Direct and Indirect Contact Filmwise as well as Dropwise Condensation of Water Vapour with and without Noncondensible Gas-A Review

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Abstract - *A review on condensation is presented in this study. Investigations for direct as well as indirect contact condensations are included here. Condensation is a phase change process which has countless industrial applications starting from power generation, desalination, air conditioning to chemical processing. Effect of noncondensible gas like air on condensation process is also highlighted here. Presence of air in water vapour deteriorates the condensation process drastically. This is due to noncondensing envelop created by the air at the water vapour-air mixture and condensate interface. Thus, inlet air mass fraction percentage is one of the key deciding factor for the condensation process. Other main governing parameters of condensation are inlet Reynolds number, inlet temperature, inlet concentration of water vapour, dimension and type of the surface. Even if many researchers contributed towards condensation of water vapour, still there is a scope for improvement. Sustainable dropwise condensation with nano-engineered surface coating is the new emerging area through which compact and highly efficient condensing devices may be designed.*

***Key Words*:** Filmwise condensation, dropwise condensation, heat and mass transfer, Reynolds number, noncondensible gas, nano-engineered surface.

1. INTRODUCTION

T Phase change form gaseous to liquid state with simultaneous heat and mass transfer is known as condensation. Condensation may be classified as direct contact condensation and indirect contact condensation. In direct contact condensation, direct contact between working or hot fluid and cold fluid occurs where as in indirect contact condensation a medium mostly solid exist between the hot and cold fluid. Industrial application of indirect contact condensation is relentless where as direct contact condensation is noticed in many natural processes. Indirect contact condensation is the main governing mechanism in many engineering applications like power generation, refrigeration, cold storage, nuclear reactor, desalination, chemical processing, heating ventilating and air conditioning (HVAC). Direct contact condensation is noticed in cooling tower, jet type condenser, many chemical processing industries etc. Therefore, it is essential to investigate both direct as well as indirect contact condensation. Again in indirect contact condensation itself water vapour may condense on a cooled surface by two different modes: namely (i) filmwise condensation and (ii) dropwise condensation. This classification depends primarily on the wettability of the intermediate surface. A continuous condensate film results when the surface is wetted fully by the condensate, while condensation occurs in the form of drops on a non-wettable surface. On a surface over which the degree of non-wettability varies, both drops and patches of film may be seen. The drops are usually less regular in shape than those associated with the term "ideal drop condensation" and falling drops tend to leave streaks of condensate behind them. This is termed "mixed" condensation. Filmwise condensation generally occurs on clean uncontaminated surfaces. The thickness of film covering entire surface grows as it moves downward under the influence of gravity. There exists a thermal gradient in the film which acts as a resistance to heat transfer. This resistance can be minimized by using short vertical surfaces. In dropwise condensation, surface may be covered by drops involving a size of few micrometers to visible size. Due to discontinuity of condensate film, in dropwise condensation a large portion of the area of the plate is directly exposed to the vapour which enhances the heat transfer rate much higher than filmwise condensation. Although dropwise condensation would be preferred to filmwise condensation, yet it is extremely difficult to achieve or maintain. This is because after being exposed to condensing vapour over a period of time, most surfaces become wetted. Dropwise condensation can be achieved under controlled condition with the help of certain additives to the condensate and various surface coatings but its commercial viability has not yet been proved. Therefore condensing equipment in use is designed on the basis of filmwise condensation.

In actual practice some amount of noncondensable gas may present in the vapour. Presence of noncondensable gas like air in the condensing vapour significantly influences the condensation process. It has been observed that even in small amounts of noncondesable gases can deteriorate the condensation process strongly. This is due to the fact that the noncondensable gas is left at the interface, when vapour containing non-condensable gas condensed. Any farther condensation at the surface will occurs only after incoming vapour has diffused through this non-condensable gas in the vicinity of the surface. The non-condensable gas adjacent to the surface, acts as a thermal resistance to the condensation process. As the presence of non-condensable gas in a condensing vapour is undesirable, the general practice in condenser design should be to vent the non-condensable gas to the best of possible extent.

