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The effect of modifying the external surface of copper tubes used in a falling film fluid of a horizontal tube bundle

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ABSTRACT

This paper reports on an experimental investigation of a falling fluid coverage over plain and longitudinally enhanced horizontal copper tubes. Four different fluid distributors made out of Ø15 mm copper pipe were prepared by drilling a linear array of 11 holes along the tube length. Distributor (a) had an array of 4.5 mm holes, distributor (b) had 3.5 mm, distributor (c) had 2.5 mm, and distributor (d) had 1.5 mm. Holes of all distributors were drilled at the same center-to-center pitch of 8 mm. A horizontal tube bundle of four Ø15 mm copper tubes was also prepared. The study aimed to investigate the fluid coverage on the horizontal tubes using varied distributors at 25 mm and 45 mm height between the distributor and tube bundle. It was established that not only radial enhancement on tubes can improve the falling fluid film but also the longitudinally arranged enhancement can improve the fluid flowing around the horizontal tubes.

Second International Conference on Aspects of Materials Science and Engineering (ICAMSE 2021).

1. Introduction

Boiling a dynamic thin film of fluid is cheaper than boiling a stagnant pool of fluid. The falling film and pool boiling evaporators are based on these respective principles. Flooded evaporators are energy-intense due to their nature of having a submerged heating element to overcome a temperature difference of a large pool of fluid. Unlike the flooded evaporator, the falling film evaporator has to overcome a temperature difference of a thin falling film of fluid to produce vapor. The falling film evaporator has geometric, structural, and thermodynamic parameters that contribute to the heat transfer which is reflected by the throughput quantity of the evaporator [1,2]. Falling film evaporators have gained popularity over the flooded evaporators for large- and small-scale processing plants. Evaporators are important devices that are used in research and industrial sectors dealing with fluids that require phase change by using very low-temperature differences when processing. These processes include distillation plants, desalination of brackish and seawater, dairy products processing, and other related processing methods. The use of horizontal and vertical falling film evaporators has gained momentum over the years. Vertical falling film evaporators have been the most used form of falling film evaporator, which is evident in the dense literature available on this kind of evaporator. The vertical falling film evaporator is still the most preferred over the horizontal falling film evaporator due to the considerable amount of space it occupies on the factory floor. The fundamentals behind the falling film evaporators are the thermodynamic principle of heat exchangers that is influenced by various parameters. In both these evaporators, there is a top distributor of the falling film fluid that falls externally onto the circumference of a tube bundle, that is vertically or horizontally arranged. The falling film evaporator is classified with respect to its tube bundle arrangement. In both cases, the film is distributed from the top, with various suitable distributors for the fluid type [3–7].

The focus of this study is on the physical aspects of the horizontally arranged tubes and the behavior of falling film that undergoes various stages as it falls down the tubes, hence the literature reviewed. Geometrics within the falling film evaporator is equally important as the structural and thermodynamic parameters of the device. Hence, it is critical that the right fluid flow pattern over the horizontal tubes is established before focusing on heat transfer. To date, there are three main falling film patterns (Fig. 1) that literature shows from numerical and experimental observations [8–10]. It is evident that if the right flow over the tube bundle is not established then this affects the heat transfer that yields an inefficient evaporator [8]. It should be noted that this study does not cover the heat transfer of the falling film to the tube bundle, but the focus is only on the geometrics and structural parameters that

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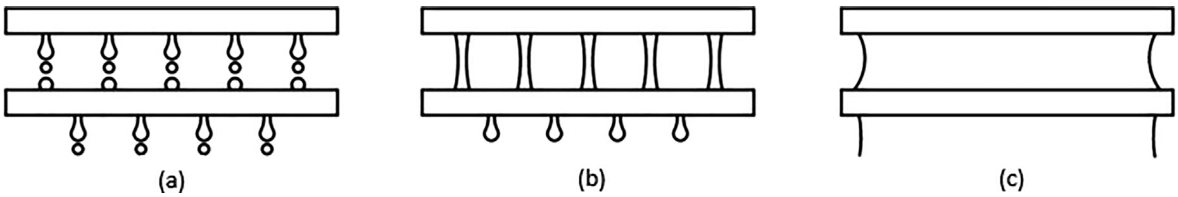

Fig. 1. Film flow pattern, (a) Droplets pattern; (b) Column pattern; (c) sheet pattern.

