Module II

CONVECTIVE HEAT TRANSFER

Course material Adapted from:

1. Warren. L, McCabe, Julian,C. Smith and Peter Harriott, “Unit Operations of Chemical Engineering”, 7th Edn., McGraw Hill International Edition, NewYork 2005.

2. Holman. J.P., “Heat Transfer” , 9th Edn., Tata McGraw Hill Book Co., New Delhi, 2008.

3. R.C.Sachdeva, “Fundamentals of Engineering Heat and Mass Transfer”, 4th Edition,New Age International Publishers,2010

4. http://nptel.ac.in/courses/103103032/- Dr. Anil Verma Dept. of Chemical Engineering,IIT Guwahati

5. www.che.utexas.edu/course/che360/lecture_notes/chapter_2.ppt

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Heat flux, average temperature of fluid stream, overall heat transfer coefficient, LMTD, individual heat transfer coefficients, relationship between individual and overall heat transfer coefficients. Concept of heat transfer by convection, natural and forced convection, application of dimensional analysis for convection, heat transfer to fluids without phase change: heat transfer coefficient calculation for natural and forced convection, heat transfer to fluids with phase change: heat transfer from condensing vapours, dropwise and film-type condensation, heat transfer coefficients calculation for film-type condensation.

2.1. Heat flux, average temperature of fluid stream Heat flux:

Heat transfer calculations are based on the area of the heating surface area. The rate of heat transfer per unit area is called the heat flux. Bulk mean temperature: When a fluid is heated or cooled the temperature will vary throughout the cross section of the stream. Because of these temperature gradients throughout the stream it is necessary to state what is meant by the temperature of the stream. It is the temperature that will be attained if the entire.

fluid stream flowing across the section are withdrawn and mixed adiabatically to a uniform temperature. This is also called as average or mixing cup stream temperature.

Film temperature: It is the average between the temperature of the surface and the fluid.

2.2. Overall Heat Transfer Coefficient

Let us consider a plane wall of thickness x_w and thermal conductivity k_w. The warm fluid at a mean temperature of T_h is flowing through the inside surface of the wall. The cold fluid at a mean temperature of T_c is flowing through the outside surface of the wall. The inside surface temperature is T_{wh} and outside surface temperature is T_{wc}.

The overall heat transfer coefficient is constructed from the individual coefficients and the resistances of the wall in the following manner.

(i) Overall Heat transfer Coefficient based on outside surface area

The rate of heat transfer from the warm fluid to the inner surface of the wall in differential form:

$$\frac{dq}{dA_i} = h_i\left(T_h - T_{wh}\right) \qquad (1)$$

By rearranging eqn(1), we get

$$dq = \frac{\left(T_h - T_{wh}\right)}{\dfrac{1}{h_i dA_i}}$$

The rate of heat transfer through the wall in differenti=al form

$$\frac{dq}{d\bar{A}_L} = \frac{k_w\left(T_{wh} - T_{wc}\right)}{x_w} \qquad (2)$$

By rearranging eqn(2), we get

$$dq = \frac{(T_{wh} - T_{wc})}{\dfrac{x_w}{k_w d\bar{A}_L}}$$

The rate of heat transfer from the outer surface of the wall to the cold fluid in differential form:

$$\frac{dq}{dA_o} = h_o (T_{wc} - T_c) \qquad (3)$$

By rearranging eqn(3), we get

$$dq = \frac{(T_{wc} - T_c)}{\dfrac{1}{h_o dA_o}}$$

If the eqns(1) to (3) are solved for the temperature differences and the temperature differences added, the result is

$$(T_h - T_{wh}) + (T_{wc} - T_c) + (T_{wc} - T_c) = T_h - T_c = \Delta T = dQ\left(\frac{1}{h_i dA_i} + \frac{x_w}{k_w d\bar{A}_L} + \frac{1}{h_o dA_o}\right) \qquad (4)$$

Assume that the heat transfer rate is arbitrarily based on the outside area. If the eqn(4) is solved for dQ, and if both sides of the resulting equations are divided by dAo, the result is

$$\frac{dQ}{dA_o} = \frac{T_h - T_c}{\dfrac{1}{h_i}\left(\dfrac{dA_o}{dA_i}\right) + \dfrac{x_w}{k_w}\left(\dfrac{dA_o}{d\bar{A}_L}\right) + \dfrac{1}{h_o}\left(\dfrac{dA_o}{dA_o}\right)} \qquad (5)$$

$$\frac{dA_o}{dA_i} = \frac{r_o}{r_i} \quad ; \qquad \frac{dA_o}{d\bar{A}_L} = \frac{r_o}{\bar{r}_L}$$

Eqn (5) becomes

$$\frac{dQ}{dA_o} = \frac{T_h - T_c}{\dfrac{1}{h_i}\left(\dfrac{r_o}{r_i}\right) + \dfrac{r_o}{k_w}\ln\left(\dfrac{r_o}{r_i}\right) + \dfrac{1}{h_o}} \qquad (6)$$

From eqn (6), the **overall heat transfer coefficient based on outside surface area** is,

$$U_o = \frac{1}{\frac{1}{h_i}\left(\frac{r_o}{r_i}\right) + \frac{r_o}{k_w}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_o}} \quad (7)$$

(ii) **Overall heat transfer coefficient based on inside surface area**

The rate of heat transfer from the warm fluid to the inner surface of the wall in differential form:

$$\frac{dq}{dA_i} = h_i\left(T_h - T_{wh}\right) \quad (1)$$

By rearranging eqn(1), we get

$$dq = \frac{\left(T_h - T_{wh}\right)}{\frac{1}{h_i dA_i}}$$

The rate of heat transfer through the wall in differential form

$$\frac{dq}{d\bar{A}_L} = \frac{k_w\left(T_{wh} - T_{wc}\right)}{x_w} \quad (2)$$

By rearranging eqn(2), we get

$$dq = \frac{\left(T_{wh} - T_{wc}\right)}{\frac{x_w}{k_w d\bar{A}_L}}$$

The rate of heat transfer from the outer surface of the wall to the cold fluid in differential form:

$$\frac{dq}{dA_o} = h_o\left(T_{wc} - T_c\right) \quad (3)$$

By rearranging eqn(3), we get

$$dq = \frac{\left(T_{wc} - T_c\right)}{\dfrac{1}{h_o dA_o}}$$

If the eqns(1) to (3) are solved for the temperature differences and the temperature differences added, the result is

$$\left(T_h - T_{wh}\right) + \left(T_{wc} - T_c\right) + \left(T_{wc} - T_c\right) = T_h - T_c = \Delta T = dQ\left(\frac{1}{h_i dA_i} + \frac{x_w}{k_w d\bar{A}_L} + \frac{1}{h_o dA_o}\right) \quad (4)$$

Assume that the heat transfer rate is arbitrarily based on the inside area. If the eqn(4) is solved for dQ, and if both sides of the resulting equations are divided by dAi, the result is

$$\frac{dQ}{dA_i} = \frac{T_h - T_c}{\dfrac{1}{h_i}\left(\dfrac{dA_i}{dA_i}\right) + \dfrac{x_w}{k_w}\left(\dfrac{dA_i}{d\bar{A}_L}\right) + \dfrac{1}{h_o}\left(\dfrac{dA_i}{dA_o}\right)} \quad (5)$$

$$\frac{dA_i}{dA_o} = \frac{r_i}{r_o} \quad ; \quad \frac{dA_i}{d\bar{A}_L} = \frac{r_i}{\bar{r}_L}$$

