Influence of the static contact angle on the liquid film coverage for falling-film systems

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Abstract

The coverage of the liquid film over the horizontal tubes, particularly the wetting ratio, is important for gravity-driven evaporators and absorbers to achieve a better heat transfer mechanism. A 2D, two-phase CFD model was developed to examine the falling-film hydrodynamics and transient flow mechanism for Reynolds numbers ranging from 100-500, static contact angles spanning from 0°/30°/60°/90°, and tube-to-tube distance of 10 mm. The VOF method is used in this article to capture the liquid-gas interface. The findings showed that the complete spreading of the liquid film is difficult at low Reynolds numbers and high contact angles. The formation of dry regions on the tube wall as a result of insufficient liquid supply, liquid film breakage, and liquid film shrinkage. Furthermore, as the Reynolds number increases and contact angle decrease, the wetting ratio over the tube surface increases. It is worth noting that each contact angle must have a minimum Reynolds number in order to keep the surface completely wet. The research also revealed that for higher Reynolds numbers, the influence of contact angle on wettability of tube wall can be ignored. For the same Reynolds number, the liquid propagation time required to wet the tube surface increases as the contact angle value increases. Fouling over the tubes can be aided by the formation of air voids near the lower stagnation zone.

1. Introduction

Horizontal falling-film systems have a broad array applications in industry and scientific research. At present most of industrial heat wasted in to the environment without being properly utilized especially at the coastal areas [1]. Economic and environmental factors are the main important reasons to initiate strong intention of improving efficiency of the thermal systems, which is mainly initiated by improving heat exchanger performance. Horizontal tube array type falling-film heat exchangers have been actively utilized in process industries such as food industries [2], desalination [3, 4], refrigeration [5, 6], chemical, and petroleum refineries [7] and natural cooling methods [8]. The functional advantage of the gravity driven falling-film heat exchangers over the flooded heat exchangers makes them a better choice [9-10].

The liquid exits the distributor holes and falls onto the inline horizontal tube bank, spreading over the tube surface in falling-film evaporators (FFE). The liquid film flows downward from preceding to the next subsequent tube under chosen working conditions. The hydrodynamics of the liquid film and transient film coverage are the important concerns in the gravity driven falling-film flow application areas including condensation, absorption and evaporation.

The liquid film profile over the tube wall is the primary thermal energy carrier, and it is highly dependent on the wettability parameter to achieve the desired heat transfer and operating performance. Despite the numerous benefits listed above, gravity-powered FFES have major downsides such as improper liquid film distribution, the formation of dry spots and flooding, and waste of fluid and energy [11]. All of the factors mentioned above are strongly linked to the heat transfer mechanism [12]. Dry spots on the tube walls and uneven liquid film coverage have all led to a substantial deterioration in the evaporation process. According to the studies, the flow hydrodynamics, film coverage and flow characteristics are directly
related to the wettability parameter. Thus, it is important to investigate microscopic flow mechanism, film coverage and flow hydrodynamics in order to improve flow characteristics in these systems.

The present study, on the other hand, provides insight into the hydrodynamic behavior of the falling-film using an established 2-D model, allowing us to extrapolate it to other application areas.

**State of art**

The existing literature has revealed the following principal flow modes between the horizontal tubes, including the droplet mode, column flow pattern, sheet flow mode and intermediate flow regimes are droplet-column mode, column-sheet mode [13, 14]. Chen et al. [15] investigated computationally and experimentally to examine the different flow regime transformations between the horizontal tubes. Kandukuri et al. [16] experimentally investigated the different phases in the column flow regime as well as examined flow parameters such as axial film thickness and jet diameter using image analysis approach.

The flow regimes between the tubes and its characteristics were strongly influenced by the distributor type, height of the distributor, and orifice spacing [17, 18]. Mohamed [19] carried out experiments to analyze the influence of the rotational speed of the test tube on flow pattern transformations. When the falling liquid comes in contact with a horizontal spinning tube, the flow transformation begins at a lower Reynolds number (Re).