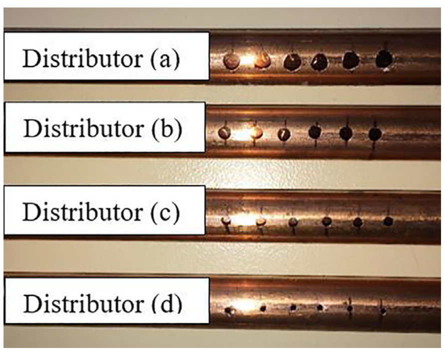

Fig. 2. Top distributors arrangement.

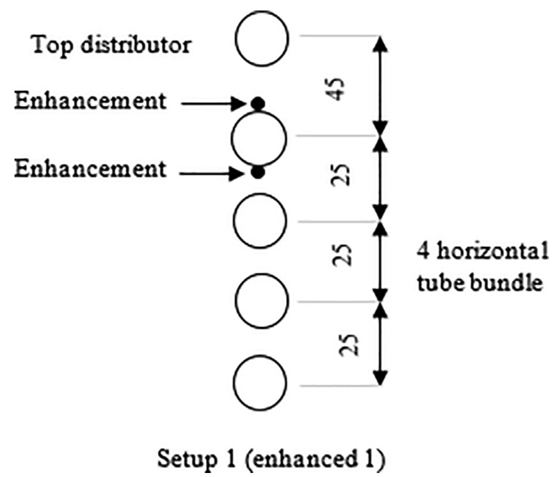

Fig. 4. Schematic diagram depicting one enhanced horizontal tubes for setup 1.

directly affect the fluid flow patterns occurring over the plain copper tube bundles.

The intense research and development on the falling film fluid flow patterns show the interest and necessity of investigating these flow patterns in depth. Ding et al., conducted a study that theoretically established that the falling film flow pattern is reactive to the initial wetting conditions. Their study focused on the behavior of the fluid flow patterns by adjusting the fluid flow and the contact angle parameters of the fluid distributed onto the horizontal tube bundle [9]. Austegard et al., [11] studied the fluid flow patterns on the horizontal tubes for Liquefied Natural Gas (LNG) heat exchanger. They observed that the traditional three flow patterns behavior are not in line with that of LNG based refrigerants.

Due to the challenge of not being able to achieve an entirely wet horizontal tube that results in undesirable dry spots, an emerging study on how to wet the horizontal tube by rotating it is being developed by various researchers. In the numeric investigation that was experimentally validated, a horizontal tube was tested by rotating it at varying speed of 100, 200, 300, and 400 rpm while the falling film which (it's thickness and velocity) was also varied as it was descended onto the circumference of the tube. It was observed that when the horizontal tube was stationary the film was equally and symmetrically dispersed over the circumference of the tube. It was also observed that the rotation mode influenced the thickness and volume of the falling film that fell off the horizontal tube. Moreover, the rotational speed and its direction influenced the angle and volume of the film as it departs the circumference of the horizontal tube [12]. This would then affect the film that would fall on the tubes below the initial rotation tube. Similar studies on rotating horizontal tubes were conducted to develop this idea [13–17].

