Design of heat exchangers

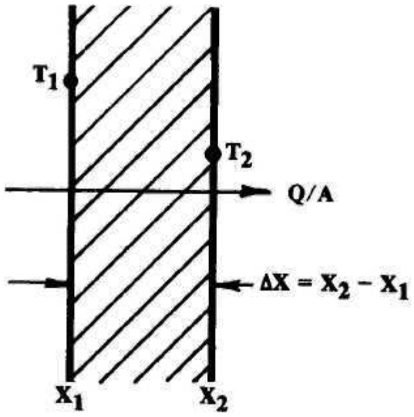
Heat transfer calculation

The basic mechanisms of beat transfer are generally considered to be conduction, convection and radiation. Of these, radiation is usually significant only at temperatures higher than 500°C. In this section, the emphasis will be upon a qualitative description of the processes and a few very basic equations.

Conduction

Conduction in a solids or stationary fluids is largely due to the random movement of elections through the matter. The electrons in the hot part of the solid have a higher kinetic energy than those in the cold part and give up some of this kinetic energy to the cold atoms, thus resulting in a transfer of heat from the hot surface to the cold.

The details of conduction are quite complicated but for engineering purposes may be handled by a simple equation, usually called Fourier's equation. For the steady flow of heat across a plane wall (see the figure) with the surfaces at temperatures of T_1 and T_2 where T_1 is greater than T_2 the heat flow Q per unit area of surface A (the heat flow) is



$$\frac{Q}{A} = q = k\left(\frac{T_1 - T_2}{X_1 - X_2}\right) = k\frac{\Delta T}{\Delta X} \quad [\mathrm{W/m^2}] \quad (1)$$

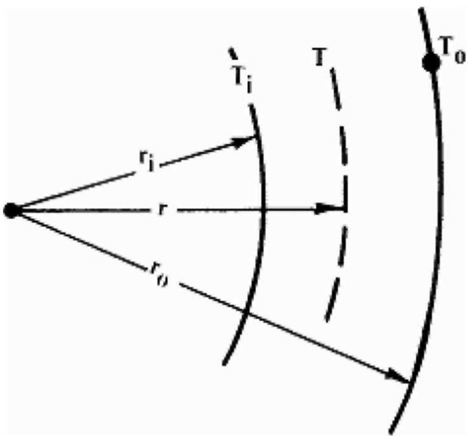
The quantity *k* is called the thermal conductivity and is an experimentally measured value for any material.

<u>Conduction through a tube wall</u>

The above equation can be written in a more general form if the temperature gradient term is written as a differential

$$\frac{Q}{A} = -k\frac{dT}{dx} \qquad (2)$$

The negative sign in the equation is introduced to account for the fact that heat is conducted from a high temperature to a low temperature. The main advantage of equation is that it can be integrated for those cases in which the cross-sectional area for heat transfer changes along the conduction path e.g. in tube. A section of tube wall is shown in figure. *Q* is the total heat conducted through the tube wall per unit time. At the radial position *r* in the tube wall ($r_i \le r \le r_o$), the area for heat transfer for a tube of length *L* is A = $2\pi rL$. Putting these into Eq. (2) gives



$$\frac{Q}{2\pi rL} = -k\frac{dT}{dx} \qquad (3)$$

which may be integrated to

$$Q = \frac{2\pi L\ k(T_i - T_o)}{\ln(r_o/r_i)} \qquad (4)$$

If $T_i < T_o$, *Q* comes out negative: this just means that the heat flow is inward, reversed from the sense in which we took it. For thin-walled tubes, the ratio of the outer to the inner radius is close to unity, and we can use the simpler equation,

$$Q = \frac{2\pi r_o L\ k(T_i - T_o)}{r_o - r_i} \qquad (5)$$

with very small error.

