The falling liquid film heat transfer outside horizontal tubes

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Abstract: - In this paper, an experimental research of the heat transfer of water falling film on a tube bundle is presented. First part states current knowledge review which is focused on the problematic falling liquid mode. This mode is significant for the heat transfer characteristics of the film and wetting. Subsequently the paper is concentrated on the essential transition criteria such as Galileo, Reynolds and Nusselt number. Experiments examine the local heat transfer coefficient behavior in an low-pressure environment formed in the heat exchanger chamber by vacuum pump. This research has positive results for the development of main components (heat exchangers for condensation and evaporation) in absorption units.

Key-Words: - heat transfer, spreading liquid, falling film, under-pressure chamber, droplet, jet

1 Introduction

Heat exchangers are widely used in many cases for instance in refrigeration, chemical, petroleum and energy industries. One kind of exchanger is to use thin film flowing down around horizontally arranged pipes. Due to lower thermal flows and small flow rates is possible to reach high transfer-heat coefficients in these pipes. This kind of exchanger and its efficiency is crucial for cooling technology using absorption cycle which uses solution LiBr for absorbing water vapor. Absorption applications utilize both exchanger modes such as evaporation mode and condensation mode. Mentioned modes are carried out during under-pressure 1-10 kPa of absolute pressure and thus they are placed in under-pressure chambers of these devices.

Horizontal exchangers utilize forming liquid film principle based on sprinkling liquid by distributing pipe on pipe bundle. Issues about liquid distribution, film formation as well as conditions having influence on heat transfer are described by Mitrovic [1] as well as by Yundt [2]. Exchanger feature is to stabilize one of the flowing liquid modes from one pipe row to another one situated below. There are three essential sorts of modes: droplet, jet and sheet. To compare results of our experiment, we tend to mode formulations created by Jacobi and Hu [3]. In this work are first summarized findings were the description and the type of film, the liquid feeder configuration and degree of influence another condition of the heat transfer coefficient [7].

2 Flow patterns studies

When the liquid film flow down a series of horizontal tube bundle is created at the bottom of one of three basic types of flow as follows:

a) droplet mode
b) jet (column) mode
c) sheet mode

This form may vary between successive rows of tubes. The types mentioned above were first described by Mitrovic [1] together with transition modes (patterns) as shown in Fig.1.

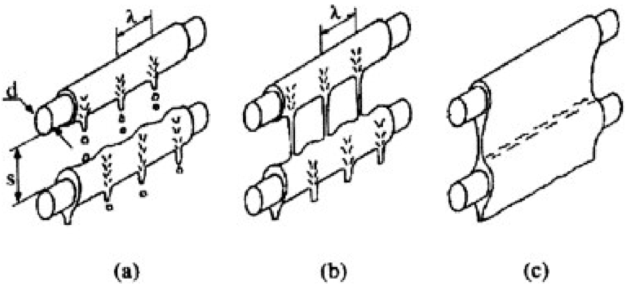

Fig. 1 Idealized modes (patterns) of liquid flow between two horizontal tubes: (a) droplets, (b) jet and (c) sheet.

2.1 Mathematical description

Derivation of mathematical relation for determining the individual modes is given by the relation between Reynolds number and modified Galileo number (based on capillary length scale), which can be interpreted as a proportional to gravitational forces and by viscous forces and it is also described as a reciprocal to Kapitze number:

$$Ga_{\mathrm{mod}} \approx \frac{1}{Ka} = \frac{\rho \cdot \sigma^3}{\mu^4 \cdot g} \tag{1}$$

where the result (general) according to the relation by Mitrovic [1] is:

$$\mathrm{Re} = A \cdot Ga_{\mathrm{mod}}{}^{0,25} \tag{2}$$

where A is empirical constant. This expression corresponds to the most elemental types but does not reflect the exact diameter of the pipe, or their specific surface treatment.

Experiments were carried out by Jacobi [3] and in the study would be published by Muhammad [5] who determined this ratio using the empirical constant A and B:

$$\mathrm{Re} = A \cdot Ga_{\mathrm{mod}}{}^{B} \tag{3}$$

where the transition modes are evaluated in Table 1 together with the RMS deviations.

Table 1 Falling film mode transitions correlations constants published by Mohamed [5] for study.