Nusselt first proposed falling film theory, assuming a sheet flow mode from one tube to another subsequent tube. He proposed the undermentioned expression to find the liquid film thickness for different radial angles, which is given below [20],

\[ \delta = \left( \frac{3 \mu_L \Gamma}{\rho_L (\rho_L - \rho_G) g \sin \theta} \right)^{1/3} \]  

(1)

The film Reynolds number can be expressed as follows,

\[ Re = \frac{4 \Gamma}{\mu_L} \]

Hou et al. [21] used a displacement micrometer to measure the film thickness on the surface of the inline horizontal tubes. All experiments were conducted with varying peripheral angles ranging from 15° to 165°, outside tube diameters ranging from 20–32 mm, and different tube spacing. The liquid film thickness was found to be the thinnest between 90°-115°. They developed the following correlation to assess the thickness of the liquid profile for different peripheral angles based on Nusselt's Eq. (1). The values of coefficient (C) and exponent (n) are given in the circumferential angle ranges 0° < θ ≤ 90° and 90° < θ ≤ 180°.
Wang et al. [22] developed a numerical model to examine the insight details of the column flow regime. Based on the simulation results, the following correlation is established to quantify the peripheral distribution of film thickness:

\[
\delta = C \left( \frac{3 \mu L \Gamma}{\rho L (\rho L - \rho G) g \sin \theta} \right)^{1/3} \left( \frac{s}{D} \right)^n
\]  

Furthermore, different techniques have been employed in the existing literature to estimate the film thickness, such as the optical-electronic method [23], double-fiber, optical probe [24], laser-induced fluorescence technology [25], laser confocal displacement meter [26], and air-coupled ultrasonic transducer [27].

Qiu et al. [28] performed numerical simulations to explore variation in radial film thickness on the surface of a fully wetted tube. It was revealed that a distinct visible liquid-free zone forms extremely close to the lower stagnation region. As the Re number increases, so does the size of the zone. Zhao et al. [29] investigated numerically the propagation of liquid film over horizontal tube walls. The film thickness on the tube surface was found to increase with Re while decreasing with increase in liquid temperature, tube diameter, and liquid sprayer height. Han et al. [30] adopted a 2D numerical model to study the falling-film flow mechanism over the tube surface for different tilting and sloshing conditions. Both the tilting angle of the tube and the sloshing conditions influenced the liquid film coverage.

de Arriabe et al. [31] carried out simulations to analyze the flow mechanism and to estimate the wetted area in the LiBr-H\textsubscript{2}O absorber. It was observed that each Re has a maximal static contact angle to continuously wetting the entire tube surface. Ji et al. [32] implemented a 2D numerical model to study the variation in film thickness with the Re and contact angle. Ding et al. [33] investigated numerically to explore the spreading of a droplet and liquid jet regimes over the tube surface. The contact angle influences the wettability factor and liquid profile coverage for the droplet mode and column flow regimes.

Tahir et al. [34] implemented a 2D numerical model to analyze the effect of test liquid viscosity and surface tension on flow hydrodynamics. An increase of 72% rise in film thickness is observed with the fluid properties. Wang et al. [35] implemented a 3D CFD model to measure the film thickness for a column flow. The effect of Re number varying from 221 to 295 and tube spacing ranging from 10 mm to 30 mm was investigated.

1.1 Constraints in the literature survey
The above literature review indicates some of the research have been done on horizontal tube falling-film. In the open literature numerous experimental and simulation studies focused on the several factors such as inter tube flow patterns, tubes configuration, distributor type, flow rate of a liquid/gas phases, falling liquid type, and fluid properties. The majority of numerical studies were performed on single tube to understand the falling-film distribution over the tube wall. However, further research into three specific aspects is still required. Firstly, substantial numerical simulations on a two-tube design model are still needed for further exploration due to a paucity of study. Secondly, the impact of static contact angle on falling-film hydrodynamics and wettability characteristics over the tubes have not explored exhaustively in the existing literature. Thirdly, most of the numerous studies considered in the previous literature did not thoroughly quantify the finer details of flow parameters such as film thickness, liquid film propagation and breaking of a liquid film to the best knowledge of authors. The design and functioning of horizontal tube bank FFEs, involve careful consideration in order to prevent flooding or poor wetting phenomena over the tube surface.

