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THE ORIGIN OF THE EQUATION FOR THE INTERFACIAL COEFFICIENT OF HEAT TRANSFER

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SUMMARY

Among the few assumptions that Nusselt made in deriving his widely used equation for the condensate film heat transfer coefficient was the one which stated that the condensate film offers the only resistance to the heat transfer. This means that the effect of the vapour phase on the heat. transfer is negligible and that the surface temparature of the condensate is equal to the saturation temperature of condensing vapour. However, there are practical situations where this assumption is not valid in which case one has to take the so-called interfacial resistance into account.

INTRODUCTION

When a liquid is in equilibrium with its vapour, the number of molecules leaving the surface of the liquid in unit time is equal to the number of the molecules from the vapour which condenses in the surface in unit time. When evaporation is to take place, the number condensing from the vapour, and for condensation to occur the reverse must be the case. Now the number of vapour molecules which strike the surface per unit time can be calculated from the kinetic theory when the pressure and temperature are known (Moore 1978, Daniels 1966, Castellan 1971). From kinetic theory an attempt has been made to show the derivation of the so-called interfacial heat transfer coefficient, that signifies the resistance to the rates of transport at the vapour-liquid interface, during condensation or evaporation process. Also its possible effects on operating conditions such as temperature and pressure are reviewed and discussed.

THE KINETIC THEORY

1. The pressure of a gas:

The simplest kinetic theory model of a gas assumes that the volume occupied by the molecules may be neglected completely compa-

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red to the total volume. It is further assumed that the molecules behave like rigid spheres, with no forces of attraction or repulsion between them except during actual collisions.

In order to calculate the pressure in terms of molecular quantities, let us consider a volume of gas contained in a cubical box of side l (Fig. 1b). The velocity C of any molecule may be resolved into components U, V, and W, parallel to the three mutually perpendicular to X, Y, and Z, so that its magnitude is given by (Fig.1a).

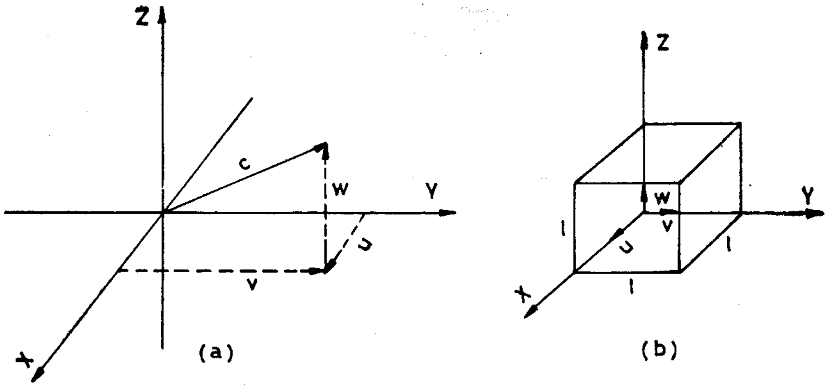


Figure 1 Components of the velocity vector

$$C^2 = U^2 + V^2 + W^2 \tag{1}$$

Collisions between a molecule and the walls are assumed to be perfectly elastic; the angle of incidence equals to the angle of reflexion, and the velocity changes in direction but not in magnitude. At each collision with a wall that is perpendicular to v, the velocity component u changes sign from u to -u, or vice versa; the momentum component of the molecule accordingly changes from $\pm$ mu to $\mp$ mu, where m is the mass of the molecule. The magnitude of the change in momentum is therefore 2mu.

