# FALLING FILM MODE TRANSITION IN AN ARRAY OF HORIZONTAL TUBES: EFFECT OF TWO DIMENSIONAL AND THREE DIMENSIONAL FINS

Zhixian Ma, Jingdong Chen, Jili Zhang*
*Author for correspondence
Institute of Building Energy,
Dalian University of Technology,
Dalian, 116024,
China,
E-mail: mazhixian@dlut.edu.cn

## ABSTRACT

Problem of falling film heat transfer is widely associated with many processes, such as shell side condensation and falling film evaporation in shell and tube heat exchangers. Efficient design of such heat exchangers can't be succeed without detailed knowledge of the falling film flow charts in a tube bundle, especially those consists of two or three dimensional finned tubes. A falling film bundle test facility was built for the above problem. Using water as a cyclic working medium, the effect of tube surface structures on falling film Reynolds number(*Re*) were investigated under the same flow mode. And falling film mode transitions were observed by image collection system. The results show: 1) Compared with the smooth tube, two dimensional enhanced tube has improved the mode transitions. 2) For two dimensional enhanced tube, surface structure caused the hysteresis occurred in the droplet and droplet-column, droplet-column and column modes. 3) For three dimensional enhanced tube, the hysteresis of it was lower than two dimensional tube occurred in the droplet and droplet-column, droplet and column. Under droplet and droplet-column, column and column-sheet, the transitions were lower than two dimensional tube. The results is the basic reference for the falling film heat transfer problem, and they can be used to guide the development of high efficient falling film evaporator with two and three dimensional finned tubes.

## INTRODUCTION

The energy and environment have been today's theme. For chemical processing, refrigeration, petroleum refining, food industries and desalination and so on, high efficiency and compact heat exchanger is required. So the falling film evaporator emerges as required. Compared with traditional flood evaporator, they provide higher heat transfer coefficients and operate with smaller liquid inventories, and they also offer advantages in dealing with liquid distribution, noncondensable gas, fouling, and other problems[1]. It is facing the key and foundation problem for researching falling film flow to develop new high efficiency falling film evaporator. A large amount of basic research were conducted by investigators on falling film flow modes.

Based on researching flow modes for smooth tube, when the liquid flows from one horizontal tube to another below it, there are three major intertube flow patterns, which are commonly designated as the droplet, column and sheet, as shown in Fig. 1. Based on identifying flow modes, Armbruster and Mitrovic[2], Hu and Jacobi[3] and Roques and Thome[4] proposed a flow mode transition correlation between Reynolds number *Re* and Galileo number *Ga* (*Re*=A*Ga*b), where A and b are the empirical constants. Kutateladze[5] gave a mathematical relationship between *Re* and Archimedes number *Ar* (*Re*=*f*(*Ar*)) to describe the transition.

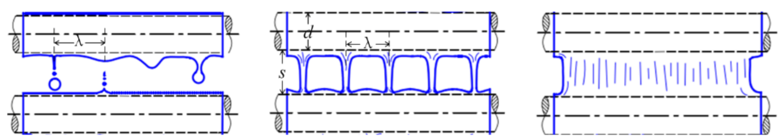



**Fig 1** falling film modes((a)droplet；(b)column；(c)sheet)

For intertube flowing feature, in the droplet and column modes, the liquid fell from the tube at sites that were a fixed distance apart, wavelength($\lambda$) (see Fig.1 (a), (b)). This behavior appeared to be related to the Taylor instability. Taghavi and Dhir [6], Tang and Lu [7], Mitrovic and Ricoeur [8], Hu and Jacobi [9]. They have reported relevant data wavelength on effects occurred in column and droplet departure wavelengths.

The film thickness plays a more important role for heat transfer coefficient on a horizontal. Such as Thomson[10], Rogers and Goindi[11], Bergelin[12], Zhang et al.[13], they have been investigated experimentally by different techniques. There were micrometer measurement, capacitance method and video camera.

Based on above works, there was a deep research for smooth tube, which will lay the foundation for enhanced tube. The enhanced tubes are core parts of falling film exchanger, they have a direct effect for heat transfer performance. Roques and Thome[4,14] predicted the flow mode transition for six types tubes(smooth, turbo-BII, thermoexcel-C and low finned( 19fpi, 26fpi, 40fpi)). The coefficients of flow mode transition relation were obtained with spacing effect. Wang and Jacobi[15] observed the falling film mode and derived flow mode transition for the flat tube. Meanwhile, because of the complexity of surface structure, the more research was required.