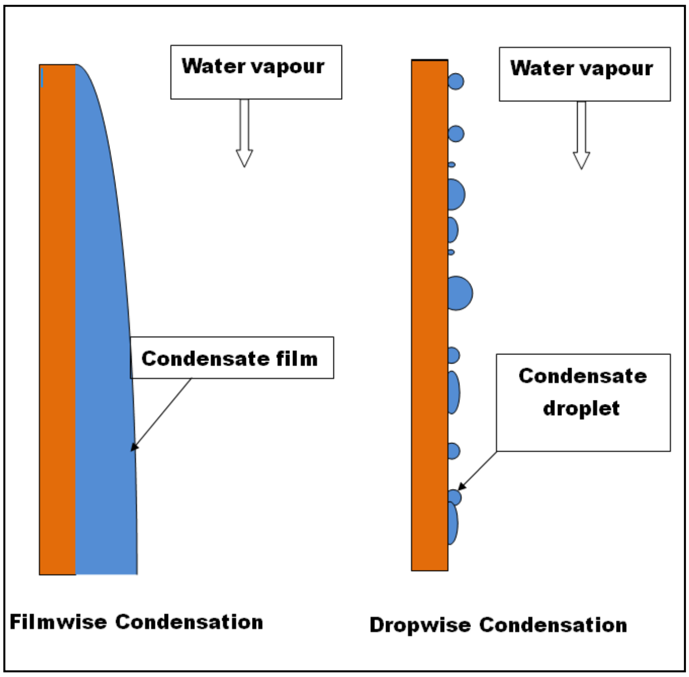

Fig. 1. Schematics of filmwise and dropwise condensation on a flat surface

2. DIRECT CONTACT CONDENSATION

Direct contact condensation occurs when vapor is brought into contact with a cold liquid. In cooling tower/jet condenser direct contact condensation occurs when cooing water sprayed over exhaust hot gases. As sprayed water comes in direct contact with hot gases, large amount of latent heat liberated from the hot gases to cold liquid. Due to its practical utilities many researchers has contributed in this field. Some of these are sited here:

Taitel et al. [1] report direct contact condensation on the falling liquid water film considering water vapour and air as working fluid. Result shows that increase of air or decrease of water vapour drastically reduces the interface temperature. This effect is noticeably high close to the leading edge region. Experimental study on direct contact condensation of air-water vapour mixture in a closed enclose is investigated by Garimella and Christensen [2]. Initial concentration of air in water vapour-air mixture mainly decides the performance of the system only when air concentration is small. But, for large initial air concentration other governing parameters like fluid inlet temperature, cooling water temperature dominates the process. Chan and Yuen [3] investigated direct contact condensation of air steam mixtures on a horizontally stratified liquid water film which concluded that for high condensation rate the presence of air significantly reduces the heat and mass transfer process. In all this studies presence of noncondensible gas i.e. air degrades the efficiency of the system as it directly hindes the heat transfer process thereby forming noncondesing envelope at the air water vapour mixture condensation layer interface.

3. INDIRECT CONTACT CONDENSATION

Direct contact of working fluid with the cooling medium is avoided in this type of condensation. Usually, a metallic surface is used in between the cold and hot fluid. One side of the metallic surface is cooled by cooling fluid whereas other side of the metallic fluid is exposed to the hot fluid to be condensed. As temperature of the exposed surface is cooled bellow the dewpoint temperature, the hot water vapour starts condensing on the surface. If the surface is completely wetted by the condensate than that type of condensation is termed as filmwise condensation. Otherwise for non wettable surfaces dropwise condensation occurs.