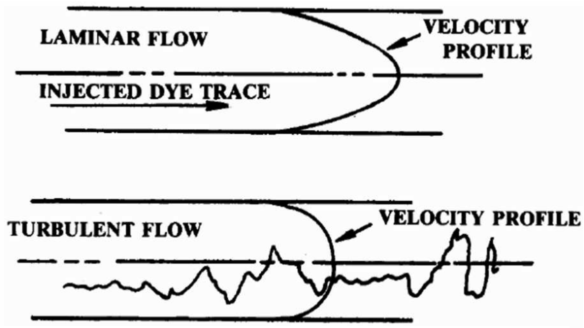
Convection

Convective heat transfer is closely connected to the mechanism of fluid flow near a surface, so the first matter of importance is to describe this flow.

Single phase flow must be characterized by both the geometry of the duct through which the flow occurs and by the flow regime of the fluid as it goes through the duct. There are two basically different types of duct geometry:

- constant cross-section, in which the area available for flow to the fluid has both the same shape and the same area at each point along the duct,
- varying cross-section, in which the shape and/or the area of the duct vary with length, usually in a regular and repeated way.

The most common constant cross-section duct geometry that one deals with in process heat transfer applications is the cylindrical tube. In a cylindrical geometry, it is assumed that all parameters of the flow are a function only of the radial distance from the axis of the cylinder (or equivalently from the wall) and of the distance from the entrance (entrance effects). The flow in ducts of varying cross section is e.g. flow across tube banks which will be the case of interest here.



The type of flow in a duct can also be characterized by the flow regime; that is, laminar flow, turbulent flow, or some transition state having characteristics of both of the limiting regimes. All of the exact definitions of laminar flow are very complex, and an illustration (like in figure) is much more useful.

If we have a round tube with a liquid flowing in it at a steady rate, and if we inject a dye trace with a needle parallel to the axis of the tube, one of two things can happen:

1) The dye trace may flow smoothly down the tube as a well-defined line, only very slowly becoming thicker, or
2) The dye trace may flow irregularly down the tube moving back and forth across the diameter of the tube and eventually becoming completely dispersed.

The first case is laminar flow and the second is turbulent flow. Laminar flow corresponds to the smooth movement of layers of fluid past one another without mixing: turbulent flow is characterized by a rapid exchange of packets or elements of fluid in a radial direction from one part of the flow field to another through turbulent eddies.

There are differences in the velocity pattern also. In laminar flow, the velocity at a given point is steady, whereas in turbulent flow the velocity fluctuates rapidly about an average value. If one measures the local velocity at various positions across the tube, one finds that laminar flow gives a parabolic velocity distribution whereas turbulent flow gives a blunter velocity profile, as shown in figure. In both flows, the fluid velocity is zero at the wall and a maximum at the centerline.

The flow regime that exists in a given case is ordinarily characterized by the Reynolds number. The Reynolds number has different definitions for flow in different geometries. For flow inside tubes it is defined as follows

$$\mathrm{Re} = \frac{d_i \rho V}{\mu} = \frac{d_i G}{\mu} \qquad (6)$$

where d_i is the inside diameter of the tube, V is the average velocity in the tube, ρ the density of the fluid, and μ the viscosity of the fluid. Laminar flow is characterized by low Reynolds numbers, turbulent flow by high Reynolds numbers.

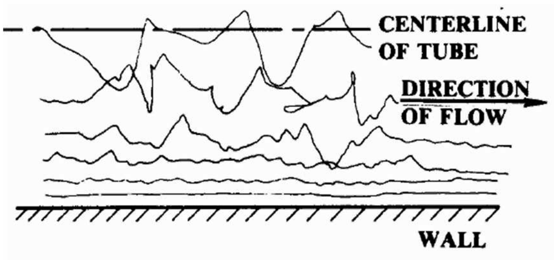
<u>Heat Transfer to a Flowing Fluid (Convection)</u>