1.2 Focus of the present study

Experiments make it difficult to quantify the finer details of flow parameters, such as variation in transient film thickness, liquid profile coverage, and tube wettability for different peripheral angles. Because of the challenges in carrying out experimental work for various parametric conditions, numerical simulations play an important role in the investigation of falling-film flow behavior. It is easier to study the nature of the falling-film flow behavior with the help of CFD software for different operating conditions and distinct instances. A 2D numerical model was established to computationally investigate the flow mechanism over the tubes. The VOF method is employed in this article along with the Continuum Surface Force (CSF) approach to capture the gas-liquid interface. The present work examines the systematic research on the effect of static contact angle \(0^\circ \leq \Psi \leq 90^\circ\) and Re \(100 \leq \text{Re} \leq 500\) on flow characteristics. Furthermore, the flow characteristics such as liquid film hydrodynamics, circumferential film thickness, spreading of the liquid film at upper and lower stagnation zones, and including wettability of the falling liquid over the tubes were meticulously elucidated. In addition, the peripheral distribution of the liquid film for the stabilizing and test tube and thinnest region also presented and discussed in detail.

2. Numerical Approach And Method

2.1 Geometry analysis and boundary conditions

The half domain symmetrical geometry is generated using the ANSYS Fluent software. Because the problem and geometry is symmetric, only half of the solution domain is designated for ANSYS CFD calculations to save computing time, as depicted in Fig. 1. The width of the solution domain and the diameter of the inline horizontal tubes are both 31 mm. The liquid feeder height (H) is 2 mm for all domains, tube spacing (S) is 10 mm and a 1 mm liquid phase inlet orifice is provided at the top. The first tube near the liquid distributor is referred to as the stabilizing tube, and the second tube is referred to as
the test tube. The liquid feeder height is kept at 2 mm from the stabilizing tube to ensure uniform
distribution of droplets or liquid film over the tubes by minimizing impact force [36].

As depicted in Fig. 2, the inlet water flow boundary is on the top surface. It was configured as a velocity
inlet for the liquid phase, where the selected fluid with a velocity flows downward. The remaining section
at the top side was designated as the inlet pressure, while the bottom and right side boundaries were
assigned as outlet pressure. The model front sides are configured as symmetrical boundaries. The
properties of the test liquid can be seen in Table 1.

<table>
<thead>
<tr>
<th>Test liquid</th>
<th>Density (kg/m$^3$)</th>
<th>Viscosity (Pa-s)</th>
<th>Surface tension (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>998.2</td>
<td>0.001</td>
<td>0.0712</td>
</tr>
</tbody>
</table>

2.2 Fluid properties and assumptions

The following are the assumptions made in this study to ease of the numerical analysis,

(a) The liquid is incompressible.

(b) The surface of the tube is completely wetted with a liquid.

(c) All the properties of the fluid are constant.

(d) The surface of the horizontal circular tube is smooth and the effect of surface roughness is remiss.

2.3 Governing equations

Hirt et al. [37] implemented and proposed the VOF technique for accurately capturing the interface
between the gas-liquid phases. In this study, the Pressure Implicit with Splitting of Operator (PISO)
algorithm and the Geo-Reconstruct scheme are used. The working fluid is incompressible, and the fluid
flow is transient and laminar. The governing equations for the mass, momentum and volume fraction can
be defined as follows,

Mass equation:

$$\nabla \cdot (\vec{\rho}) = 0$$

4

Momentum equation:
\[
\frac{\partial}{\partial t} \left( \rho \mathbf{v} \right) + \nabla \cdot \left( \rho \mathbf{v} \mathbf{v} \right) = -\nabla P + \nabla \left[ \left( \mu \nabla \mathbf{v} \right) \right] + \rho \mathbf{g} + \mathbf{F}
\]

5

Volume fraction:

\[
\frac{\partial}{\partial t} (\alpha_q) + \mathbf{v} \cdot \nabla \alpha = 0
\]

6

The CSF model [38] is utilized in this study to add surface tension force to the momentum equation. In the CSF model the surface tension force term is as follows,

\[
F = \sigma \kappa n \rho \frac{\rho}{(\rho_l + \rho_g)/2}, \quad n = \nabla \alpha, \quad k = -\nabla \cdot \left( \frac{n}{|n|} \right)
\]

In the VOF approach, if the volume fraction of the liquid phase is 1, then the cell belongs to liquid phase. However, at the gas-liquid interface region the volume fraction is ranges between 0 and 1. The CSF method is implemented in this analysis to effectively characterize the gas-liquid phase interface, where surface tension impacts cannot be ignored. To account for the influence of the tube wall property, a wall adhesion model [38] is adopted in conjunction with the surface tension method. The circular tubes and test liquid in this work are assumed to be copper and water, respectively.

