Abstract—The goal of the paper is to introduce liquid film formation and heat transfer on the bundle of horizontal tubes in atmospheric pressure. The investigations were done for different types of the tubes surface structure, namely smooth surface tubes, ribbed tubes, fin tubes. The work is focused on water falling film in atmospheric pressure were the film formation is accompanied with phase change. The paper presents results of parametrical studies focused on expression of horizontal tube spacing and falling liquid flow rate influence on falling film formation and heat transfer. Due to the complexity of the problem the research was done experimentally on an experimental set-up with a bundle of horizontal replaceable tubes.

Keywords—falling film, heat transfer, tube bundle

I. INTRODUCTION

Utilizing of water as refrigerant is dynamically increasing requirement of cooling applications. Pure water as refrigerant is currently the most frequently used in different types of sorption cycles that represent an alternative to the predominant vapor compressor cooling cycles. Disadvantage of the sorption cycles is the necessity to create a plant of a bigger size that is more complex if compared with the vapour compressor cycles. For this reason, the sorption cycles are used predominantly in large industrial plants and the development of the sets with smaller capacities is conditioned by better knowledge of processes taking place in the key parts of the sorption cycles that can help to design small compact units.

Utilizing of water as refrigerant is connected with low pressure working conditions for evaporation of water in temperature levels close above the freezing temperature. In these conditions, the design of the key elements for heat transfer is frequently based on a falling film tube bundle with horizontally oriented tubes.

Although there are several studies focused on the heat transfer and vaporization on falling film tubes these are usually carried out for smooth surface tube bundles, e.g. [1], [2], [3]. Insufficient number of studies was issued on falling film heat transfer on bundles composed from tubes with enhanced surface (ribbing, single and double grooved tubes, tubes with corrugated surface, and industrial tubes with protrusions). These surface structures influence liquid film flow character and significantly enhance heat transfer [4].

Film of the liquid phase flowing off the tubes must cover as much as possible from the surface of the tube. This helps to maximize the use of the heat transfer surface. During the heating of the liquid film and the vaporization, the heat is transferred from the liquid circulating in the tube via tube wall into the falling film on the tube. The liquid film therefore needs to be continuously present at the widest possible surface of the falling film tubes, and at the same time, an intensive transfer of heat energy from the tube walls into the liquid film must be ensured. This is a very demanding task because the initial creation of the film on the tube wall is connected with the distribution of the liquid on the tube and with the size of drops, their frequency and impact velocity.

The characteristics of the liquid film, its stability and the heat transfer from the tube wall in the liquid film are considerably influenced by the working conditions and the tube surface modification. Forming and stability of the liquid film is influenced by the film surface tension. The surface
tension value generally decreases with rising temperature. Influence of pressure on the surface tension value is limited, but rising pressure causes obviously decrease of the surface tension too. Real value of the surface tension influences spreading of the liquid film, breaking of the film and forming of the drops. Additional impact on the flow characteristics of the falling film may arise from application of surfactants.

In commercial applications, the use of falling film tube bundles composed of plain tubes still prevails. However, numerous tubes of different surface structure are available on market (micro ribbed, cross and bias grooving, corrugated surface etc.). Based on the available literature, these can increase the heat transfer by 1.5 – 5 times if compared with the plain tubes [4]. In boiling conditions, convenient modification of outside of the tube enhances the initiation of nucleate boiling sites, thus improving significantly the over all heat transfer coefficient too.

Different studies were carried out on more or less detail modelling of falling film heat transfer [5], [6]. But complexity of this problem is still beyond boarders of the utilized models and the experimental research still stays the only possible way for correct detail evaluation of heat transfer on falling film tube bundles in various conditions and modifications.

II. EXPERIMENTAL FALLING FILM TUBE BUNDLE

The experimental set-up was build up for better understanding of the processes behind the formation of a liquid film as well as heat transfer between the tube surface and the liquid film.

A. Experimental set-up

The goal of the study is to obtain new pieces of knowledge in the field of heat transfer, creation and stability of the liquid film on a wetted tube bundle with a structured surface in the atmospheric pressure. The contribution presents carried up experiments in the atmospheric pressure.

The first step of work included the design and building of an experimental set-up for the part of a falling film tube bundle. The investigated falling film tube bundle was composed of horizontal copper tubes in a vertical adjustment.

Above the top tube of the falling film tube bundle there is a distribution tube connected to the cycle of the falling film liquid, see fig. 2. Testing of the tube bundles with different tube surface modification is facilitated by a removable connection of pipes. The impact of the tube surface structure is eliminated by using of a reference sample falling film tube bundle.

Fig. 2 Principle scheme of the experimental set-up

This reference sample tube bundle is composed from smooth cooper tubes. Water was used as a falling film liquid for all experiments. For the purposes of visual assessment of the spread of the liquid film over the tube surface of the falling film tube bundle, there were the glass front wall. The visual records was used for an overall evaluation of the quality of how the liquid spreads over the tubes, as well as for assessing of the characteristics of drops creating and the liquid flowing off.

Fig. 3 Photo of the experimental set-up

The experimental tube bundle enables to investigate tubes with diameter 12 mm. The set-up enables to change the spacing of the tubs in following steps 15, 20, 25 a 30 mm. The experimental tube bundle is capable to involve up to 20 tubes each with effective length 1 m.