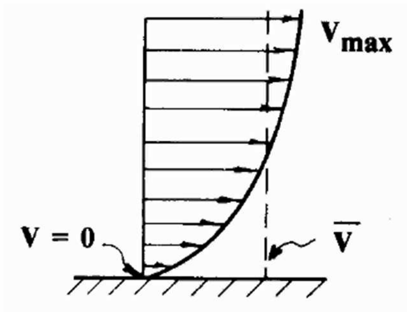
Convection heat transfer can be defined as transport of heat from one point to another in a flowing fluid as a result of macroscopic motions of the fluid, the heat being carried as internal energy. The convection process has received a great deal of both experimental and analytical attention and, although we are mainly concerned with using the results of these studies, a cursory look should be taken at the physical process of convection, both to define terms and to establish some intuitive sense of what really the correlations we use are trying to represent.

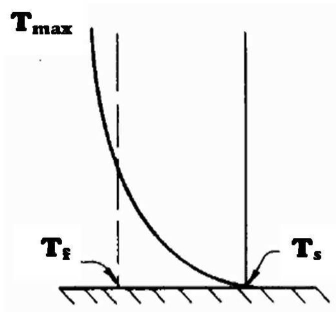
In laminar flow past a hot wall the heat is transferred from the tube surface to the fluid. Within the fluid, heat is transferred from "layer" to "layer" of the fluid by conduction. There are no fluid motions perpendicular to the direction of flow to transport the heat by any other mechanism. Since the different "layers" of fluid are moving at different velocities, however, the conduction process is much more complex to analyze than for the solid wall previously discussed.

If we look at a fluid in turbulent flow past a hot surface and mark a few representative elements of fluid in order to trace their paths, we would obtain a picture something like follows.

The flow near the wall has only a few small eddies, so that the predominant mechanism for heat transfer is conduction. At the wall, the fluid velocity is zero and the fluid temperature is the same as the wall. The velocity and temperature gradients near the wall are much steeper than those in the bulk flow where eddy transport becomes dominant. It is important to note that when we refer without further qualification to the velocity or temperature of a stream, we mean the volume-mean values shown on the figures as V and T_f. However, it is important to remember that some portions of the fluid are at possibly significantly higher or lower temperatures, where thermal degradation or phase change might occur.







For many convective heat transfer processes, it is found that the local heat flux is approximately proportional to the temperature difference between the wall and the bulk of the fluid, i.e.,

$$\frac{Q}{A} \approx \left(T_s - T_f\right)$$

which causes us to define a constant of proportionality, called the "film coefficient of heat transfer" usually denoted by h:

$$\frac{Q}{A} = h \cdot \left(T_s - T_f\right)$$

The value of h depends upon the geometry of the system, the physical properties and flow velocity of the fluid.

The concept of a heat transfer coefficient is useful to the designer only if there exists a quantitative relationship between these variables and the heat transfer coefficient. It is important also that this relationship be reasonably valid for the conditions existing in the particular application. These relationships, or correlations, may come from either theoretical or experimental studies, or from a combination of both. The correlation may be expressed as an equation, a graph, a table of values, or a computational procedure. These forms are more or less readily convertible from one into another according to the needs and convenience of the user. In using the correlation, the designer needs to know, at least roughly, how accurate the results are likely to be in his application.

Radiation

All matter constantly radiates energy in the form of electromagnetic waves. The amount of energy emitted depends strongly upon the absolute temperature of the matter and to a lesser extent upon the nature of the surface of the matter. The basic law of radiation was derived by Stefan and Boltzmann and may be written for our purposes as:

$$\frac{Q}{A} = \sigma\varepsilon T_{abs}^4$$

where σ is the Stefan-Boltzmann constant (equal to $5{,}6687 \cdot 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$) and T_{abs} is the absolute temperature in K. ε is the emissivity and has a value between 0 and 1. For a perfect reflector ε = 0 and for a perfect emitter, a so-called "black body[11], ε =1.

