Chapter I

A Study of Heat-Transfer by free and forced convection

Introduction

It is well known that Heat transfer takes place by the processes of conduction, convection and radiation. We are concerned here exclusively with convection. In this process, the fluid and the heat contained in it move in a systematic manner so as to transport heat from one region to another. Heat transfer by convection means the exchange of heat energy between moving parts of the fluid or between these parts and other surfaces at a different temperature. Now convection can be of two types (i) natural or free convection and (ii) Artificial or forced convection. In natural or free convection the motion of the fluid is caused solely by gravity forces due to difference of density between the hotter and cooler parts. The lighter parts which generally are those of higher temperature, move upwards while the heavier ones fall down under the action of gravity. In forced convection the fluid motion is caused by forces independent of the temperature of the fluid, such as externally applied pressure differences as in the flow through a tube. Streams of air rising about warm surfaces like that of a hot metal cylinder are examples of free(natural) convection whereas the heating of a vessel by a current of hot air and the cooling of a surface with an electric fan are examples of forced convection.

A knowledge of the convective processes of heat transfer and the laws governing them is very important and useful in various branches of engineering like electrical,chemical, mechanical etc. It is finding an ever increasing application in nuclear engineering because in almost all nuclear reactors it is the process of forced convection by which heat is removed from the fuel.

In the following sections we shall discuss the fundamental and basic equations of thermal convection and obtain from them the various dimensionless groups that are frequently used in our investigations of heat transfer by free and forced convection. The dimensionless groups will be first derived by means of differential equations and later by using the dimensional equations. The last section of this chapter will deal with the importance of these dimensionless groups.

Thermal convection:-

Thermal convection may be regarded as a combination of fluid flow and heat conduction, or it can be looked upon as a hydrodynamical flow accompanied by a thermal flow. In obtaining basic equations of thermal convection therefore, we must consider the equations of mechanical (hydrodynamical) flow and the equation of thermal conductivity.

Equations of Fluid Flow:-

The mechanical flow of fluids is governed by Newton's Second law of motion Viz:-

Force=Mass X acceleration . . . . (1)

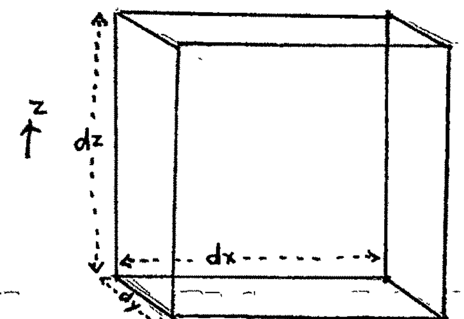

FIG. 1

We can obtain an expression for the acceleration by considering the change of velocity v_z of a fluid in a path element dz and in time interval dt. Let us imagine a parallelopiped of volume dx dy dz at a distance x, y, z, from the origin. If we consider the fluid flow along the direction of z axis with velocity v_z at distance z and at time t, we can express the change in the velocity v_z as

$$dV_z = \frac{\partial V_z}{\partial t} dt + \frac{\partial V_z}{\partial z} dz \quad - - - - (2)$$

The first term in the above expression for dv_z represents the change of velocity at a fixed distance z in the time interval dt while the second term denotes the difference of velocity at time t between two points in the fluid separated by a distance dz

Dividing by dt throughout we get

$$\frac{dV_z}{dt} = \frac{\partial V_z}{\partial t} + V_z \frac{\partial V_z}{\partial z} \quad - - - - - - - - (3)$$

In the above equation the first term on the right, $\left(\frac{\partial V_z}{\partial t}\right)$ may be called local acceleration, since it arises from a change of state of flow at the point z while the second term $\left(V_z \frac{\partial V_z}{\partial z}\right)$ may be called convective acceleration because it arises from the fact that the particle under consideration comes from a neighbouring place where it had a different velocity. For simplicity we restrict ourselves to unidirectional flow and neglect the velocity components V_x & V_y in the directions x and y.

