Numerical investigation of film thickness variation on falling film tubular heat exchangers at different Reynolds number

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Abstract: Horizontal tube falling film tubular heat exchanger is extensively used in modern heat transfer processes. It has a broad area of application like desalination, refrigeration, processing and food Industries. The most important phenomenon in this heat transfer process is the extraction of latent heat by the spraying fluid from the outer surfaces of the heated tubes. Numerical Simulation of falling film thickness around the circumference of the tube is performed to analyze the film thickness and circumferential velocity over falling film tubular heat exchangers by Volume of Fluid (VOF) technique using Computational Fluid Dynamic (CFD) software, ANSYS 15.1. The effect of feed rate, tube diameter, and tube spacing are investigated. It is observed that the film thickness is directly influenced by Reynolds number and the film velocity reaches its maximum value at the end of fully developed zone. The results are in good agreement with the published data.

Keywords: Falling film, Film thickness, Horizontal tube, Computational Fluid Dynamics.

1. Introduction

In modern heat transfer processes the falling film heat exchanger plays a vital role in efficient utilization of energy. Falling film tubular heat exchanger has a wide range of applications in modern heat transfer process like desalination, refrigeration, processing and food Industries etc. Less energy consumption and easy accessibility make it popular in the recent heat transfer applications. A number of researchers are continuously trying to improve their performance through experimental as well as numerical approaches. The heat and mass transfer processes are greatly affected by the liquid film enveloping the outer surface of tubes. The film thickness plays a very crucial role in heat transfer process. A low Reynolds number implies a dry out condition, hence sharply reduces the heat transfer coefficient while a high Reynolds number significantly reduces the heat transfer coefficient. This implies that an optimal thickness is to be maintained throughout the process for smooth and efficient operation.

A landmark analytical study was conducted by Nusselt et al. (1916), to find out the film thickness around the fully wetted tube. However, this classical expression neglects the momentum effect.

\[
\delta = \left( \frac{3 \mu \Gamma}{\rho_l (\rho_l - \rho_g) g \sin \beta} \right)^{\frac{1}{2}}
\]  

(1)

In Fig. 1 the mechanism of flow is shown schematically. An important consideration in the falling film evaporation process is to maintain a constant mode of flow. There are mainly three types of flows (shown in Fig. 2) droplet mode, column mode and sheet mode of flow. However it is further extended to five distinct modes of flow in falling film evaporation: 

**Droplet mode:** When the flow of liquid between tubes appears in distinct droplet mode of flow.

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Droplet-Columns mode: - Droplet-column mode of flow is the intermediate flow between droplet and column mode of flow. This happens when at least one liquid column mode of flow continuously appears between the tubes in addition to distinct droplet mode of flow.

Column mode: - This mode of flow appears when there are only liquid columns between the tubes. This mode of flow is inline at lower flow rate and staggered at high flow rate.

Column-Sheet mode: - In column-sheet mode of flow, both appear simultaneously at a time. This occurs when at least one sheet mode of flow continuously exists between the tubes in addition to the column mode of flow. By merging of two nearby liquid columns a sheet mode of flow is formed.

Sheet mode: - Sheet mode of flow has been thoroughly investigated by a number of researchers. This mode of flow appears when the liquid flows continuously in a sheet mode.

Wang et al. (2010) experimentally observed falling film flowing on flat tubes using water and ethylene glycol as working fluids. The flow patterns were classified and the transitions Reynolds numbers were well quantified. Wang et al. (2014) performed a thermodynamic analysis to predict the transition between these modes and a scaling relation is developed for the transitional Reynolds number. They generalized the theoretical approach to predict the transition between these modes. This approach offers insight into the physics and suggest a tube spacing effect on the mode of transition which was not previously been anticipated. Hou et al. (2012), conducted experiments and measured the thickness of liquid film falling around a horizontal smooth and scaled tube with the help of displacement micrometer.
They concluded that the distribution characteristics are mainly affected by circumferential angle, intertube spacing, film Reynolds number and by the outside diameter of the tube to a lesser extent. A correlation was also suggested by them to predict the film thickness.

\[ \delta = \left( \frac{3\mu_t \Gamma}{\rho_l (\rho_l - \rho_g) g \sin \beta} \right)^{\frac{1}{7}} \left( \frac{S}{D} \right)^{\omega} \]  

Qiu et al. (2015) performed numerical investigations to find out the film thickness characteristics over fully wetted horizontal tube in a falling film evaporator.

