Falling film heat exchange and backsplash on horizontal tube bundles

Jiri Pospisil, Libor Chroboczek, Zdenek Fortelny and Pavel Charvat

***Abstract*—** Tube bundles represent a very common type of heat exchanger that is used in many technical applications. The problem of heat and mass transfer in tube bundles attracts a lot of attention in connection with falling films in absorption processes employed in absorption cooling and refrigeration cycles. 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 in atmospheric pressure. 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 vapour 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 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.

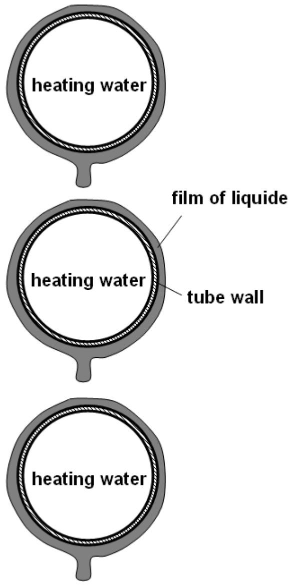

Fig. 1 Falling film tube bundle

Tube bundles represent a very common type of heat exchanger that is used in many technical applications. The absorption processes usually take place at very low pressures and they can involve various mediums. That limits the applicability of numerical simulations because not enough input data is usually available to obtain reliable results. The influence of many factors is still under investigation (e.g. the influence of tube surface finishing on falling film formation). Therefore, experimental investigations seem to be the best source of information at the moments.

Many authors have reported the results of their investigations into heat and mass transfer in falling films in the last two decades. The [1] presents experimental investigation of heat-transfer coefficients of aqueous LiBr solution on an absorber with plain and knurled tubes. The [2] reports investigation of heat fluxes in wavy falling film as an inverse heat conduction problem. Experiments were performed with a falling film on a wall with electrical heating element. A loudspeaker was used to produce 2D waves. The heat flux on the inaccessible side of the film was identified from the infrared camera measurements and electrical heating power.

Beside the experimental investigations a number of paper reports numerical simulations and development of simplified

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calculation methods. Killon and Garimella [3] give a critical review of mathematical models of coupled heat and mass transfer in falling film absorption. Fujita and Hihara [4] introduce a calculation method for heat and mass transfer coefficients of falling films over a vertical tube or plate type surface. The authors compared the results of the method with the results of numerical simulation and come to a conclusion that it gives better results than the earlier used “conventional” method. Islam et al. [5] describe development of a linearized coupled model for heat and mass transfer in falling-film absorbers. Kim and Infante Ferreira [6] propose a new method for determination of heat and mass transfer coefficients from experimental data. The authors reprocessed some experimental data from the literature and came to a conclusion that the previously obtained results were incorrect due to misinterpretation of experimental data and errors of conventional methods.

Another development that can be seen in the area of falling films is the enhancement of heat transfer by additives. Daiguji et al. [7] describe a numerical and experimental study aimed at the use of surfactants to increase heat transfer. Yoon et al. [8] investigated the heat transfer enhancement in aqueous LiBr solutions with addition of octyl-alcohol as a surfactant. The experiments were performed on horizontal tube bundles with three types of tubes: bare tubes, floral tubes and hydroscopic tubes. Cheng et al. [9] present an experimental study on the effect of additive on falling film absorption of water vapour into aqueous LiBr. The 2-ethyl-l-hexanol and 1-octanol were used as additives. The maximum enhancement effect was observed for a certain (optimal) concentration of additive. The enhancement effect decreased with increasing Reynolds number. The use of nano-fluids could possibly become another way heat transfer enhancement in the falling films. Vadasz et al. [10] present a theoretical investigation of the heat transfer enhancement in nano-fluid suspension.

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. [11], [12], [13]. 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 [14].

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 [14]. 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 [15], [16]. But complexness 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 the 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.