Now the force in Newton's second law of motion is composed of three different types of forces (a) Inertia force F_g due to gravity (b) frictional force F_μ due to viscosity and (c) dynamical force F_p due to pressure drop. Thus Newton's equation (1) applied to the motion of unit volume of the fluid in the direction of z-axis becomes,

$$\rho \frac{dV_z}{dt} = \rho\frac{\partial V_z}{\partial t} + \rho V_z \frac{\partial V_z}{\partial z} = F_g + F_\mu + F_p \qquad \text{----(4)}$$

The inertia force F_g generally occurs as a buoyancy and according to Archimedes principle, the unit volume of fluid of density ρ in a medium of density ρ_0 is subjected to a buoyancy force given by $(\rho_0 - \rho)g$. Thus we get

[redacted]

$$F_G = (\rho_0 - \rho) g \qquad \text{------ (5)}$$

The difference $(\rho_0 - \rho)$ in a homogeneous fluid is caused by a corresponding temperature difference $(T - T_0)$ and we have

$$\rho_0 = \rho\left\{1 + \beta(T - T_0)\right\} \quad \text{or} \quad (\rho_0 - \rho) = \rho\beta(T - T_0) = \rho\beta\theta$$

where θ stands for $(T - T_0)$. Thus we get

$$F_G = (\rho_0 - \rho) g = \beta\rho\theta g \qquad \text{--------(6)}$$

The frictional force F_μ due to viscosity μ. may be obtained as follows:-

The force due to viscous drag over an element of surface $dy \cdot dz$ at distance x is $\left(\mu \frac{\partial V_z}{\partial x} dy \cdot dz\right)$ and that at a distance $(x+dx)$ is

$$\mu \frac{\partial}{\partial x}\left(V_z + \frac{\partial V_z}{\partial x}\right) dy \cdot dz$$

Thus the net force over the element of surface (dy × dz) will be

$$\left(\mu \frac{\partial V_z}{\partial x} + \mu \frac{\partial^2 V_z}{\partial x^2} dx - \mu \frac{\partial V_z}{\partial x}\right) dy \cdot dz = \mu \frac{\partial^2 V_z}{\partial x^2} dx \cdot dy \cdot dz.$$

Hence for unit volume, the viscous force is given by

$$F_\mu = \mu \frac{\partial^2 V_z}{\partial x^2} \text{ - - - - - - - - - - - (7)}$$

The dynamical force F_p due to pressure drop of a fluid which flows in the direction z apparently is $-\left(\frac{\partial p}{\partial z}\right) dz$ related to the length dz and the unit of the cross-sectional area perpendicular to z. For unit volume it becomes

$$F_p = -\left(\frac{\partial p}{\partial z}\right) \text{ - - - - - - - - - - - (8)}$$

Substituting for F_g F_μ and F_p from (6),(7),(8) in equation (4) we get

$$\rho \frac{\partial V_z}{\partial t} + \rho V_z \frac{\partial V_z}{\partial z} = \beta \rho \theta g + \mu \frac{\partial^2 V_z}{\partial x^2} - \frac{\partial p}{\partial z} \text{ - - - - (9)}$$

Equations of Heat Convection

If T be the temperature at a distance z and (T - dT) at a distance (z + dz), the quantity of heat absorbed by the volume element dx × dy × dz per second will be

$$\rho\, dx \cdot dy \cdot dz\; q \frac{dT}{dt} = \rho q V_z \frac{\partial T}{\partial z} \cdot dx \cdot dy \cdot dz.$$

where $V_z = \left(\frac{\partial z}{\partial t}\right)$. Now the amount of heat entering per second at z will be $K\, dx \cdot dy \frac{\partial T}{\partial z}$ and the heat leaving per second at (z + dz) will be $k\, dx \cdot dy \frac{\partial}{\partial x}\left(T - \frac{\partial T}{\partial z} dz\right)$. Hence the net amount of heat absorbed will be $K \frac{\partial^2 T}{\partial z^2} dx \cdot dy \cdot dz$. Writing the heat balance equation, we get,

$$\rho c_p V_z \frac{\partial T}{\partial z} = k \frac{\partial^2 T}{\partial z^2} \quad \text{------ (10)}$$

Again the heat transfer by conduction and convection is given by the general expression

$$dQ = -k \frac{dT}{dz} dA = h \Delta T \cdot dA \quad \text{---- (11)}$$

Where z is the direction of heat normal to surface element and K is the thermal conductivity of fluid close to the surface. Here $k/\partial z$ is replaced by h, which is known as heat transfer coefficient. Equations (9),(10) and (11) may be regarded as the fundamental or basic equations of thermal convection from which we can derive the various dimensionless numbers (groups) which have been used in the present work.