Eqn (5) becomes

$$\frac{dQ}{dA_i} = \frac{T_h - T_c}{\dfrac{1}{h_i}\left(\dfrac{r_i}{r_i}\right) + \dfrac{r_i}{k_w}\ln\left(\dfrac{r_o}{r_i}\right) + \dfrac{1}{h_o}\left(\dfrac{r_i}{r_o}\right)} \quad (6)$$

From eqn (6), the **overall heat transfer coefficient based on inside surface area** is,

$$U_i = \frac{1}{\dfrac{1}{h_i} + \dfrac{r_i}{k_w}\ln\left(\dfrac{r_o}{r_i}\right) + \dfrac{1}{h_o}\left(\dfrac{r_i}{r_o}\right)} \quad (7)$$

Fouling factors

In actual service, heat transfer surfaces do not remain clean. Scale, dirt and other solid deposits form on one or both the sides of the tubes, provide additional resistances to heat flow and reduce the overall coefficient. The effect of such deposits is taken into account as fouling factors in design calculation of heat exchangers. h_{di}, h_{do} are the fouling factors for the scale deposits on the inside and outside tube surfaces.

Overall heat transfer coefficient based on outside surface area

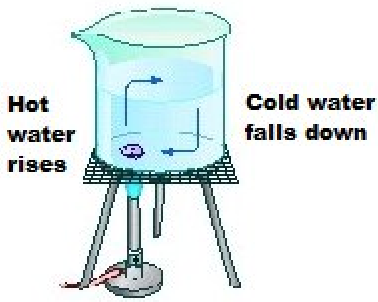
$$U_o = \frac{1}{\frac{1}{h_i}\left(\frac{r_o}{r_i}\right) + \frac{1}{h_{d\,i}}\left(\frac{r_o}{r_i}\right) + \frac{r_o}{k_w}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_{d\,o}} + \frac{1}{h_o}}$$

Overall heat transfer coefficient based on inside surface area

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{1}{h_{d\,i}} + \frac{r_i}{k_w}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_{d\,o}}\left(\frac{r_i}{r_o}\right) + \frac{1}{h_o}\left(\frac{r_i}{r_o}\right)}$$

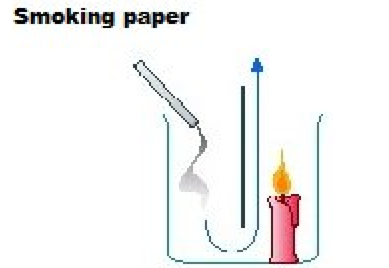
2.3. Concept of heat transfer by convection, natural and forced convection

When a current or macroscopic particle of fluid crosses a specific surface, it carries with it a definite quantity of enthalpy. Such a flow of enthalpy is called convection. Convection can refer to the flow of heat associated with the movement of fluid, such as when hot air from a furnace enters a room, or to the transfer of heat from a hot surface to a flowing fluid.



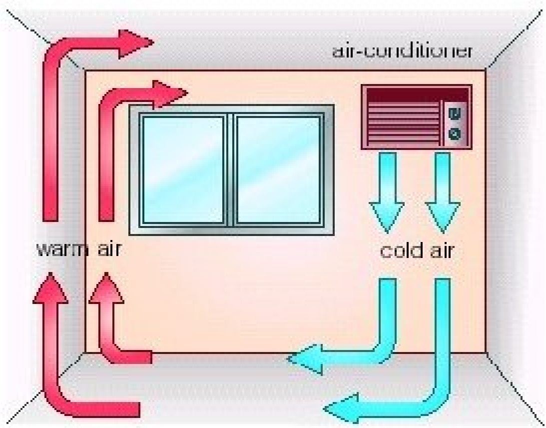
Convection current in water

(a)



Convection current in air

(b)



Convection current in an air conditioned room

(c)

Fig.1. Convection

The two types of convection are Natural convection and forced convection.

Natural convection: If the convection currents are the result of buoyancy forces generated by the differences in density and the differences in density are in turn caused by temperature gradients in the fluid mass, the action is called natural convection.

Forced convection: If the convection currents are set in motion by the action of a mechanical device such as pump or agitator, the flow is independent of density gradients, it is called forced convection.

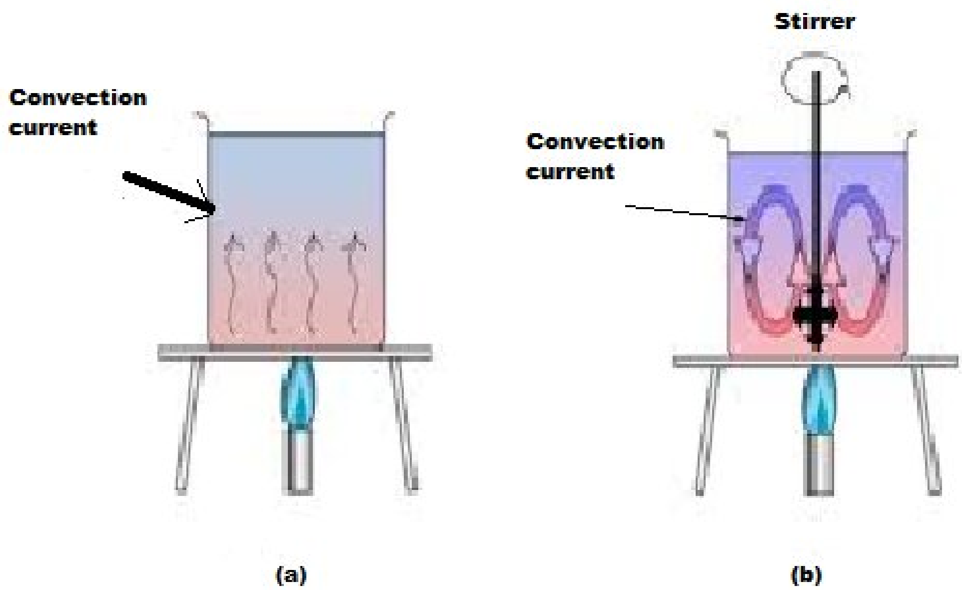


Fig.2.(a) Natural Convection (b) Forced Convection

2.4. Newton's law of cooling

According to **Newton's law of cooling**, convective heat flux is proportional to the difference between the surface temperature and the temperature of the fluid.

$$\frac{Q}{A} \alpha \Delta T$$

$Q = h A (T_s - T_f)$

Where

Q = rate of heat transfer

h= heat transfer coefficient

A = heat transfer area

$\Delta T = (T_s - T_f)$ = temperature difference

T_s = surface temperature

T_f = bulk temperature of fluid

2.5. Application of dimensional analysis for convection

Many engineering problems can't be solved completely by theoretical or mathematical methods. Problems of this type are common in fluid flow, heat flow. One method of attacking a problem for which no mathematical equation can be derived is that of empirical experimentation. The empirical method of obtaining an equation, is laborious, and it is difficult to organize or correlate the results so obtained into a useful relationship for calculation. There exists a method intermediate between mathematical equation and empirical equation. It is based on the fact that if a theoretical equation does exist among the variables involved in the process, that equation must be dimensionally homogeneous. It is possible to group many factors into a smaller number of dimensionless groups of variables. The groups themselves appear in the final equation. This method is called dimensional analysis.

(i) Natural convection

Let us consider the case of natural convection from a vertical plane wall to an adjacent fluid.

