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A Comprehensive Study of Surface Geometry, Humidity and Dry Patches on Falling Film Heat Transfer

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Abstract: **-- Heat transfer through falling film evaporation has wide industrial applications like cooling towers of thermal power plants and refrigeration and air conditioning industries. There are various factors which can improvise the falling film evaporation performance or effectiveness like enhanced tube surface geometry and working conditions. The relative humidity of air has a great influence on falling film evaporation. Also, dry out of the surface of the tubes because of excessive thermal loading or less flow rate of cooling water film has a significant role in the effectiveness of falling film evaporation. Thus, a comprehensive review has been conducted to study the effects of surface geometry (horizontal smooth and plain tubes, porous structures, finned and enhances surfaces, liquid feeder configuration, etc.), falling film pattern, dry out crisis phenomenon and relative humidity of air. Finned and enhanced surfaces were supposed to increase the heat transfer rate than the others. Dry out phenomenon which occurs due to instability problem can be checked by stability factor or minimum wetting rate. Humidity of air leads to an increment in mass transfer coefficient and heat flux.**

I. INTRODUCTION

Falling film heat transfer has been broadly used process in petroleum, chemical, refrigeration, desalination and food industries. Earlier in 1980s research had been limited to ocean thermal energy conversion also called as OTEC pilot plants where most researchers used water or ammonia as working fluid due to the second oil crisis but during 1990s usage of CFCs and HCFCs in heat transfer systems were restricted due to their global warming potential or ozone layer depletion. Therefore natural refrigerants like carbon dioxide, ammonia etc. were supposed to be the alternative and should be investigated in future. Although falling film evaporators found its extensive applications in chemical industries due to the minimum stay time of fluids and increased rates of heat transfer with lower temperature differences but the usage is limited as compared to refrigeration industries. Flooded tube evaporators have potential benefits in comparison with horizontal falling film evaporators.

Early in 1999, Thome conducted a falling film evaporation study on a single tube and a tube bundle [1]. A critical review was carried out specially emphasising on refrigeration applications [2]. Further the concept of fluid dynamics and heat transfer in evaporative falling film considering film breakdown, heat transfer coefficients for different configurations etc. which could be useful in design of falling film evaporator has been considered [3]. Recently, falling film type horizontal tube evaporators emphasizing on characteristics of mass transfer and heat transfer under various enhancement techniques have been studied [4]. The effect of nano-fluids, pressure losses and cost effects were also considered. Present review briefly discuss horizontal tube falling film evaporation considering tabular study of surface geometry, effect of dry patches on heat transfer aspect of falling film evaporators. Among various factors affecting heat transfer performance, the effect of relative humidity on mass transfer coefficient and heat flux in falling film evaporator was specially studied.

Evaporation of falling film is a process which depends mainly upon conduction and convection while both can co-exist together. Working fluid falls on the bundles of tubes which contains hot fluid inside it comes out as cold fluid while combined effect of air & water increases the effectiveness of spray heat exchanger. It has been known that there are three distinct regimes which occur in falling film heat transfer systems namely a low temperature, transition temperature and higher temperature regimes.

II. INFLUENCE OF SURFACE GEOMETRY ON FALLING FILM HEAT TRANSFER

Horizontal tube evaporators subjected to falling film, although belongs to overfeed evaporators but have shown an applicable substitute for both the refrigeration and air-conditioning applications because of their lesser costs, less environmental impacts and reduced refrigerant charges [5]. Finned surfaces have been observed to improvise the effectiveness of even and plain tubes. Artificial cavities have been formed which helps in accelerating nucleate boiling at low temperature difference and to enhance heat transfer surface area. Initial work has been reported by Zeng et al. [6], while studying evaporation of ammonia spray over a single tube with fin and corrugated tube. Conventional plain shell and tube evaporators have been in use till date in developing countries [7]. The effects of both the spray inclination angles and improved surfaces have been analyzed considering PF-5060 as the working fluid [8]. Due to multi-nozzle array stagnation phenomenon straight finned surfaces shows best performance and spray angles (> 15deg) removes all liquid on the heaters surface. A proposal has been suggested for compact heat exchangers using ammonia refrigeration involving multiple tube types with higher efficiencies [9]. Fin and tube evaporator was studied and a model was given by Oilet et al. [10] to reveal the potential of the model. Christians and Thomes [11] tested different augmented tubes like turbo-B5 wolverine and Wind Gewa-B5 (two enhanced boiling tubes) using refrigerants R-134a and R-236fa showing that R-236fa was outperformed. The effects of various surface geometries have been shown in tabular form in Table 1.

