MATHEMATICAL MODELING ON DROPWISE CONDENSATION

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Abstract:-The phenomenon of dropwise condensation, in which the condensate forms into drops rather than covering the entire cooling surface with a continuous film.Dropwise condensation produces heat transfer coefficients as much as 2 to 10 times greater than those produced by film wise condensation. Hence dropwise condensation is always desirable as it is more effective method of heat transfer than filmwise condensation.Dropwise condensation can be promoted by applying (i) Suitable organic promoter (ii) Thin layer of special metal (iii) Coating with polymer film on condenser surface. Due to successful application of dropwise condensation in small scale industry compound metal films are considerable.Special treatment like chrome plating on condenser surface is required for dropwise condensation.Higly polished surfaces also practice dropwise condensation.A overall heat transfer coefficient model is to be developed for dropwise condensation based on following two parameters.

(i) Plating thickness of condenser surface
(ii) Surface finishing of plated material.

Correlations for variation of the overall heat transfer coefficient with above two parameters are to be calculated by keeping one as constant and other as a variable. Under Dropwise condensation laboratory conditions, some permanent-type coatings, e.g.,gold, silver,teflon have been found to be effective dropwise condensation promoters. However, the effective lives of some of these promoters have been short, possibly due to surface removal of the coating in service. Furthermore, the effectiveness of' permanent type promoters in maintaining dropwise condensation is limited by their low thermal conductivity and the coating thickness.In effect of Condenser Surface with morer polish increased life of brass surface promoted as much as upto 4 times for finishes with numbers 3-0000 grades of emery paper.In experiments it is also noted that very clean and smooth surface actually caused filmwise condensation at first which later changes to dropwise condensation.

Keywords: Overall heat transfer coefficient, Plating Thickness, Surface finish.

I. INTRODUCTION

Whenever a saturated vapour comes in contact with lower temperature surface condensation occurs.There are mainly two mode of condensation processes known as film wise condensation and dropwise condensation. If condensate tends to wet the surface and there by forms a liquid film, then processes of condensation is known as film wise condensation & on the other hand if condensate does not tends to wet the surface, the condensate forms the droplets on the surface and every time fresh surface is exposed to the vapour. By specially treating the condensing surface the contact angle can be changed & the surface become 'non – wettable′.Very high heat transfer rate are reported in dropwise processes due to the good contact between the vapour and surface.[1] Condensation is the change of phase from the vapour state to the liquid or solid state.Condensation plays a major role in the heat rejection parts which generally involve pure substances. The random nucleation, growth and departure of droplets results in a certain size distribution of droplets on the condenser surface.[2] The drop size distribution and the heat transfer through the individual droplets must be known in order to calculate the heat flux with dropwise condensation. Dropwise condensation has been obtained on these types of surface by one of three methods i) Coating the surface with certain chemical substances called promoters ii) Coating the surface with a solid hydrophobic non-metallic material iii) Coating the surface with a noble metal.The thickness of the promoter layer on the condensation surface also affects the type of condensation, if the layer is too thin filmwise condensation occurs whereas excessive amounts of promoter increases the wettability of the surface.[3]

II DROPWISE CONDENSATION

Fig.1 Dropwise Condensation

Dropwise condensation occur when saturated pure vapour comes in contact with the cold surface such has copper tube. When considering surface is contaminated with substance which prevents condensate from the wetting surface ,the vapour will condense in drops instead of a continuous film.Though dropwise condensation would be preferred to filmwise condensation yet it is extremely difficult to achieve or maintain it for long time because most surfaces becomes wetted after being exposed to condensing vapour over a period of time .Dropwise condensation can be obtained under control conditions with the help of certain additives to the condensate and various surfaces coatings but it is commercial viability has not yet been approved for this reason the condensing equipment in use is designed on the basis of filmwise &dropwise condensation.[4]The vapour starts condensing on a surface when the vapour saturation temperature is more than the surface temperature,.the temperature of the condensate formed on the surface is less than its saturation temperature and it becomes sub-cooled, more vapour will condensate on the exposed surface or on the previously formed condensate as the temperature of the previous condensate is less than the saturation temperature of vapour.[6]