Variables	Symbol	Dimension
Length	L	L
Fluid density	ρ	ML^{-3}
Fluid viscosity	μ	$ML^{-1}t^{-1}$
Fluid heat capacity	Cp	$L^2t^{-2}\theta^{-1}$
Fluid coefficient of thermal expansion	β	θ^{-1}
Acceleration due to gravity	g	Lt^{-2}
Temperature difference	ΔT	θ
Heat transfer coefficient	h	$Mt^{-3}\theta^{-1}$
Fluid thermal conductivity	k	$MLt^{-3}\theta^{-1}$

Number of π groups = number of variables(N) – number of fundamental dimensions(m)

Number of π groups = 9-4 = 5

$\pi_1 = L^{a1}\ \mu^{b1}\ k^{c1}\ g^{d1}\ \ \rho$

$\pi_2 = L^{a2}\ \mu^{b2}\ k^{c2}\ g^{d2}\ \ Cp$

$\pi_3 = L^{a3}\ \mu^{b3}\ k^{c3}\ g^{d3}\ \ \beta$

$\pi_4 = L^{a4}\ \mu^{b4}\ k^{c4}\ g^{d4}\ \ \Delta T$

$\pi_5 = L^{a5}\mu^{b5}\ k^{c5}\ g^{d5}\ \ h$

$\pi_1 = (L)^{a1}\ (ML^{-1}t^{-1})^{\ b1}\ (MLt^{-3}\theta^{-1})^{c1}\ (Lt^{-2})^{d1}\ \ ML^{-3}$

By equating the net dimensions of mass, length, time and temperature to zero, we get

$b_1+c_1+1 = 0$ (1)

$a_1 - b_1 + c_1 + d_1 - 3 = 0$ (2)

$-b_1 - 3c_1 - 2d_1 = 0$ (3)

$-c_1 = 0$ (4)

By solving these equations, we get

$c_1 = 0$

$b_1 = -1$

$d_1 = ½$

$a_1 = 3/2$

$\pi_1 = L^{3/2}\ g^{1/2}\ \ \rho\ /\ \mu$

Squaring of both sides

$$\pi_1 = \frac{L^3 g \rho^2}{\mu^2}$$

$\pi_2 = (L)^{a2}\ (ML^{-1}t^{-1})^{\ b2}\ (MLt^{-3}\theta^{-1})^{c2}\ (Lt^{-2})^{d2}\ \ L^2t^{-2}\theta^{-1}$

By equating the net dimensions of mass, length, time and temperature to zero and solving those equations, we get

$$\pi_2 = \frac{\mu C_p}{k} = N_{\Pr}$$

$\pi_3 = (L)^{a3} (ML^{-1}t^{-1})^{b3} (MLt^{-3}\theta^{-1})^{c3} (Lt^{-2})^{d3} \ \theta^{-1}$

By equating the net dimensions of mass, length, time and temperature to zero and solving those equations, we get

$$\pi_3 = \frac{L\mu g\beta}{k}$$

$\pi_4 = (L)^{a4} (ML^{-1}t^{-1})^{b4} (MLt^{-3}\theta^{-1})^{c4}(Lt^{-2})^{d4} \ \theta$

By equating the net dimensions of mass, length, time and temperature to zero and solving those equations, we get

$$\pi_4 = \frac{k\Delta T}{L\mu g}$$

$\pi_5 = (L)^{a5} (ML^{-1}t^{-1})^{b5} (MLt^{-3}\theta^{-1})^{c5}(Lt^{-2})^{d5} \ Mt^{-3}\theta^{-1}$

By equating the net dimensions of mass, length, time and temperature to zero and solving those equations, we get

$$\pi_5 = \frac{hL}{K} = N_{Nu}$$

Combining $\pi_{1,}\ \pi_{3,}\ \pi_4$;

$$\frac{L^3\rho^2 g\beta\Delta T}{\mu^2} = N_{Gr}$$

$\therefore$ $N_{Nu} = f(N_{Gr}, N_{pr})$

Where N_{Nu} = Nusselt number

N_{Gr} = Grashof number

N_{pr} = Prandtl number

(ii) Forced Convection

Let us consider the flow of fluid through a hot tube.

Variables	Symbol	Dimension
Tube Diameter	D	L
Fluid density	ρ	ML^{-3}
Fluid velocity	u	Lt^{-1}
Fluid viscosity	μ	$ML^{-1}t^{-1}$
Fluid heat capacity	Cp	$L^2t^{-2}\theta^{-1}$
Fluid thermal conductivity	k	$MLt^{-3}\theta^{-1}$
Heat transfer coefficient	h	$Mt^{-3}\theta^{-1}$

Number of π groups = number of variables(N) – number of fundamental dimensions(m)

Number of π groups = 7-4 = 3

$\pi_1 = D^{a1}\ \mu^{b1}\ u^{c1}\ k^{d1}\ \ \rho$

$\pi_2 = D^{a1}\ \mu^{b1}\ u^{c1}\ k^{d1}\ \ Cp$

$\pi_3 = D^{a1}\ \mu^{b1}\ u^{c1}\ k^{d1}\ \ h$

$\pi_1 = (L)^{a1}\ (ML^{-1}t^{-}1)^{b1}\ (Lt^{-1})^{c1}\ (MLt^{-3}\theta^{-1})^{d1}\ \ ML^{-3}$

By equating the net dimensions of mass,length,time and temperature to zero, we get

$b_1 + d_1 + 1 = 0$ (1)

$a_1 – b_1 + c_1 + d_1 -3 =0$ (2)

$-b_1 –c_1 -3d_1 = 0$ (3)

$-d_1 =0$ (4)

By solving these equations, we get

$d_1 = 0$

$b_1 = -1$

$c_1 = 1$

$a_1 = 1$

$$\pi_1 = \frac{D\rho u}{\mu} = N_{\mathrm{Re}}$$

$\pi_2 = (L)^{a2}\ (ML^{-1}t^{-1})^{b2}\ (Lt^{-1})^{c2}\ (MLt^{-3}\theta^{-1})^{d2}\ \ L^2t^{-2}\theta^{-1}$

By equating the net dimensions of mass,length,time and temperature to zero and solving those equations, we get

$$\pi_2 = \frac{\mu C_P}{k} = N_{\mathrm{Pr}}$$

$\pi_3 = (L)^{a3}\ (ML^{-1}t^{-1})^{b3}\ (Lt^{-1})^{c3}\ (MLt^{-3}\theta^{-1})^{d3}\ \ Mt^{-3}\theta^{-1}$

By equating the net dimensions of mass,length,time and temperature to zero and solving those equations, we get

$$\pi_3 = \frac{hD}{k} = N_{Nu}$$

$\therefore$ **$N_{Nu} = f(N_{Re}, N_{pr})$**

Where N_{Nu} = Nusselt number

N_{Re} = Reynolds number

N_{pr} = Prandtl number

2.6. HEAT TRANSFER TO FLUIDS WITHOUT PHASE CHANGE

Heat transfer coefficient calculation for forced convection:

Empirical equations for laminar flow:

An empirical equation for moderate Graetz numbers is

$$Nu = 2\ Gz^{1/3}$$

For viscous liquids with large temperature drops, a modification of the above equation is required to account for differences between heating and cooling. Therefore a correction factor is added with that equation to give the final equation for laminar flow heat transfer.

$$Nu = 2\ Gz^{1/3}\ \phi_v = 2\left(\frac{mCp}{kL}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Empirical equations for turbulent flow:

One empirical correlation for long tubes with sharp-edged entrances is the **Dittus-Boelter** equation.

$$\text{Nu} = \frac{h_i D}{k} = 0.023\,\text{Re}^{0.8}\,\text{Pr}^{n}$$

n= 0.4 when the fluid is heated, n= 0.3 when the fluid is cooled

A better relationship for turbulent flow is known as the **Sieder- Tate** equation.

$$\text{Nu} = \frac{h_i D}{k} = 0.023\,\text{Re}^{0.8}\,\text{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

The correction factor $\left(\frac{\mu}{\mu_w}\right)^{0.14}$ accounts for the heating and cooling for fluid. μ is the absolute of viscosity of fluid at bulk mean temperature and μ_w is the absolute of viscosity of fluid at surface temperature.

