Applied Energy Symposium 2021: Low carbon cities and urban energy systems
September 4-8, 2021, Matsue, Japan
Paper ID: 52

Influence of Horizontal Tube Bundle Arrangement on Flow and Heat Transfer Properties of Oily Wastewater Spray Falling Film

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ABSTRACT

Recently, the spray heat exchanger became an important technology in a sewage source heat pump (SSHP) to recover thermal energy from oily wastewater. Hence, it's necessary to study the heat transfer properties and its enhancements. Among all of the influential factors, the arrangement of the tube bundle is a critical factor that influence the liquid film flow of the falling film, and further has a great impact on heat transfer. Therefore, in this paper, a three-dimensional numerical model of the arrangement of triangular tube bundles is established, using a glycerin-water mixed solution to simulate oily wastewater. The flow pattern of the liquid film under different tube row modes and the influence of heat transfer effects are compared, and the temperature inside the liquid film is analyzed. It was found that there is an obvious difference in the falling film flow outside the horizontal tube between the triangular tube bundle arrangement and the in-line tube bundle arrangement. The liquid film flow in the triangular arrangement is more unstable and has a greater impact on the heat transfer of the upper half of the tube. The same phenomenon is observed for the tube bundle below the top row. The local heat transfer coefficient along the circumferential direction of the triangular arrangement is greater than that of the in-line arrangement. Besides, both of the tube bundle arrangements have the phenomenon that the local heat transfer coefficient decreases with the increase in oil content.

Keywords: falling film, tube bundle arrangement, oily wastewater, heat transfer

NONMENCLATURE

Symbols	
Ti	*Spray Temperature, ºC*
ρ	*Density, kg/m3*
μ	*Viscosity, kg/(m·s)*
Cp	*Specific Heat Capacity, J/(kg·k)*
M	*Molecular weight, kg/kmol*
σ	*Surface Tension, N/m*
Γ	*Spray Density, kg/(m·s)*
D	*Diameter, mm*
S	*Tube Spacing, mm*
hϑ	*Local Heat Transfer Coefficient, kW/(m²·K)*
ϑ	*circumferential angle,°*
Tw	*Wall Temperature, ºC*
q	*Heat Flux Density, kW/m²*

1. INTRODUCTION

Because of its simple structure, high heat transfer efficiency, and convenient maintenance, the external heat transfer of the horizontal falling film tube of the shower type heat exchanger is widely used in large-scale industrial sewage treatment, seawater desalination, petrochemical and other fields.

Mao et al.[1-3] studied the influence of sewage with different oil content on the unevenness of falling film heat transfer was studied. The results have shown that when the glycerin content of sewage increases, the unevenness of the top heat transfer coefficient increases, while the local heat transfer coefficient decreases. This is because the higher the glycerin content, the higher the viscosity of the fluid. Qiu et al. [4] studied that because of its greater viscosity, ethylene glycol is easier to form in-line jets, and has a greater impact on the heat transfer in the upper part of the tube than in the lower part. Yang et al. [5] studied the effect of tube spacing on falling film heat transfer under the rotating triangle arrangement. The results show that

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different tube spacing has little effect on the top discharge film thickness, and the discharge film thickness of other tubes decreases with the increase of tube spacing. The same point is also reflected in the research of Qiu et al. [6]. As the distance between the tubes increases, the thickness of the liquid film on the wall of the second row of tubes gradually decreases. R. Kouhikamali et al. [7] simulated that the heat transfer coefficient of the vertically arranged tubes in the triangular arrangement in the multi-effect desalination device is greater than that of the horizontal arrangement. Wang et al. [8] suggested that the upper and lower parts of the horizontal falling film tube bundle should be arranged separately, and suggested that a secondary liquid distribution plate should be added between the upper and lower tubes. The research of Jiao et al. [9] showed that the comprehensive heat transfer performance of the staggered round fin heat exchanger is better than that of the in-line heat exchanger.