Table 1: Effects of surface geometries on falling film heat transfer

Contributor	**Fluid used**	**Surface under consideration**	**Remarks**
Armbuster et al. [12]	Water	Smooth horizontal tubes	Inter tube spacing; circumferential angle and Reynolds number of falling film have major effect on falling film heat transfer.
Hou et al. [13]	Water	Smooth horizontal tubes	New correlation to predict the film thickness has been given in terms of film flow rate, viscosity and density.
Xu et al. [14]	Water	Horizontal and smooth tubes	Heat transfer coefficient has been observed to be increasing with increase in distributor height, piping diameters reduction, evaporation boiling point increment and total temperature difference reduction.
Fujita et al. [15]	Water	Horizontal tubes	Critical point has been observed for heat transfer coefficient with the increase in film flow rate due to transition phase i.e. in between laminar and turbulent flow of film.
Mohamed [16]	Water and mixture of 50% water and 50% ethylene glycol)	Horizontal rotating tube	Influence of tube rotational speed on horizontal film behavior has been studied and recommended the rotational speed of tube not to go beyond maximum rotational speed.
Weise et al. [17]	Pure liquids	Horizontal and smooth tubes	Influence of pure liquids on falling film evaporation has been studied.
Chun et al. [18]	Water	Vertical plain tube	Studied falling film heat transfer coefficient in both the turbulent and laminar flow regimes and suggested a specified Weber number for the same.
Fletcher et al. [19]	Water	Plain horizontal tube	Water distribution system has been studied along the axis of the tube.
Danilova et al. [20]	R-11, R-22, R-114	Horizontal, plain tube and staggered bundles up to 40 rows deep and 330 mm long	Three different zones of heat transfer namely film evaporation zone, transition zone and developing boiling zone have been studied. Also a correlation has been proposed for film vaporization with Reynolds number and Prandtl number of the film.
Yung et al. [21]	Water	Single, horizontal plain tube of	Developed a combined model for film evaporation and nucleate boiling in liquid films. Observed mean heat transfer

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		circumferential length L	coefficient as the sum of nucleate boiling coefficient over the entire length, convective heat transfer in thermally developing region of length and that of fully developed region.
Forrest et al. [22]	Water	Nano-porous structure	The nano-porous structure leads to enhanced boiling heat transfer.
Wang et al. [23]	Water	Nano-porous structure	Thermal tracing technique has been used to study the mixing effect of falling film on coated division tubes.
Putilin et al. [24]	Water	Horizontal and profiled tubes	Mechanism of heat transfer of flowing fluids that were moving downwards was analyzed.
Kim et al. [25]	R-410A	Oval and flat tube	Coefficient of heat transfer of evaporation increases with rise in heat and mass flux and at increased aspect ratios.
Li et al. [26]	Water	Horizontal tube arrays with enhanced outer and inner surfaces	Enhancement in heat transfer of the falling film evaporator has been decreased with increase in Reynolds number.
Tatara and Payvar [5]	Water	Distributor plate put under tube bundle	Arrangement of distributor plate improves the heat transfer. Increase in feeder height also affects the heat transfers and results in better distribution of spray.

III. FALLING FILM BREAKDOWN AND DRY PATCH STUDY

Although the concept of falling film evaporation is significant in terms of coefficient of heat transfer and liquid minuscule as compared with flooded tube evaporators but appearance of dry patches on tubes results into drastic reduction is overall coefficient of heat transfer and excessive heating of the tube surface which may cause the dry out of the tube or duct. Appearance of dry patches and its effect has been observed by several researchers beginning from 1961. Hartley and Murgatroyd established a criterion for thin liquid layers breakup for isothermal flow over solid unheated surfaces [27]. Some stability criterion were derived which could predicted the conditions necessary to maintain complete wetting of unheated surface i.e. minimum film thickness and minimum liquid flow rate. In their continued investigation they carried out analysis for laminar and turbulent flows over isothermal unheated surfaces and stated that the contact angle affects minimum falling film flow rate and thus dry patch formation. Hsu et al. [28] agreed on the fact that dry patches occurs due to the shear of vapour flows and film becomes thinner and breakdown may happen in presence of boiling and evaporation. Zuber et al. [29] extended the study of Hartley at al. to take into account of thermal effects which became important in liquid films over heated surfaces. They observed in case of liquids having higher wettability like liquid metals that thermocapillary effects predominant over vapour thrust forces and other forces in determining the stability of dry patches.