3.1. Filmwise condensation of water vapour without noncondensible gas

Ir The pioneering work on laminar film condensation may be dated back from the work of Nusselt [4], who treats the problem in the condensate layer by the balance of viscous and gravity forces for the momentum equation while simple heat balance is used for energy equation. Inertia force and convective energy are paid little attention. Modification to Nusselt's theoretical solution is made by a number of researchers. Bromley [5] assumes a linear temperature distribution in the liquid film model. Rohsenow [6] extends the analysis by incorporating the convective heat transport paying less attention to inertia forces in momentum equation. Sparrow and Gregg [7] further extends the problem of condensation including inertia force in the momentum equation and convective heat transport in the energy equation by using similarity transformation. The solution of the problem categorized in the rank of the boundary-layer family. The use of the equations of fluid mechanics to solve the condensation problems is proposed by Cess [8]. Koh et al. [9] applied two phase boundary layer equation in laminar film condensation and formulated an exact boundary layer solution. It is found that for liquid metal interfacial shear stress substantially reduces heat transfer. Darbin and Thorsen [10] provide an analysis of forced flow filmwise condensation of a pure saturated water vapour inside a vertical tube. Investigation is done for fully developed flow and constant wall temperature. The whole phenomena is mainly governed by the ratio of vapor Froude to Reynolds number, buoyancy force, vapor to liquid viscosity ratio, liquid Prandtl number and degree of Subcooling. Numerical findings are compared with Nusselt analytical results. For high Prandtl number with high pressure and high ratio of Froude to Reynolds number, Nusselt analytic solution underpredicts the condensation length and film thickness and overpredicts the inter-phase mass and heat transfer. This is presumably due to the fact that Nusselt neglects the inertia term, while Darbin and Thorsen [10] include the same in the model. Narain and Kizilyallia [11] examine pressure driven flow of pure saturated vapor undergoing laminar film condensation between parallel plates. Orientations of the plates are considered horizontal. Condensation on bottom plate is only taken into account. Mixed differential approach is used to predict condensation rate, heat transfer rate and film thickness. Prediction of the model provides that for higher inlet mass flow rate (i.e. an increase in inlet Reynolds number) with constant temperature difference reduces the film thickness, increases pressure drop and heat removal rate from the bottom plate. Decrease in temperature difference at constant Reynolds number makes condensate layer thickness thinner and reduces heat transfer rate. Shear stress is found constant across and along the condensation film. The method encountered the limitation that the non-linearity of the various functions are handled through computer generated functions and therefore one do not know their behavior until after the computations.

3.2. Filmwise condensation with noncondensible gas

Presence of air i.e. noncondensible gas with water vapour in actual practice is unavoidable. This leads to reduce condensation heat transfer enormously and deteriorate the performance of devices. Therefore, study of water vapour condensation in presence of non-condensation gas/air is essential.

Colburn and Hougen [12] provide a theory for condensation mass transfer controlled by the mass concentration gradient through non-condensable layer. The heat transfer process is described as the sum of sensible heat and latent heat flow. Later Corradini [13] introduced a correction factor which takes care of the suction effect at high mass transfer rates across the liquid-gas interface. Then, Kim and Corradini [14] incorporate the effects of film roughness on the gas phase heat and mass transfer for a flat plate.

Sparrow and Eckert [15] demonstrates that the presence of a few percent of noncondensable gas in the vapour prominently reduces the surface heat transfer. Srzic et a [16] analyzed the laminar mixed convection condensation on isothermal plates using the boundary layer equations for mixtures of a vapour and a lighter gas and found that the reduction in heat transfer is more pronounced for lighter gases than for heavier gases. Numerical investigation by Volchkov et al. [17] is made on laminar and turbulent flow of humid air with surface steam condensation. It is found that the total heat transfer on the wall can be significantly increased due to the phase-transition heat. Further with increasing moisture content, the heat-transfer can be increased. The relative convective heat flux component and the heat released due to steam condensation are practically independent of the particular flow regime and coincide with the relations obtained from the balance equations of energy and mass conservation at the wall invoking the condition of similarity between the heat and mass transfer processes. Analysis also supports the possibility of using the integral methods for calculating heat and mass transfer processes in laminar and turbulent humid-air flows in a duct. Cheng and Junming [18] computationally reports condensation for the case of laminar forced convection over a vertical plate treating humid air as the medium of convective transport. Analysis provides that it is not convincing to neglect the condensate film from the point of its thickness only. Although condensate layer film thickness, interface temperature drop and the interface tangential velocity affect the physical fields weakly, other parameters like the effect of sub-cooling and the interface normal velocity are essential to be considered before the simplification is made. The advection mass transfer contributed much to the total mass transfer especially for higher wall temperature. Therefore, the boundary conditions are the crucial to judge the rationality of neglecting the condensate film for numerical solutions. Lebedev et al. [19] report a combined experimental study of heat and mass transfer associated with condensation of vapor from humid air over a rectangular duct in a horizontal longitudinal flow. It is observed that condensation heat transfer increases with relative humidity of the air. It is also highlighted that the larger the air velocity and the lower the temperature drop, the more intensive is the total transfer process. Panday [20] develops a methodology to determine heat transfer for two dimensional film condensation of laminar and turbulent vapour flowing inside tube and between parallel flat plates. Solution of the fully coupled boundary layer equations for two different problems without neglecting inertia and convection terms in the governing equations is made. For the flow at high velocities, turbulence in the liquid and vapour phases increases heat transfer. However results do not show much difference for horizontal or vertical orientation. Coupling of the continuity, momentum, concentration and enthalpy equations is also exercised for liquid and vapour phase flow of R123/R134a between parallel plates and solution is obtained in linearized form using an implicit finite difference scheme. Results obtained from calculation, is then compared with experimental values for pure R123. Numerical investigation of Siow et al. [21] reports two-phase model for laminar film condensation from steam-air mixtures in a vertical parallel-plate channels. It is found that increase in inlet concentration of noncondensable gas causes significant decreases in the film thickness, local Nusselt number, and axial pressure gradient. Dharma Rao et al. [22] theoretically provides the case of convective condensation of water vapor from humid air in turbulent flow in a vertical duct. The leading parameters governing the problem are inlet temperature, gas phase inlet temperature, relative humidity, and inlet pressure. The author numerically estimates the effect of the above system parameters on local and average condensation heat transfer coefficients and also computes the gas phase convection Nusselt and Sherwood numbers for the problem. Siow et al. [23] numerically examine the fully coupled system of boundary layer equations for condensation from binary mixtures of gases in an inclined, rectangular channel. It is found that the most important parameter affecting condensation heat transfer process is the film Reynolds number. Dharma Rao et al. [24] investigate the case of convective condensation of vapor in laminar flow in a vertical parallel plate channel in the presence of a high-concentration noncondensable gas. Aforesaid analysis also formulated a theoretical model. From the numerical results the local Nusselt number, condensation Reynolds number, and gas-liquid interface temperature were estimated. Benelmir, et al. [25] performs a simulation of water-vapour condensation in the presence of non-condensable gas between two vertical plane plates and in a plate fin-and-tube heat exchanger in static mode using FLUENT software and found that the condensation rate and the heat transfer coefficient increase with the inlet velocity of the mixture. Giri et al [26] numerically analyse mixed convection condensation of water vapour mixture inside a parallel plate channel. Main governing parameters considered in the study are inlet Reynolds number, channel dimension, inlet temperature and inlet concentration of the working fluid. Correlations for Heat transfer as well as condensing Nusselt number for different governing parameters are also proposed the study. Recently, Bhuyan et al [27] proposed a numerical method to predict exact fan velocity/Reynolds number for mixed convection condensation problem. Working fluid for the study is considered as air-water vapour mixture. Entropy analysis also performed in the study.