In the past, most researches on the heat transfer of horizontal falling film flow focused on the level of a two-dimensional single-tube model with pure water as the working fluid. This is far from the actual engineering, and most scholars have different variables thermodynamic parameters in the same arrangement, but there are few studies on the structural parameters of heat exchangers. Therefore, this paper studies the influence of oily sewage on the heat transfer performance of the horizontal falling film under the triangular arrangement and sequential arrangement of the three-dimensional model. Based on the research of the falling film heat transfer law of different glycerin content.

2. METHODOLOGY

2.1 Assumptions

Since the flow and heat transfer mechanism of the actual falling film heat transfer process is very complicated, it is difficult to achieve all of them by simulation, so various assumptions are needed to simplify the model. The following are some hypotheses based on this research.

(1) The fluid must not be compressed continuously.

(2) The thickness of the liquid film is much smaller than the pipe diameter.

(3) The flow is laminar, and the liquid distributed by the spray holes is uniform; the liquid film is symmetrically distributed on both sides of the pipe wall.

(4) The gas-liquid interface is in thermodynamic equilibrium.

The fluid physical properties are shown in Table 1.

Table 1 Physical properties of oily wastewater

Glycerin	T_i ºC	ρ kg/m^3	μ 10^6 kg/(m·s)	C_p J/(kg·k)	M kg/kmol	σ N/m
2 %	46	986.9	657.4	4192	18.31	0.06842
4 %	46	982.5	693.4	4159	18.61	0.06840
6 %	46	978.2	732.0	4127	18.93	0.06838
8 %	46	973.9	773.4	4095	19.25	0.06836
10 %	46	969.9	817.9	4063	19.59	0.06834

2.2 Physical model and mathematical method

2.2.1 Physical model

In order to compare the heat transfer of the horizontal falling film flow between different cross-row arrangement modes and in-line arrangement modes, this paper selects the physical parameters in the Hao et al.[1] simulation. For the three fork-row arrangement modes, the regular triangle arrangement mode is selected, and the purpose of different arrangement modes is achieved by changing the distance between different tubes. The selected pipe spacing is 25.45*mm*, 29.05*mm*, and 34.05*mm*. See Fig.1 for details; other physical parameters are consistent with Hao, respectively, the spray hole diameter is 3*mm* and the distance between adjacent spray openings is 2*mm*; the distance from the spray hole to the top row is 3*mm*; the pipe diameter is 19.05*mm*. In addition, the order of the tube bundles in the article is named the first row, the second row, and the third row from top to bottom.

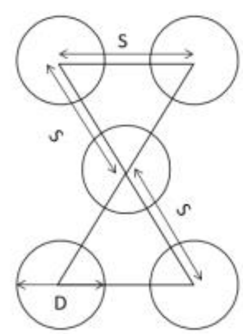


Fig.1 Schematic diagram of the arrangement of the triangular tube bundle

2.2.2 mathematical method

Calculate through continuity equation, energy equation, momentum equation

(1) Continuity equation

$$\rho = Const$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0$$

(2) Momentum equation (Navier-Stokes equations)

$$\rho\frac{\partial u_x}{\partial t}+\nabla(\rho u_x V)=\rho f_x+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}-\frac{\partial P}{\partial x}$$

$$\rho\frac{\partial u_y}{\partial t}+\nabla(\rho u_y V)=\rho f_y+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{zy}}{\partial z}-\frac{\partial P}{\partial y}$$

$$\rho\frac{\partial u_z}{\partial t}+\nabla(\rho u_z V)=\rho f_z+\frac{\partial \tau_{zz}}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}-\frac{\partial P}{\partial z}$$

Where f is the mass force; P is the surface force, that is, the interaction force on the contact surface of the two fluids; τ is the shear stress.

(3) Energy equation

$$\frac{\partial(\rho T)}{\partial t}+div(PUT)=div\left(\frac{\lambda}{\rho}gradT\right)+S_T$$

Among them, for ideal gases, liquids and solids, there can be $\lambda=C_pT$, where C_p is constant; Take the dissipation function *Φ* into the source term S_T as a negative source.

