Heat Transfer

Convection - Introduction

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September 25, 2019

Objectives

- To give an overview about the variables of importance in convective heat transfer

Outcome

- To group the variables in terms of dimensionless numbers for forced and free convection heat transfer.

Introduction

Three factors play major roles in convection heat transfer: (i) fluid motion, (ii) fluid nature, and (iii) surface geometry.
Using experimental observations by Isaac Newton, it is postulated that surface flux in convection is directly proportional to the difference in temperature between the surface and the streaming fluid. That is,

$$q \propto (T_s - T_\infty)$$

T_s is surface temperature and T_∞ is the fluid temperature far away from the surface. Introducing a proportionality constant to express this relationship as equality, we obtain

$$\boxed{q = h(T_s - T_\infty)}$$

This result is known as *Newton's law of cooling*. The constant of proportionality h is called the heat transfer coefficient.

Heat Transfer Coefficient

Unlike thermal conductivity k, the heat transfer coefficient is not a material property. Rather it depends on geometry, fluid properties, motion, and in some cases temperature difference, $\Delta T = (T_s - T_\infty)$. That is

$$h = f(\text{geometry, fluid motion, fluid properties}, \Delta T)$$

$$q = -k \left. \frac{\partial T}{\partial y} \right|_{y=0} = h(T_s - T_\infty)$$

$$h = \frac{-k}{T_s - T_\infty} \frac{\partial T(x, 0, z)}{\partial y}$$

Since fluid motion is central to convection heat transfer we will be concerned with two common flow classifications:
(a) **Forced convection**. Fluid motion is generated mechanically through the use of a fan, blower, nozzle, jet, etc.. Fluid motion relative to a surface can also be obtained by moving an object, such as a missile, through a fluid.
(b) **Free (natural) convection**. Fluid motion is generated by gravitational field. However, the presence of a gravitational field is not sufficient to set a fluid in motion. Fluid density change is also required for free convection to occur. In free convection, density variation is primarily due to temperature changes.

Significant Parameters in Convective Heat Transfer

The molecular diffusivities of momentum and energy (heat) have been defined previously as

$$\text{momentum diffusivity:} \qquad \nu = \frac{\mu}{\rho}$$

$$\text{thermal diffusivity:} \qquad \alpha = \frac{k}{\rho C_P}$$

Both have same dimensions L^2/t; thus their ratio must be dimensionless. This ratio, that of molecular diffusivity of momentum to the molecular diffusivity of heat, is designed the Prandtl number.

$$\boxed{\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{C_P \mu}{k}}$$

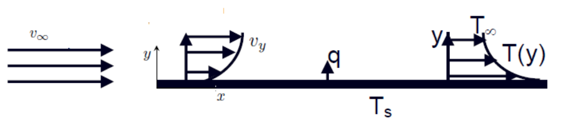
Prandtl number is observed to be a combination of fluid properties; thus Pr itself may be thought of as a property. Primarily it is a function of temperature.

Prandtl Number of Typical Fluids

Fluid	Pr
Liquid metals	0.004 – 0.030
Gases	0.7 – 1.0
Water	1.7 – 13.7
Light organic fluids	5 – 50
Oils	50 – 100,000
Glycerin	2000 – 100,000

Prandtl number depends on the temperature of the substance.

Significant Parameters in Convective Heat Transfer (contd..)



Near any wall, there is a stagnant sub layer. Since there is no fluid motion in this layer, heat transfer is by conduction in this layer. Above the sub layer is a region where viscous forces retard fluid motion; in this region some convection may occur, but conduction may well predominate.

$$q = -k \left. \frac{\partial T}{\partial y} \right|_{y=0} = h(T_s - T_\infty)$$

Significant Parameters in Convective Heat Transfer (contd..)

Hence,

$$h = \frac{-k \left. \dfrac{\partial T}{\partial y} \right|_{y=0}}{T_s - T_\infty}$$

$\left. \dfrac{\partial T}{\partial y} \right|_{y=0}$ depends on the whole fluid motion, and both fluid flow and heat transfer equations are needed to find this.

Variables: $h, D, v, \rho, \mu, k, C_P$
Dimensions: M, L, t, T

$$\text{No. of dimensionless numbers} = \text{No. of variables} - \text{No. of dimensions} = 7 - 4 = 3$$

$$\boxed{\text{Nu} = \phi(\text{Re}, \text{Pr})}$$

Forced Convection

$$h = f(D, v, \rho, \mu, k, C_P)$$

These 7 variables with totally 4 basic dimensions of M, L, t, T shall be written as 3 dimensionless groups.

Variable	Symbol	Unit	Dimensions
heat transfer coefficient	h	W/(m^2.K)	$Mt^{-3}T^{-1}$
thermal conductivity	k	W/(m.K)	$MLt^{-3}T^{-1}$
specific heat	C_P	J/(kg.K)	$L^2t^{-2}T^{-1}$
diameter	D	m	L
velocity	v	m/s	Lt^{-1}
density	ρ	kg/m^3	ML^{-3}
viscosity	μ	kg/(m.s)	$ML^{-1}t^{-1}$

Requirements:

- Gravitational field
- Density change with temperature

Variables: $h, L, \rho, \mu, k, C_P, \beta, g, \Delta T$
β is the coefficient of thermal expansion.

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$$

For ideal gases, $\beta = 1/T_\infty$
Dimensions: M, L, t, T, Q
(where Q is the dimension for energy).

Natural Convection - Dimensional Analysis (contd..)

Grashof number (Gr):

$$\mathrm{Gr} = \frac{g\beta\rho^2 L^3 (T_w - T_\infty)}{\mu^2}$$

Heat Transfer Correlation:

$$\boxed{\mathrm{Nu} = \phi(\mathrm{Gr}, \mathrm{Pr})}$$

$$\mathrm{Re} = \frac{Dv\rho}{\mu} = \frac{Dv\rho}{\mu}\frac{Dv}{Dv} = \frac{\rho D^2 v^2}{D\mu v} = \frac{\rho D^2 v(D/t)}{D^2\mu\frac{v}{D}}$$

$$= \frac{\rho D^3(v/t)}{D^2 \times \mu\frac{v}{D}} = \frac{ma}{A\tau} = \frac{\text{Inertial force}}{\text{Viscous force}}$$

Thermally developing flow

Graetz number (Gz):

$$\mathrm{Gz} = \frac{\mathrm{Re}\,\mathrm{Pr}}{x/D}$$