Heat transfer coefficient calculation for natural convection

Equations for heat transfer in natural convection between fluids and solids of definite geometric shape are of the form

$$\text{Nu} = b\,(\text{Gr Pr})^{n}$$

Where, b,n = constants. Values of the constants b and n for various conditions are given in table.

System	Range of Gr Pr	b	n
Vertical plates, vertical cylinders	$10^4 - 10^9$	0.59	0.25
	$10^9 - 10^{12}$	0.13	0.333
Horizontal plates: Heated, facing upward or cooled, facing down	$10^5 - 2 \times 10^7$	0.54	0.25
	$2 \times 10^7 - 3 \times 10^{10}$	0.14	0.333
Cooled, facing upward or heated,facing down	$3 \times 10^5 - 3 \times 10^{10}$	0.27	0.25

2.7. HEAT TRANSFER TO FLUIDS WITH PHASE CHANGE:

2.7.1. Heat transfer from condensing vapours, dropwise and film-type condensation,

A vapour may condense on a cold surface in one of two ways, which are dropwise and filmwise condensation. In **film wise condensation**, the liquid condensate forms a film, or continuous layer of liquid that flows over the surface of the tube under the action of gravity.

In **dropwise condensation**, the condensate begins to form at microscopic nucleation sites. The drops grow and coalesce with their neighbors to form visible fine drops. The fine drops inturn, coalesce into rivulets, which flow down the tube under the action of gravity.

In dropwise condensation, large areas of the tube surface are covered with an extremely thin film of liquid of negligible thermal resistance. Because of this the heat transfer coefficient at thesse areas is very high;the average coefficient for dropwise condensation may be 5 – 8 times that for film-type condensation.For normal design,film-type condensation is assumed.

(a) (b)

Fig.3. (a) Filmwise condensation (b) Dropwise condensation

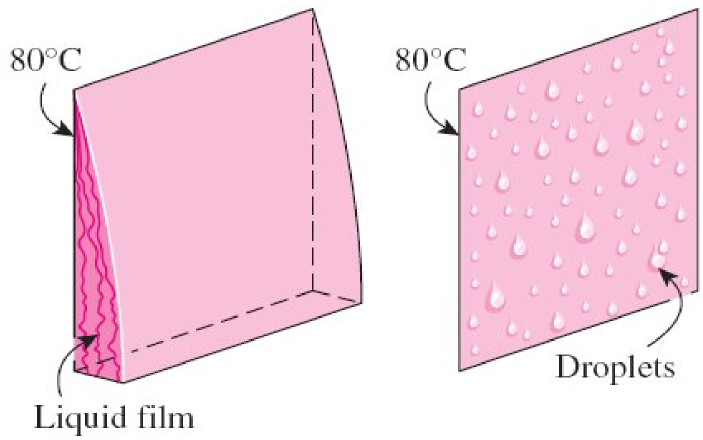


Fig.4. (a) Film condensation (b) Dropwise condensation

Heat transfer coefficient in dropwise condensation is 10 times higher than in filmwise condensation.

Much of the experimental work on the dropwise condensation of steam is summarized as follows:

(1) Film-type condensation of water occurs on tubes of the common metals if both the steam and the tube are clean, in the presence or absence of air, on rough or on the polished surfaces.

(2) Dropwise condensation is obtainable only when the cooling surface is not wetted by the liquid. In the condensation of steam it is often induced by contamination of the vapour with droplets of oil.. It is more easily maintained on a smooth surface than on a rough surface.

(3) The quantity of contaminant or promoter required to cause dropwise condensation is minute, and apparently only a monomolecular film is necessary.

(4) Effective drop promoters are strongly adsorbed by the surface, and substances that merely prevent wetting are ineffective. Some properties are especially effective on certain metals.

(5) The average coefficient obtainable in pure dropwise condensation may be as high as 115 kw/m^2 K.

The effect of non condensable gases on condensation.

The presence of even small amounts of noncondensing gas in a condensing vapour seriously reduces the rate of condensation. When a vapour containing non-condensable gas condenses, the noncondensable gas is left at the surface. Any further condensation will occur only after the incoming vapour has diffused through this noncondensable gas which does not move toward the condensate. As condensation proceeds, the relative amount of this inert gas in the vapour phase increases significantly. The noncondensable gas acts as a thermal resistance to the condensation process.

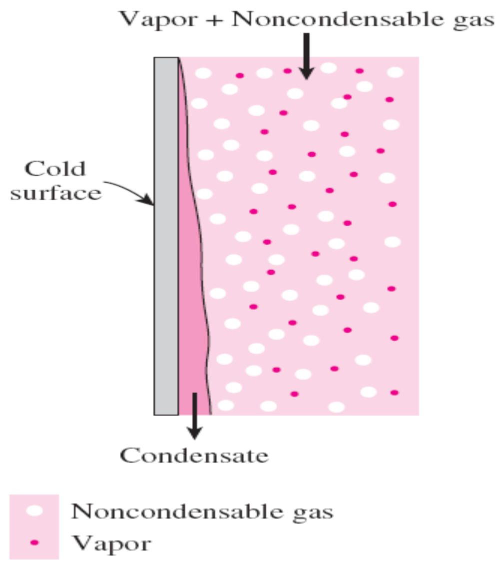


Fig.5. Condensation of vapour containing noncondensable gas

Heat transfer coefficients calculation for film-type condensation.

The assumptions used in Nusselt's equation for condensation to determine film thickness.

(i) The vapour and liquid at the outside boundary of the liquid layer are in thermodynamic equilibrium.

(ii) The only resistance to heat flow is offered by the layer of condensate flowing in laminar flow.

(iii) The velocity of the liquid at the wall is zero.

(iv) The temperatures of the wall and the vapour are constant.

(v) Condensate is assumed to leave the tube at the condensing temperature.

(vi) The fluid properties are taken at the mean film temperature.

Film wise condensation on horizontal pipe

$$h = 0.729\left[\frac{k_f^3 \rho_f^2 g \lambda}{\Delta T D \mu_f}\right]^{1/4}$$

Film wise condensation on vertical pipe

$$h = 0.943\left[\frac{k_f^3 \rho_f^2 g \lambda}{\Delta T L \mu_f}\right]^{1/4}$$

Where

k_f = thermal conductivity of condensate

ρ_f = density of condensate

g = acceleration due to gravity

λ = latent heat of condensation

μ_f = absolute viscosity of condensate

D = Pipe diameter

L = pipe length

ΔT = temperature difference

2.7.2. Heat Transfer To Boiling Liquids

Heat transfer to a boiling liquid is a necessary step in evaporation, distillation, and steam generation, and it may be used to control the temperature of a chemical reactor.

Boiling occurs at the solid–liquid interface when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid.