The number of collisions in unit time with the two walls perpendicular to X is equal to u/l, and thus the change in the v component of momentum in unit time is

$$2mu.(u/l) = 2mu^2/l$$

If there are N molecules in the box, the change in momentum in unit time becomes 2 $(Nm(\bar{u}^2)/l)$, where $(\bar{u}^2)$ is the average value of the square of velocity component u. This rate of change of momentum is simply the force exerted by the molecules colliding against the two container walls normal to v, whose area is $2l^2$. Since pressure is defined as the force normal to unit area.,

$$P = \frac{2Nm(\bar{u}^2)/l}{2\ l^2} = \frac{Nm(\bar{u}^2)}{l^3} = \frac{Nm(\bar{u}^2)}{V} \qquad (2)$$

There is nothing to distinguish the magnitude of one particular component from another in equation (1) so that on the average $(\bar{u}^2) = (\bar{v}^2) = (\bar{w}^2)$. Thus, $3\ (\bar{u}^2) = c^2$ and the expression for the pressure becomes

$$P = \frac{Nm(\bar{c}^{-2})}{3V} \qquad (3)$$

The quantity $(\bar{c}^2)$ is called the mean square speed of the molecules, and may be given the special symbol c^2. Then $c = (\bar{c}^2)^{1/2}$ is called the root mean square speed. The total translational kinetic energy E_K of the molecules is $\frac{1}{2}$ Nmc^2. Therefore from equation (3).,

$$PV = \frac{1}{3}\ Nmc^2 = \frac{2}{3}\ E_K \qquad (4)$$

2. Molecular Speeds:

From equation (4) it may be written

$$P = \frac{Nm}{V} \cdot \frac{c^2}{3} = \rho \cdot \frac{c^2}{3}$$

This, c^2. $= \frac{3\ P}{\rho}$ (5)

Where $\rho = \frac{Nm}{V}$ is the density of the gas.

From equation (4) and an ideal-gas equation we obtain for the root mean square speed c, if M is the molecular weight, and from the ideal gas equation

$$P = \frac{w}{V} \cdot \frac{RT}{M} = \rho \cdot \frac{RT}{M} \tag{6}$$

where w is the weight of gas.

From equations (5) and (6) we obtain,

$$c = \sqrt{\frac{3RT}{M}} \tag{7}$$

3. The average speed, $\bar{c}$:

Representing the fraction of molecules having a velocity between u and u + du by dn/n_0, this law may be written from the Boltzmann distribution law or the barometric formula,

$$P = P_0 \exp(-\varepsilon_p/kT) \tag{8}$$

where P, P_0 are the pressures at any height and zero, respectively.

ε_p is the potential energy of the individual molecule,

k is the Boltzmann constant and T is the absolute temperature.

The equation (8) states that if n_0 is the number of molecules in any given state, the number n in a state whose potential energy is ε above that of the given state is

$$n = n_0 \exp(-\varepsilon/kT) \tag{9}$$

The motion of a molecule with an upward velocity u is just like that of a ball thrown vertically into the air. If its initial velocity is u_0, it will rise with continuously decreasing speed, as its kinetic energy is transformed into the potential energy according to the equation as follows.

$$mgx = \frac{1}{2} mu_0^2 - \frac{1}{2} mu^2 \tag{10}$$

where x is the height at any time.

The distribution of kinetic energies ε_K among the molecules follow an exponential law just as the potential energy distribution does similar to equation (8). The fraction of molecules having a velocity between u and u + du by dn/n_0, this law may be written from equation (9) as

$$\frac{dn}{n_0} = A \exp(-\varepsilon_K/kT)\, du \tag{11}$$

Here A is a constant whose value has to be determined.

This distribution law is completely unaffected by collisions between molecules, since a collision results only in an interchange of velocity components between two molecules.

The constant A, in equation (11), may be evaluated from the fact that the sum of all the fractions of molecules in all the velocity ranges must be unity. Thus, integrating over all possible velocities from $-\infty$ to $+\infty$, we have

$$A \int_{-\infty}^{+\infty} e^{-mu^2/2kT}\, du = 1 \tag{12}$$

Letting $\frac{mu^2}{2kT} = x^2$ and subscribing into equation (12) we obtain as

$$A \left(\frac{2kT}{m}\right)^{1/2} \int_{-\infty}^{+\infty} e^{-x^2}\, dx = 1 \tag{13}$$