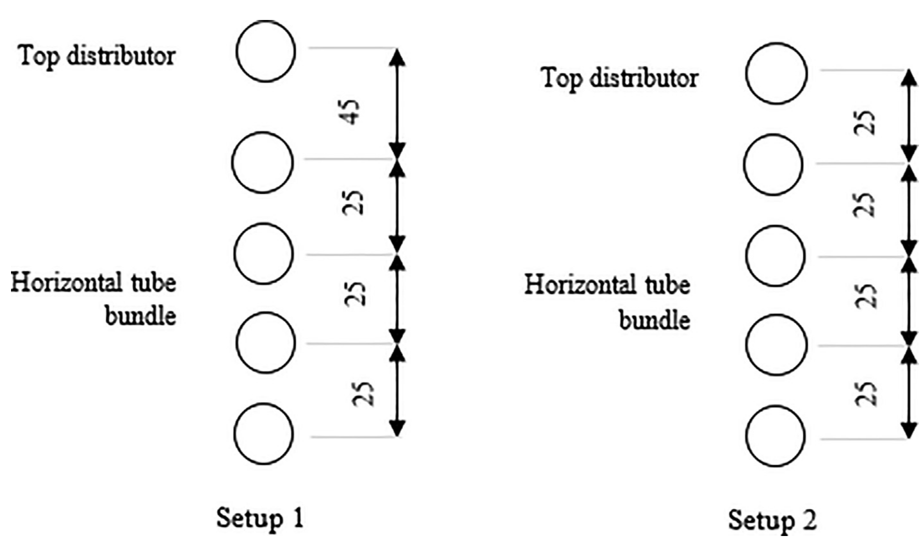

Fig. 3. Schematic diagram of cross-sectional plain of horizontal tubes for setup 1 and 2.

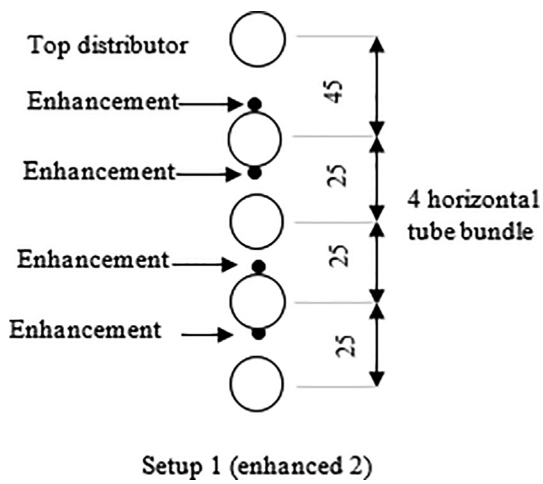

Fig. 5. Schematic diagram depicting two enhanced horizontal tubes for setup 1.

Unlike Mitrovic's [2] and Austegard et al., [11] suggestion that the horizontal tube spacing is irrelevant, Hao et al., [18] have demonstrated this to be otherwise when they investigated the fluid film behavior taking the tube spacing into consideration. In this investigation, the inter-tube spacing was varied from 10 mm, 16 mm, 33 mm, and 40 mm. It was experimentally established that increasing the inter-tube space decreases the mass or thickness of the film as it cascades vertically down the circumference of the horizontal tubes. This then implies that the positioning of the horizontal tubes relative to one another is indeed a critical parameter in achieving an optimal heat transfer coefficient. This is achieved by having a correct volume of the falling film fluid that would allow a good flow to be carried throughout the horizontal tubes. This analysis concurs with that of the predecessors that consider the geometric parameter effect as an important parameter that cannot be overlooked [19–22].

It is evident that the geometric parameters are a critical parameter that influences the thermodynamics of the falling film. Another developing geometric parameter is a tube bundle arrangement that is generally, in three modes a square pitch, staggered triangular pitch, and line pitch. The falling film from the distribution outlet to the last horizontal tube is influenced by many factors as compared to the film falling onto the inter-tube bundle only. The surface preparation affects only this falling film passing the inter-tube bundle. The surface preparation can be depicted as a structural parameter that, influences the thermodynamics and fluid flow behavior pattern of the falling film fluid at the inter-tube bundles [23]. Experimental and numerical studies on the enhancement of the horizontal tubes have established this [24–28].