2.4 Methodology

In this study, the commercially accessible CFD software “ANSYS Fluent v 21.0” is used. The solution domain is interconnected by quadrilateral dominant mesh elements. The boundary layers of the circular tube wall and inter tube distance are finely meshed to precisely obtain the gas-liquid interface. The PISO coupled algorithm was employed for full pressure-velocity coupling, and the Pressure Staggering Option (PRESTO) scheme was adopted for pressure interpolation. In this study, the VOF model was used in conjunction with the CSF technique and the Geo-reconstruct scheme. To compute the solution, the transient method is combined with an adaptive time stepping scheme and a multi-phase specific method. The model settings are VOF explicit method, volume fraction cutoff is $10^{-6}$ and courant number is 0.25, which is a VOF method stability criterion.

2.5 Verification of mesh independence

The grid independence study is important factor in CFD modeling. The number of elements in the computational zone 23543, 32162, and 40379 were chosen for the optimal mesh selection to analyze the film thickness distribution under the same input conditions, i.e. Re = 500 and tube distance of 10 mm, in order to examine mesh independence. Figure 3 depicts the spreading of the film thickness is almost same and super imposed for the 32162, and 40379 grid elements. Thus, the grid number 32162 was preferred in this article as to save the computing time.

2.6 Numerical Model validation
Figure 4 depicts the comparison of simulation results with the values reported by Hou et al. [21], Ji et al. [32]. For the established 2D model, the spreading of the film thickness trend for the Re = 574 and S = 10 mm is consistent with the experimental results. It is evident that there is a decrease in film thickness until 90° and a minimum value in the range of 90°-120°, after which there is an increase in liquid film thickness. The mean absolute percentage error for the simulation results and values reported experimental work is less than 10%. However, the simulation outcomes are in good agreement with Nusselt’s correlation. Thus, the established 2D model is competent to examine and analyze the film hydrodynamics over the horizontal tube surface.

3. Results And Discussion

The fluid with a predetermined velocity is falling on the top of the inline horizontal tubes under the influence of gravity and flows downwardly as shown in Fig. 5a. In this stage, the falling fluid reaches the top portion of the stabilizing tube can be called as upper stagnation zone, as illustrated in Fig. 5a. The fluid begins to spread over the surface of the tubes in circumferential direction, as seen from Fig. 5b. In the next stage, the falling-film continues to spread over the tube surface and bottom half of the tube, which is known as the liquid film developing stage. The majority of the tube portion was spread by falling liquid under the influence of gravitational force. Thereafter, the surface of the tube has been completely covered by the liquid profile during the fully developing stage, as shown in Fig. 5c. Following that, a part of the liquid film departs underneath the tube from the lower stagnation zone in the form of either droplet mode or jet mode and falls on the next tube as seen from Fig. 5d. It can be illustrated from Figs. 5e, f, and g the coverage of a liquid film over the surface of the test tube and it eventually departs from the beneath the tube. Based on the above observations here so far, it is worth mentioning that the spreading of the falling liquid over inline horizontal tubes is closely related to the circumferential angle.

3.1 The effect of static contact angle on liquid film coverage

Wettability of a liquid film has noteworthy influence on the efficiency of falling-film heat exchangers, which includes condensers and evaporators under different operating parameters. Therefore, it is important to analyze the impact of static contact angle on wettability properties and film hydrodynamics. The present study examines the impact of static contact angle (Ψ) from 0°-90° on the falling-film flow mechanism and the liquid coverage percentage on the surface of the tubes for the Re ranging from 100 to 500. Figure 6 depicts a schematic view of droplet wetting over a solid surface for different Ψ values.

The development of dry spots, mal-distribution, and uneven liquid film coverage for a given Re has a negative impact on the operating performance of FFEs. Figures 7, 8, 9, 10, and 11 illustrate the influence of Re and Ψ on film hydrodynamics such as wetting ratio, liquid film coverage, and liquid film breakage.