2.3 Numerical simulation approach

2.3.1 Simulation setup

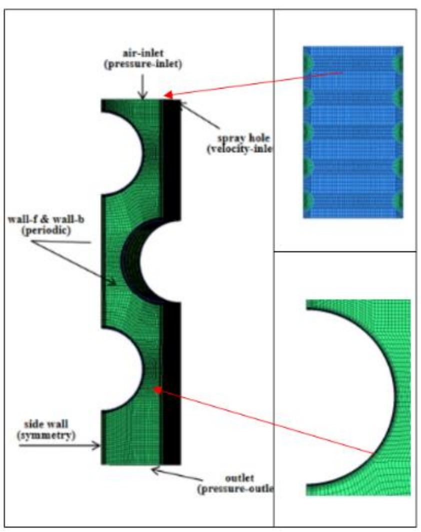


Fig. 2 Grid diagram and boundary conditions

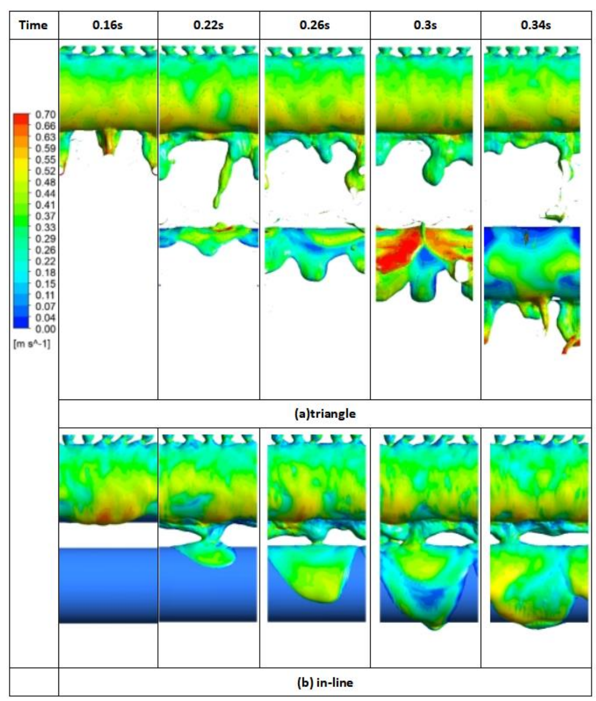
In order to simplify the model, take the symmetrical grid model as shown in the figure. It is considered that the flow difference on both sides of the pipe wall is negligible. Therefore, the circumferential angle of 0-180° is also selected in the post-processing data. Secondly, for the reliability of calculation, the boundary layer around the pipe wall is locally encrypted. Fig.2 shows the grid map imported into the simulation software, and the edge of the sprinkler and the heat transfer tube has been locally encrypted. The spray density of the inlet is 0.119 *kg/(m·s)*, the pipe wall is set with a constant heat flow density of -47.3 KW/m^2, the inlet temperature of the water-containing glycerin is 319.15*K*, and the inlet flow rate is 0.17*m/s*. The boundary condition of the sprinkler outlet is set as the speed inlet, the air inlet is set as the pressure inlet, the periodic boundary is set before and after, and the left and right are set as symmetrical boundaries.

2.3.2 Solver settings

In this study, ANSYS FLUENT simulation software is used for calculation, considering the heat transfer process of the falling film of two-phase flow, the contact interface of the fluid is constantly moving and deforming. Therefore, in order to accurately capture the trajectory of the falling film flow, when importing ANSYS FLUENT, the VOF model is selected to dynamically track the gas-liquid interface; the pressure-velocity coupling uses the PISO algorithm, and the pressure interpolation scheme selects the weighted weight and the PRESTO algorithm, and the momentum and energy are discretized. The method selects the second-order upwind equation. This research is based on the wall contact model, and this research uses copper tubes for research. According to related experimental research Wang et al. [10] the double-sided and contact angle of the fluid is set to 10.

