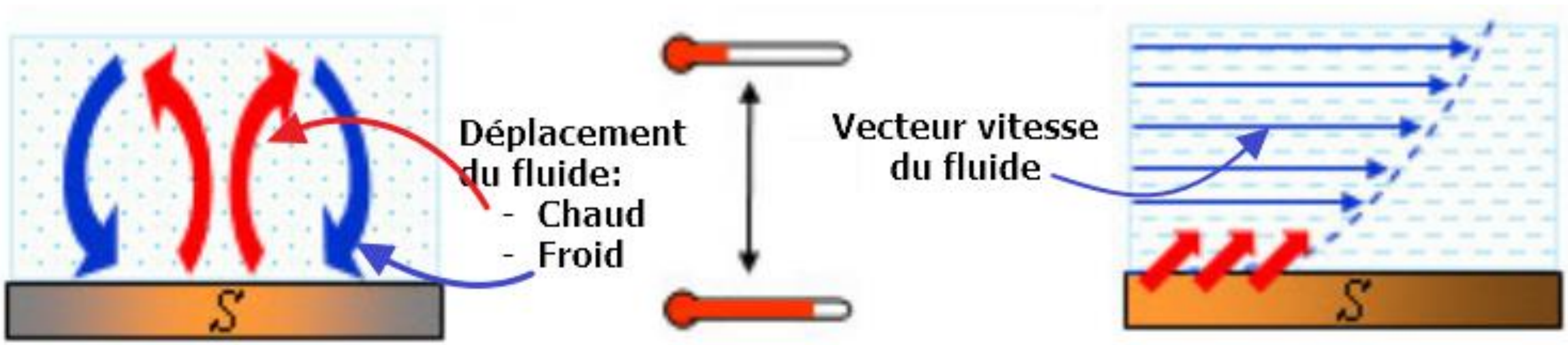

Covection Naturelle

Convection forcée

Note :

In both natural and forced convection, the rate of heat transfer is governed by the **convective heat transfer coefficient (*h*)**. The convective heat transfer coefficient represents the **effectiveness** of the fluid in transferring heat and is influenced by factors such as fluid properties, flow conditions, and surface characteristics.

$$Q = hA\Delta T$$

IV - 2. Reminders about dimensional analysis

i. Introduction

Dimensional analysis is a **powerful** tool in convection heat transfer to develop **dimensionless groups** (dimensionless parameters) that can represent the physical phenomena in a more general form.

These dimensionless groups provide insights into the important parameters governing the convective heat transfer process and are often used to correlate experimental data, design experiments, and develop empirical relations.

Here are a few important dimensionless groups commonly used in convection heat transfer:

ii. Nusselt Number (Nu)

Définition It is a dimensionless number. It relates heat transfer by convection to heat transfer by conduction. The higher Nu is, the more convection predominates over conduction. It is used to characterize the type of heat transfer between a fluid and a wall.

Formula : The Nu number is then given by the ratio of thermal resistance by conduction to thermal resistance by convection:

$$N_u = \frac{\frac{D}{\lambda}}{\frac{1}{h}} = \frac{hD}{\lambda}$$

h: heat transfer coefficient ;

D (sometimes L) : characteristic length (in m);

λ : thermal conductivity of the fluid (W.m-1K-1)

Note: the characteristic length D(or L) depends on the geometry of the exchange surface: for example, in the case of flow through a pipe, we take the internal diameter D of the pipe. For a wall, we take its length.

iii. Reynolds Number Re

The Reynolds number represents the ratio of inertial forces to viscous forces and is crucial in distinguishing between laminar and turbulent flow in forced convection.

$$Re = \frac{U.L}{\nu}$$

U: (or V): characteristic fluid velocity (m/s) (this is the velocity at a distance from the wall) ;

L (or D) characteristic dimension (m) (plate length, tube inner diameter, cylinder outer diameter, etc.) ;

ν is the kinematic viscosity of the fluid ($m^2.s^{-1}$);

Example:

Consider a pipe with a circular cross-section, the characteristic dimension being the diameter D.