Therefore, it is facing the foundation problem for intertube falling film behaviour to design optimization falling film heat exchanger. So the paper aims at solving the flowing problem of horizontal tubes with experiment study. The surface structure of enhanced tube was explored for falling film flow on horizontal tube. The results can be used to guide the development of high efficient falling film evaporator with two and three dimensional finned tubes.

## NOMENCLATURE

| | | |
|---|---|---|
| *Re* | [-] | transitional Reynolds number |
| *Ga* | [-] | Galileo number |
| *Ar* | [-] | Archimedes number |
| *s* | mm | Tube spacing |
| *2D* | [-] | two dimensional enhanced |
| *3D* | [-] | three dimensional enhanced |
| *SM* | [-] | Smooth tube |
| *d* | mm | diameter |
| *p* | mm | fit pitch |
| *h* | mm | fit high |
| *D-DC* | [-] | droplet and droplet column |
| *DC-C* | [-] | droplet column and column |
| *C-CS* | [-] | column and column sheet |
| *CS-S* | [-] | column sheet and sheet |
| Special characters | | |
| $\lambda$ | mm | instability wavelength, spacing between neighboring columns or droplets |
| Subscripts | | |
| *o* | | Out: out diameter |
| *i* | | Inner: inner diameter |

## EXPERIMENT

Experiment system

The schematic diagram of the experimental apparatus is shown in Fig. 2. It consisted of high-level water tank, test section, back-water tank, flow rate distribution device, valve and pump. The experimental system included water loop, temperature control, image collection and data measurement. These were described below.

Test liquid circulation system

The high-level tank provided a constant potential head, level distribution device assured that water distributed evenly and stability. For falling film process, the valves of outlet water and bypass control the falling film flow rate. And it was measured by the weigh device. Then, the backwater was delivered by circulation pump into the high-level tank.

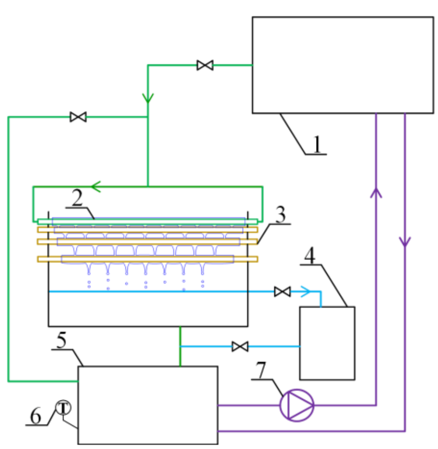



**Fig 2** Schematic diagram of the experimental apparatus
1-high water tank 2-flow rate distribution device 3-test tube
4-weigh device 5-backwater tank 6-temperature sensor
7-circulation pump

Image collection system

The steady light source and reflector background wall were provided to have a clear intertube flow mode. There were adjustable height tripod and camera combination to capture transition mode photos. The image collection system showed in Fig.3.

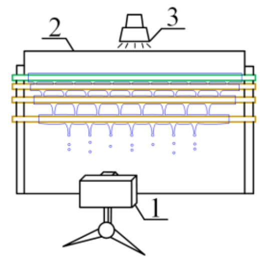



**Fig 3** Image collection
1-camera 2-background wall 3-light source

Test liquid and conditions

The water was used as cyclic test liquid. The flow rate of test section was controlled from increasing to decreasing and reverse respectively. There were four types of flowing mode and enhanced tube. The tube spacing remained the same( *s*=10mm ).The test condition listed in Table1.

Table1 Test conditions

| type | tube spacing | flow rate | transition mode |
|---|---|---|---|
| smooth | | | droplet and droplet column(D-DC) |
| 2D enhanced | 10mm | 14g/s-79g/s | droplet column and column(DC-C) |
| | | | column and column sheet(C-CS) |
| 3D enhanced | | | column sheet and sheet(CS-S) |

Test tube

The specific parameters of tube and surface structure were shown in Table2. The test tubes included smooth(SM), two and three dimensional enhanced(2D, 3D). The inner and outer diameter of tube used as $d_i$ and $d_o$. The fit pitch and high used as *p* and *h*. The figure 4 showed the structure parameters of 2D enhanced tube.