Saturated Boiling

Boiling of liquid When the temperature of the liquid is equal to the saturation temperature.

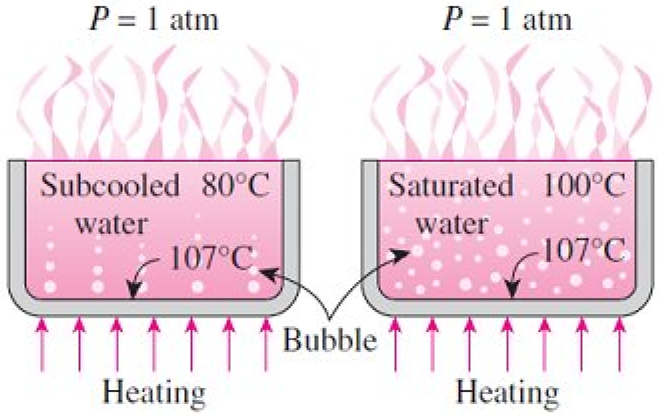


Fig.6 (*a*) Subcooled boiling (*b*) Saturated boiling

Pool boiling of saturated liquid

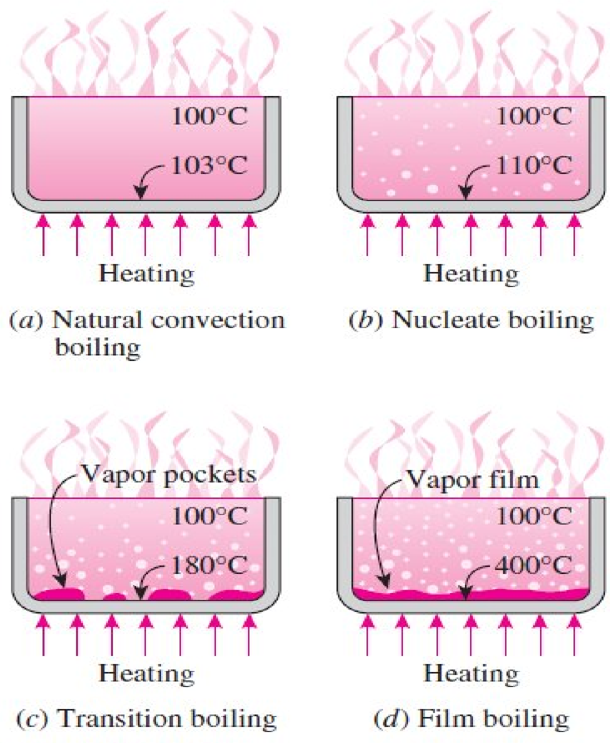


Fig.7. Pool boiling of saturated liquid

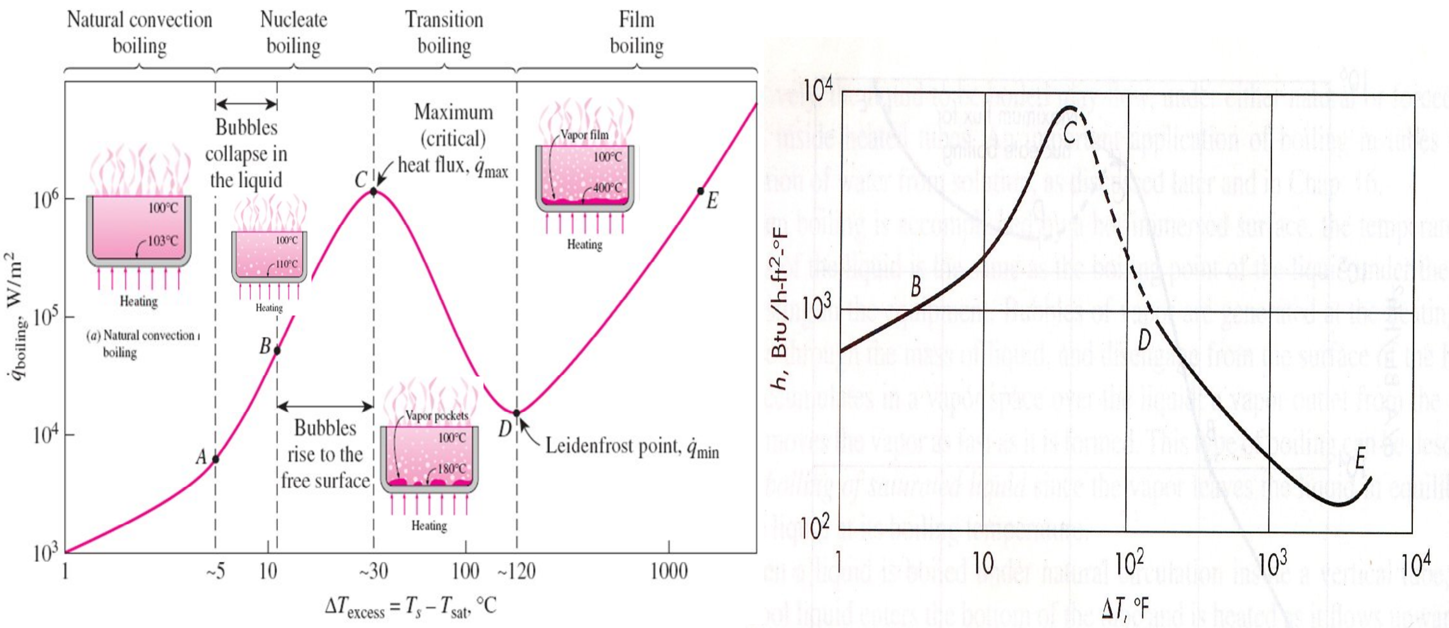


Fig. 8. (a) q/A Vs ΔT diagram (b) h Vs diagram

When boiling is accomplished by a hot immersed surface, the temperature of the mass of the liquid is same as the boiling point of the liquid under the pressure existing in the equipment. Bubbles of vapour are generated at the heating surface, rise through the mass of liquid, and disengage from the surface of the liquid. Vapour accumulates in a vapour space over the liquid, a vapour outlet from the vapour space removes the vapour as fast as it is formed. This type of boiling can be described as **pool boiling of saturated liquid** since the vapour leaves the liquid in equilibrium with the liquid at its boiling temperature.

Consider a horizontal, electrically heated wire immersed in a vessel containing a boiling liquid. Assume that q, heat flux, and ΔT, the difference between the temperature of the wire surface, T_w and that of the boiling liquid T are measured. Start with a very low temperature drop. Now raise T_w and increase the temperature drop by steps, measuring q and ΔT at each step, until very large values of ΔT are reached. A plot of q vs ΔT on logarithmic coordinates will give a curve of the type shown in figure. This curve can be divided into four segments.

Each of the four segments of the graph corresponds to a definite mechanism of boiling. In the first section, at low temperature drops, the mechanism is that of heat transfer to a liquid in natural convection. Bubbles form on the surface of the heater, are released from it, rise to the surface of the liquid, and are disengaged into the vapour space, but they are too few to disturb the normal currents of free convection. This segment is called **natural convection zone**.

At larger temperature drops the rate of bubble production is large enough for the stream of bubbles moving up through the liquid to increase the velocity of circulation currents in the mass of liquid, and the coefficient f heat transfer becomes greater than in undisturbed natural convection. As ΔT is increased, the rate of bubble formation increases and the coefficient increases rapidly.