$$I_1 = \int_{-\infty}^{+\infty} e^{-x^2}\, dx \tag{14}$$

The value of equation (13) can be found as $\sqrt{\pi}$, and thus

$$A = \left(\frac{m}{2\pi kT}\right)^{1/2} \tag{15}$$

Therefore, equation (11) becomes

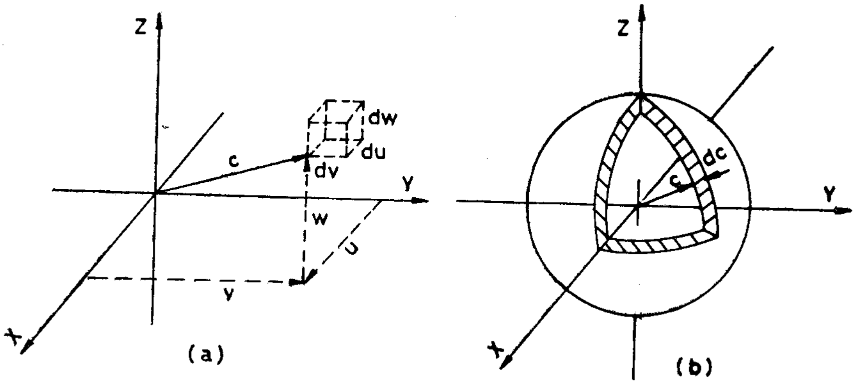
$$\frac{dn}{n_0} = \left(\frac{m}{2\pi kT}\right)^{1/2} \exp\left(-\frac{mu^2}{2kT}\right) du \tag{16}$$

The tree-dimensional distribution law may now be obtained by a simple extension of this treatment. The fraction of molecules having simultaneously a velocity component between u and u + du, v and v + dv, and w and w + dw, is

$$\frac{dn}{n_o} = \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left[-\frac{m(u^2+v^2+w^2)}{2kT}\right] dudvdw \quad (17)$$

Now an expression is desired for the number with a speed between c and c + dc, regardless of direction, where $c^2 = u^2 + v^2 + w^2$.

These are the molecules whose velocity points lie within a spherical shell of thickness dc at a distance c from the origin (Figs. 2a and 2b). The volume of this shell is $4\pi c^2 dc$, and therefore desired distribution function is



(a)

(b)

Figure 2. (a) Three dimensional velocity
(b) Spherical shell

$$\frac{dn}{n_o} = 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{mc^2}{2kT}\right) c^2 dc \quad (18)$$

3. The average speed:

The average speed value $\bar{r}$ of any property r of the molecules is obtained by multiplying each value of r, r_i, by the number of molecules n_i having this value, adding these products, and dividing by the total number of molecules. Thus,

$$\bar{r} = \frac{\sum_j n_i r_i}{\sum_j n_i} = \frac{\sum_j n_i r_i}{n_o} \quad (19)$$

In case n is known as a continuously varying function of r, n(r), instead of the summation of equation (18) the integrations may be obtained

$$r = \frac{\int_0^\infty r \, dn(r)}{\int_0^\infty dn(r)} = \frac{1}{n_0} \int_0^\infty r \, dn(r) \qquad (20)$$

The calculation of the average molecular speed c may be done in a similar way, using equation (18).

$$\bar{c} = \frac{1}{n_0} \int_0^\infty c \, dn = 4\pi \left(\frac{m}{2\pi kT} \right)^{3/2} \int_0^\infty \exp \left(- \frac{mc^2}{2kT} \right) c^3 \, dc \quad (21)$$

The evaluation of this integral can be done in a similar way to that,

$$I = \int_0^\infty e^{-ax^2} x^3 \, dx$$

The value of integral I can be found as follows

$$I = \int_0^\infty e^{-ax^2} x^3 \, dx = \frac{1}{2a^2}$$

Therefore obtaining $\bar{c}$

$$\bar{c} = \left(\frac{8kT}{\pi m} \right)^{1/2} \qquad (22)$$

4. Molecular effusion:

A direct experimental illustration of different average speeds of molecules of different gases can be obtained from the phenomenon called molecular effusion. Consider the arrangement shown in Fig.3a. Molecules from a vessel of gas under pressure are permitted to escape through a tiny orifice, so small that the distribution of the velocities of the gas molecules remaining in the vessel is not affected in any way; that is, no appreciable mass flow in the direction of the orifice is set up. The number of molecules escaping in unit time is then equal to the number that, in their random motion, happen to hit the orifice, and this number is proportional to the average molecular speed.