The literature reviewed is the majority of the physical aspects that affect the falling film fluid. The fundamentals of how the falling film affects the heat transfer coefficient are not encompassed in this paper, external literature is available. In the subsequent sections, the experimental setup will be briefly presented. The results and discussions will then follow demonstrating the impact of the enhancing tube bundle on the falling film fluid. Thereafter the observations of the study will be concluded. The literature reviewed shows that attempts has beenpreviously made to modify the horizontal tube bundle of a falling film fluid evaporator; inorder to achieve an efficient film of falling fluid and heat transfer on the tube bundle. This study has focused on experimenting on enhancing the horizontal tube bundle longitudinally. This is a dif-

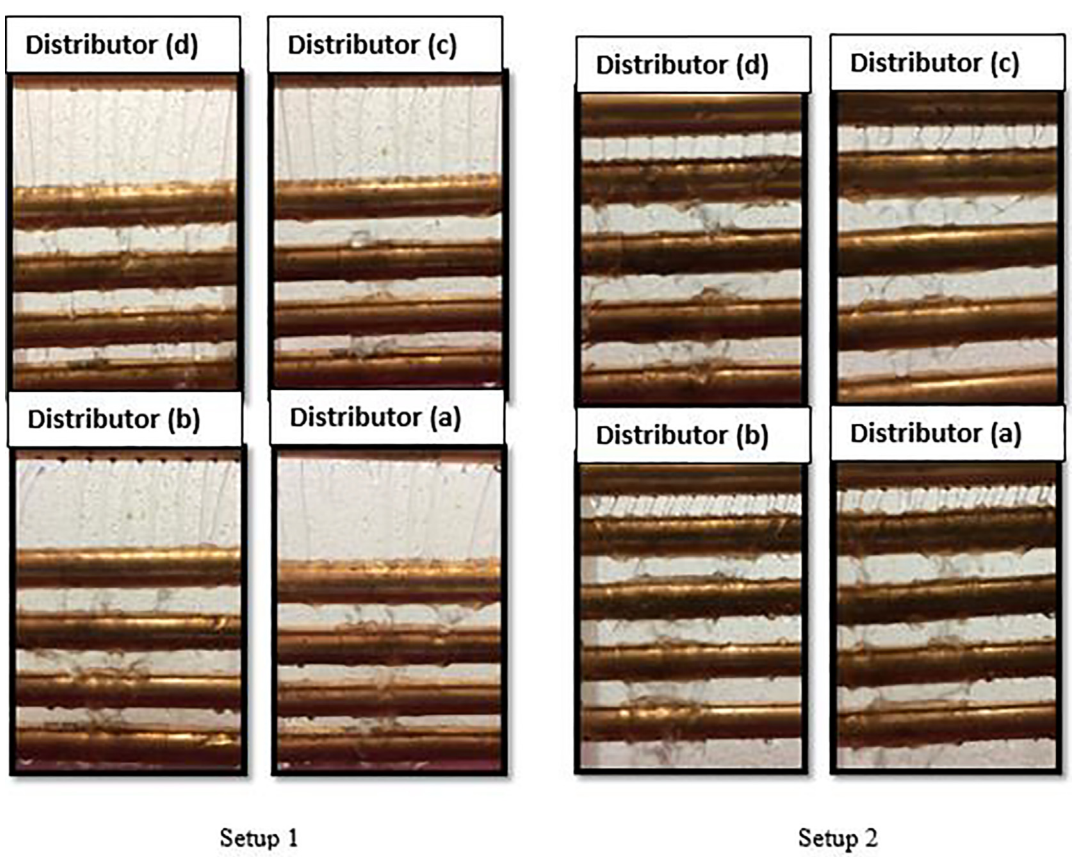

Fig. 6. Plain tube bundle for setup 1 and 2.