The action occurring at temperature drops below the critical temperature drop is called **nucleate boiling**, in reference to the formation of tiny bubbles on the hating surface. During nucleate boiling, the bubbles occupy a small portion of the heating surface at a time, and most of the surface is in direct contact with the liquid. The bubbles are generated at localized active sites, usually small pits or scratches on the heating surface. As the temperature drop is raised, more sites become active, improving the agitation of the liquid and increasing the heat flux and the heat transfer coefficient.

Eventually, however, so many bubbles are present that they tend to coalesce and cover portions of the heating surface with a layer of insulating vapour. This layer has highly unstable surface. This type of action is called **transition boiling**. The heat flux and the heat transfer coefficient both fall as the temperature drop is raised.

Near the Leidenfrost point another distinct change in mechanism occurs. The hot surface becomes covered with the film vapour, through which heat is transferred by conduction and by radiation. The random explosion characteristic of transition boiling disappear and are replaced by the slow and orderly formation of bubbles at the interface between the liquid and the film of hot vapour. As temperature drop increases, the heat flux rises, slowly at first and then more rapidly as radiation heat transfer becomes important. The boiling action in this region is known as **film boiling**.

Subcooled Boiling

In some types of forced-circulation equipment, the temperature of the mass of the liquid is below that of its boiling point, but the temperature of the heating surface is considerably above the boiling point of the liquid. Bubbles form on the heating surface, but on release from the surface are absorbed by the mass of the liquid. This type of heat transfer is called subcooled boiling, even though the fluid leaving the heat exchanger is entirely liquid.

PROBLEMS

P.No.1. Water heated to 80°C flows through a 2.54cm I.D and 2.88cm O.D steel tube (k = 50 W/m K). The tube is exposed to an environment which is known to provide an average convection coefficient of h_o = 30800 W/m^2 K on the outside of the tube. The water velocity is 50 cm/s. Calculate the overall heat transfer coefficient based on the outer area of the pipe. Properties of water at bulk mean temperature of 80 °C: ρ=974 kg/m^3, γ = 0.364 x 10^{-6} m^2/sec, k= 668.7 x 10^{-3} W/m K, Pr = 2.20.

Solution:

$$U_o = \frac{1}{\frac{1}{h_i}\left(\frac{r_o}{r_i}\right) + \frac{1}{h_{d\,i}}\left(\frac{r_o}{r_i}\right) + \frac{r_o}{k_w}\ln\left(\frac{r_o}{r_i}\right) + \frac{1}{h_{d\,o}} + \frac{1}{h_o}}$$

r_i	-	0.0127 m
r_o	-	0.0144 m
h_o	-	30800 W/m^2 K
k_w	-	50 W/m K

Dittus-Boelter equation

$N_{Nu} = 0.023(N_{Re})^{0.8}(N_{Pr})^{0.3}$ = 125.48

$N_{Re} = \frac{D_i \rho u}{\mu}$ = 34890.10

hi = $\frac{N_{Nu} k}{D_i}$ = 3303.48 W/m^2 K

U_o = 2428.23 W/m^2 K

P.No.2. Air at 2 atm and 200°C is heated as it flows at a velocity of 12m/s through a tube with a diameter of 3cm.The tube wall temperature is 20°C above the air temperature all along the length of the tube. Calculate the rate of heat transfer per unit length of the tube.The properties of air at bulk mean temperature are; Pr = 0.681; μ = 2.57 x 10^{-5} kg/ms; k = 0.0386 W/mK and Cp = 1.025 kJ/kg K

Solution:

D	-	3 x 10^{-2} m
u	-	12m/s
Tb	-	200°C
Pr	-	0.681
μ	-	2.57 x 10^{-5} kg/ms
k	-	0.0386 W/mK
Cp	-	1.025 kJ/kg K

$N_{\mathrm{Re}} = \dfrac{D_i \rho u}{\mu}$ = **21137**

Dittus-Boelter equation

$N_{Nu} = 0.023 (N_{\mathrm{Re}})^{0.8} (N_{\mathrm{Pr}})^{0.3}$ = **59.12**

h = $\dfrac{N_{Nu} k}{D_i}$ = **76.07**W/m^2 K

Newton's law of cooling

Q = h A ΔT= h πDL ΔT

Q/L = **143.32 W/m**

P.No:3. A horizontal cylinder, 3.0 cm in diameter and 0.8 m length is suspended in water at 20°C. Calculate the rate of heat transfer if the cylinder surface is at 55°C.Given Nu = 0.53 (Gr x Pr) $^{0.25}$. The properties of water at average temperature are as follows: Density = 990 kg/m^3, Viscosity = 2.47 kg/hr.m,
k = 0.534 kcal/hr.m.°C, Cp = 1 kcal/kg°C,

Solution:

D	-	3 x 10^{-2}m
L	-	0.8m
T_b	-	20°C
T_s	-	55°C
ρ	-	990 kg/m^3
μ	-	2.47 kg/hr.m
k	-	0.534 kcal/hr.m.°C
Cp	-	1 kcal/kg°C

$N_{Gr} = \frac{D^3 \rho^2 g \beta \Delta T}{\mu^2}$ = **6.216 x 10^7**

$N_{\Pr} = \frac{\mu C_P}{k}$ = **4.6255**

Nu = 0.53 (Gr x Pr) $^{0.25}$ = **69.01**

h = $\frac{N_{Nu} k}{D}$ = **1228.4kcal/h m^{2}K**

Newton's law of cooling

Q = h A ΔT= h πDL ΔT = **3240.03kcal/h**

P.No:4. Liquid sodium is to be heated from 120 °C to 149 °C at a rate of 2.3 kg/sec in a 2.5 cm diameter electrically heated tube (constant heat flux). Calculate the heat transfer coefficient. The properties of sodium at 134.5°C are: ρ=916 kg/m^3, C_p= 1.3565 kJ/kg K, γ=0.594 x 10^{-6} m^2/sec, k=84.90 W/m K,
Pr= 0.0087. Given N_{Nu} =4.82 + 0.0185 $N_{Pe}^{0.827}$

Solution:

$$h = \frac{N_{Nu} k}{D_i}$$

N_{Nu} =4.82 + 0.0185 $N_{Pe}^{0.827}$ = 14.22

N_{pe} = N_{Re} x N_{pr} = 1871.08

$N_{Re} = \frac{D_i \rho u}{\mu}$ = 215067.34

N_{Pr} = 0.0087

h = 48291.12 W/m^2 K

Assignment:

Convection without phase change:

Forced convection

1. Water is flowing in a horizontal 1 in schedule 40 steel pipe (ID = 0.0266m , OD = 0.0334m)at an average temperature of 65.6°C and a velocity of 2.44 m/s. The tube wall is maintained at 80°C. Calculate the heat transfer coefficient for water inside the pipe. The properties of water at bulk mean temperature are: ρ=980 kg/m^3; μ= 4.32×10^{-4} N.s/m^2;;k= 633×10^{-3} W/mK; Pr =2.72

2. Air at atmospheric pressure and 100°C enters a 2m long tube(4cm diameter) with a velocity of 9m/s. Air leaves the tube at a temperature of 193°C. The properties of air at mean bulk temperature are ρ=0.84 kg/m^3; γ=28.8×10^{-6} m^2/s; k=0.026W/mK ; p_r =0.683.Calculate the heat transfer coefficient

3. Water at a mean temperature of 40^oC flows through a 2 cm I.D. pipe with a velocity of 1.5 m/s. The tube wall is 20^oC above the mean water temperature Determine (i) Heat transfer coefficient (ii) Total heat transfer rate to water for 1m length of the pipe. Physical properties of water at 40^oC are ; γ=0.7×10^{-6} m^2/s; k =0.6 kcal/hr m^oc and Pr =0.92 .