A) Effect of plating thickness :-

Experimentation to study the behavior of a 0.00025-inch thick film of teflon to promotion of dropwise condensation on a 112- inch 0.D. Aluminium tube. The tube was mounted horizontally and both the dropwise and filmwise condensations were studied. It is found that curves of heat transfer coefficients versus vapor to surface temperature drop in dropwise and filmwise condensation lowered as the temperature drop become large. This was caused by the rapid formation of drops which rend to blanket the condenser surface with liquid at high heat fluxes. It is also found that highest heat transfer coefficients were obtained with thinnest teflon film because of the high thermal resistance of teflon. A teflon film thickness of 0.00025-inch provided 12.5 times as thermal resistance as the 0.02-inch thick aluninun wall of the condenser tube and about 3 times more than the condensIng film itself. This shows thar the thickness of the reflon film is an i:nportant parameter and it should be kept at a minimum to imorove the overall perforrance of the tef lon coated condenser tubes. [7]

B) Effect of Surface Roughness :-

Experimentation on dropwise condensation shows that highly polished surfaces produces dropwise condensation in absence of oil or fatty acids. On the other hand filmwise condensation can occur on very rough or very foul surfaces.Polish surface also affect the life of a brass surface..The basic mechanism of maintenance of dropwise condensation in the fact that the condenser surface should be nonwettable to the condensing vapor. All surface treatment, including application of dropwise preorders, which will cause the surface to become non wettable will be effective in promoting dropwise condensation. Therefore it becomes apparent that the nature of the metal surface and material determines to some extent if a given promoter will be successful in promotion of dropwise condensation The use of different promorers on the same metal surface caused dropwise condensation fordifferent durations in time.It is noted that using- a mixture of oleic acid and light lubricating oil of a promoter on the surfaces of mirror smooth chrome-plated copper and No 6J emery paper treated stainless steel, the useful promoter life for chrome-plated copper was twice as long as for stainless steel. It is also found that a promoter of some sort was necessary for dropwise condensation that highly polished surface alone will not cause dropwise condensation.[7]

III MATHEMATICAL ANALYSIS

A) Effect of Plating Thickness

In dropwise condensation is modeled including the effect of substrate material. Differentials equations are obtained for temperature distribution in the substrate and the droplet. Since analytical solution of the differential equation system is quite complicated by the known methods, no attempt is made to solve these equations analytically. Instead of solving the differential equations of the drop and the substrate simultaneously, the diffusion equation of the droplet is replaced by the equivalent thermal resistances and these resistances are used as boundary condition for the diffusion equation for the substrate material. Temperature distribution in the substrate material is obtained with finite difference method and the calculations are performed for different substrate materials and for various drop radii. Heat transfer and heat flux are calculated through a single droplet with the use of temperature distribution, then total heat transfer and flux is obtained by integrating the heat transfer through a single drop for the entire drop population. Finally heat transfer coefficient for dropwise condensation is determined by using the total heat flux and average surface temperature of the drop to substrate interface. Previous analytical and theoretical models of dropwise condensation used expressions for the heat transfer through single droplets of specific sizes and then the total heat transfer is determined by integrating over the distribution of sizes. Such an analysis will also be followed here. [6] Following assumptions are made in the analysis of this study :

- The vapor is at uniform temperature.
- Heat transfer from vapor to substrate is carried out only by condensation.
- Substrate material, although it has a finite thickness in typical applications, will be assumed to be a semi-infinite body since its thickness is considerably large for the majority of the droplets on the surface of condensation.
- The area between the droplets can be considered as thermally insulated.

We will first find the heat transfer coefficient inside the condenser under test.for this properties of water are taken at the bulk mean temperature of water e.g. $(T_{wi} + T_{wo})/2$ where Twi and Two are water inlet & outlet temperature. Following properties are required:

where g = acceleration due to gravity =9.8 m/sec2 =1.27 × 108 m/hr2

L = Length of condenser =160 mm

Overall heat transfer coefficient (U) can be calculated as

$$1/U = [\ 1/h_i + D_i/D_o \times 1/h_o\ ] \times 4.1868/3600 \text{ KW/ m}^2\text{-K} \quad \text{-----------------------------------(1)}$$

Where hi = Inside heat transfer coefficient.
ho = Outside heat transfer coefficient.
Di = Inside diam. Of wall.
Do= Outside diam. of wall.