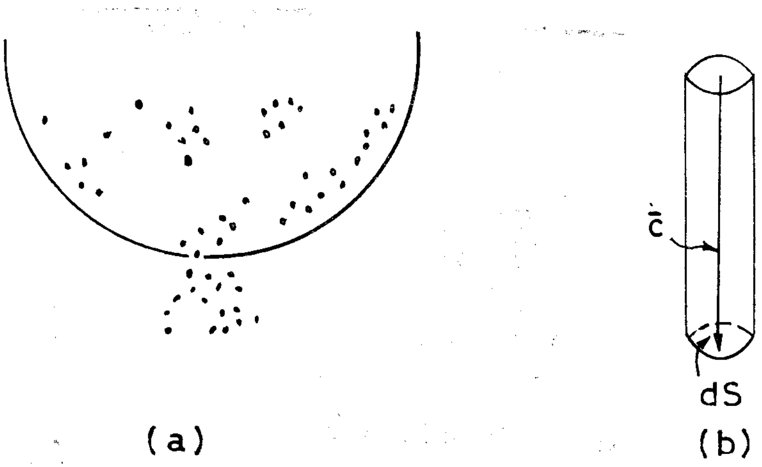


Figure 3. Effusion of gases

In Fig. 3b is shown an enlarged view of the orifice, having an area dS. If all the molecules were moving directly perpendicular to the opening with their mean speed $\bar{c}$, in one second all those molecules would hit the opening that were contained in an element of volume base dS and height $\bar{c}$, or volume $\bar{c}dS$, for a molecule at a distance $\bar{c}$ will just reach the orifice at the end of one second. If there are n molecules per cm^3, the number striking would be $n\bar{c}dS$.

If the direction of the molecules is no longer normal to the wall, instead of situation of Fig. 3, we have that of Fig.4a. For any given direction the number of molecules hitting dS in unit time will be those contained in a cylinder of base dS and slant height $\bar{c}$. The volume of this cylinder is $\bar{c}$ CosθdS, and the number of molecules in it is $n\bar{c}$CosθdS.

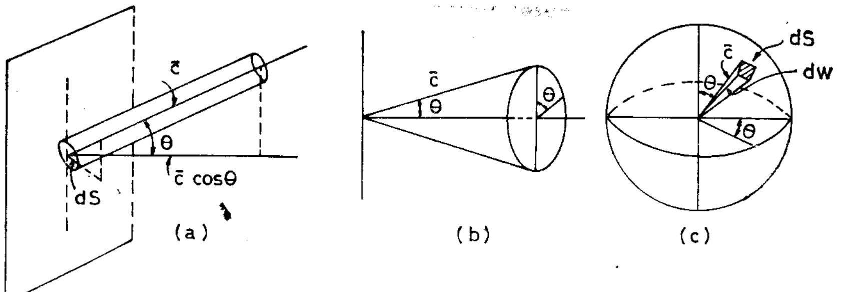


Figure 4. Calculation of gaseous effusion

The next step is to discover how many molecules out of the total volume have velocities in the specified direction. The velocities of the molecules will be referred to a system of polar coordinates (Fig.4b) with its origin at the wall of the vessel. We call such a representation a plot of the molecular velocities in "velocity space". The distance from the origin $\bar{c}$ defines the magnitude of the velocity, and the angles θ and $\varnothing$ represent its direction. Any particular direction from the origin is specified by the differential solid angle dw. The fraction of the total number of molecules having their velocities within this particular spread of directions is $dw/4\pi$, since 4π is the total solid angle subtended by the surface of a sphere. In polar coordinates this solid angle is given by $\mathrm{Sin}\theta d\theta d\varnothing$.

