1

General Notions

1.1. General notions

The transport of heat from one point to another in space is the result of three fundamental modes: radiation, conduction and convection.

First, let us remember that heat results from the kinetic energy of molecules for a gas or a liquid, or of atoms for a solid. These molecules are indeed, at any temperature, subject to erratic movements and collisions. The atoms of a crystal are more bonded and vibrate around their equilibrium position. Boltzmann related the temperature to the root mean square value of the velocity of these elements in thermal motion. The transfer of this thermal motion from one point to another therefore results from three processes.

Radiation constitutes a singular point: energy is transported in the form of an electromagnetic wave. Here, there is a phenomenology at two scales: the scale of the fluid and the scale of the atom. It is not thermal motion that is transmitted. The shocks resulting from the temperature cause electronic transitions that generate radiation. When this radiation is sent through a solid (surface) or a fluid, this electromagnetic energy is absorbed by the atoms of the receiver, which transform it back into kinetic energy. The molecules or atoms are thermalized. There is absorption.

Thermal motion being the result of shocks, thermal kinetic energy can be transmitted by shocks from a zone of a medium to another zone of the same medium, where the thermal motion has a lower level or at an interface to another medium (gas–solid transfer, liquid–solid transfer, for example). This transfer by shocks is the basis of ***thermal conduction***.

Finally, when a certain amount of heat has been transmitted to a medium, this medium can be moved in space. This is the phenomenon of convection.

Anyone who heats water in a pot and moves that pot to the mug in which they are making their tea is performing ***convection***; many do so without knowing it.

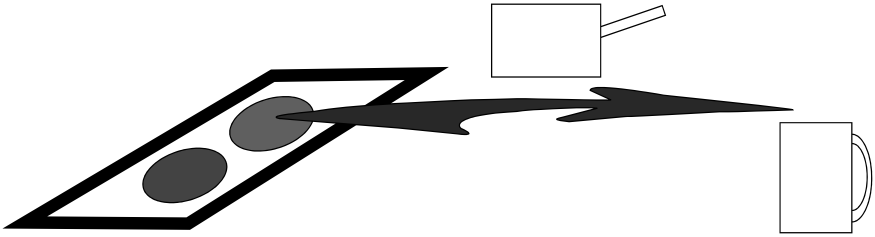

Figure 1.1. *A very basic form of convection. For a color version of this figure, see www.iste.co.uk/ledoux/heat3.zip*

In practice, heat is transferred through a flow, which allows for, among other things, a continuous process. Convection then becomes a chapter of fluid mechanics.

We have two types of problems to solve:

– The generation of the flow and its behavior from the place of "heat collection" to the place of "heat deposition".

– The transfer of heat from a source to the flow. This transfer is generally done at a solid interface. A set of specific phenomena involving coupling between the effects of viscosity and thermal conduction appears. The flow stratifies in speed and temperature, leading to significant thermal gradients perpendicular to the wall. This is called the boundary layer.

The first of these two problems is largely related to "pure" fluid mechanics. We refer to the two works by the same authors devoted to this subject.

Radiation and conduction can be distinguished. We have devoted two previous volumes to them in this series.

The second problem, heat transfer from a source to the carrier fluid, is in fact the main subject of what is called *thermal convection* in the literature. This will be one of the focuses of this work.

This classification, which is necessary for the structuring of books, should never make us lose sight of the fact that the different modes of transfer are, in practice, very often coupled. We have already experienced this in the two previous books devoted respectively to conduction and radiation.

1.2. Forced convection, natural convection

In the exchanges between a panel and a fluid, two fundamental situations can be isolated.

a) The flow of the fluid along the panel is imposed by adequate mechanical means. This is called forced convection.

The flow of the fluid (liquid or gas) can be guided by a conduit: this is internal forced convection. This is also called the internal boundary layer or flow velocity profile.