	Droplet/ droplet-jet	Droplet-jet/jet	Jet/jet-sheet	Jet-sheet/sheet
A	0.0785	0.0978	1.5031	1.491
B	0.2965	0.2998	0.2273	0.2353
RMS %	7.95	5.2	4.8	3.3

2.1.1 Mass flow rate

The mass flow of spray liquid is used according to the relation [3]:

$$\Gamma = 0.81 \frac{\rho}{\lambda} \frac{\pi d_P^3}{6} \left(\frac{2\pi\sigma}{\rho\lambda^3} \right)^{\frac{1}{2}} \tag{4}$$

where

$$\lambda = \xi \sqrt{4\pi^2 n} \tag{5}$$

In Eq.5 is n=2 constant appearing, d_P the diameter of primary drops, experimentaly determinated for water to be equal tree times to capillary given by:

$$\xi = \sqrt{\frac{\sigma}{\rho g}} \tag{6}$$

$$d_P = 3\xi \tag{7}$$

2.1.2 Heat transfer coefficient

For evaluating a heat transfer coefficient outside of the tube was used common expression published by Giondi and Rogers [6]:

$$h_{OUT} = \frac{q_0''}{T_0 - T_f} \tag{8}$$

where q''_0 is the local heat flux at the outer tube surface and T_0 is the temperature also at outer tube surface and T_f is bulk fluid inlet temperature.

Effects of the heat flux was considered in the work of Jacobi [3], where experimental results confirmed a significant effect on the increase in the heat transfer coefficient, Even if the surface temperature with increasing heat flux increased.

Significant influence, however, shows a change of Nusselt number [8] for which the empirical relation established by Mitrovic [1] and later revised by Giondi [6] and for a range $160 \le \mathrm{Re} < 560$:

$$Nu = 0.01374\,\mathrm{Re}^{0.349}\,\mathrm{Pr}^{0.5}\,\beta \tag{9}$$

where

$$\beta = \left(1 + \frac{s}{d}\right)^{0.158} \left[1 + \exp(3.2 \cdot 10^{-3} \cdot \mathrm{Re}^{1.32})\right]^{-1} \tag{10}$$

2.2 Objectives

Chapter 2.1.1 and 2.1.2 briefly describe the general problems of finding the heat transfer coefficients. The following chapters give description of experimental equipment. In order to adequately compare the results with previous work written by previously mentioned authors we apply the above description of the hydrodynamics of liquid film. In order to measure the influence of different finishes tube bundle, the effect of changes in pipe diameter or behavior than other solutions to water (alcohol, LiBr). In this experiment description of hydrodynamics were used for comparison against a smooth copper tube.

3 Experimental procedure

3.1 Apparatus

The heat transfer research of a water sprayed tube bundle at atmospheric conditions is associated with development of the tube bundle situated inside a chamber where the pressure is kept below an atmospheric one by means of an ejector vacuum pump. In this way, both boiling and condensation over the tube bundle can be simulated using the chamber in Fig. 5. The vacuum (under-pressure) stand chamber is in fact a cylindrical vessel 1.2 m in length fitted with three peep holes in which the tube bundle of 940 mm in length is located. Three closed loops are connected to the chamber. The ones on sides are designed to withstand 1 MPa of gauge pressure and supply the chamber with heated or chilled liquid. The third, central loop feeds in the spreading water. Each loop includes a pump, a governing valve, a flow meter and a plate heat exchanger.

The tube bundle contains a set of holes of various spacing to allow for different tubes spacing (s). Tubes of 12 mm in diameter (d) make up the tube bundle. The distribution tube has 1 mm holes in it 9.2 mm apart along 940 mm of the tube.

3.2 Results

In experiment were observed droplet, jet and especially droplet-jet transition mode as shown in Fig.4.

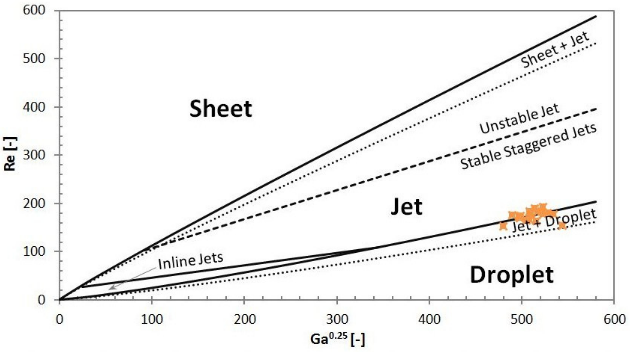

Fig. 2 Flow mode map for increasing flow rate (from the Table 1)