IV. EFFECT OF RELATIVE HUMIDITY ON HEAT AND MASS TRANSFER ASPECTS

There are various factors that affect heat and mass transfer coefficients like surface geometry, falling film breakdown, Reynolds number of air and cooling water & relative humidity. The effect of relative humidity on falling film heat transfer has been rarely reported so far. It has been observed that water temperature reduction to be dependent on air velocity, tube spacing and relative humidity. Direction of heat flux gets reversed at a water temperature lesser then air temperature whereas the mass flow rate depends on relative humidity of air [30]. Relative humidity is an important factor which deals with ability of air to absorb the moisture and thus surely affects the heat flux and mass transfer coefficient. An experimental study with main focus on effects of variation of relative humidity was carried out by Rajneesh and Raj Kumar [31]. Permanent and onset heat flux as well as coefficient of mass transfer for dry out conditions have been studied experimentally on bundle of tubes of an evaporative tubular dissipator. Heat transfer has been observed to be increased slightly for relative humidity ranging from 50-60% with air velocity ranging from 0.8-1.6 m/s. However, a rapid increment in heat transfer has been observed at high relative humidity range 70-90% but with high air velocity i.e. ranging from 2.4-3.2 m/s. The results were also presented in graphical form as shown in Figure 1 and 2. Correlation for mass transfer coefficient, heat flux, evaporative effectiveness in term of Reynolds number of cooling water and air were also derived over a wide range of relative humidity of up streaming air

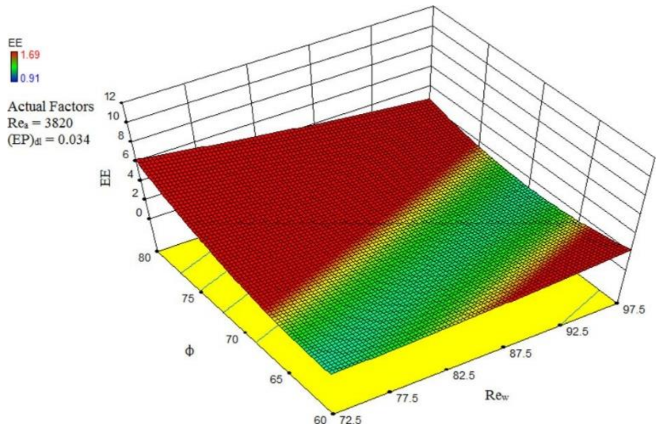

Figure 1. Effect of film Reynolds number of cooling and relative humidity on evaporativ effectiveness [31].

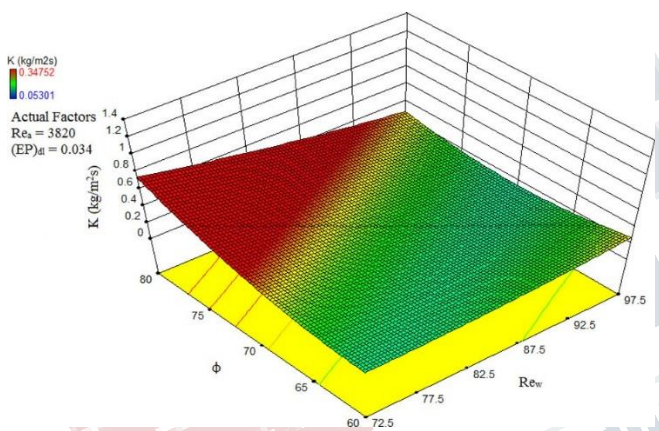

Figure 2. Effect of film Reynolds number of cooling and relative humidity on mass transfer coefficient [31].

V. CONCLUSION

Heat transfer through falling film evaporation has significant applications in many industries like thermal power plants, petroleum, refrigeration and air conditioning etc. Some key parameters like surface geometry, dry out phenomenon, falling film modes and relative humidity have been studied and thus following conclusions have been made:

i. Traditional plain shell and tube evaporators still find its applications in some developing countries but there is need of further design specially for finned tubes and enhances surfaces so as to increase the effectiveness of such systems.

ii. There are various types of modes observed in different studies but droplet mode, column mode and sheet mode are common. Further study can be done on intermediate modes for better performance of falling film evaporators.

iii. Staggered arrangement of tubes in evaporative heat dissipators have shown better performance and better heat transfer rates.

iv. Appearance of dry patches on tubes might leads to overheating of surfaces due to drastic reduction in overall heat transfer coefficient, therefore some stability criterion has to be derived which could predict the conditions necessary to maintain complete wetting of unheated surface i.e. minimum film thickness and minimum liquid flow rate. Some of the ranges of film Reynolds number of cooling water and air have been suggested [32].

v. Relative humidity of up streaming air played significant role in enhancing the performance of falling film evaporators. Reynolds number of air should be higher for better cooling effects for higher RH (relative humidity) range. Heat flux and evaporative effectiveness have also observed to be increasing with increasing humidity of air.

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