Figure 7 depicts the spreading of the liquid film for Re = 100 and various Ψ values ranging from 0° to 30°, 60°, and 90°. Water volume fraction contours were used to visualize transient liquid film coverage for
various time frames in each case. Water flows downward from the distributor hole at a predetermined velocity and under the influence of gravity. After reaching the upper stagnation zone, it extends circumferentially. The droplet formation can be seen beneath the stabilizing tube, when $\Psi = 0^\circ$ and $Re = 100$. The developed droplet also known as the primary droplet, also mentioned this behavior [39, 40]. The developed primary droplet has a hemispherical shape at the liquid head, and due to the low $Re$, the droplet made contact with the test tube and began to spread as a thin film. The temporary formation of a neck for the earlier wetting of a tube wall can be seen at this stage. Because the tube has ideal wettability properties at this stage [32], the thin liquid film completely wets the stabilizing and test tube walls without any breakages. Due to insufficient liquid sprinkle density, the developed neck becomes weak and unable to sustain over time. As a result, the liquid neck thins out, eventually breaking at the weakest point and forming tiny droplets. Another source of concern from Fig. 7 at 0.59 s is the neck breaking that occurred after one cycle of complete wetting of both the stabilizing and test tubes. There are no dry zones on either tube wall due to ideal wetting conditions at $\Psi = 0^\circ$, but the developed liquid profile is very thin due to low $Re$.

Furthermore, for the same $Re$ and $\Psi = 30^\circ$, the liquid film first wets the stabilizing tube wall in the same way as in the previous case. The shape of the developed primary droplet for $\Psi = 30^\circ$ is different, as explained clearly in the following segments about inter tube flow regimes. Due to the increased $\Psi$ value, the developed neck lasted only a short time and began to break before complete wetting of a test tube. It is important to note that the development of dry zones close to the upper stagnation zone of the test tube can be seen in Fig. 7b as a result of increasing the $\Psi$ value from $0^\circ$ to $30^\circ$. Furthermore, as time progresses, the size of the dry zone for the test tube grows, and the major portion of the tube wall appears dry without a thin liquid film, as can be seen in Fig. 7b. However, after the neck breaks in both stages described above, the remaining liquid is retracted by the stabilizing tube because surface tension forces outweigh gravitational forces [34, 39]. When the $\Psi$ value is increased to $60^\circ$ and $90^\circ$, the liquid film from the feeder hole reaches the upper stagnation zone. However, the liquid film profile's coverage over the tube perimeter is limited. In this regard, the liquid film profile did not completely cover the tube surface. Increase the liquid sprinkle rate to ensure that the liquid film meticulously distributes the tube surface with the least amount of film thickness to avoid dry spots, especially when the tube surface wettability is low [32].

Figure 8 portrays the coverage of the liquid profile for $Re = 200$ and $\Psi$ values ranging from $0^\circ$ to $90^\circ$. To comprehend the liquid film coverage for different values, the contours of water volume fraction photographic evidences for the chosen time frames were demonstrated. When $\Psi = 0^\circ$, $30^\circ$, and $Re = 200$, the liquid film wets both the stabilizing and test tubes without a liquid profile breaking over the tube wall. The development of a neck can be seen in Fig. 8a, b. Because of the increase in $Re$, a continuous neck is formed between the stabilizing and test tubes, and it remains intact. However, due to sufficient liquid sprinkle density, there is no neck breaking and no retraction process is noticed. The $\Psi$ value for the same $Re$ influences the inter tube flow pattern in this case as well.
When the $\Psi$ value is increased to $60^\circ$, the liquid film exiting the distributor broadens in the upper stagnation zone. Following that, the liquid film wets the stabilizing tube and begins to break the liquid profile just after making contact with the next tube. The shape of the inter tube flow regime is neck in the previous two cases, but it is close to droplet shape here. Furthermore the droplet made contact with the test tube and formation dry zones very close to the lower stagnation region of a stabilizing tube due to the breaking of a liquid film. The inter tube droplet detaches from the stabilizing tube and spreads across the test tube. Another important point highlighted from the Fig. 8c is that the detached droplet beneath the stabilizing tube began to spread as an uncoupled liquid film. The liquid film from the upper portion of the stabilizing tube wall began to break and commute as unattached liquid film as time progressed. In this sequence, the liquid film uncovers the major portion of both tubes, but a small developed droplet is attached beneath the tubes. This stage is also known as the periodic wetting process for the selected Re and $\Psi$ values. Furthermore, as the $\Psi$ value approaches $90^\circ$, the liquid film begins to shrink in the upper stagnation zone, limiting its wetting area. The liquid coverage area is minimal at this stage and does not wet the entire tube.