Derivation of dimensionless groups

According to the principles of similarity, the following equations should be valid for two similar systems, denoted by suffixes (1) and (2)

$$\left.\begin{array}{l} V_{z_2} = \omega V_{z_1}, \; x_2 = \lambda x_1, \; z_2 = \lambda z_1, \; \theta_2 = \varphi \theta_1, \; T_2 = \eta T_1 \\ \rho_2 = \sigma \rho_1, \; \mu_2 = n \mu_1, \; g_2 = r g_1, \; \beta_2 = b \beta_1, \; c_{p_2} = s c_{p_1} \\ k_2 = i k_1, \; h_2 = \psi h_1, \; t_2 = \delta t, \; \text{and} \; p_2 = \alpha p_1 \end{array}\right\} \text{---- (12)}$$

Here the Greek letters $\alpha, \delta, \omega, \lambda, \varphi, \eta, \sigma, \psi$ and the letters n, r, b, s, and i without subscript designate constants. We rewrite the basic equations (9), (10) and (11) for systems (2) and (1) as follows.

$$\left.\begin{array}{l} \rho_2 \dfrac{\partial V_{z_2}}{\partial t_2} + \rho_2 V_{z_2} \dfrac{\partial V_{z_2}}{\partial z_2} = \rho_2 \beta_2 \theta_2 g_2 + \mu_2 \dfrac{\partial^2 V_{z_2}}{\partial x_2^2} - \dfrac{\partial p_2}{\partial z_2} \text{ -- (i)} \\ \rho_2 c_{p_2} V_{z_2} \dfrac{\partial T_2}{\partial z_2} = k_2 \dfrac{\partial^2 T_2}{\partial z_2^2} \text{ --- (ii)} \qquad k_2 \dfrac{\partial T_2}{\partial z_2} = h_2 \Delta T_2 \text{ --- (iii)} \end{array}\right\} \text{--- (13)}$$

and

$$\left.\begin{array}{l} \rho_1 \dfrac{\partial V_{z_1}}{\partial t_1} + \rho_1 V_{z_1} \dfrac{\partial V_{z_1}}{\partial z_1} = \rho_1 \beta_1 \theta_1 g_1 + \mu_1 \dfrac{\partial^2 V_{z_1}}{\partial x_1^2} - \dfrac{\partial p_1}{\partial z_1} \text{ --- (i)} \\ \rho_1 c_{p_1} V_{z_1} \dfrac{\partial T_1}{\partial z_1} = k_1 \dfrac{\partial^2 T_1}{\partial z_1^2} \text{ --- (ii)} \qquad k_1 \dfrac{\partial T_1}{\partial z_1} = h_1 \Delta T_1 \text{ --- (iii)} \end{array}\right\} \text{---- (14)}$$

Substituting from (12) in (13) we get

$$\frac{\omega\sigma}{\delta} \rho_1 \frac{\partial V_{z_1}}{\partial t_1} + \frac{\sigma\omega^2}{\lambda} \rho_1 V_{z_1} \frac{\partial V_{z_1}}{\partial z_1} = \sigma b \varphi r \rho_1 \beta_1 \theta_1 g_1 + \frac{n\omega}{\lambda^2} \mu_1 \frac{\partial^2 V_{z_1}}{\partial x_1^2} - \frac{\alpha}{\lambda} \frac{\partial p_1}{\partial z_1} \text{ --- (i)}$$

$$\frac{\sigma s \omega}{\lambda} \rho_1 c_{p_1} V_{z_1} \frac{\partial T_1}{\partial z_1} = \frac{i}{\lambda^2} k_1 \frac{\partial^2 T_1}{\partial z_1^2} \text{ ---- (ii)}$$

$$\frac{\eta i}{\lambda} k_1 \frac{\partial T_1}{\partial z_1} = \eta \psi h_1 \Delta T_1 \text{ ------ (iii)} \qquad \text{----- (15)}$$

Now equations (15) must be indentical with equation (14) and this will occur only if the following relations are satisfied:-

$$\frac{\omega\sigma}{\delta} = \frac{\omega^2\sigma}{\lambda} = (\sigma b \varphi r) = \frac{n\omega}{\lambda^2} = \frac{\alpha}{\lambda} \text{ ------ (16)}$$

$$\frac{\sigma s \omega}{\lambda} = \frac{i}{\lambda^2} \text{ ----- (17)} \qquad \frac{i}{\lambda} = \psi \text{ ------ (18)}$$