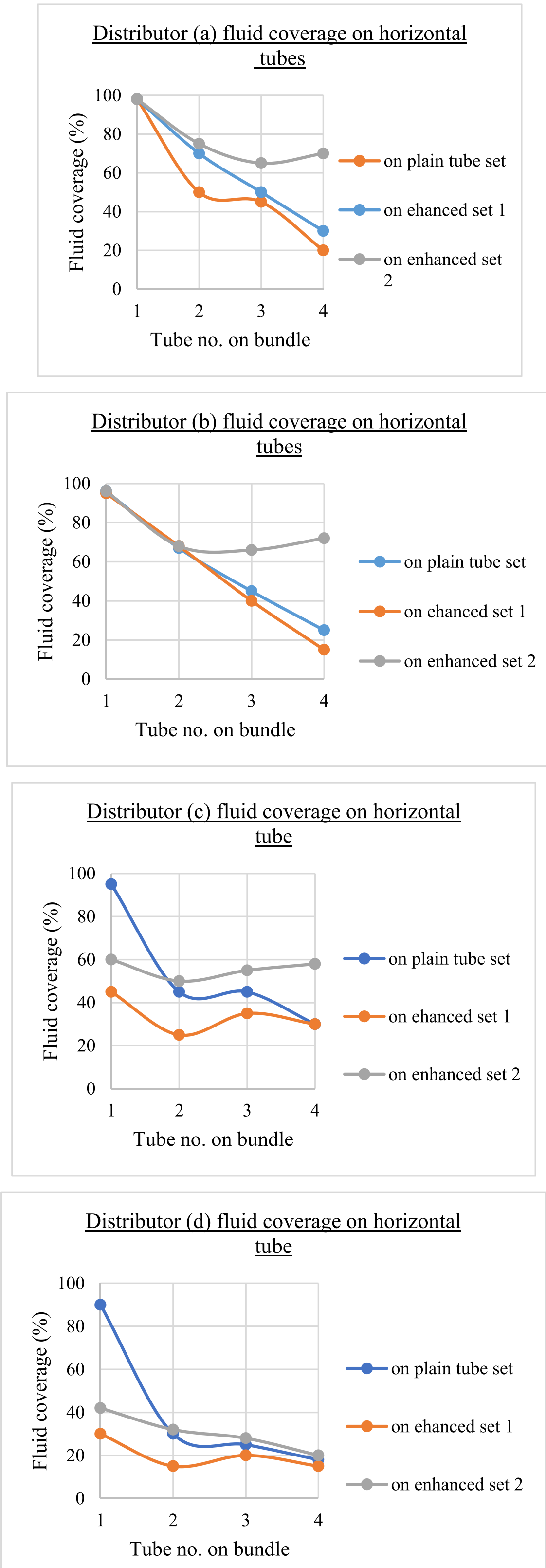

Fig. 7. Graphs representing the fluid coverage on horizontal tubes with varying distributors.

ferent approach of enhancing the tube bundle as compared to radially enhancing the tube bundle and other geometric and structural modifications previously performed [15–26].

2. Experimental setup and performance

Three different experimental setups were prepared for this investigation. Setup 1 had the tube bundle below the distributor at a pitch of 45 mm and set 2 was 25 mm, Fig. 3. The tube bundle was kept constant at 25 mm throughout the investigation. The top disturber pipe was varied for four different holes drilled on it. The top distribution tubes were prepared out of a 15 mm copper tube that was drilled holes of 1.5 mm-distributor (d), 2.5 mm-distributor (c), 3.5 mm-distributor (b), and 4.5 mm- distributor (a), see Fig. 2. All the distributor pipes drilled 11 holes at 8 mm pitch.