Figure 9 clearly demonstrates the liquid solution coverage profile for various $\Psi$ values and $\text{Re} = 300$. The falling liquid begins to spread across the tube wall when $\Psi = 0^\circ, 30^\circ$. There is no widening of the liquid film in the upper stagnation zone. The liquid profile coats both the stabilizing and test tubes. Furthermore, the liquid film completely covers the entire surface of the tube without breaking. Because of a sufficient supply of liquid sprinkle density, there is no neck breaking and retraction process for the same Re and $\Psi = 0^\circ, 30^\circ$.

When $\Psi = 60^\circ$ for the chosen Re, the wetting process changes as shown in Fig. 9c. During the early stages of the wetting process, the liquid film expanded at the upper stagnation zone and then spread. The liquid film first wets the entire perimeter of the stabilizing tube before moving on to the next tube. However, the breaking in the liquid film profile began at the lower portion of the stabilizing tube after the liquid film made contact with the next tube. Following liquid film breaking, both individual liquid film profiles flow downward under the influence of gravity for a short period of time, as shown in Fig. 9c. The stabilizing tube appeared to be completely wet after a short span of time, but not the test tube. The main reason for complete wetting of the stabilizing tube, which is placed close the liquid distributor. On the test tube wall, liquid film breakage and the formation of dry zones can be seen. The liquid coverage area for a given same Re, $\Psi = 90^\circ$ is limited and does not wet the entire tube.

Figure 10 demonstrates the transient liquid film coverage for different $\Psi$ values and $\text{Re} = 400$. The liquid solution profile wets the entire tube when $\Psi = 0^\circ, 30^\circ$, and $60^\circ$. Because of the adequate liquid sprinkle density, there is no breaking and retraction process for the $\Psi = 0^\circ, 30^\circ, 60^\circ$, and given Re, as discussed in the preceding stages. The development of a tiny droplet connected to the liquid film head is clearly visible for the $\Psi = 30^\circ, 60^\circ$. Furthermore, as shown in Fig. 10b, c, the developed tiny droplet at the liquid head collapses beneath the test tube, resulting in the formation of air voids for a short time.
Another significant aspect for the same Re and $\Psi = 90^\circ$ is the liquid film leaving position. As the $\Psi$ value increased to 90°, the liquid film first wets the stabilizing tube wall during the early stages of the wetting process. The liquid film leaves the stabilizing tube wall before reaching the lower stagnation zone in this sequence. The liquid film falls on the next tube after leaving the stabilizing tube wall as droplets. The test tube, on the other hand, experienced the same thing during the first cycle of the wetting process. After a while, the liquid film completely wets both tubes.

Figure 11 illustrates the contours of the water volume fraction results for Re $= 500$ and different $\Psi$ values. The liquid profile covers and completely wets the entire tube for $\Psi = 0^\circ$-90°. It can be seen that as Re increases, so does the wettability of the tube surface. When $\Psi = 0^\circ$, the liquid film contacts the upper stagnation zone and slowly and surely spreads circumferentially to wet the entire tube. For the same Re, the sample flow time to cover the liquid over the tube surface increases as the $\Psi$ value increases [32]. When the $\Psi$ value ranges from 30° to 90°, the formation of tiny droplets at the liquid film head is ascertained. The $\Psi$ value for a given Re increases the size of the tiny droplet.

When $\Psi = 90^\circ$, the liquid film leaves the tube surface as a tiny droplet regime without reaching the lower stagnation zone, as can be seen in Fig. 11. The liquid film leaves the tube perimeter without covering the entire tube in the initial stage of the wetting process and spreads progressively to wet the entire tube. Furthermore, the numerical results revealed that each Re has the highest $\Psi$ value possible for gradually wetting the entire tube surface. When the $\Psi$ value is less than this maximum, the wettability over the tubes is unaffected. When the $\Psi$ value is increased, the liquid film wetting area over the tubes decreases.

### 3.2 Inter tube flow regime

Figures 12, 13, 14, 15, and 16 illustrate the inter tube flow patterns for various Re and $\Psi$ values. According to the existing literature, the transition of flow regimes from tube to tube is based on Re [13–16]. It is noticed that the inter tube flow regimes are primarily the result of Re. Furthermore, the present study unearthed the effect of Re and $\Psi$ on flow structures. The liquid profile formation process on the subsequent bottom tube is greatly influenced by the flow mode structures beneath the tube. The flow pattern is droplet when Re $= 100$. When $\Psi = 0^\circ$, the droplet has a hemispherical cap at the liquid head due to droplet extension in the vertical direction. Furthermore, when $\Psi = 30^\circ$, the droplet's shape changes to a spherical shape and attempts to detach from the liquid head. Due to non-wetting of tube walls, this phenomenon was ignored for the $\Psi = 60^\circ$, 90°.