3.3. Dropwise condensation

In dropwise condensation condensate formed at the surfaces in the form of drop. Unlike filmwise condensation it does not form continuous envelop of condensate over the cooled surface. This makes dropwise condensation more suitable theoretically as exposed/heat transfer area is more. But, dropwise condensation is less preferred in industrial practice may be due to its less sustainability. To enhance its sustainability commercially viable suitable coating/ nano-engineered surfaces are required.

McCormick and Westwater [28] uncover that dropwise condensation after nucleation is sustained up to a specific droplet radius. Beyond this critical radius, body/ gravity force exceeds the surface tension holding the droplet on the surface; thus, causing the droplets to collapse or depart from the surface. Collapsing of numbers of droplets converts dropwise condensation to filmwise. There are various methods to enhance sustainability of dropwise condensation such as coating the surface with polymers like Teflon [29], organic promoters such as fatty acids [30, 32] or by implanting low energy ions[33] . Sustainability of dropwise condensation also can be improved by injecting a promoting specialty chemical into the working fluid [34,35] . This methods will work only for a limited durations ranging from ~100 hours to 4 years [36] under certain thermo-physical conditions. Other techniques for achieving sustainable dropwise condensation are structural surface modifications [37,38]. Well proportionate combination of surface coating, nano-engineered structural modifications, and periodic injection of promoters may contribute to achieve sustainable dropwise condensation of water vapour commercially.

4. CONCLUSIONS

Condensation is a phase change process which occurs when gaseous phase is exposed to a temperature bellow the saturation temperature of the fluid. It is a heat transfer process where huge amount of latent heat is liberated from the hot fluid to the cold fluid. Condensation may be direct or indirect contact condensation. Depending on wettability of the surface indirect contact condensation can be further classified as dropwise or filmwise condensation. Presence of noncondensible gas/air is unavoidable with water vapour in practice which reduces the performance efficiency of condensing equipments drastically. Although large numbers of literature is present in the field of condensation, well diversified research of condensation is still realized for the efficient condenser design. Scope of improvement in condenser design may also be achieved by introducing sustainable dorpwise condensation as it promotes more heat and mass transfer. This can be achieved by introducing nano-engineered coating on the surfaces where condensation occurs.

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