To further explore the behavior of the falling film fluid over the bundle the first horizontal tube was enhanced. It was observed in the literature reviewed that there is no published data of observations on enhanced horizontal tubes that have longitudinal fins arrangement on the outside body of the tubes. Most publications are based on radially enhanced horizontal tubes. This was explored, Fig. 4 shows the enhancement that was set on the horizontal tubes. For experimental purposes, a cylindrical enhancement of Ø5 mm was attached along the top and bottom length (see Fig. 4) of the first of the four tubes of the bundle. The second, enhancement setup (on Fig. 5) was on the third horizontal tube.

Therefore, there were three types of test conditions that were prepared in this section, the plain bundle, the enhanced bundle (only the first tube), and another enhanced bundle set with the first and third tube enhanced. In the next section, a brief analysis and discussion of the experimental observations then will be presented.

3. Results and discussions

After the two setups and the four distributors were prepared observations of the fluid flow coverage over the horizontal tubes were made. In this section, the observations of the fluid coverage over plain and two stages of the enhanced horizontal tube are subsequently presented. These results are discussed and compared.

Initially, plain copper tube bundles were observed for both setup 1 and 2. In the setups the distributor was varied, all four top distributors were inserted, and the following observations were made. Observations for each set will be discussed. It should be noted that the fluid flow rate was kept constant and the water temperature was at room temperature (20^{O}C). The distributors were changed after each observation was made. The observation was filmed by a digital camera and then replayed in slow motion for analysis. In the observation, the outside surface circumferential wettability (fluid coverage) of the horizontal tubes in each row was recorded. Therefore, each row was deemed as 100 percent wet if the fluid flowing around the horizontal tube covered the entire pipe below the holes of the distributor. However, it was observed that 100 percent coverage was not achieved in all of the horizontal tubes but rather reduced significantly as the film cascaded down the bundle. Fig. 6 is a graphical representation of the film coverage on each tube as it progressed down the bundle for both setups as the distributors, shown in Fig. 2, were varied.

In the literature reviewed it was established that wetting the entire surface area of the horizontal tube is important. It was observed that the film was not consistent over the only plain horizontal tube bundle. Therefore, enhancing the horizontal tube was explored. There is no published data on longitudinally enhanced horizontal tubes, hence in this study, it will be tested in attempts to improve the fluid coverage (wettability) over the horizontal tubes. Only setup 1 was enhanced and observed, distributors on

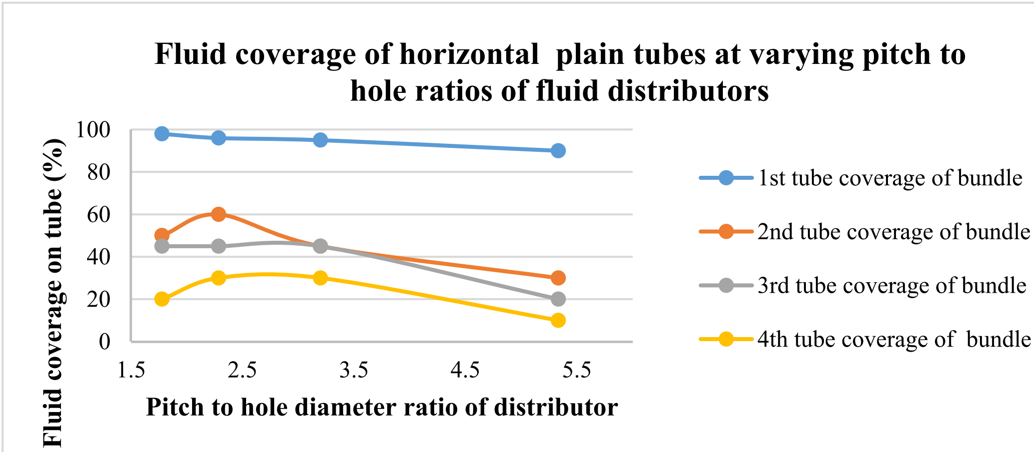

Fig. 8. Graph representing the relationship of fluid coverage on tube vs the pitch to hole ratio of the four distributors.