Table 2 Structure parameter of enhanced tube

| Type | $d_o$ mm | $d_i$ mm | $p$ mm | $h$ mm |
|---|---|---|---|---|
| SM | 19.05 | 16.50 | — | — |
| 2D1 | 18.93 | 16.45 | 2.8 | 0.503 |
| 2D2 | 18.93 | 16.29 | 2.52 | 0.512 |
| 3D1 | 18.93 | 15.00 | 0.635 | 1.219 |

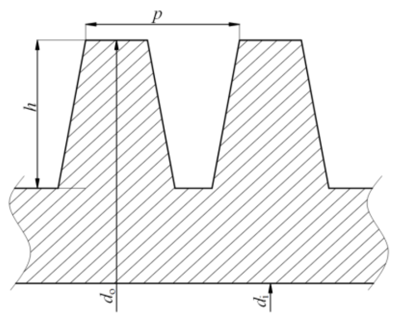



**Fig 4** Surface structure of 2D enhanced tube

Experimental procedure

The test liquid(water) flowed into the level distribution device from the high-level tank, its function provided a uniform liquid distribution. The spacing tube and enhanced tubes set as test condition. For the intertube falling film process, the circulating water was measured until the test tubes fully wetted. Under the flow rate of falling film transitions measured, it was controlled from small gradually to large, and used the same way in reverse again. The purpose of flow rate measuring observed the effect for hysteresis phenomenon between mode transitions. At the same time, the flow modes were recorded by the camera.

Experiment error

The dimensionless of *Re* applied to describe the flow mode transitions. Based on the error calculation method of literature[16], the paper obtained the test deviation of *Re*. The analysis result showed that it was less than 2%. The range of deviation value was from 0.147 to 11.89.

Calibration model test

The tube spacing($s$=10mm) has chosen as the condition of calibration model test. Compared the experiment results with correlation equation which Hu et.al.[17] provided, the deviation was shown in Table3. It was less than 8%. They agreed well with each other.

Table3 film Re of mode transitions for smooth tube

| Item | Relative tube spacing ($s/d$) | film Re of mode transitions value | | | |
|---|---|---|---|---|---|
| | | D-DC | DC-C | C-CS | CS-S |
| Model value | 0.52 | 102.4 | 132.6 | 404.7 | 449.7 |
| Test value | | 106.0 | 138.2 | 375.1 | 420.3 |
| deviation | | 3.5% | 4.0% | 7.9% | 6.9% |

## RESULT AND DISCUSSION

Effect of two-dimensional tube on falling film mode transition

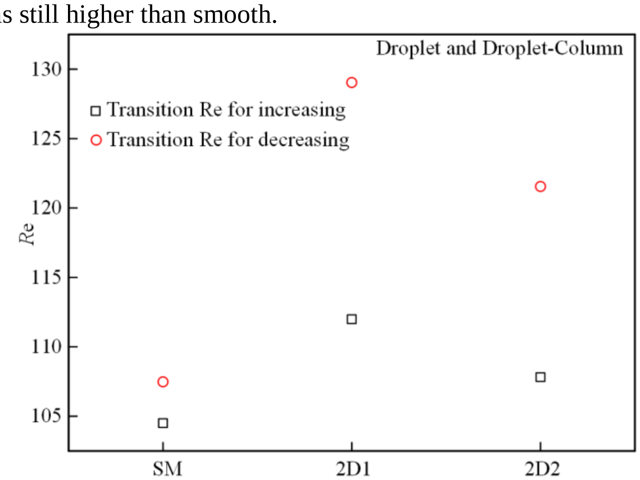
For the surface structure of two-dimensional(2D) enhanced tube, the falling film transitions were researched at tube spacing($s$=10mm). Experiments were conducted for decreasing and increasing flow rates. It was very significant for falling film modes influence. As shown in Fig.5.

**Droplet and Droplet-Column** For the mode transitions, the 2D enhanced tubes improved than smooth. For increasing flow rate, the mode transitions were mostly below the decreasing. The reason that the surface structure of tube caused the hysteresis. But the mode transitions were improved for decreasing. For decreasing flow rate, the mode transitions of 2D tube has obvious increasing, which compared with smooth.