Now from (16) $\quad \omega^2 = b \varphi r \lambda$ -------- (19)

and $\dfrac{n^2\omega^2}{\lambda^4} = \sigma^2 b^2 \varphi^2 r^2$ whence $n^2 = \lambda^3 \varphi \sigma r b \left(\dfrac{\lambda \varphi r b}{\omega^2}\right)^2$ --(20)

From (19) and (20) $n^2 = \lambda^3 \varphi \sigma^2 r b$ - - - - - (21)

Substituting from (12) gives

$$\frac{\mu_2^2}{\mu_1^2} = \frac{l_2^3}{l_1^3} \cdot \frac{\theta_2}{\theta_1} \cdot \frac{\rho_2^2}{\rho_1^2} \cdot \frac{g_2}{g_1} \cdot \frac{\beta_2}{\beta_1}$$

Where l = z or x stands for any considered length (e.g. diameter of cylinder or sphere)

Thus

$$\frac{l_2^3 \theta_2 \rho_2^2 g_2 \beta_2}{\mu_2^2} = \frac{l_1^3 \theta_1 \rho_1^2 g_1 \beta_1}{\mu_1^2} = \frac{l^3 \theta \rho^2 g \beta}{\mu^2} = Gr. \text{ (Grashof Number)}$$

Again From (17) $i = \lambda \sigma \Delta \omega$

and from (16) $n = \lambda \sigma \omega$

Hence $i = n s$

or $$\frac{\mu_2 c_{p_2}}{\mu_1 c_{p_1}} = \frac{k_2}{k_1} \quad \text{or} \quad \frac{c_{p_2}\mu_2}{k_2} = \frac{c_{p_1}\mu_1}{k_1} = \frac{c_p \mu}{k} = Pr. \text{ (Prandtl Number)}$$

Similarly from (12) and (18) we have

$$\frac{k_2}{k_1} \cdot \frac{l_1}{l_2} = \frac{h_2}{h_1} \quad \text{or} \quad \frac{h_2 l_2}{k_2} = \frac{h_1 l_1}{k_1} = \frac{h l}{k} = Nu. \text{ (Nusselt Number)}$$

and substituting (12) in (16) we obtain

$$\frac{\rho_1 l_1}{\mu_1} V_{z_1} = \frac{\rho_2 l_2}{\mu_2} V_{z_2} = \frac{\rho l}{\mu} V = Re. \text{ (Reynolds Number)}$$

Finally from (17) and (18) we get $\psi = i/\lambda$

and $i = \lambda \sigma \Delta \omega$ Hence $\psi = \sigma \Delta \omega$

Thus

$$\frac{h_2}{h_1} = \frac{\rho_2}{\rho_1} \frac{c_{p_2}}{c_{p_1}} \frac{V_{z_2}}{V_{z_1}} \quad \text{or} \quad \frac{h_1}{\rho_1 c_{p_1} V_{z_1}} = \frac{h_2}{\rho_2 c_{p_2} V_{z_2}} = \frac{h}{\rho c_p V_z}$$

$$= St. \text{ (Stanton Number)}$$

Derivation of dimensionless groups by the dimensional method

Let us suppose that for free convection the heat transfer coefficient 'h' is giving by the relation:-

$$h = C\, l^{a}\, \theta^{b}\, \rho^{f}\, \mu^{i}\, \beta^{j}\, c_p^{m}\, g^{n}\, k^{r} \quad \text{------} \quad (22)$$

where C is a constant, l is the characteristic length (e.g. diameter of a cylinder or a sphere) μ is viscosity, K is the thermal conductivity and the other symbols have their usual meaning. Since 'h' denotes the heat loss per unit area per unit time per unit change of temperature, its dimensions will be those of heat divided by $L^{2}T\theta$ Thus we can write:-

$$[h] = [H T^{-1} L^{-2} \theta^{-1}] \quad \text{------} \quad (23)$$

The letters M, L, T, H and θ are used here for the basic units of mass, length, time, heat and temperature, respectively.