The flow structures beneath the stabilizing tube wall are portrayed in Fig. 13 for Re $= 200$ and $\Psi = 0^\circ$, 30°, and 60°. When $\Psi$ values range from 0° to 30°, 60°, the shape of the developed droplet becomes narrow for $\Psi = 30^\circ$ and spherical front followed by weak neck for $\Psi = 60^\circ$.

The inter tube flow regimes for Re $= 300$ and $\Psi = 0^\circ$, 30°, 60° are seen in Fig. 14. The droplet made contact with the next tube and began spreading on the tube wall when $\Psi = 0^\circ$. The neck is formed between the tubes as a column flow pattern is established in this sequence. The flow structure is spherical front...
connected by a small column of liquid film when $\Psi = 30^\circ$ for the same Re. Furthermore, $\Psi$ values increased to $60^\circ$, it is noticed that the small volume of the liquid droplet connected to the liquid head. At this point, the flow pattern is attempting to transition from column flow pattern to droplet flow pattern. Due to poor wettability, the phase is ignored for the $\Psi = 90^\circ$.

The continuous neck is developed for all values in the Re = 400, 500 cases, as seen in Figs. 15 and 16. When $\Psi = 0^\circ$, $30^\circ$, the spherical front is followed by the fluid column. When the $\Psi$ value is increased to $60^\circ$, $90^\circ$, a greater volume of fluid is collected beneath the tubes due to the formation of tiny droplets. Furthermore, when Re = 500 and $\Psi = 60^\circ$, $90^\circ$, the formed tiny droplets collide beneath the tube, resulting in the formation of air voids and a recirculation zone in the flow field. The formation of air voids beneath the tube can have a negative impact on the heat transfer mechanism.

### 3.3 Liquid film wetting time

Figures 17 and 18 demonstrate the propagation time for the stabilizing tube and test tube, as well as the time taken into account for the inter tube commuting of liquid film. The propagation time in this study is defined as the time required for the liquid film to completely wet the stabilizing tube and test tube in one cycle. Another concern highlighted by Figs. 17 and 18 is that the propagation time required to wet the tube surface increases as the $\Psi$ value for the same Re. Furthermore, as Re increases, the wetting time decreases. The propagation time of 0 indicates that the wettability is low due to insufficient liquid film coverage of the tube wall for the selected Re and $\Psi$ value. For Re = 100, the wetting time difference is large for $\Psi = 0^\circ$, $30^\circ$, whereas for Re 200–500, the wetting time difference is small. In all cases, a significant difference in wetting time is observed for the $\Psi = 60^\circ$, $90^\circ$, as shown in Figs. 17 and 18.

The aforementioned water volume fraction contours revealed that the Re and $\Psi$ have significant influence on the liquid film coverage over the tube walls. The development of dry spots over the tubes may have a negative impact on the operational performance of FFEs. For a given instance, the wetting ratio over the tubes can be defined as ratio of wetted perimeter to the total perimeter.

The results indicated that the wetting ratio over the tubes increases with the increase of Re and decreases with $\Psi$. When the Re = 100, which represents the solution spray density from the distributor, the solution does not wet the whole tube and wetting ratio is greater for the $\Psi$ values $0^\circ$, than for other contact angles of the same Re. The wettability is low in this case due to insufficient liquid spray density. Lower Re makes it difficult to spread the liquid film, and dry spots form on the tube surface as a result of falling liquid film breakage and shrinkage. As illustrated in Figs. 17 and 18, the liquid film starts to cover the tube perimeter for $\Psi = 0^\circ$, and a continuous liquid film is formed. However due to the low Re, the liquid film does not cover the tube without breaking for $\Psi = 30^\circ$. The wetting ratio is low for other contact angles. Furthermore, when Re = 200, the liquid film wets the entire tube for both $\Psi = 0^\circ$, $30^\circ$, and the wetting ratio is 1. For other values of $\Psi$ and same Re, the wetting ratio begins to decrease and becomes low.