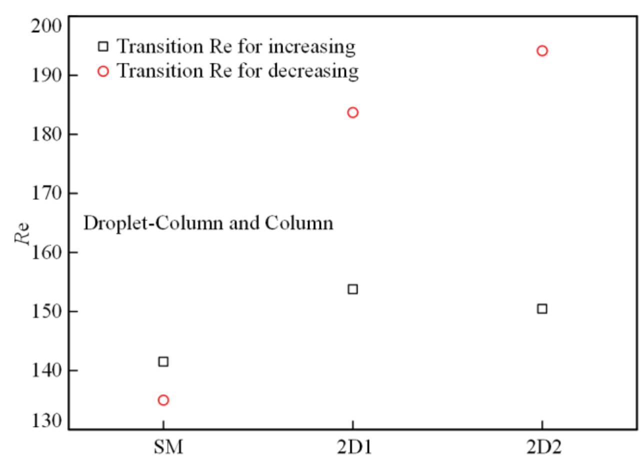
**Droplet-Column and Column** The mode transition of 2D tube was still higher than smooth. For increasing flow rate, there was a similar trend with the droplet and droplet-column. Because of the surface structure, the mode transitions of 2D tube has obvious increasing for decreasing flow rate. The hysteresis of tubes can be enhanced.

**Column and Column-Sheet** Compare with the first two flow modes, difference of transition was reduced for increasing flow rate and decreasing. But the transition of smooth tube showed the increasing phenomenon for decreasing flow rate.

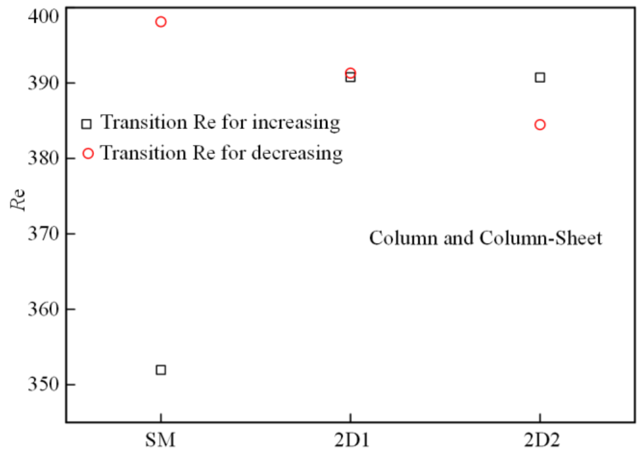
**Column-Sheet and Sheet** Transitions reached the maximum. But the maximum value appeared at the flow rate increasing, there was a difference with first flow modes. The enhanced tube was still higher than smooth.



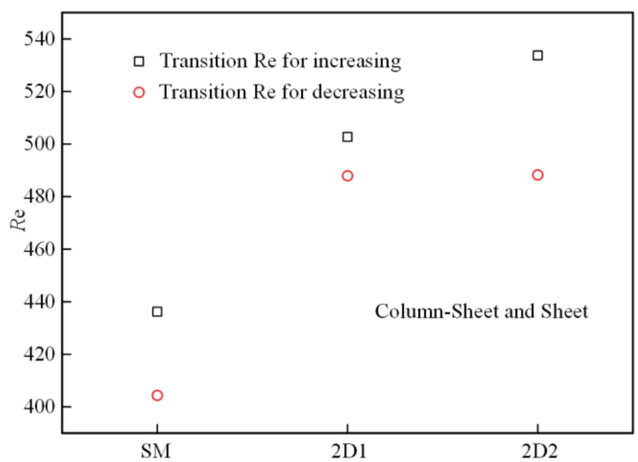

(a)D-DC




(b)DC-C




(c)C-CS




(d)CS-S

**Fig 5** Falling film mode transition with different 2D enhanced tubes

Effect of three-dimensional tube on falling film mode transition

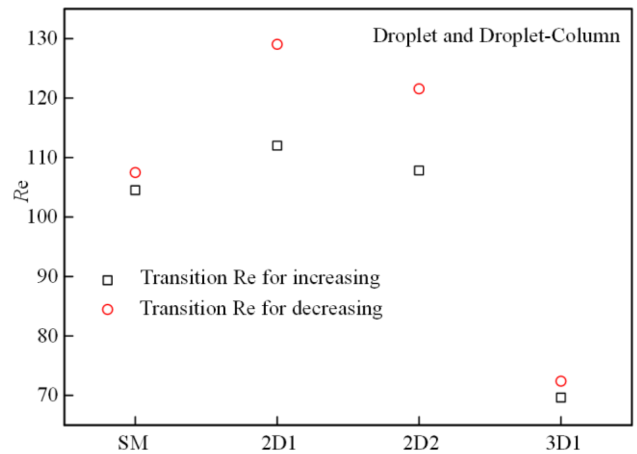
As the same way, the three- dimensional(3D) enhanced tube was researched. Compared with 2D and smooth tube, the surface structure has an effect on falling film process. As shown in Fig. 6.