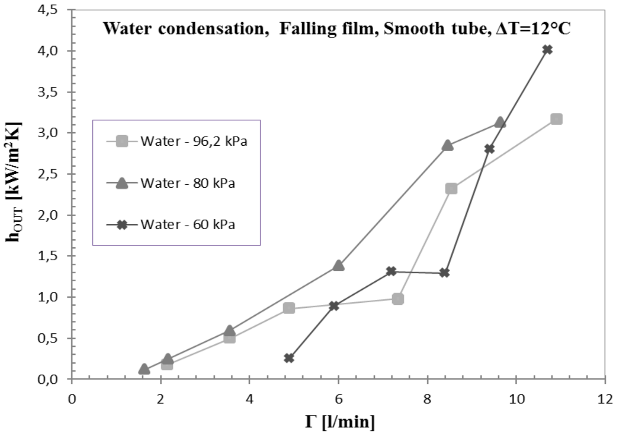

Fig. 3 Falling film condensation heat transfer coefficient outside of the tube

Measured data was compared with empirical criteria expression and it is plotted in Fig.2. Any sheet mode hasn't been observed because of the low mass flow rates adjusted during the experiment.

The heat transfer coefficient was closely related to the mass flow rate. The influence of heat flux for increasing heat transfer coefficient was obvious.

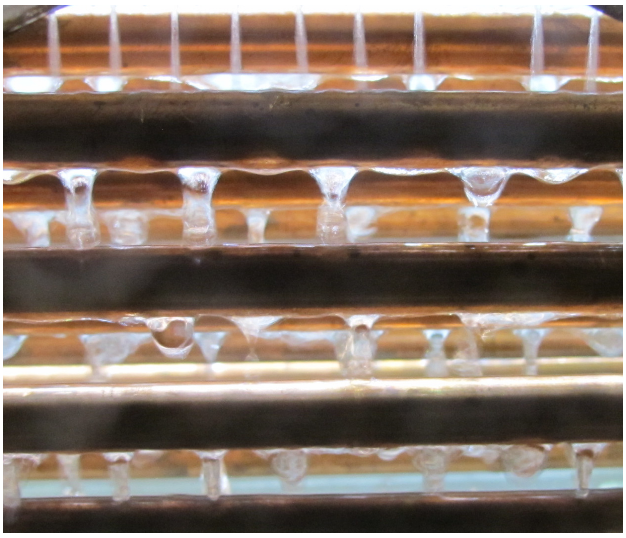

Fig. 4 Jet-Droplet transition mode in vacuum (under-pressure) apparatus.

4 Conclusion

The transition mode behavior in the vacuum (under-pressure) chamber corresponds to the theory described in the references. The heat transfer coefficient increases with the mass flow rate of the spreading fluid. Galileo's number corresponds to the Jet-Droplet transition. The influence of the vacuum (under-pressure) environment is shown in the Fig. 3. This research states positive results for the development main components (heat exchangers for condensation and evaporation) also in absorption units.

Acknowledgement

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References:

[1] Mitrovic, J., Influence of Tube Spacing and Flow Rate on Heat Transfer From a Horizontal Tube to a Falling Liquid Film, *Proceedings of*

the 8th International Heat Transfer Conference, San Francisco, Vol. 4, pp. 1949-1956, 1986.

[2] Yundt, B., R Rhinesmith, Horizontal Spray-Film Evaporation, *Chern. Eng. Proceedings*, Vol. 77, pp. 69-73, 1981.

[3] Hu, X. and A. M. Jacobi, The Intertube Falling Film: Part-I Flow Characteristics, Mode Transitions, and Hysteresis, *Journal Heat Transfer*, Vol. 118, pp. 616-625, 1996.

[4] Ribatski G., A. M. Jacobi, Falling-film evaporation on horizontal tubes—a critical review, *International Journal of Refrigeration* Vol. 28, pp.635–653, 2005

[5] Mohamed, A.M.I., Flow Behaviour of Liquid Falling Film on a horizontal rotating tube, Experimental Thermal and Fluid Science, Vol. 31, pp. 325-332, 2007

[6] Rogers, J. T., Giondi, S.S., Experimental Laminar Falling Film Heat transfer Coefficients on a Large Diameter Horizontal Tube*, The Canadian Journal of Chemical Engineering,* Vol. 67, pp.3-12, 1989

[7] Parken W.H., Heat transfer to thin films on horizontal tubes, PhD Thesis, Rutgers University, 1975.