The number of the molecules hitting the surface dS in unit time from the given direction $(\theta, \varnothing)$ becomes

$(1/4\pi)\ n\bar{c}\mathrm{Cos}\theta\mathrm{Sin}\theta d\theta d\varnothing dS$. Or, for unit surface, it is

$(1/4\pi)\ n\bar{c}\mathrm{Cos}\theta\mathrm{Sin}\theta d\theta d\varnothing$. In order to find the total number striking

from all directions, $\dfrac{dn'}{dt}$, this expression must be integrated.

$$\frac{dn'}{dt} = \int_{o}^{\pi/2} \int_{o}^{2\pi} (1/4\pi)\ n\bar{c}\mathrm{Cos}\theta\mathrm{Sin}\theta d\varnothing d\theta \qquad (23)$$

The limits of the integration of $\varnothing$ are from 0 to 2π, corresponding to all the directions around the circle at any given θ. Then θ is integrated from 0 to $\pi/2$. The final result for the number of molecules striking unit area in unit time is then

$$\frac{dn'}{dt} = n\bar{c}/4 \qquad (24)$$

If ρ is the gas density, the weight of gas that effuses in unit time is

$$dw/dt = \rho\bar{c}/4 \qquad (25)$$

From equation (22) we obtain

$$dw/dt = \rho \left(\frac{RT}{2\pi M}\right)^{1/2} \qquad (26)$$

Since $k = R/N$, where N is the Avogadro number, and M is the molecular weight.

Using an ideal gas equation

$$\mu = dw/dt = P(M/2\pi RT)^{1/2} \qquad (27)$$

where, μ is the weight of gas that effuses per unit time per unit area, $kg.\ Sec^{-1}.\ m^{-2}$,

P is the pressure of gas, $N\ m^{-2}$,

M is the molecular weight of gas, $kg.kmol^{-2}$,

R is the ideal gas constant ($8.314\ kJ.kmol^{-1}.K^{-1}$) and

T is the absolute temperature, K

This can apply to condensation or evaporation at the liquid vapour interface in a similar way. Having found equation (27), it may be assumed that a proportion f of the molecules which strike the surface of the liquid condense in it. The mass of molecules which strike unit area per unit time μ, then $f\mu$ is the mass of those which condense in unit area of the liquid per unit time or condensation flux. It follows that $f\mu$ must be the rate of escape of molecules from the saturated liquid surface.

In case evaporation or condensation should occur, we must have two different rates μ_1 and μ_2, so that $f(\mu_1 - \mu_2)$ will represent the net rate of evaporation or condensation, where f is the condensation or evaporation coefficient.

From equation (27), we obtain the net rate of evaparation or condensation across a surface will be

$$m = f\left(\frac{M}{2\pi RT_1}\right)^{1/2} (P_1 - P_2) \qquad (28)$$

In equation (28) the approximation has been made by taking $T_1 = T_3$, which is valid for the case of the condensation or evaporation of water, since the temperatures are absolute and differences are small.

The accepted physical model of evaporation and condensation is based on proposals of Hertz (1882) and of Knudsen (1915). This is known as the Hertz-Knudser model. All earlier experimental determinations of f refer to those evaluated from equation (22). Later Schrage (1953) modified the equation (28) to account for the effect of net bulk vapour motion on the molecular velocity distribution. Based on this work, the more recent investigations usually refer to the modified equation, given approximately by (Tamir 1971, Nabavian 1963, Mills 1967)

$$m = \frac{f}{1\text{-}0.5\ f} \left(\frac{M}{2\pi RT_1} \right)^{1/3} (P_1 - P_3) \tag{29}$$

It can be seen from the above equation that for f = 1, the rate predicted by the Schrage equation is twice that is given by the Hertz-Kundsen model, but for values of f lower than, say 0.2, the correction term 0.5 f can be ignored.