**Droplet and Droplet-Column** For 2D and smooth tube, the mode transitions of 3D tube has obvious decreasing. From the hysteresis effect, 3D tube was lower than the 2D.

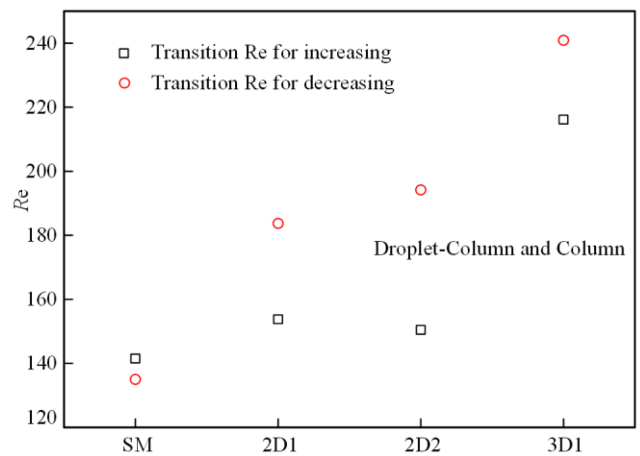
**Droplet-Column and Column** Compared with 2D and smooth tube, the mode transition of 3D tube was higher. But the hysteresis of it was also lower than 2D.

**Column and Column-Sheet** The mode transition of 3D tube was lower than the 2D. The hysteresis of it was increasing for comparing with 2D, and kept consistent with smooth.

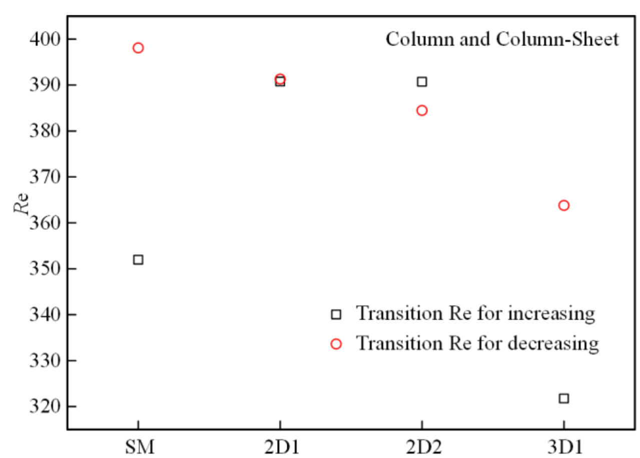
**Column-Sheet and Sheet** The maximum value appeared at the flow rate increasing. It was similar to 2D for column-sheet and sheet, and the hysteresis was the highest for 2D and smooth.



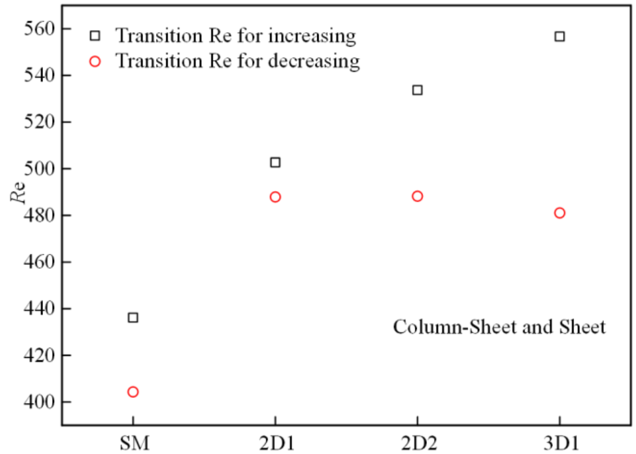

(a)D-DC




(b)DC-C




(c)C-CS




(d)CS-S

**Fig 6** Falling film mode transition with different enhanced tubes

## CONCLUSION

The falling-films modes on enhanced tubes were observed and the results were presented for different falling film modes. And the tube spacing remained the same(s=10mm). It provides the reference for more research this kind of question. Conclusions are summarized as follows:

(1)Compared with the smooth tube, 2D enhanced tube has improved the mode transitions. But the 3D enhanced tube seemed to be different with 2D. For DC-C and CS-S, the transition was similar to the 2D. The other transition was lower than 2D.