In order to increase U, ho should be increased

$$h_o = 0.943[\ \Lambda \times \zeta^2 \times g \times k^3 / \ (T_s - T_w)\ \mu \times L\ ]^{0.25}$$

Where Λ = Heat of evaporation at B.M.T.(Bulk Mean Temp)
ζ = Density of water at B.M.T.
μ = Dynamic viscosity at B.M.T.

Consider a vertical plate of height L and width b maintained at a constant temperature Ts that is exposed to vapor at the saturation temperature Tsat. The downward direction is taken as the positive x-direction with the origin placed at the top of the plate where condensation initiates, as shown in Figure 2. The surface temperature is below the saturation temperature ($T_s<T_{sat}$) and thus the vapor condenses on the surface. The liquid film flows downward under the influence of gravity. The plating thickness δ and thus the mass flow rate of the condensate increases with x as a result of continued condensation on the existing film. Then heat transfer from the vapor to the plate must occur

through the film, which offers resistance to heat transfer. Obviously the thicker the plating, the larger its thermal resistance and thus the lower the rate of heat transfer.The analytical relation for the heat transfer coefficient in film condensation on a vertical plate described above was first developed by Nusselt in 1916. [8]

Then Newton's second law of motion for the volume element shown in Figure 2 in the vertical x-direction can be written as

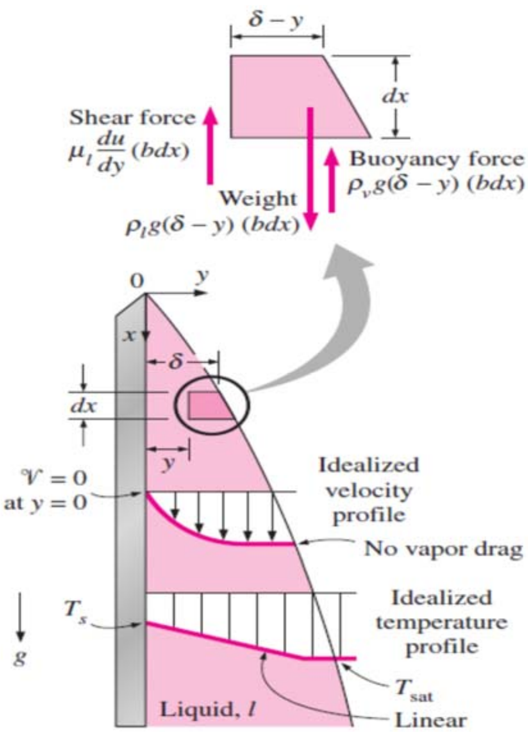

Fig.2 Condensate on vertical plate

Fig.2 The volume element of condensate on a vertical plate considered
In Nusselt's analysis.

$$\sum Fx = ma_x = 0$$

Since the acceleration of the fluid is zero. Noting that the only force acting downward is the weight of the liquid element, and the forces acting upward are the viscous shear (or fluid friction) force at the left and the buoyancy force, the force balance on the volume element becomes

$$F_{downward\downarrow} = F_{upward\uparrow}$$

Weight= viscous shear force + Buoyancy force

$$\rho_l g(\boldsymbol{\delta} - y)\ (bdx) = \mu_l\ du/dy\ (bdx) + \rho_v g(\boldsymbol{\delta} - y)(bdx)$$

Canceling the plate width b and solving for du/dy gives

$$\frac{du}{dy} = g(\rho l - \rho v)g(\boldsymbol{\delta} - \boldsymbol{y})/\boldsymbol{\mu l}$$

Integrating from y=0 where u=0 (because of the no-slip boundary condition)

To y =y where u=u(y) gives

$$U(y) = \frac{g(\rho l - \rho v)g}{\mu l}$$

$$u(y) = \frac{g(\rho l - \rho v)g}{\mu l}\left(y\delta - \frac{y2}{2}\right) \qquad (2)$$

The mass flow rate of the condensate at a location x, where the boundary layer thickness is δ ,is determined from

$$M(x) = \int_A \rho l u(y) dA = \int_{y=0}^{\delta} \rho l u(y) b dy \qquad (3)$$

Substituting the u(y) relation from Equation 1 into Eq. 2 gives $m(x) = \frac{gb\rho l(\rho l - \rho v)\delta^3}{3\mu l}$ (4)