When the Re = 300, the continuous liquid film is developed for the $\Psi = 0^\circ$ and $\Psi = 30^\circ$. Another point of concern is noted from the Figs. 17 and 18 is the development of dry spots for the $\Psi = 60^\circ$, despite of liquid
film covering the entire tube. The wettability is low for the other $\Psi = 90^\circ$. When $Re = 400, 500$ the wetting ratio is 1 for the $\Psi = 0^\circ, \Psi = 30^\circ, \Psi = 60^\circ$, and $\Psi = 90^\circ$ which represents the liquid film covers the whole tube surface. Another important point to take away from Figs. 17 and 18 is that as the $\Psi$ value for a given Re increases, so does the flow time required to wet the entire tube. It can be noted that there is a minimal Re for each $\Psi$ value in order to keep the surface completely wet. The research also revealed that at higher Re, the $\Psi$ value influence on the wettability factor can be disregarded.

4. Conclusion

A 2D and two phase model was developed to study the gravity driven falling-film flow distribution over the inline horizontal tubes for the Re ranging from 100 to 500, $\Psi$ value varying from $0^\circ/30^\circ/60^\circ/90^\circ$ and inter tube spacing of 10 mm. Overall, this research revealed that the $\Psi$ value and Re have a substantial impact on liquid film hydrodynamics and can be considered in FFEs for droplet mode and column flow regimes. The proposed approach is an important tool for designing efficient gravity driven FFEs. The transient behavior of the liquid film and spreading of the falling liquid under various operating parameters were examined in detail with key conclusions as follows:

1. It is difficult to meticulously distribute the liquid film for low Re and high contact angles. The development of dry regions on the tube surface due to inadequate supply, liquid film breakage and shrinkage of liquid film. The wetting ratio over the tube surface increases with the increase of Re and decrease of static contact angle.
2. The $\Psi$ values have had a significant impact on the inter tube flow regimes for a given Re. The formation of air voids near the lower stagnation zone can exacerbate fouling over the tubes, lowering the FFE’s performance.
3. It is worth noting that each contact angle has a minimum Re in order to keep the surface completely wet. The study also demonstrated that for higher Re, the contact angle influence on wettability over the tube surface can be ignored.
4. The influence of static contact angle on the distribution of film thickness for different peripheral angles can be disregarded at higher values of Re.

Abbreviations
Declarations

Declaration of Interest Statement

The authors declared that there is no conflict of interest.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

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Sandip Deshmukh: Visualization, Supervision, Reviewing and Editing.

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References


Figures

Figure 1

(a) Schematic of the inline horizontal tube array (b) Sketch of computational solution domain.
Figure 2

2-D Half symmetrical model with boundary conditions.
Figure 3

Comparison of film thickness for different mesh numbers.
Figure 4

Comparison of numerical outcomes with the published literature [20, 21, 32].
Figure 5

Falling-film coverage for different time frames.

Figure 6

Schematic of droplet wetting over the solid surface.
Figure 7

(a) Liquid profile coverage for Re = 100, (a) $\Psi = 0^\circ$ (b) $\Psi = 30^\circ$ (c) $\Psi = 60^\circ$ (d) $\Psi = 90^\circ$. 
Figure 8

(a) Liquid profile coverage for Re = 200, (a) $\Psi = 0^\circ$ (b) $\Psi = 30^\circ$ (c) $\Psi = 60^\circ$ (d) $\Psi = 90^\circ$. 
Figure 9

(a) Liquid profile coverage for Re = 300, (a) $\Psi = 0^\circ$ (b) $\Psi = 30^\circ$ (c) $\Psi = 60^\circ$ (d) $\Psi = 90^\circ$. 
Figure 10

(a) Liquid profile coverage for Re = 400, (a) $\Psi = 0^\circ$ (b) $\Psi = 30^\circ$ (c) $\Psi = 60^\circ$ (d) $\Psi = 90^\circ$. 
Figure 11

(a) Liquid profile coverage for Re = 500, (a) $\Psi = 0^\circ$ (b) $\Psi = 30^\circ$ (c) $\Psi = 60^\circ$ (d) $\Psi = 90^\circ$. 
Figure 12

Inter tube flow pattern for Re = 100.

Figure 13

Inter tube flow pattern for Re = 200.

Figure 14

Inter tube flow pattern for Re = 300.
**Figure 15**

Inter tube flow pattern for $Re = 400$.

**Figure 16**

Inter tube flow pattern for $Re = 500$. 
Figure 17

Variation in propagation time for complete domain.
Figure 18

Variation in propagation time for stabilizing tube.

Supplementary Files

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