(2)For the 2D enhanced tube, surface structure caused the hysteresis. It included the D-DC and DC-C. More research is needed for other flow mode.

(3)For the 3D enhanced tube, the hysteresis of it was lower than 2D tube. It included the D-DC and DC-C. In contrast, there were higher the hysteresis for C-CS and CS-C. Under D-DC and C-CS modes, the transitions were lower than 2D tube. It was opposite phenomenon for other modes.

From the above, the research work of paper is the base for the heat transfer characteristic of falling film flow. The relevant results provides reference evidence for high efficient falling film evaporator.

## REFERENCES

[1] Yundt, B., and Rhinesmith, R., Horizontal spray-film evaporation, *Chemical Engineering Rroceedings*, Vol.77, 1981, pp. 69-73.

[2] Armbruster, R., Mitrovic, J., Patterns of falling film flow over horizontal smooth tubes, *Proceedings of 10th International Heat Transfer Conference, Brighton*, *UK*, Vol. 3, 1994, pp. 275–280.

[3] Hu, X., and Jacobi, A.M., The intertube falling film 1. flow characteristics, mode transitions, and hysteresis, *Journal of Heat Transfer – Transactions of the ASME*, Vol. 118, 1996, pp. 616–625.

[4] Roques, J.F., Thome, J.R., Falling film transitions between droplet, column, and sheet flow modes on a vertical array of horizontal 19 fpi and 40 fpi low-finned tubes, *Heat Transfer Engineering*, Vol. 24 2003 pp. 40–45.

[5] Kutateladze, S. S., Gogonin, I. I., and Sosunnv V. I., The influence of condensate flow rate on heat transfer in film condensation of stationary vapour on horizontal tube banks, *International Journal of Heat and Mass Transfer*, Vol. 28, 1985, pp. 1011-1018.

[6] Taghavi. K., Dhir, V. K., Taylor instability in boiling, melting, condensation or evaporation, *Heat Mass Transfer*, Vol. 23, 1980, pp. 1433–1445.

[7] Tang, Z., Lu, B. Y. C., Droplet spacing of falling film flow on horizontal tube bundles, *Proc. 18th International Congress of Refrigeration*, *Montreal*, 1991, pp. 474–478.

[8] Mitrovic, J., Ricoeur, A., Fluid dynamics and condensation heating of capillary liquid jets, *Heat Mass Transfer*, Vol. 38, 1995, pp. 1483–1494.

[9] Hu, X., and Jacobi, A. M., Departure-site spacing for liquid Droplets and jets falling between horizontal circular tubes, *Experimental Thermal and Fluid Science*, Vol.16, 1998, pp. 322–331.

[10] Thomson, A. K. G., Heat transmission in film-type coolers, *Journal of the Society of Chemical Industry*, *Japan*, Vol. 40, 1937, pp. 380T–384T.

[11] Rogers, J. T., and Goindi, S. S., Experimental laminar falling film heat transfer coefficients on large diameter horizontal tubes, *Can*. *J*. *Chem*. *Eng*., Vol. 67, 1989, pp. 560–568.

[12] Dukler, A. E., and Bergelin, O. P., Characteristics of flow in falling liquid films, *Chem*. *Engineering Progress*, Vol. 48, 1952, pp. 557–563.

[13] Zhang, J. T., Wang, B. X., and Peng, X. F., Falling liquid fin thickness measurement by an optical-electronic method, *Review of Scientifique Instruments*, Vol. 71, 2000, pp. 1883–1886.

[14] Roques, J. F., Dupont, V., Thome J. R., Falling film transitions on plain and enhanced tubes, *Journal of Heat Transfer*, Vol, 124 , 2002, pp. 491-499.

[15] Wang, X. F., Hrnjak, P. S., Elbel, S., Jacobi, A. M., He, M.G., Flow modes and mode transitions for falling films on flat tubes, *Journal of Heat Transfer*, Vol, 134, 2012, pp. 1-9.

[16] MA, Z. X., Experiment and theory of film condensation heat transfer on horizontal tube bundle, *Ph.D*. *Thesis*, *Harbin: Harbin Institute of Technology*, 2012.

[17]Hu, X., The intertube falling-film modes: transition, hysteresis, and effect on heat transfer, *Ph.D. Thesis*, *University of Illinois at Urbana-Champaign*, *Urbana*, *IL*. 1995.