From the Clapeyron equation.

$$\frac{dP}{dT} = \frac{\lambda}{(V_1 - V_3)\ T_1} \tag{30}$$

If we assume that difference $P_1 - P_2$ is small as is indeed the case for condensing steam under practical conditions. we have the associated temperature difference as approximately

$$\frac{\Delta P}{\Delta T} = \frac{\lambda}{T_1(V_1 - V_2)}$$

where $\Delta P = P_1 - P_2$ and $\Delta T = T_1 - T_2$. Furthermore the term V_2 can be dropped from the above equation, since $V_1 \gg V_2$. Obtaining

$$T_1 - T_2 = \frac{T_1\ V_1}{\lambda} (P_1 - P_2) \tag{31}$$

where T_1, T_2 are the absolute temperatures, $P_1 - P_2$ are the pressures, V_1, V_2 are the volumes of vapour and liquid phases, respectively, and λ is the latent heat of vaporization. Substituting equation (31) into equation (28)

$$m = f \left(\frac{M}{2\pi RT_1} \right)^{1/2} \cdot \frac{\lambda(T_1 - T_2)}{T_1\ V_1} \tag{32}$$

Since m is the weight condensed per unit area per unit time or the condensation flux, the interfacial heat transfer coefficient h_i may be obtained.

$$h_i = \frac{m\lambda}{T_1 - T_2} \tag{33}$$

Substitution from equation (33) into equation (32) gives

$$h_i = f \left(\frac{M}{2\pi R T_1} \right)^{1/2} \cdot \frac{\lambda^2}{T_1 V_1} \tag{34}$$

Equation (34) can be used to calculate from the "Steam Tables" the value of h_i for steam condensing in a vessel wherein the steam pressure is P_1. When the value of f is known it becomes possible to determine the difference of pressure necessary to obtain a certain rate of condensation and so the theory can be applied to the steam-side heat transfer rate in condensers. (Silver 1946, Silver 1963–1964, Silver 1961) The phenomenon is something which provides an effective extra heat transfer resistance, to that already present in the liquid film on the tube. It can be regarded as a surface resistance or the so-called interfacial resistance. Its reciprocal would be called the interfacial heat transfer coefficient. If h_f is the heat transfer coefficient for the water film calculated by the Nusselt formula and h_i is the interfacial heat transfer coefficient, the overall heat transfer coefficient for the steam side h will be given as follows

$$\frac{1}{h} = \frac{1}{h_i} + \frac{1}{h_f} \tag{35}$$

To show how this may be used in conjunction with Nusselt's theory, we have the Nusselt film coefficient equation for the vertical tubes as (Mc Adams 1954), then obtaining

$$h_f = 0.943 \left[\frac{k^3 \rho^3 g \lambda}{L \mu \, \Delta t} \right]^{0.25} \tag{36}$$

where k is the thermal conductivity of condensate film,

ρ is the density,

g is the acceleration of gravity,

λ is the latent heat of condensation,

μ is the dynamic viscosity,

L is the length of the condenser, and

Δt is the temperature difference between the saturated vapour and condenser surface.

RESULTS AND CONCLUSIONS

The interfacial resistance is of importance in determining condensation rates at low pressures, its importance depending on the value of the condensation coefficient f. Table 1 shows value of h_i so obtained for an appropriate range of condenser pressure (Silver 1946).

Table 1. h_i as a function of conderser pressure.

Conderser temperature, K	Pressure, $N.m^{-2}$ abs.	h_i, kW/m²K
299.8	3494	19.4
300.9	3729	20.4
302.0	3978	21.6
303.2	4240	22.7
304.3	4519	24.0
305.4	4813	25.3
306.5	5123	26.6
307.6	5450	27.9
308.7	5795	29.4

From Table 1 can be seen that the interfacial resistance decreases as the pressure of condenser increases.

Nabavian and Bromley (1963) have searched the condensation of pure steam in a system designed to minimize all thermal resistance in series with the interfacial vapour-liquid thermal resistance, From the numerous measurements at steam temperatures of near 10 °C and 50 °C, it was possible to calculate values for the condensation coefficient f, as given by the Hertz-Knudsen equation (28), The results indicate a probable range for f of $0.43 < f < 2.0$. They plotted values of h_i/f as a function of liquid-vapour temperature as calculated from the below equation which is similar to equation (34).

$$h_i = f \left(\frac{M}{2\pi R T_{av}} \right)^{1/2} \cdot \frac{\lambda^2}{T_2 \; V_1} \tag{37}$$

where $T_{av} = \frac{1}{2} (T_1 + T_2)$ and $T_1 \; . \; T_2$ are the absolute temperatures of vapour and liquid phases, respectively. h_i/f increases as the liquid-vapour surface temperature decreases.