- Flow is laminar when the Reynolds number is below a critical value, at which point there is a fairly abrupt transition to turbulent flow. 2400 is the value generally used for this transition.
- but, under the right conditions (particularly smooth wall, stable velocity), the transition can occur at a higher value. The transition is often considered to occur between 2,000 and 3,000.

iv. Prandtl Number (Pr)

Définition : This is a dimensionless number. It is the ratio of the diffusivity of momentum to that of heat.

Formula :

$$Pr = \frac{\nu}{\alpha} = \frac{\mu\, c_p}{\lambda}$$

ν : kinematic viscosity (m^2/s) ; μ : dynamic viscosity

α : Themal diffusivity (m^2/s) ; λ thermal conductivity

c_p : Specific capacity

A high Prandtl number indicates that the temperature profile in the fluid will be strongly influenced by the velocity profile. A low Prandtl number (e.g. liquid metals) indicates that heat conduction is so rapid that the velocity profile has little effect on the temperature profile.

For example:

Pr=7.01 for water at 20°C; Pr=0.707 for air at 25°C.

v. Grashof Number (Gr)

- **Definition:** The Grashof number is essential in natural convection and represents the ratio of buoyancy forces to viscous forces.
- **Formula:** $Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$
- where g is the acceleration due to gravity, β is the volumetric thermal expansion coefficient, T_s is the surface temperature, T_∞ is the fluid temperature away from the surface, L is a characteristic length, and ν is the kinematic viscosity.

IV - 3.Heat transfer between solid and fluid walls

The amount of heat transmitted between a solid wall and a fluid by convection is given by the convection equation:

$$\phi = h\,S\,(T_P - T_\infty)$$

And $$\varphi = h\,(T_P - T_\infty)$$

ϕ: heat flux (in Watt);

φ: Heat flux density (W/m²)

h : convective exchange coefficient (>0) ($W.m^{-2}K^{-1}$) ;

S : exchange surface;

T_P: fluid temperature at the surface of the solid wall;

T_∞: fluid temperature "far" from the surface S ;

This equation appears simple. In fact, the convective heat exchange coefficient h is closely linked to the nature of the fluid, its temperature and the type of flow. It controls convective heat transfer just next to the exchange surfaces.

In the case of heat transfer from several elements, the overall heat transfer coefficient is applied.

- **Vertical wall with natural air flow**

In the case of a vertical wall with natural air flow, and if temperatures are close to room temperature (300K), the coefficient h is given by the following approximate formula :

$$h = 10.45 - c + 10\sqrt{c}$$

c : is the air speed around the object.

The above approximate expression is valid for air speeds varying between 5 and 18 ms^{-1}.

- **Horizontal or vertical walls**

Let's consider a horizontal or vertical wall of thickness d and material with thermal conductivity coefficient λ . The coefficient h is then determined as follows :

$$\frac{1}{\mathrm{h}} = \frac{1}{\mathrm{h}_1} + \frac{\mathrm{d}}{\lambda} + \frac{1}{\mathrm{h}_2}$$

h and $\mathrm{h_i}$ in W.m-2K-1 ; d in m ; λ in Wm-1K-1.

Note that the values of $\frac{1}{\mathrm{h_i}}$ vary with the direction of vertical or horizontal flow, and convection (natural or forced). If the wall is :

- Vertical with natural convection : $\frac{1}{h_i} = 0.11$
- Vertical forced convection: $\frac{1}{h_i} = 0.06$
- Horizontal with natural convection: $\frac{1}{h_i} = 0.09$
- Vertical forced convection: $\frac{1}{h_i}$ =0.05