Fig. 2 were varied and setup on Fig. 4 was used. The first horizontal row tube was enhanced the other three horizontal tubes were kept plain for setup 1. Then later the third tube of the bundle was enhanced as seen in Fig. 5.

3.1. Summary of comparative analysis

Below is a graphic representation of the behavior observed, on Figs. 7 & 8, of the fluid coverage over the horizontal tubes. An ideal case scenario of the graphs in this section is a flat curve at 100% fluid coverage for all tubes of the bundle. However, this case was not reached. The progressive enhancement of the bundle was aiming at bringing the curve close to 100% for all tubes for each distributor set.

It was observed that a bundle that consisted of only plain tubes was outperformed by a set of bundles that consisted of tubes that were enhanced. It was observed in all sets that enhancing the first and third tubes of the bundle improved the fluid coverage of the tubes. Bundles of the distributor (a) and (b) had a high fluid coverage than that of (c). However, distributor (c) had the potential of yielding a flat curve but at 60% coverage. This was due to the pitch to hole diameter ratio of the distributor being lower than 3.2. When the columns of fluid descended from the distributor onto the first tube's enhancement there was no overlapping of these fluid columns. This was due to the small diameter holes on the distributors at a pitch that wasn't enough to allow the fluid column to overlap. This resulted in the fluid covering this bundle to have a low fluid coverage. Distributor (d) has 1.5 mm hole diameters which were still below 3.2 and it behaved similarly to the distributor (c) but yielding a much lower fluid coverage**.**

The distributors pitch to hole diameter ratio for the distributor (a) was 1.8, for the distributor (b) it was 2.3, for the distributor (c) was 3.2, and for the distributor (d) was 5.3. The behavior of the fluid covering the plain copper tube of the bundle was observed (Fig. 8) and analyzed against these ratios and it was seen that as the ratio increased the fluid coverage gradually decreased down the horizontal tube bundle. However, an inconsistent outlying behavior of the fluid on the distributor (b) was observed. This was successfully improved by enhancing the tube bundle. This ratio could also imply that reducing the pitch of the holes on the distributors could improve the fluid coverage. It should be noted that an improved wetted area of the tube bundle was achieved in previous studies reviewed. This was attained through raidially enhancining the surface area of the tube and rotating the the tubes of the bundle so that the bundle achieves optimal falling fluid coverage. Lin et al., [12] established in the numeric study that was experimentally validated that the falling film coverage varied with the change in rotational speed. They also noticed that the inconsistant falling film liquid over the horizontal tube was due to excessive rotational speed. This observation does not contradict the outcome of this study. Both these studies aim at attaining an optiomal fluid coverage but using different approach.

4. Conclusion and future work

In conclusion, this study experimentally emphasized the following:

- that the geometric and structural parameters are important in attaining a full falling fluid coverage around the horizontal tube bundle.
- Longitudinal enhancement on the tube bundle showed significant improvements as compared to the plain tube's fluid coverage. Due to the surface tension of the fluid and the force of gravity, 100% fluid coverage was not possible, the fluid tends to gravitate inwards as it fell off the tubes.
- It was observed that the hole diameter of the distributor is directly proportional to the fluid coverage when the pitch of the distributor holes was kept constant. This was evident in the distributor (d), on enhanced set 2, a coverage of 60% was reached but there were too many dry patches in-between the fluid. The enhanced set 2 for the distributor (a) and (b) were optimal sets because of their high consistent fluid coverage that had no dry patches.
- Finally more experiments can be performed to further test the longitudinal enhancement on the tube by having a tube bundle with an increased no of horizontal tubes. Also, different sizes and shapes of longitudinal enhancement can be tested for future works.

CRediT authorship contribution statement

Zamavangeli Mdletshe: Data curation, Formal analysis, Writing - original draft. **Velaphi Msomi:** Conceptualization, Supervision, Funding acquisition. **Ouasini Nemraoui:** Methodology, Validation, Writing - review & editing.

Declaration of Competing Interest

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.

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