Mills and Seban (1967) have investigated filmwise condensation of steam at low pressure on a vertical plate in order to ascertain the existence of an interfacial heat transfer. Data were presented for the condensation of saturated steam between 7 °C and 10 °C at heat fluxes between 3700 and 5000 W/m². It was found that no significant interfacial resistance was present. Furthermore they obtained the values of the interfacial heat transfer coefficient as a function of saturation temperature for the condensation coefficients of unity and 0.036, as shown in Table 2.

Table 2. Values of the interfacial heat transfer coefficient for condensation coefficients of unity and 0.036.

Temperature, K	h_i (kW/m²K)	
	f = 1.0	f = 0.036
316	2561	44.8
305	1607	28.1
294	863	15.1
283	466	8.1
272	244	4.3

It was found that the interfacial resistance would be negligible in industrial applications of filmwise condensation when the condensation coefficient, based on the Schrage model in equation (29), is greater than 0.45.

Tamir and Hasson (1971) have performed two series of experiments (evaporation and condensation) under similar vacuum conditions., corresponding to a saturation temperature in the range of 40 °C to 60 °C. The values of condensation coefficient, based on the Hertz-Knudsen model, were found to be 0.23 and 0.11at the saturation temperatures of 50 °C and 104 °C, respectively. It was concluded that the condensation coefficients might be temperature dependent.

The very low values of f found for water (usually 0.03 to 0.04) are widely attributed to'surface contribution' or non-condensible gases at the interface. It has been established that the condensation coefficient for water falls rapidly as the time of exposure of the evaporating or condensing interface is increased (Johnstone 1966). Theoretical values of f have been calculated by Danon (1962) from a consideration of the energy necessary to relaese molecules from the interface. Table 3 compares the predicted ^{r}values with those measured experimentally for a number of common liquids.

Alad'yev and Kondrat'yev (1971) worked out certain relationships governing the thermal resistance of phase transition R_{ph} and conden-

Table 3. Values of the condensation coefficient calculated by the method of Danon.

Fluid at 0°C	f calculated	f observed (range of measurements)
Carbon tetrachloride	1.01	1.0
Benzene	0.92	0.85–0.95
Chloroform	0.17	0.16
Ethyl alcohol	0.014	0.02–0.024
Methyl alcohol	0.023	0.045
Water	0.051	0.04
Toluene	0.59	0.45–0.85

sation coefficient f during condensation of potassium and sodium vapours. It has been found that R_{ph} and f do not depend on the vapour velocity, heat flux, shape of its condensation surface and its location in space, and has been correlated by the following equations within the range of experimental results:

$$h_i = \frac{1}{R_{ph}} = 100\ P_s^{0.22} \qquad (38)$$

$$\text{and } f = 0.0585\ P_s^{-0.5} \qquad (39)$$

where P_s is the vapour pressure in bars,

h_i is the phase heat transfer coefficient in kW/m²K.

Equation (39) is valid for P_s of 0.035 to 1 bar. It follows from the above argument that the condensation coefficient decreases with increasing pressure. Experiments carried out by some other investigators (Labuntsov 1966, Alod'yev 1966, Barry 1966, Kroger 1967) support the findings of these workers and indicate a considerable reduction in the value of the condensation coefficient from near unity a tlow pressure to below 0.1 near atmospheric pressur. A similar type of behaviour also has been reported with water (Mendelson 1965).

In conclusion it is worth noting that the effect of the interfacial resistance. which is appreciable, in limiting possible rates of heat transfer is entirely due to the low value of the coefficient f in equation (34). If this had the higher value, which is sometimes anticipated, values of h_i would be much greater and as a result of this the resistance would be negligible compared to the condensate film resistance.

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