Whose derivative with respect to x is

$$\frac{dm}{dx} = \frac{gb\rho l(\rho l - \rho v)\delta^2}{\mu l}\frac{d\delta}{dx} \qquad (5)$$

which represents the rate of condensation of vapor over a vertical distance dx. The rate of heat transfer from the vapor to the plate through the liquid film is simply equal to the heat released as the vapor is condensed and is expressed as

$$dQ = hfg\, dm = k_l\,(bdx)\, \frac{Tsat - Ts}{\delta} \rightarrow$$

$$\frac{dm}{dx} = \frac{k_l\, b}{h_{fg}}\, \frac{Tsat - Ts}{\delta} \qquad (6)$$

Equating Eqs. 4 and 5 for dm· /dx to each other and separating the variables give

$$\delta^3 d\delta = \frac{\mu_l\, k_l (T_{sat} - T_s)}{g\rho_l(\rho_l - \rho_v)\, h_{fg}}\, dx \qquad (7)$$

Integrating from x=0 where δ =0 (the top of the plate) to x=x where

$\boldsymbol{\delta} = \boldsymbol{\delta}(x)$

the liquid film thickness at any location x is determined to be

$$\delta(x) = \left[\frac{4\,\mu l\, kl\,(Tsat - Ts)\,x}{g\rho_l(\rho_l - \rho_v)\, h_{fg}}\right]^{1\backslash 4} \qquad (8)$$

The heat transfer rate from the vapor to the plate at a location x can be
expressed as

$$q_x = h_x(Tsat - Ts) = k_l\, \frac{Tsat - Ts}{\delta} \rightarrow h_x = \frac{kl}{\delta(x)} \qquad (9)$$

Substituting the δ(x)expression from Eq. 7, the local heat transfer coefficient hxis determined to be

1/U = [1/hi + Di/Do x 1/ho + ∂/K] x 4.1868/3600 KW/ m²-K (10)

B) Effect of Surface Roughness :-

In conclusion, we have shown that for relatively low humidity capillary forces are present in the case of smooth surfaces, and surpasses in magnitude any dispersion and electrostatic forces. In addition, an enormous decrease in the capillary force was observed by increasing the roughness amplitude a few nanometers in the range ~1-10 nm. Considering the rapid fall off in the capillary force and the two limits (a smooth limit where the whole surface contribute to the capillary force, and a rough limit where only a single or a few asperities contribute), the crossover regime might in turn depend on the contact angle and any lateral roughness features. Both could be an intersecting direction for further study of this phenomenon in the design MEMS (micro electromechanical systems) if stiction poses a problem. The total adhesion force can be divided into a capillary force and an interfacial tension force due to surface tension acting tangentially to the interface along the contact line with the solid body.The Laplace pressure, while ignoring contributions from surface tension.

Fup= 4π ν Rh CosΘ. (11)

Where ν = Liquid vapour pressure,

Rs = Surface roughness,

Θ = contact angle of vapour with condenser surface.

For the contact angle of water onto Au surfaces we obtain for Θ =70°,Rs=50μm, Fup=1.5X10^4 nN It appears that the smooth limit is reached for the Au/mica film. For the roughest films the values found are up to ten times higher than that of a single asperity, indicating a capillary interaction of a multitude of asperities

For a increase in 100% roughness, capillary force reduces up to 1/10 times applicable only after 60% rise in roughness. [5]This will effect condensation in the same manner. From this result alongwith equation (1) and (11) we can write as

1/U = Rm/10[1/hi + Di/Do x 1/ho] x 4.1868/3600 KW/ m²-K - ---------------------------------- (I)

Where Rm= Number of times of original roughness value.

IV. CONCLUSION

In this paper through mathematical mode finally observed that the heat transfer coefficient (h W/m2K) associated with dropwise condensation is decreases with increase in plating thickness of coatings. It can be calculated depending on the formula with respect to plating thickness. The drop wise condensation is also affected by roughness of coated surface. In mathematical mode finally it is observed that the heat transfer coefficient (h W/m2K) associated with dropwise condensation is decreases with increase in roughness of coated plate. Plating thickness of coatings. It can be calculated depending on the formula with respect to plating thickness.

And also this paper suggest that whenever the requirement of condensation is more ,the surface should be with minimum plating thickness and with minimum value of surface roughness.

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