Substituting the dimensions of $l, \theta, \rho, \mu, \beta, c_p, g$ and K in equation (22) and using (23) we get,

$$[H T^{-1} L^{-2} \theta^{-1}] = C \times L^{a-3f-i+n-r} \times M^{f+i-m} \times T^{-i-2n-r}$$
$$H^{m+r} \times \theta^{b-j-m-r}$$

Hence,

$$-2 = a - 3f - i + n - r$$
$$-1 = b - j - m - r$$
$$0 = f + i - m$$
$$-1 = -i - 2n - r$$
$$1 = m + r$$

From these equations we can express the five exponents a, b, f, i, r in terms of the remaining three viz:- j, m, n thus:

$$a = 3n-1, \quad b = j, \quad f = 2n, \quad i = m-2n, \quad r = 1-m$$

Substituting these in equation (22) we get,

$$h = C\, l^{3n-1} \times \theta^{j} \times \rho^{2n} \times \mu^{m-2n} \times \beta^{j} \times c_p^{m} \times g^{n} \times k^{1-n}$$

$$\text{or} \quad \frac{hl}{k} = C \left(\frac{l^3 \rho^2 g}{\mu^2}\right)^n \left(\theta\beta\right)^j \left(\frac{\mu c_p}{k}\right)^m.$$

Since g, β and θ appear only in the form of a product in equations (6), & (9), they must have the same exponent. Therefore j = n and the above equation

becomes $$\frac{hl}{k} = C \left(\frac{l^3 \rho^2 g \beta\theta}{\mu^2}\right)^n \left(\frac{\mu c_p}{k}\right)^m$$

It can be easily seen that the terms in brackets have zero dimensions and they are known as Nusselt number $\left(Nu = \frac{hl}{k}\right)$ Grashof number $\left(G_r = \frac{l^3\rho^2 g \beta\theta}{\mu^2}\right)$, and Prandtl number $\left(P_r = \frac{c_p \mu}{k}\right)$ as already indicated in the derivation by the method of differntial equations.

Again let us assume that in the case of forced convection, the heat transfer coefficient 'h' is given by:-

$$h = C\, V^a l^b \mu^f k^j \rho^m c_p^n \quad \text{-----} (24)$$

where C is a constant, l is the characteristic length, e.g. diameter of a cylinder or sphere, V is the velocity of the fluid and the other symbols have their usual meaning. Thus we write, as in the case of free convection, for the dimensions of 'h'

$$[h] = [H T^{-1} L^{-2} \theta^{-1}] \quad ------ (25)$$

Substituting the dimensions of V, l, μ, k, ρ, and c_p in equation (24) and using (25) we get

$$H T^{-1} L^{-2} \theta^{-1} = C \times M^{f+m-n} \times L^{a+b-f-j-3m} \times T^{-a-f-j} \times H^{j+n} \times \theta^{-j-n}.$$

Comparing indices

$$j+n = 1$$
$$-j-n = -1$$
$$-a-f-j = -1$$
$$a+b-f-j-3m = -2$$
$$f+m-n = 0$$

from these equations we can express the four exponents, a, b, f, j in terms of the remaining two viz: m and n. Thus we have

$$a = m$$
$$b = m-1$$
$$f = n-m$$
$$j = 1-n$$

Substituting these in equation (24) we get

$$h = C \frac{k}{l} \left(\frac{\rho l}{\mu} V \right)^m \left(\frac{c_p \mu}{k} \right)^n$$

$$\text{or} \quad \frac{hl}{K} = C \left(\frac{\rho l}{\mu} V \right)^m \left(\frac{c_p \mu}{k} \right)^n$$

The terms in brackets which have zero dimensions are known as Nusselt Number $\left(Nu = \frac{hl}{k}\right)$ Reynolds number $\left(Re = \frac{\rho l}{\mu} V\right)$ and Prandtl Number $\left(Pr = \frac{c_p \mu}{k}\right)$ as already indicated.

Finally we may assume that in the case of forced convection the force upon the body, placed in a fluid stream depends upon, μ, ρ, l, and V where the letters have their usual meanings. Thus we may write

$$F = c\,\mu^{a}\,\rho^{b}\,l^{c}\,V^{d}$$

where C is a constant

Substituting the dimensions of the various quantities we get

$$MLT^{-2} = C\ M^{a+b} \times L^{-a-3b+c+d} \times T^{-a-d}$$

Equating indicies

$$a + b = 1$$

$$a - 3b + c + d = 1$$

$$-a - d = -2$$

Expressing b, c, d in terms of a we have

$$b = 1 - a, \quad c = 2 - a = d$$

Thus $$F = C\left(\frac{\mu}{\rho V l}\right)^{a} \rho V^{2} l^{2}$$

or $$\frac{F}{A\left(\frac{\rho V^{2}}{2}\right)} = 2C\left(\frac{\mu}{\rho V l}\right)^{a}$$