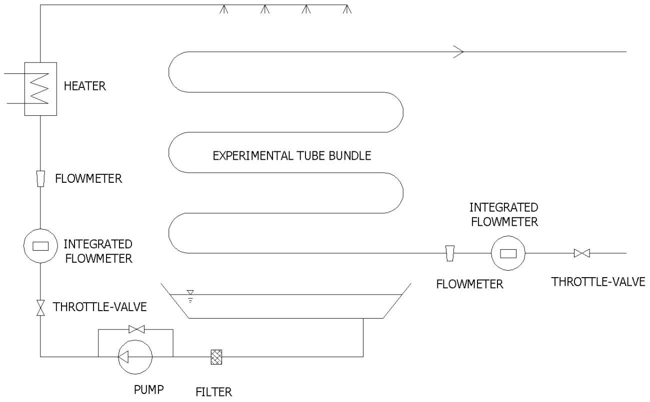
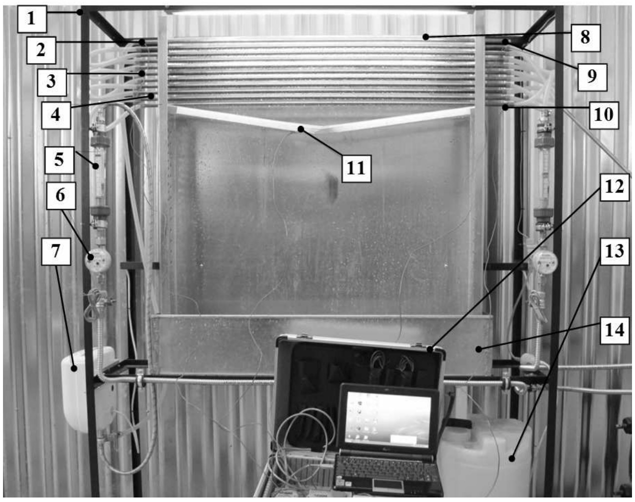


Fig. 2 Principle scheme of the experimental set-up

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.



1) base frame, 2) temperature measurement of inlet falling fluid, 3) testing tube bundle, 5) flow meter, 6) integration flow meter, 7) heater

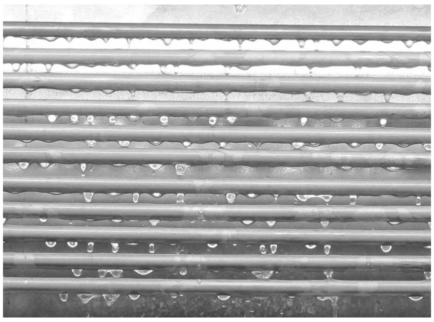
Fig. 3 Photo of the experimental set-up

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.

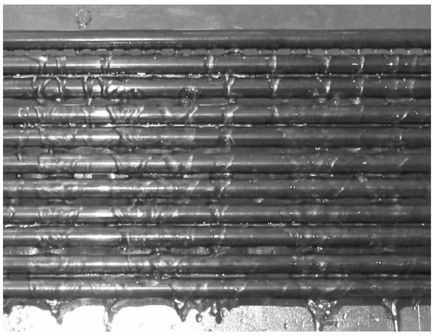
B. *Falling film formation*

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 behaviour 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.



water drop formation



water fall formation

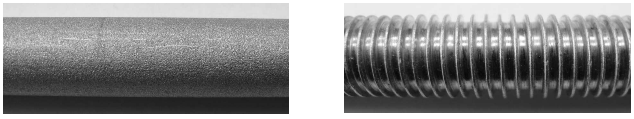
Fig. 4 Character of falling film on tube bundle

C. *Heat transfer*

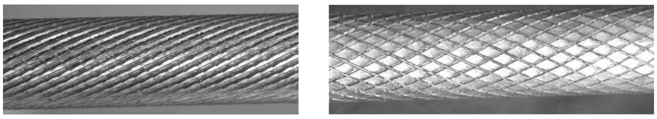
Heat transfer assessment on the falling film tube bundle is based on detecting of temperature change, temperature of the liquid flowing through the tube bundle and temperature of the falling film liquid with simultaneous measuring of the current flow of liquids. This way, the real value of the heat transfer is determined at the tube bundle working under the set conditions. And subsequently, the corresponding heat transfer coefficient can be determined.

The modification of the outside surface of the tubes that were used for the tested experimental tube bundles were selected with respect to actual market offer. These are namely sand dressed tubes, tubes with ribbing, single and double grooved tubes, see the Fig. 5. Since the continuity of the structure on a relatively long tube section is required, no own production of surface structure of the tubes was used.