A two dimensional multi-phase flow model for numerical simulation was used by them under adiabatic conditions. They observed that the film thickness decreases from the top of the horizontal tube and then increases after reaching the minimum value. The minimum value appears approximately in the circumferential angle range between 90° and 140°. Film thickness increases with increase in film Reynolds number and it is directly affected by the liquid flow rate.

A bench mark experiment was conducted by Gstoehl et al. (2004) to measure the film thickness using laser measurement technique. They concluded that at the lower portion of the tube, there is no reasonable prediction by Nusselt falling film theory, it is overestimated in this zone, and hence a corrective approach should be applied. Similar experiments were conducted by Wang et al. (2009) to measure the film thickness for plain tubes and for Turbo-CII tube under different flow rate conditions with different inter tube spacings. The trend for both the tubes is almost similar and shows very little variation.

2. Numerical Investigation

The tube bundle is arranged horizontally and the flow domain is shown in Fig. 3. Due to symmetrical structure, to minimize computational time the solution domain is selected as zone-II. The fluid used in falling film flow over horizontal cylinder is taken as incompressible fluid, having very low velocity. The properties of liquid are assumed to be constant throughout the process and surroundings conditions are at normal temperature and pressure (NTP).

At the outer face inflation technique is used and it is very finely meshed to capture the small changes for getting precise information in that particular region. The wall surface is taken as smooth with no slip boundary condition and with no heat flux.
The top most section is divided into two parts, the small left part is velocity inlet and the remaining is set as pressure inlet. At the bottom the pressure outlet boundary condition is applied. The right vertical side of solution domain is also set as the pressure inlet and on the left side a symmetry boundary condition is applied.

3. Computational Method

In addition to the three fundamental equations namely continuity, momentum, and energy equations, the material conservation equation and volume fraction equation are also used. In the present study Eulerian multiphase model and Volume of Fluid (VOF) method are used to distinguish the interface of fluids. These two methods are used to analyze the physical phenomena more precisely. A finite volume approach is used to solve the partial differential equations explicitly. Pressure Implicit with Splitting of operator (PISO) method is used to solve the Navier-Stokes equation. It is a pressure-velocity calculation procedure which uses one predictor step and two corrector steps to satisfy the conservation of mass. Geometric Reconstruction Scheme is used for interface between fluids using a piecewise linear approach. Initially it is assumed that the solution domain is primarily filled with air for which volume of fraction ($\alpha_g$) is taken as zero and the secondary fluid is water which will fill the solution domain and the volume of fraction for water ($\alpha_l$) is taken as one. The wall contact angle is set to be zero for complete wetting of the surfaces. Simulations are done for different diameters, Reynolds numbers and different tube spacings. The simulations are performed under adiabatic conditions.

A grid independence study is carried out to determine the optimal number of nodes when an accurate solution is to be found at the expense of least computational resources. Grid independence test is run for 25000, 30000, and 35000 number of node points of which 30000 number of nodes is found good enough to capture all the necessary flow features.

A variable time step starting from 0.0001s is taken to maintain a consistent level of accuracy. As the VOF model also includes the effect of surface tension along the interface between each pair of phases, here we have taken a constant value 0.072 for air and water interface.
These are the following important governing equations used in CFD simulation:

Mass Conservation Equation:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0
\]  

(3)

Momentum Conservation Equation:
\[
\begin{aligned}
X- \text{Component:} & \quad \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u \mathbf{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \rho f_x \\
Y- \text{Component:} & \quad \frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v \mathbf{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \rho f_y,
\end{aligned}
\]  

(4)

Energy conservation equation:
\[
\frac{\partial}{\partial t} \left[ \rho \left( e + \frac{\mathbf{V}^2}{2} \right) \right] + \nabla \cdot \left[ \rho \left( e + \frac{\mathbf{V}^2}{2} \right) \mathbf{V} \right] = \rho \dot{q} + \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) - \frac{\partial (u \tau_{xx})}{\partial x} - \frac{\partial (v \tau_{yy})}{\partial y} + \rho f \cdot \mathbf{V}
\]  

(6)

Material Equation:
\[
\begin{aligned}
\rho &= \alpha_i \rho_i + \alpha_g \rho_g \\
\mu &= \alpha_i \mu_i + \alpha_g \mu_g \\
\end{aligned}
\]  

(7)

(8)

Volume Fraction:
\[
\frac{\partial \alpha_i}{\partial t} + \mathbf{V} \cdot \nabla \alpha_i = 0
\]  

(9)

Nusselt Equation:
\[
\delta = \left( \frac{3 \mu_i \Gamma}{\rho_i (\rho_i - \rho_g) g \sin \beta} \right)^{1/3}
\]  

(10)

4. Results and Discussion

4.1 Validation and comparison of two different numerical methods

Fig.4 gives a comparison of two different numerical methods with the experimental result of Gstoehl et al. (2004) and with Nusselt correlation. It is observed that the results with two different numerical methods are very similar in nature; the only major differences are their computational time and reliability. The two numerical approaches used to obtain results are Volume of Fluid method and Eularian multiphase model approach.