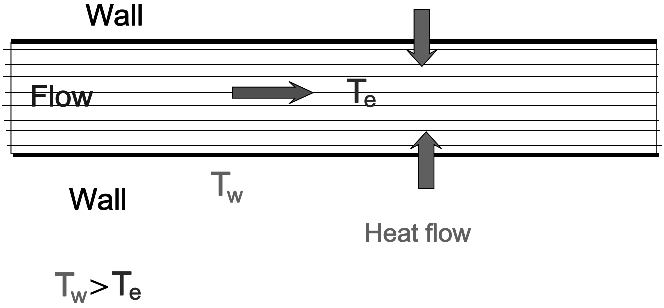

Figure 1.2. *Internal forced convection. For a color version of this figure, see www.iste.co.uk/ledoux/heat3.zip*

The fluid flow can be of indefinite extension and touch the panel. This is called external forced convection. It is also called the external boundary layer. In these problems, the observed velocity profile shows a strong normal gradient to the panel over a “small” thickness, and an asymptotic connection to the “far” flow.

b) Flow can be determined by the temperature difference between the fluid and the wall. For both liquids and gases, the density can vary with temperature. Fluids lighten with temperature (at constant pressure). In the case where temperature gradients lighten the fluid located at the bottom of a device, gravity forces generate a flow. This takes the form of a "convection cell": the fluid "descends" away from the panel and consequently "rises" to the panel. This happens regardless of the inclination between the panel and the horizontal side.

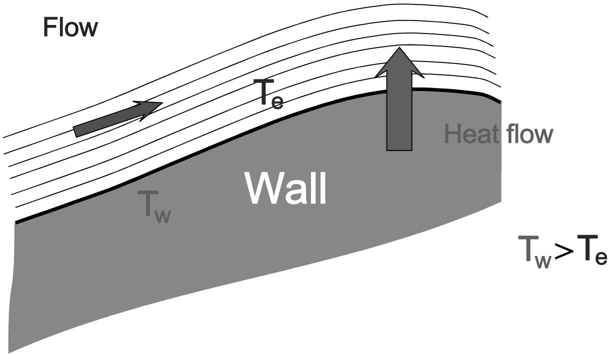

Figure 1.3. *External forced convection. For a color version of this figure, see www.iste.co.uk/ledoux/heat3.zip*

This phenomenon defines natural convection. We sometimes come across the term "free convection".

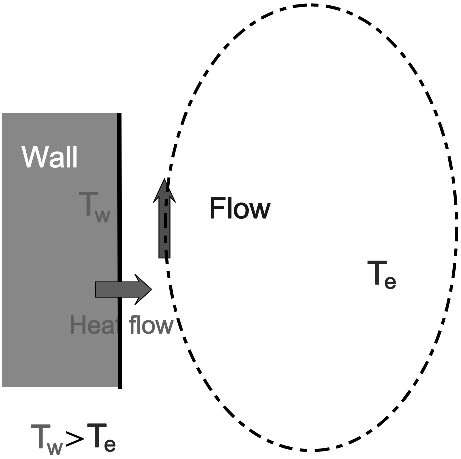

Figure 1.4. *Natural convection. For a color version of this figure, see www.iste.co.uk/ledoux/heat3.zip*

1.3. The calculation of heat transfer

In these two cases of convection, the treatment of a problem can often be carried out in two steps:

a) Determination of the non-transfer flow, in other words, determining the internal velocity field of the fluid in a conduit.

b) Calculation of the temperature field and the parietal flows.

This procedure will be developed further below. The two-step presentation corresponds to many practical cases. Some problems can, unfortunately, be more complex. The properties of the fluid (density, viscosity) can strongly depend on the temperature. As we will see in Chapter **3**, in this case, we have to solve three coupled equations: the continuity equation and momentum equation for the flow, and the energy equation for the temperature field. In most practical problems, the transfer is carried out in the steady state. If this is not the case, we are working in the "input regime". The velocity profile is then variable from one tube section to another.

In many practical cases, we seek to simplify the problem as much as possible. Thus, empirical relations are used to calculate the transfer. These relations can be the result of an experimental study or of a theoretical calculation that has been previously made and published in the literature.

In this type of approach, the convection coefficient becomes an essential element.

1.4. Convection coefficient

For the practical calculation of heat exchange between a solid panel and a flow that flows along this panel, an intermediate calculation called the convection coefficient is used.

Φ is the heat flux (measured in) that is transferred through a panel surface S. T_e is a characteristic temperature of the fluid flow, and T_W is a parietal temperature.