- **Air Convection:**
  - Free convection (natural convection) for air: 5 - 25 $W/(m^2 \cdot K)$
  - Forced convection for air (typical range): 10 - 100 $W/(m^2 \cdot K)$
  - Forced convection for air (high speed, turbulent flow): 50 - 1000 $W/(m^2 \cdot K)$
- **Water Convection:**
  - Free convection for water: 50 - 1000 $W/(m^2 \cdot K)$
  - Forced convection for water (typical range): 100 - 10,000 $W/(m^2 \cdot K)$
  - Forced convection for water (high speed, turbulent flow): 1,000 - 20,000 $W/(m^2 \cdot K)$
- **Steam Convection:**
  - Steam convection (low pressure): 50 - 500 $W/(m^2 \cdot K)$

- Steam convection (high pressure): 500 - 5000 W/(m²·K)

- **Boiling and Condensation:**
  - Boiling (water at atmospheric pressure): 2,000 - 50,000 W/(m²·K)
  - Condensation (steam on a cold surface): 5,000 - 20,000 W/(m²·K)
- **Metal Surfaces : 50 - 500 W/(m²·K)**
  - Copper: 100 - 400 W/(m²·K)
  - Aluminum: 50 - 250 W/(m²·K)
  - Steel: 10 - 100 W/(m²·K)
  - Stainless Steel: 10 - 200 W/(m²·K)

IV - 4.Correlations and empirical relationships and h

Various correlations and empirical relationships have been developed to estimate convective heat transfer coefficients in different situations.

The choice of correlation often depends on the :

i. specific geometry,

ii. flow conditions,

iii. and characteristics of the heat transfer process.

We can cite some common methods and correlations used to determine convective heat transfer coefficients:

i. Dittus-Boelter Equation ;
ii. Sieder-Tate Equation,
iii. Churchill-Chu Equation,
iv. Gnielinski Correlation ,
v. Petukhov Correlation

a. Dittus-Boelter Equation

Definition : The Dittus-Boelter equation is an empirical correlation commonly used to estimate the Nusselt number (Nu) in forced convection heat transfer for internal flows, particularly in pipes and tubes.

Formulation :

$$\boldsymbol{Nu = 0.023\, Re^{0.8} \,.\, Pr^{0.3}}$$

The Dittus-Boelter equation is applicable to turbulent flows in smooth tubes, where the flow is well-developed and fully developed. It provides a simple and widely used approach for estimating the Nusselt number in such conditions.

b. Sieder-Tate Equation

The Sieder-Tate equation is an empirical correlation used to estimate the Nusselt number (Nu) in forced convection heat transfer, specifically for flow inside tubes. This correlation is an extension of the Dittus-Boelter equation and is suitable for both laminar and turbulent flow regimes.

For laminar flow:

$$Nu = \frac{3.66 - \frac{1.05}{\sqrt[3]{Pr}}}{\sqrt[4]{Re}}$$

For turbulent flow:

$$Nu = \frac{0.027 \cdot Re^{0.8} \cdot Pr^{0.3} \cdot (Pr/Pr_s)^{0.14}}{(1 + (\frac{0.02}{Pr})^{2/3})^{0.25}}$$

Prs : Prandtl number at the surface temperature.

Use :

The Sieder-Tate equation is particularly useful for situations where both laminar and turbulent flows are encountered. It accounts for the transition from laminar to turbulent flow, and the use of Prs allows for a more accurate representation of the Prandtl number in the temperature range of interest.

Note :

It's important to note that while empirical correlations like the Sieder-Tate equation are widely used for practical calculations, they are based on experimental data and are generally valid within specific ranges of Reynolds and Prandtl numbers.