4. Water at 50^oC enters a 1.5 cm dia. and 3m long tube with a velocity of 1 m/s. The tube wall is maintained at a constant temperature of 90^oC. Calculate the heat transfer coefficient and the total amount of heat transferred if the exit water temperature is 64^oC.The properties of water at mean bulk temperature are : ρ=990 kg/m^3; γ=0.517×10^{-6} m^2/s; Cp=4184 J/kgK, k=0.65 W/mK ; p_r =3.15.

5. Water flows in a 50 mm dia tube 3m long at an average temperature of 30^oC. The tube wall temperature is maintained at 70^oC and the flow velocity is 0.8 m/s. Estimate the heat transfer coefficient using the Dittus-Boelter correlation. The properties of water at mean bulk temp are ρ=1/1.012×10^{-3} kg/m^3; μ= 550×10^{-6} N.s/m^2;Cp=4.180 kJ/kg K ;k= 642×10^{-3} W/mK; Pr =3.5 .

6. Water at a mean temperature of 37.8°C flows through a 2cm dia tube with a mean velocity of 1.52 m/s. The tube wall temperature is 16.67°C above the water temperature Estimate the heat transfer coefficient. The properties of water at mean bulk temp are ; $\rho = 1/1.011\times10^{-3}$ kg/m^3; $\mu = 577\times10^{-6}$N.s/m^2; c_p=4.180 kJ/ kg K; k=640×10^{-3} W/mK; p_r=3.77.

7. Air at 206.8kPa and an average temperature of 205°C is being heated as it flows through a tube of 25.4mm ID at a velocity of 7.62m/s. The surface of the tube is at a temperature of 216°C. Calculate the heat transfer coefficient. The properties of air at bulk mean temperature are: ρ=1.509 kg/m^3; $\mu=2.6\times10^{-5}$ kg/m.s; k=0.0389W/mK ; p_r =0.686. $\mu_w=2.64\times10^{-5}$ kg/m.s.

8. Water flows at a velocity of 12m/s through a tube of 60mm diameter. The tube surface temperature is maintained at 70°C and the flowing water is heated from the inlet temperature of 15°C to an outlet temperature of 45°C. Taking the properties of water at bulk mean temperature as, ρ=996kg/m^3; $\mu=0.7\times10^{-3}$ N.s/m^2; k=62 x 10^{-2} W/mK; c_p=4.174 kJ/kg K ; μ_s for water at 70^{o}C=0.390×10^{-3}N.s/m^2, Pr = 5.42,calculate (i) heat transfer coefficient from the tube surface to the water,(ii)rate of heat transfer(iii) tube length.

9. Water flows thro' a long 2.2cm dia copper tube at an average velocity of 2m/s. The tube wall is maintained at a constant temperature of 95^{o}C where as water gets heated from 15^{o}C to 60^{o}C while passing thro' the tube. Find the average heat transfer coefficient by using the sieder-Tate eqn. The properties of water at mean bulk temperature are, ρ=990kg/m^3; $\mu=0.69\times10^{-3}$ N.s/m^2; k=0.63 W/mK; c_p=4160 J/kg K ; μ_s for water at 95^{o}C=0.030×10^{-3}N.s/m^2

LIQUID METALS

1. A liquid metal flows at a rate of 4 kg/s through a tube having an inside diameter of 0.05m. The liquid enters at 227°C and is heated to 232°C in the tube. The tube wall is maintained at a temperature of 30K above the

fluid bulk mean temperature and constant heat flux is maintained. Calculate the required tube length. The properties of fluid at bulk mean temperature are: ρ=7400 kg/m^3; μ=7.1×10^{-4} kg/m.s; C_p=120 J/kg K, k =13 W/mK.

2. A Liquid metal flows at the rate of 4kg/s through a 6cm ID tube in a nuclear reactor under constant heat flux condition. The fluid at 200°C is to be heated with the tube wall 40°C above the fluid temperature. Determine the length of the tube required for 25°C rise in bulk fluid temperature, using the following properties: ρ=7700 kg/m^3; γ=8×10^{-8} m^2/s; Pr= 0.011; C_p=130 J/kg K, k =12 W/mK.
3. Liquid mercury flows at a rate of 1.6kg/s through a copper tube of 20mm diameter. The mercury enters the tube at 15°C and leaves at 35°C. Calculate the tube length for constant heat flux at the wall which is maintained at an average temperature of 50°C. The properties of mercury at bulk mean temperature are; ρ=13582 kg/m^3; γ=1.5×10^{-7} m^2/s; Pr= 0.0248; C_p=140 J/kg K, k =8.69 W/mK.
4. Liquid sodium is to be heated from 120°Cto 149°C at a rate of 2.3kg/s in a 2.5 cm dia. electrically heated tube (constant heat flux). Calculate the minimum length of the tube if its wall temp is not to exceed 200°C. The properties of sodium at mean bulk temperature are, ρ=916 kg/m^3; γ=0.594×10^{-6} m^2/s; p_r= 0.0087; c_p=1.3565 kJ/kg K, k =84.90 W/mK.
5. Liquid bismuth flows at a rate of 4.5kg/s thro' a 50mm dia. Stainless steel tube. The inlet and exit temp of liquid bismuth are 415°C and 440°C respectively. If a constant heat flux condition is maintained at the tube wall and the wall temp is 20°C above the bismuth bulk temp all along the length of the tube, how long must the tube be accomplish this heating? The properties of bismuth at mean bulk temperature are ρ=10kg/m^3; γ=1.2×10-6m^2/s; p_r=0.011, c_p=0.1444 kJ/kg K; k=15w/mk.

Laminar flow heat transfer in tubes

1. Water at 60°C flows through a tube of 2.54cm diameter and 3m long at a

mean flow velocity of 2cm/s. Calculate the heat transfer coefficient.The properties of water at mean temperature are; ρ=985 kg/m^3; μ=4.71 x 10^{-4} kg/ms; cp=4.18kJ/kg K; k=0.651W/mK; Pr = 3.02; μ_w = 3.55 x 10^{-4} kg/ms.

2. A 6.35 mm I.D. tube is maintained at 37.8°C along its entire surface. Ethylene glycol at 15.6°C is allowed to flow thro' this tube with a mean velocity of 0.61 m/s. Determine the mean heat transfer coefficient over the first 1.5 m length of the tube. The properties of ethylene glycol are, μ at (15.6°C) =25.67×10^{-3} kg/ms; μ(37.8°C)=10.38×10^{-3} kg/m.s; k=0.292 w/mk; ρ=1100 kg/m^3; p_r=2.04.
3. Water at 20°C flowing at the rate of 0.015 kg/s enters a 25mm ID tube which is maintained at a temperature of 90°C. Assuming fully developed flow determine the heat transfer coefficient and the tube length required to heat the water to 70°C. The properties of water at bulk mean temperature are; ρ=1000kg/m^3; μ=0.577×10^{-3} N.s/m^2; k=640 x 10^{-3} W/m K; C_p=4181 J/kg K ; μ_s for water at 90°C=0.310×10^{-3}N.s/m^2, Pr = 3.77