Each type of tested tubes was measured in arrangement with different tube spacing, namely 15, 20, 25 a 30 mm. The falling film fluid flow rate was tested for values 100, 150, 200 and 300 litre/hour on all arrangements of the tested tube bundles. The cooling water flow rate flowing through the inner part of the tested tube bundle was set to value 150 litre/hour for all carried out measurements.



sand dressed tube tubes with ribbing



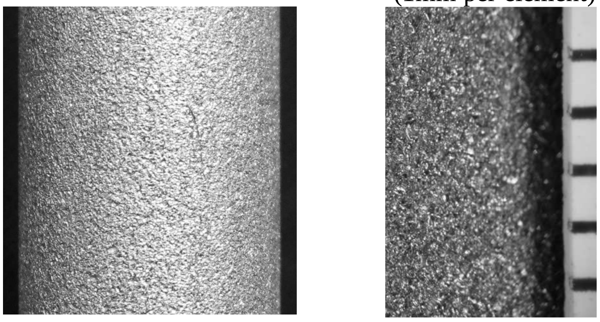
single grooved tubes double grooved tubes

Fig. 5 Tested tubes with modified outside surface

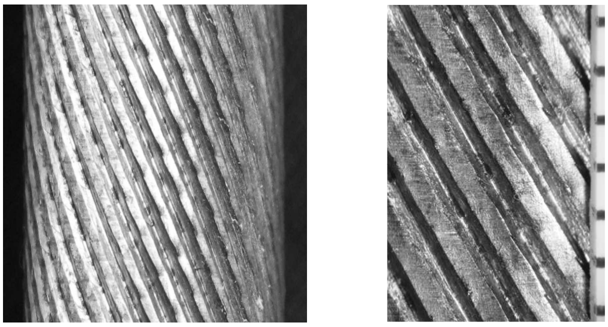
The detail analysis of photographs obtained during the measurement was carried out with the goal to determine the effectiveness of wetting at horizontal lines on the tubes surface.

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.

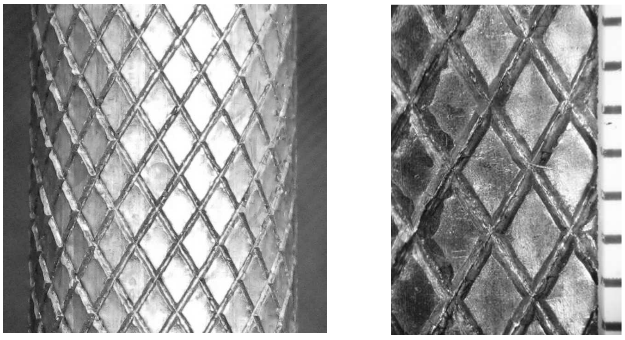
tube diameter 12 mm surface structure (1mm per element)



sand dressed tube



single grooved tubes



double grooved tubes

Fig. 6 Detail geometry of tested surfaces

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

$$k = \frac{\dot{Q}}{S\Delta T_{\ln}}, \tag{1}$$

were Q is the heat transfer rate, k is the heat transfer coefficient, S is the heat transfer area and ΔT_{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. 7 – Fig. 12 shows the graphical expression of the heat transfer coefficients obtained from the carried up measurements.