[8] Nusselt W., Der Wärmeaustausch am Berieselungskühler, Z. VDI 67 (9) pp. 206-210, 1923

Nomenclature:

d	tube diameter
d_P	diameter of primary drops
Ga_{mod}	modified Galileo number
g	acceleration due tue gravity
h_{out}	heat transfert coefficient outside of the tube
Nu	Nusselt number
q	heat flux
Re	Reynolds number
s	tube spacing
T	temperature

Greek symbol

Γ	liquid mass flow rate per unit lenght of tube
λ	instability wave lenght, spaving between neighbourning jets or droplets
μ	dynamic viscosity of the liquid
ν	kinematic viscosity of the liquid
ρ	mass density of the liquid
σ	surface tension liquid interface
ξ	capillary constant

Appendix

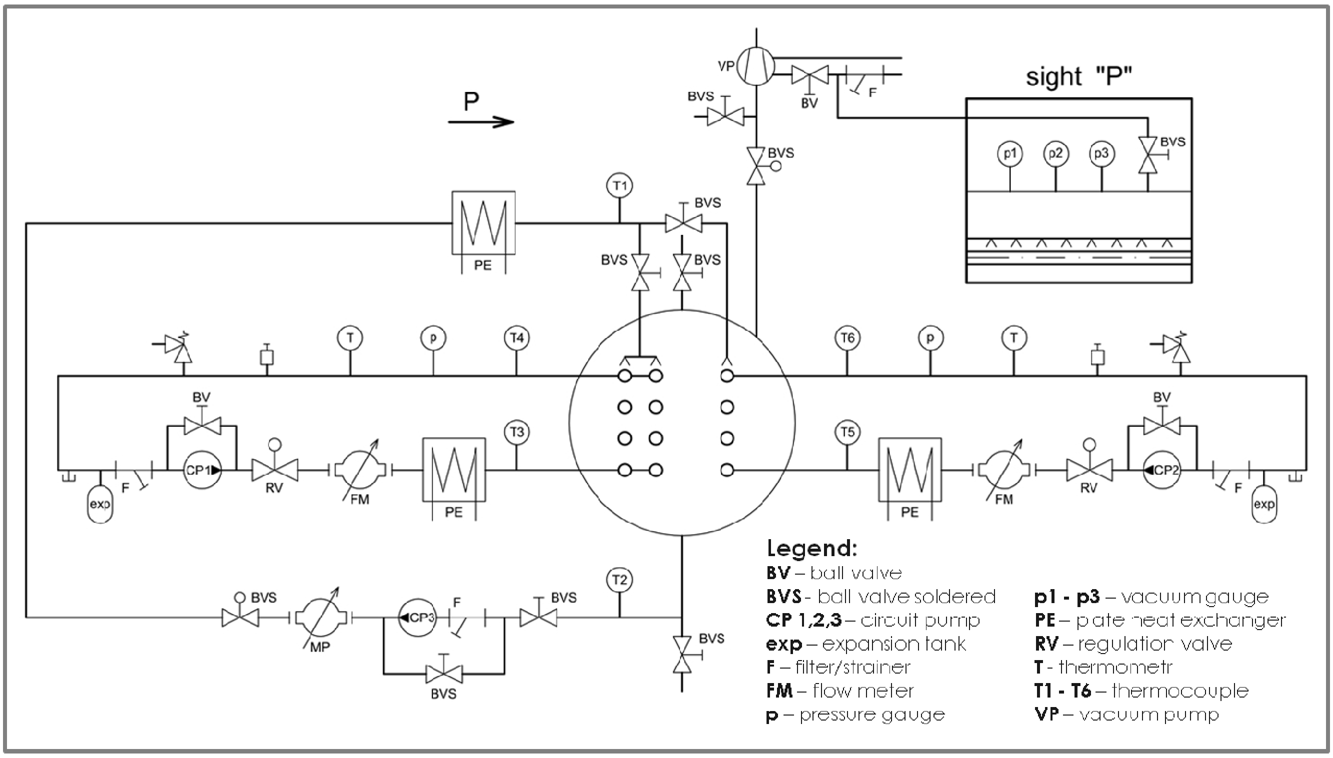

Fig. 5 A schematic of the experimental apparatus used to study the intertube falling film modes in vacuum (under – pressure) chamber