The convection coefficient, which will be noted systematically here as h, is defined by:

$$\Phi = h\,S\left(T_e - T_W\right) \qquad [1.1]$$

We can, as we will often do here, get the following in terms of heat flux density $\varphi_W = \frac{\Phi}{S}$. We then clearly have:

$$\varphi_W = h\left(T_e - T_W\right) \qquad [1.2]$$

Note that although the values of Φ or φ_W are chosen to be positive, we have just written the expression of a flow going from the wall to the fluid (heating of the fluid), which implies $T_W - T_e > 0$. In the case of a flow going from the fluid to the panel (heating of the wall), we should write $\Phi = h\,S\left(T_e - T_W\right)$ or $\varphi_W = h\left(T_e - T_W\right)$ with $T_e - T_W > 0$.

Several important points should be considered at this stage:

The definition of T_e can vary from one problem to another: T_e can be an axial temperature in a tube, a temperature "averaged" over a tube section, or the temperature of a fluid far away from the wall.

T_e as well as T_W have no purpose, except specified or assumed to be constants. They can vary with the longitudinal coordinate (noted systematically in the problem). They can vary with the longitudinal coordinate (noted systematically as x of the problem).

In this case, the expression h can be affected by the laws of variation $T_e\left(x\right)$ and $T_W\left(x\right)$.

This remark is important because, by simplification, expressions of h deduced from theories with constant T_W are often used in variable T_W problems. This is, in particular, systematically the case in the calculations of exchangers that we will discuss in Chapter **4**.

The convection coefficient is a priori a function of different parameters of the problem: physical properties of the fluid (dynamic or thermal) and dynamic characteristics of the flow. Moreover, it is not clearly universally independent of the $T_e - T_W$ temperature difference. The physical properties of the fluid are indeed, in some problems, dependent on the temperatures of the fluid.

In a case where the dynamic and thermal properties of the fluid are constant, the forced convection coefficient will be independent of the $T_e - T_W$ temperature difference.

This will not be the case in natural convection, where, as we will see, h depends on a Grashof number, itself containing the $T_e - T_W$ difference in its definition.

1.5. The program of our study

We have not yet discussed the direction of the transfer between the fluid and wall. In the case of forced convection, we will find a symmetrical problem: the same expression of the convection coefficient will intervene whether the panel is heated or cooled (in the case where the properties of the fluid are constant).

The case of natural convection is evidently asymmetrical; the panel must be heated for there to be transfer.

Using the terms provided in **section 1.3**, we will describe two approaches to the calculation of convective transfer:

a) An "empirical" approach, which will use the convection coefficient, as we will see, as well as a set of dimensionless numbers. This subject will be discussed in Chapter **2**.

b) A theoretical approach, through the boundary layer theory, more complex and also more complete. Within this approach, we will insist on the integral methods, which are approximate, but very useful in practice. This subject will be discussed in Chapter **3**.

On a practical level, we will present some notions on the theory of exchangers. Even though the framework of this book forbids an extensive treatment of the question (let us repeat that we are not writing a treatise, nor a handbook), we feel it is necessary to introduce this theory, which does not shy away from a certain level of approximation, but which still structures the design of classical exchangers, even in an increasingly digitalized space. This subject will be discussed in Chapter **4**.

A final distinction between flows has not yet been introduced here, which also segments the study of convection into two parts of unequal difficulty.

Chapter **2** to Chapter **4** will only deal with single-phase flows, which will remain either liquid or gaseous in their entirety.

In the case of heating a liquid, it can, under certain conditions, be converted into a gas. A flow of steam that is cooled can condense. This is called a two-phase flow. The heat exchange to obtain these phase changes must be consequent. Indeed, a two-phase flow mixes the exchange of sensitive heat and the exchange of latent heat.

NOTE.– Note that it takes 419 kJ to heat a liter of water from 0ºC to 100ºC, while it takes 2,257 kJ to evaporate this same liter of water to 100ºC.

It is then conceivable that the convection coefficients will be significantly increased in the presence of convection with vaporization. The calculation of such flows will become particularly complex, but this type of transfer will be favored whenever a significant "thermal load" is required. This is the case, in particular, in the nuclear steam industry for nuclear power generation.