Where A stands for area having dimensions L^2 and $\left(\frac{\rho V l}{\mu}\right)$

is the well known Reynolds number Re. Now $\frac{F}{A \rho V^2/2}$ is known as the friction drag. Coefficient C_f in aerodynamics. We have further, Stanton number $St = C_f/2$ or

$$St. = \frac{F}{A \rho V^2} = C \left(\frac{\mu}{\rho l V} \right)^{a} = C \left(Re \right)^{-a}$$

Now $C (Re)^{-a}$ can be easily shown* to be equal to $Nu/Re \cdot Pr$ which is nothing but $h/\rho C_p V$ as shown by the diffrential method given before.

Advantages of dimensionless groups

In the discussion of heat transfer by either free or forced convection, the dimensionless groups like Nusselt Number, Reynolds Number, Grashof Number etc., will occur over and over again. One great advantage of these numbers lies in the fact that any involved magnitudes can be changed in such a way that the numerical value of the dimensionless groups remains the same. Hence the effect of changing each one of these magnitudes in a group can be easily calculated

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* We know $\frac{Nu}{Re \cdot Pr} = c' (Re)^{m-1} (Pr)^{n-1}$
Where c' is a constant. Now m is always less than one as found experimentally hence $m-1 < 0$ say equal to -a and for a given fluid $(Pr)^{n-1}$ is constant = c". Thus

$$St = Nu/Re \cdot Pr = c (Re)^{-a}$$

Where C = (c' X c") = Constant.

by determining experimentally the influence of the variation of only one magnitude in that group. Equations of dimensionless groups are therefore very useful and they lead to a saving of considerable amount of work and time. For instance let us consider the well known dimensional equation of free convection:

$$Nu = c\,(Gr)^m\,(Pr)^n$$

$$\text{or} \quad \frac{hl}{k} = c\left(\frac{l^3\rho^2\beta g\theta}{\mu^2}\right)^m\left(\frac{c_p\mu}{k}\right)^n$$

If we wish to find the change in the coefficient of heat transfer 'h' in the case of a sphere of diameter 'l' for different variations of the involved magnitudes, we can proceed by changing first 'l' taking say, four different sphere diameters, then conducting experiments with each of these and with fluids of four different thermal conductivities 'k' further varying four times and repeating the process with each of the seven independent variables $l, k, \rho, \beta, \theta, \mu$ and c_p This would require 4^7 = 16384 tests. On the other hand, if we use the dimensional equation given above, it would be sufficient to conduct experiments with four different values of the Grashof number (Gr.), each with four values of the Prandtl number Pr. i.e. 4^2 = 16 experiments in order to get about the same result as with more that 16000 tests by using the direct method. In actual practice however more than the minimum of

16 tests may be necessary. Again all the variation of the seven independent variables referred to above would not be found necessary or even possible. Even then, the use of these dimensionless groups leads to an enormous saving of work and time.

Dimensions of quantities used in ths chapter.

Quality	Symbol	Dimensions in terms of Mass Length Time Heat & Temperature (M) (L) (T) (H) (θ)
Characteristic length	l	$[M]^0 [L] [T]^0 [H]^0 [\theta]^0$
Temperature difference between surface and fluid	θ	$[M]^0 [L]^0 [T]^0 [H]^0 [\theta]$
Density of fluid	ρ	$[M] [L]^{-3} [T]^0 [H]^0 [\theta]^0$
Viscosity of fluid	μ	$[M] [L]^{-1} [T]^{-1} [H]^0 [\theta]^0$
Coefficient of thermal expansion of fluid	β	$[M]^0 [L]^0 [T]^0 [H]^0 [\theta]^{-1}$
Specific heat of fluid at constant pressure	c_p	$[M]^{-1} [L]^0 [T]^0 [H] [\theta]^{-1}$
Acceleration due to gravity	g	$[M]^0 [L] [T]^{-2} [H]^0 [\theta]^0$
Thermal conductivity of fluid	k	$[M]^0 [L]^{-1} [T]^{-1} [H] [\theta]^{-1}$
Forced velocity of fluid.	V	$[M]^0 [L] [T]^{-1} [H]^0 [\theta]^0$
Heat transfer coefficient	h	$[M]^0 [L]^{-2} [T]^{-1} [H] [\theta]^{-1}$

References

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