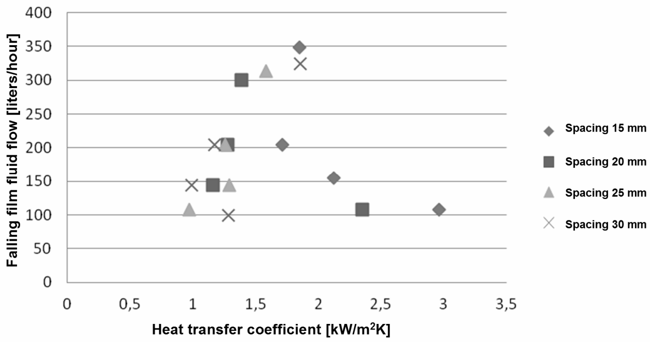


Fig. 7 The heat transfer coefficient – smooth tubes

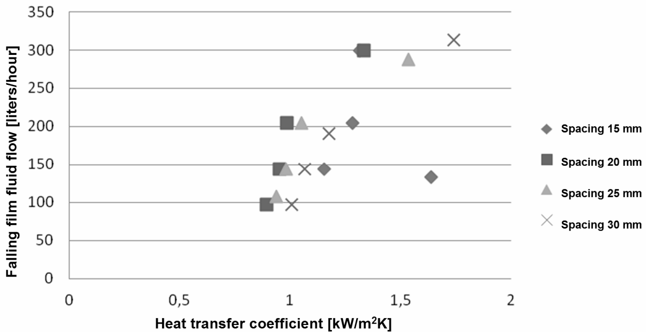


Fig. 8 The heat transfer coefficient - sand dressed tubes

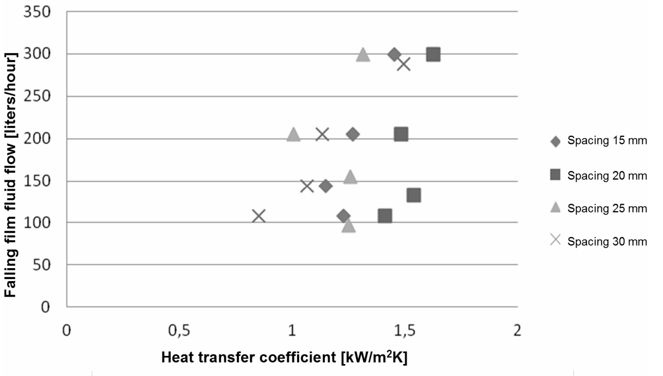


Fig. 9 The heat transfer coefficient - tubes with 1 mm ribbing

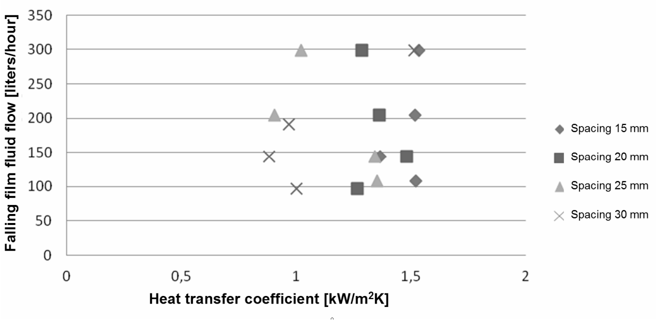


Fig. 10 The heat transfer coefficient - tubes with 2 mm ribbing

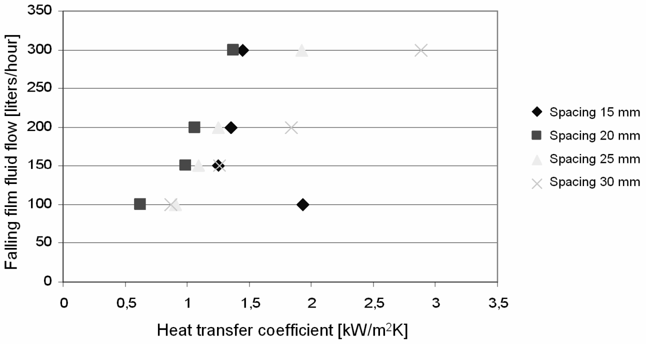


Fig. 11 The heat transfer coefficient - single grooved tubes

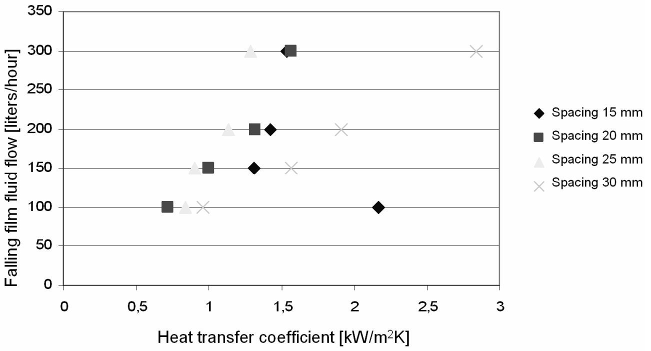


Fig. 12 The heat transfer coefficient - double grooved tubes

D. Falling film backsplash

The experimental stand was used for testing of the backsplash characteristic on smooth cooper tubes in vertical adjustment. During falling of the liquid over the tube bundle, some amount of the liquid leave the falling flow and fall separately without subsequent collision with the tubes in vertical adjustment. This part of the separated liquid represents the “backsplash”.

The parametrical studies were done for determination of the backsplash quantity on the tube bundles with different characteristics. Two different tube bundles were tested.

The first tube bundle is composed from 10 horizontal smooth cooper tubes in vertical adjustment.

10 Tubes	Flow rate (l/h)	Backsplash (%)
Spacing 15 mm	100	0,00
	150	0,00
	200	0,30
	300	1,31
Spacing 20 mm	100	6,46
	150	7,39
	200	9,33
	300	14,03
Spacing 25 mm	100	17,70
	150	21,65
	200	19,63
	300	22,26
Spacing 35 mm	100	70,78
	150	71,64
	200	75,00
	300	78,15

Tab. 1 Results of the backsplash measurement on the falling film tube bundle formed by 10 smooth cooper tubes

The second tube bundle was composed from the identical smooth cooper tubes in configuration with 20 tubes in vertical adjustment. Both tube bundles were tested with different tubes spacing, namely 15, 20, 25 and 35 mm. All configurations were tested with flow rate from 100 to 300 l/h per 1m of the tube length.