B. Falling film formation

The falling drop must have a sufficient velocity so as, after it falls down, the liquid film opens widely. When flowing off, this film extends into the whole outer surface of the tube. If the velocity of the falling drop is not sufficient, the liquid film spreads out only on limited part of the surface, and it does not
reach the whole surface of the outer tube wall. In some cases, it can fall down over one half of the tube only.

The amount and the type of distribution of the liquid in the upper part of the tube bundle have a crucial impact on the time behavior of the tube surface wetting. With a very small amount of liquid, the frequency of the falling drops is small too, and a significant part of tubes remains non-wetted between the single impacts. With increasing amount of the distributed liquid, the area of a non-wetted surface is getting smaller. If the frequency is being raised significantly, the next drop will fall on a sufficiently thick liquid film created by the spread of the previous drop, and as a result of insufficient absorption of the momentum in the boundary layer at the surface of the tube, it slides quickly off over the wetted tube surface. Further increase in the amount of the falling film liquid results in creation of streams. These streams are wetting a smaller part of the tube surface. The liquid moves on the tube wall with higher speed in such conditions, which causes its separation on the bottom of the tube in direction that significantly turns away from the required vertical. In similar cases, the falling liquid can completely leave the bundle of horizontal tubes in a vertical adjustment.

The cooling water flow rate flowing through the inner part of the tube bundle was set to value 150 liter/hour for all carried out measurements.

![Fig. 4 Character of falling film on tube bundle](image1)

![sand dressed tube](image2)
![tubes with ribbing](image3)
![single grooved tubes](image4)
![double grooved tubes](image5)

Fig. 5 Tested tubes with modified outside surface

The detail analysis of photographs obtained during the measurement was carried out with the goal to determine the effectiveness of wetting at horizontal lines on the tubes surface.

Amount of the entire heat transferred in/out working fluid was determined from the temperature difference and the corresponding fluid flow rate. The entire heat transferred involves the heat transfer between both working fluids and heat losses between the fluid flows and the ambient air. The heat really transferred between the working liquids were obtained by subtraction of the heat loss from the entire heat transfer in/out liquid.

Subsequently, the heat transfer coefficient was determined with utilizing of the equation

$$k = \frac{Q}{\Delta T_{\text{ln}}},$$

were $Q$ is the heat transfer rate, $k$ is the heat transfer coefficient, $S$ is the heat transfer area and $\Delta T_{\text{ln}}$ is the logarithmic temperature difference between the working fluid flows.

The heat loss determination between the falling film liquid and the ambient air was identified by measurement of the temperature change of the falling film liquid without cooling water flow inside the tube bundle. The significant temperature difference (1.0 °C) was identified for the lowest falling film fluid flow rate. The falling film fluid flow rate 300 liter/hour provided the temperature difference lower 0.2 °C and corresponding losses were neglected for these and higher falling film flow rates.

Similar technique was used for identification of the heat loss between the liquid flowing through the tube bundle inside and the ambient air. The temperature difference of this fluid was measured in condition without wetting of the tube bundle. The temperature difference was relatively lower in comparison with the falling film fluid heat loss.

The Fig. 6 – Fig. 11 shows the graphical expression of the heat transfer coefficients obtained from the carried up measurements.
Fig. 6 The heat transfer coefficient – smooth tubes

Fig. 7 The heat transfer coefficient - sand dressed tubes

Fig. 8 The heat transfer coefficient - tubes with 1 mm ribbing

Fig. 9 The heat transfer coefficient - tubes with 2 mm ribbing

Fig. 10 The heat transfer coefficient - single grooved tubes

Fig. 11 The heat transfer coefficient - double grooved tubes

III CONCLUSION

The experimental investigation of the heat transfer on the falling film tube bundles is still necessary evaluation of falling film heat exchangers due to the complexity of processes on the outer side of the falling film tube bundles. This paper described the atmospheric experimental set-up, built up at the Brno University of Technology for assessment of the heat transfer on falling film tube bundles.

The results presented in this contribution were obtained for tube bundles consist from the horizontal cooper tubes with the diameter 12 mm. Different surface structures of the tubes were tested, namely smooth tubes, sand dressed tubes, tubes with ribbing, single and double grooved tubes. Each type of tested tubes was measured in arrangement with different spacing, namely 15, 20, 25 a 30 mm. The falling film fluid flow rate was tested for values 100, 150, 200 and 300 liter/hour on all arrangements of the tested tube bundles.

The both tested types of the tubes with ribbings showed the lowest wetted surface for all tested tubes spacing and the falling film fluid flow rates. This is in contrast with general requirement for intensive heat transfer on the falling film tube bundles. The sand dressed tubes, single and double grooved tubes showed similar character of the falling film as the smooth tubes.

The identified heat transfer coefficients varied in the range from 0.75 kW/m²K till 3 kW/m²K. Generally, the increase in the falling film flow rate causes the increase of the heat transfer coefficient. The tube spacing 15 mm provided the highest heat transfer coefficients on smooth tubes, sand
dressed tubes and tubes with 2 mm ribbing. The tube spacing 20 mm provided the highest heat transfer coefficients on the tubes with 1 mm ribbing.

REFERENCES