Natural Convection

1. A heated vertical wall 0.305m high and 0.305m width of an oven for baking food with the surface at 232°C is in contact with air at 38°C. Calculate the heat transfer coefficient and rate of heat transfer. Given: Nu = 0.59 (Gr x Pr) $^{0.25}$. The properties of air at film temperature are as follows: ρ= 0.867 kg/m^3, μ=2.32 x 10^{-5} kg/ms, k =0.0343 W/.m.°C, N_{Pr} = 0.690 .
2. A metal plate 0.609m in height forms the vertical wall of an oven and is at a temperature of 171°C. Within the oven is air at a temperature of 93.4°C and atmospheric pressure. Given Nu = 0.548 (Gr x Pr) $^{0.25}$ .Calculate the heat transfer coefficient and rate of heat taken up by air. The properties of air at film temperature are as follows: ρ= 0.8713 kg/m^3, μ=0.232 x 10^{-4} kg/ms, k =33.2 x 10^{-6} W/.m.°C, Cp = 1.005 kJ/kg°C.
3. Determine the rate of heat loss per metre length from a 10cm outside

diameter steam pipe placed horizontally in ambient air at 30°C. The pipe has an outside wall temperature of 170°C. Given Nu = 0.48 (Gr x Pr) $^{0.25}$.The properties of air at film temperature are: γ=23.13×10^{-6} m^2/s; p_r=0.688, k=32.10 x 10^{-3} W/mK.

4. Calculate the coefficient of heat transfer by free convection between a horizontal wire and air at 25 °C. The surface of the wire is at 95°C and its diameter is 2.5mm. Given Nu = 1.18 (Gr x Pr) $^{1/8}$. The properties of air at film temperature are: γ=18.97×10^{-6} m^2/s; p_r=0.696, k=28.96 x 10^{-3} W/mK.

5. A vertical pipe of 20cm outer diameter, at a surface temperature of 100°C is in a room where the air is at 20°C. The pipe is 3m long. What is the rate of heat loss per metre length of the pipe? Given Nu = 0.10 (Gr x Pr) $^{1/3}$. The properties of air at film temperature are: γ=18.97×10^{-6} m^2/s; p_r=0.696, k=28.96 x 10^{-3} W/mK.

Convection with phase change

Condensation

1. Dry steam at 100 °C condenses on the outside surface of a horizontal pipe of O.D 2.5cm. The pipe surface is maintained at 84°C by circulating water through it. Determine the rate of formation of condensate per metre length of the pipe. The properties of condensate at film temperature are: ρ_f = 963 kg/m^3; μ_f = 306x10^{-6} N s/m^2; k_f = 677x 10^{-3} W/m K; λ = 2257 kJ/kg.

2. Saturated steam at 54.5°C condenses on the outside surface of a 25.4mm OD, 3.66m long vertical tube maintained at a uniform temperature of 43.3°C. Determine the average condensation heat transfer coefficient over the entire length of the tube and also the rate of formation of condensate. The properties of condensate at film temperature are: ρ_f = 988 kg/m^3; μ_f = 0.558x10^{-3} N s/m^2; k_f = 0.642 W/m K; λ = 2372 kJ/kg.

3. Saturated steam at 1 atm pressure condenses on a vertical tube which is maintained at a temperature of 70°C. Calculate the heat transfer coefficient. The properties of condensate at film temperature are: ρ_f = 968 kg/m^3; μ_f = 0.337x10^{-3} N s/m^2; k_f = 0.674 W/m K; λ = 2255 kJ/kg.

Overall heat transfer coefficient

1. Water heated to 80°C flows through a 2.54cm I.D and 2.88cm O.D steel tube (k = 50 W/m K). The tube is exposed to an environment which is known to provide an average convection coefficient of h_o = 30800 W/m^2 K on the outside of the tube. The water velocity is 50 cm/s. Calculate the overall heat transfer coefficient based on the outer area of the pipe. Properties of water at bulk mean temperature of 80 °C: ρ=974 kg/m^3, γ = 0.364 x 10^{-6} m^2/sec, k= 668.7 x 10^{-3} W/m K, Pr = 2.20

2. Methyl alcohol flowing in the inner of a double pipe heat exchanger is cooled with water flowing in the outer pipe. The inside and outside diameters of the inner pipe are 2.6 cm and 3.5 cm respectively. The thermal conductivity of steel is 26 cal/cm.hr °C. The individual coefficient and fouling factors are : Alcohol and water coefficient =180 and 300Kcal/hr.m^2 °C respectively. Inside and outside fouling coefficient =1000 and 500 kcal/hr.m^2 °C. Calculate the overall coefficient based on the outside area.

3. A brass (k= 111W/mK) condenser tube has a 30mm OD and 2mm wall thickness. Sea water enters the tube at 290K, and saturated low pressure steam condenses on the outer side of the tube. The inside and outside heat transfer coefficient are estimated to be 4000 and 8000 W/m^2K respectively, and a fouling resistance of 10^{-4} (W/m^2K$^{)-1}$ on the water side is expected. Calculate the overall heat transfer coefficient based on inside area.

4. In a double pipe counterflow heat exchanger the inner tube has a diameter of 20mm and very little thickness. The inner diameter of the outer tube is 30mm.Water flows through the inner tube at a rate of 0.5kg/s,and oil flows through the shell at a rate of 0.8kg/s. Take the average temperature of water and the oil as 47°C and 80°C respectively. The oil side heat transfer coefficient is 75.2 W/m2K.Determine the overall heat transfer coefficient. The properties of water at bulk mean temperature are: ρ=989 kg/m^3, γ = 0.59 x 10^{-6} m^2/sec, k= 0.637 W/m K, Pr = 3.79.

5. Toluene is cooled from 140°C to 80°C using a double pipe steel heat exchanger with the water flowing inside with a inlet temperature of 30°C and the outlet temperature of 70°C. The outside and inside diameter of the inner tube is 3.2 cm and 2.54 cm respectively. k for steel = 10.868 kW/m °C ; h for toluene = 800 kW/ m^2 °C;h for water = 1100 kW/ m^2 °C. Calculate the overall heat transfer coefficient based on inner surface area.
6. A horizontal steel pipe of 5.25cm I.D and 6.03cm O.D is exposed to atmospheric air at 20°C. Hot water at 98°C flows through this pipe with a velocity of 15m/min.Calculate the overall heat transfer coefficient based on the outer area of the pipe. k for steel = 54 W/mK ; h_i = 1961 W/ m^2 °C ; h_o = 7.91 W/ m^2 °C.
7. Water flows at 50°C inside a 2.5cm ID tube such that hi = 3500W/m^2°C. The tube has a wall thickness of 0.8mm with thermal conductivity of 16 W/m°C. The outside of the tube loses heat by free convection with ho = 7.6 W/m^2°C. Calculate the overall heat transfer coefficient.
8. Calculate the overall heat transfer coefficient between water and oil if the water flows through a copper tube of 180mm inside diameter and 15mm thick, while the oil flows through the annulus formed by this pipe and an outer concentric pipe. The thermal conductivity of the tube wall is 349 W/m K and the fouling factors on the oil and water side are 0.00086 and 0.000344 m^2 K/W respectively. The oil and water side heat transfer coefficient are 1280 and 4650 W/m^2K respectively.
9. Determine the overall heat transfer coefficient based on outer area of a 3.81cm O.D and 3.175 cm I.D brass tube(k = 103.8 W/m K) if the heat transfer coefficients for flow inside and outside the tubes are 2270 and 2840 W/m^2K respectively, and the unit fouling resistances at inside and outside are $R_{fi} = R_{fo} = 8.8 \times 10^{-3}$ m^2 K/W.