Results of the measurement are presented in the Tab. 1 and Tab 2. The graphical expression of the results is shown on the Fig. 10 and Fig. 11.

The presented results show significant increase of the backsplash fluid quantity with increase of the tubes spacing.

Increase of the falling fluid quantity results in increase of the backsplash fluid quantity.

20 Tubes	Flow rate (l/h)	Backsplash (%)
Spacing 15 mm	100	3,77
	150	2,66
	200	2,51
	300	4,18
Spacing 20 mm	100	20,36
	150	26,96
	200	24,61
	300	27,66
Spacing 25 mm	100	53,28
	150	56,52
	200	58,08
	300	60,07
Spacing 35 mm	100	87,09
	150	88,21
	200	88,80
	300	88,24

Tab. 2 Results of the backsplash measurement on the falling film tube bundle formed by 20 smooth cooper tubes

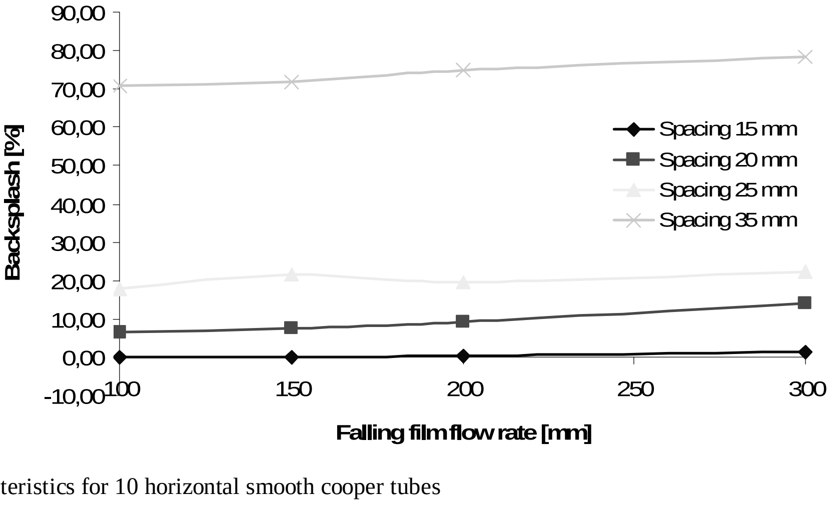


Fig. 10 Backsplash characteristics for 10 horizontal smooth cooper tubes

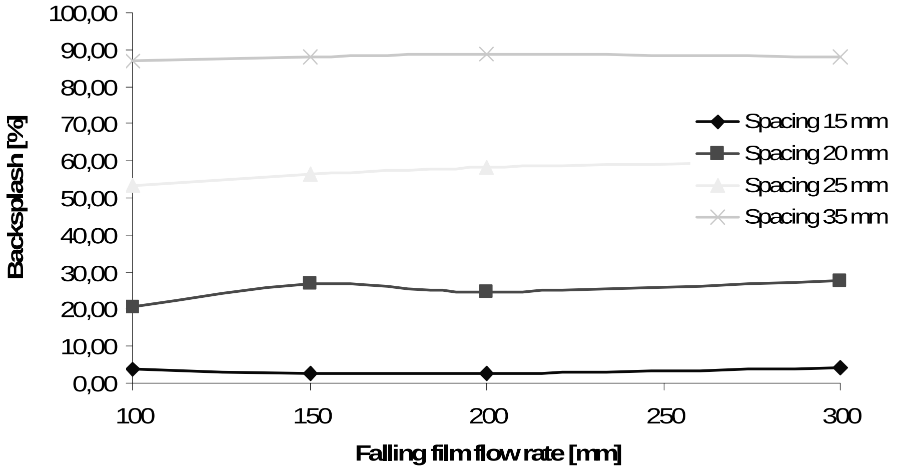


Fig. 11 Backsplash characteristics for 20 horizontal smooth cooper tubes

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/m^{2}K till 3 kW/m^{2}K. 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.

The parametrical studies focused on the determination of the backsplash falling fluid quantity show significant increase of the backsplash fluid quantity with increase of the tubes spacing. Increase of the falling fluid quantity results in increase of the backsplash fluid quantity.

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