Since all surfaces that radiate heat will also absorb heat, it follows that all surfaces that can "see" each other are exchanging heat with one another, the net rate depending upon the absolute temperatures, the emissivities, the areas and he spatial geometric relationships of the surfaces. The radiant energy transferred between two surfaces depends upon their temperatures, the geometric arrangement, and their emissivities. For two parallel surfaces, facing each other and neglecting edge effects, each must intercept the total energy emitted by the other, either absorbing or reflecting it. In this case, the net heat transferred from the hotter to the cooler surface is given by:

$$\frac{Q}{A} = \sigma\varepsilon\left(T_1^4 - T_2^4\right)$$

where 1/ ε = 1/ε_1 + 1/ε_2 – 1, ε_1 is the emissivity of the surface at temperature T_1 and ε_2 is the emissivity of the surface at temperature T_2.
At usual atmospheric temperatures, radiant heat transfer is relatively unimportant compared to most other heat transfer mechanisms, though there are a few areas where it makes a significant contribution, e.g., radiation from flame or hot flue gas to boiler walls. At higher temperatures, radiation becomes relatively more important, and at temperatures above perhaps 500 °C (depending upon the other processes), it is usually essential to take radiation into account.
The energy transfer by radiation from flame to the furnace walls is the main process which we are interesting in. Convective heat transfer compared to the radiation heat transfer is here generally lower. The definition of radiative heat transfer in the boilers or furnaces make use of necessary information of the optical properties and space distribution of the constituents that take a part in the exchange of radiative energy and of the space temperature distribution in the furnace and properties of the internal wall surfaces. In-turn, the temperatures are depending on the interference between stream, impact and burning mechanisms. The allocation of radiative heat within the furnace and across the tube walls is derived from balances of radiative energy that includes the information reduced above for the different areas.
In flame, there are free (not) radiation and radiation gas mediums. One- and two- atom gases, such as: helium, oxygen, nitrogen, etc. are practically transparent for radiation. Contents of more than two atomic gases (CO_2, SO_2 and H_2O) and solid particles (ash, char and soot) are the main variables defining the flue gas radiant properties. Similarly to solid bodies the flame emissivity ε_f is used for description of radiate heat. Let's assume, that flame has a constant temperature T_f, and a wall T_w. Accept, that flame and a wall are grey bodies descripted by emissivity ε_f and ε_w.

$$\frac{Q}{A} = \sigma\varepsilon_{fw}\left(\overline{T}_f^4 - \overline{T}_w^4\right)$$

where ε_{fw} is furnace emissivity

$$\varepsilon_{fw} = \frac{1}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} - 1}$$

<u>Combination fo Heat Transfer by Convection and Radiation</u>

In furnace and following high temperature parts of boiler heat transfer both by convection and radiation occurs simultaneously. Concept of “radiation heat transfer coefficient” is useful in solving these problems
Radiation heat transfer coefficient is defined in a manner analogous to convection heat transfer coefficient. Consider hot flue gas at a temperature T_f flowing cross a wall whose is at a temperature of T_w. Then, recollect that the convective heat flux is given by:

$$\frac{Q_{conv}}{A} = h_c \cdot \left(T_f - T_w\right)$$

where, h_c is convective heat transfer coefficient.
In a similar manner, we write for radiant heat flux from flue gas to wall:

$$\frac{Q_{rad}}{A} = \sigma\varepsilon_{fw}\left(T_f^4 - T_w^4\right) = h_r \cdot \left(T_f - T_w\right)$$

where h_r is the radiation heat-transfer coefficient

$$h_r = \sigma\varepsilon_{fw}\frac{T_f^4 - T_w^4}{T_f - T_w}$$

Total heat flux from flue gas to wall is done by combination of convective and radiation heat fluxes as follows

$$\frac{Q}{A} = \frac{Q_{conv} + Q_{rad}}{A} = \left(h_c + h_r\right)\cdot\left(T_f - T_w\right) = h_f \cdot \left(T_f - T_w\right)$$

where h_f is the total heat-transfer coefficient from flue gas to wall.