The relative error has also been calculated between the simulation results and Nusselt correlation. In the first approach the relative error is 9% and in second approach we have reached closer to the experimental result and the relative error is only 7%.
In both the cases, the general trend of results is similar and agrees well with the experimental results of Gstoehl et al. (2004). The variation of film thickness is determined at 20° intervals. Thickness of liquid film from 0° to 20° of circumferential position is not taken into consideration because in this impingement zone the film thickness does not vary in a regular manner. Only after 20° circumferential positions the normal range of consideration begins. These 2D results agree well with the experimental results and are able to capture the flow characteristics under the given condition. The thickness continuously decreases up to 120° and then it starts to increase progressively till the lower stagnation point. The variation of thickness matches well with the Nusselt correlation and a similar profile variation were obtained in both the methods. The minimum thickness is achieved at around 110° circumferential position.

4.2 Effect of Reynolds number and tube spacing

Effect of Reynolds Number and tube spacing on film thickness variation in the circumferential direction of a horizontal round tube is discussed in this section. Variation of film thickness and mode of flow are heavily dependent on film Reynolds number and tube spacing. In the simulations it is observed that the thickness is more near the upper stagnation zone of the tube and it continues to decreases up to a certain point and then it increases up to the lower stagnation zone. This is very consistent with the experiments conducted by Hou et al. (2012) who observed a similar trend.

Simulations have been carried out for three different Reynolds numbers 650, 950, 1250 and two tube spacing’s 3.2mm and 6.4mm have been considered. The film thickness has been simulated first with the fixed tube diameter of 19.05mm and fixed tube spacing has been taken as 3.2mm. Thickness is calculated at successive intervals of 20° as shown in the figure.
In the first set of flow simulations (D19.05; S3.2; Re650), it seems that the Reynolds number is very low and also tube spacing is very close, and hence the flow behavior becomes very unpredictable (Fig. 5). Mass accumulation on the lower side of the upper tube and film discontinuity in the middle portion of the tube are observed. Abraham and Mani (2015) also observed that at low Reynolds number it was very difficult to get uniform film thickness around the tube. This phenomenon happens because the fluid viscosity is predominant over the gravity free fall condition. The fluid velocity is too low so that the momentum energy required to overcome the surface tension and adhesive force generated on the surface of the tubes is insufficient.

As the Reynolds number is increased to 650 to 950 and 1250, the flow behavior becomes well organized and shows a proper stream lining during the flow at different times. Similarly when the spacing is changed from 3.2mm to 6.4mm the flow behavior becomes smooth and streamlined throughout the flow for the entire range of Reynolds numbers (650, 950, and 1250) (Fig. 6).

Fig. 5 Film thickness variation with circumferential angle (Smooth tube, D= 19.05, S = 3.2)

Fig. 6 Film thickness variation with circumferential angle (Smooth tube, D= 19.05, S = 6.4)
The circumferential distributions of film thickness for all the above sets of variable are similar. Near the impingement zone or in the upper stagnation zone where the liquid velocity approaches zero, the maximum film thickness is achieved and it decreases gradually first and then increases in the vicinity of the lower stagnation point of the tube. The change in thickness is quite different for the upper and lower sides of the tube. In earlier studies it has been concluded that the film thickness increases when Reynolds number increases but in the present study it is observed that it is not valid for all the circumferential locations under the same set of parameters. For tube circumference the film thickness is well predicted but it is not well defined near the lower stagnation zone of the tube.

5. Concluding Remarks

Under steady state conditions, the film thickness around the tube varies. This variation is closely captured by two numerical approaches and it is seen that both approaches are fully capable of capturing the variation of film thickness. The minimum thickness occurs somewhere in the range of 100° to 125° of the circumferential position of the tube and becomes critical thickness for formation of dry patch. The film thickness increases as Reynolds number increases but it is observed that this is not valid for all the circumferential positions under the same set of parameters. The minimum thickness shifts slightly lower in fully developed flow.

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