3. **Churchill-Chu Equation:**
   - Suitable for forced convection over flat plates.
   - Incorporates laminar, transition, and turbulent flow regions.
   - Equation: $Nu = 0.037 \cdot Re^{0.8} \cdot Pr^{0.3} \cdot (1 + (0.559/Pr)^{9/16})^{4/9}$
4. **Gnielinski Correlation:**
   - Widely used for forced convection in tubes.
   - Equation: $Nu = \left(0.3 + \frac{0.62 \cdot Re^{0.5} \cdot Pr^{1/3}}{\left(1+\left(\frac{0.4}{Pr}\right)^{2/3}\right)^{1/4}}\right) \cdot \left(1 + \left(\frac{Re}{282{,}000}\right)^{5/8}\right)^{4/5}$
5. **Petukhov Correlation:**
   - Applicable to forced convection in circular tubes.
   - Equation: $Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$

When using these correlations, you need to determine the Reynolds number (Re), Prandtl number (Pr), and other relevant parameters based on the specific conditions of your heat transfer system. Keep in mind that these correlations are empirical and may have limitations depending on the application, so it's important to use them within their valid range of applicability.

Exemple :

Dans le cas d'un écoulement parallèle à une surface plane isotherme :

$$\mathrm{Nu}_x = 0,332\,\mathrm{Re}_x^{1/2}\,\mathrm{Pr}^{1/3}$$

Géométrie	Corrélation	Conditions
Écoulement parallèle à une surface plane isotherme x est l'abscisse en prenant le bord d'attaque comme origine	$\mathrm{Nu}_x = 0,332\,\mathrm{Re}_x^{1/2}\,\mathrm{Pr}^{1/3}$ [3] (local) $\overline{\mathrm{Nu}}_x = 0,664\,\mathrm{Re}_x^{1/2}\,\mathrm{Pr}^{1/3}$ [3] (moyen entre 0 et x)	Écoulement laminaire $\mathrm{Re}_x < 5.10^5$ et $\mathrm{Pr} > 0,7$
	$\mathrm{Nu}_x = 0,0296\,\mathrm{Re}_x^{4/5}\,\mathrm{Pr}^{1/3}$ [4]	Écoulement turbulent $\mathrm{Re}_x > 5.10^5$ et $0,6 < \mathrm{Pr} < 60$

- En convection naturelle : $Nu = f(Gr, Pr)$; Gr est le nombre de Grashof.

Géométrie	Corrélation		Conditions
Surface plane verticale isotherme x est l'abscisse en prenant le bord d'attaque comme origine (en bas pour une paroi chaude, en haut pour une paroi froide)	$\overline{\mathrm{Nu}}_x = C\,\mathrm{Ra}_x^n$	$n = 1/4$ et $C = 0,59$ [11, 12]	Écoulement laminaire $10^4 \leqslant \mathrm{Ra} \leqslant 10^9$
		$n = 1/3$ et $C = 0,10$ [11, 12]	Écoulement turbulent $10^9 \leqslant \mathrm{Ra} \leqslant 10^{13}$
	Résultats obtenus analytiquement [13, 14] $\mathrm{Nu}_x = 0,508\,\mathrm{Ra}_x^{1/4}\left(\frac{\mathrm{Pr}}{0,952+\mathrm{Pr}}\right)^{1/4}$ $\overline{\mathrm{Nu}}_x = \frac{4}{3}\mathrm{Nu}_x = 0,667\,\mathrm{Ra}_x^{1/4}\left(\frac{\mathrm{Pr}}{0,952+\mathrm{Pr}}\right)^{1/4}$		Écoulement laminaire $\mathrm{Ra} \leqslant 10^9$
Cylindre horizontal	Morgan [15, 16] : $\overline{\mathrm{Nu}}_D = C\,\mathrm{Ra}_D^n$	$n = 0,058$ et $C = 0,675$	$10^{-10} \leqslant \mathrm{Ra}_D \leqslant 10^{-2}$
		$n = 0,148$ et $C = 1,02$	$10^{-2} \leqslant \mathrm{Ra}_D \leqslant 10^2$
		$n = 0,188$ et $C = 0,850$	$10^2 \leqslant \mathrm{Ra}_D \leqslant 10^4$
		$n = 0,250$ et $C = 0,480$	$10^4 \leqslant \mathrm{Ra}_D \leqslant 10^7$
		$n = 0,333$ et $C = 0,125$	$10^7 \leqslant \mathrm{Ra}_D \leqslant 10^{12}$