3. RESULTS AND DISCUSSION

3.1 Influence of Tube Bundle Arrangement on the Flow Pattern of Liquid Film



Γ=0.119 *kg*/(*m·s*), *D*=19.05 *mm*, *S*=25.45*mm*, T_i=46 ºC, Glycerin 10%

Fig. 3 Two arrangements of liquid film flow patterns and liquid film surface velocity changes

Fig. 3 shows the comparison of the liquid film flow patterns of the two arrangements under the same working conditions. The liquid film is arranged in a triangle shape, spreads quickly along the axial and circumferential directions, the flow of the liquid film is relatively unstable, and the internal velocity of the liquid film is relatively high. It can be seen from 0.22s and 0.3s that the initial velocity of the liquid film in the lower row of pipes is relatively large, which will make the upper part of the lower row of pipes have a larger local heat transfer coefficient. The liquid film of oily sewage arranged in line has a relatively slow diffusion speed in the axial direction. After the liquid film flow reaches a steady state, the flow pattern between the two rows of horizontal pipes is a partial curtain flow. This may be due to the staggered arrangement in the triangular arrangement, which increases the distance between two adjacent rows of tubes in the same row. The larger the distance between adjacent tubes under the action of gravity, the lower row of tubes will be larger initial speed.

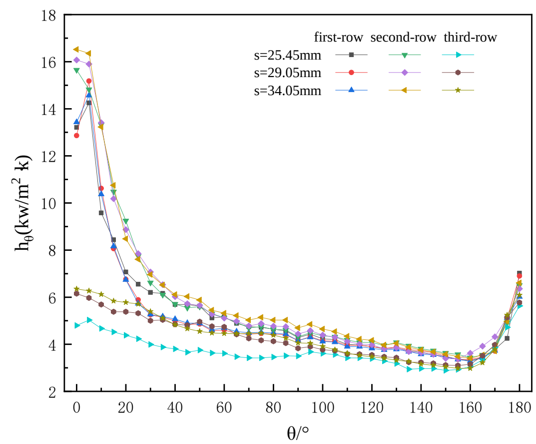
3.2 Influence of tube bundle arrangement on local heat transfer coefficient

3.2.1 Local heat transfer coefficient under different tube bundle arrangement

The local heat transfer coefficient is the most direct parameter to measure the heat transfer capacity of a heat exchanger. It is calculated by heat flux density, local wall temperature and fluid spray temperature.

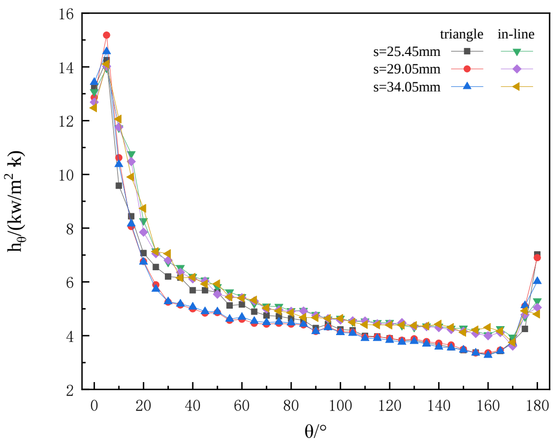
$$h_\theta = \frac{q}{T_w - T_i}$$

This section compares the local heat transfer coefficients under different layouts and discusses the influence of layouts on heat exchangers. As shown in Fig. 4, in the triangular arrangement, the tube spacing has a small effect on the local heat transfer coefficient of the first row of the two rows. At 0°-40°, as the pipe spacing increases, the local heat transfer coefficient increases. This is because the increase in the pipe spacing increases the velocity of the fluid falling to the third row of pipes, and the internal disturbance of the liquid film increases, thereby increasing the heat transfer coefficient. In addition, it can be seen that regardless of the tube spacing, the local heat transfer coefficient of the second row is greater than that of the first row than the third row. Because the first and second rows of tube bundles are closer to the spray holes, the impact of oily sewage on the top of the tube wall causes strong disturbances in the liquid film, which enhances the mixing of hot and cold fluids, and the heat exchange effect is obvious. The heat transfer coefficient of the third row is relatively small because the temperature gradually decreases during the falling film, and the temperature of the oily sewage that falls outside the second row of horizontal tubes is relatively low, resulting in a small temperature difference between the inside and outside of the horizontal heat exchange tube, which weakens the heat exchange. At 40°-180°, it can be seen that when *S*=29.05*mm*, the local heat transfer coefficient is the largest. Therefore, the arrangement of *S*=29.05mm is selected below to continue to study the influence of oil content on the heat transfer of the falling film.

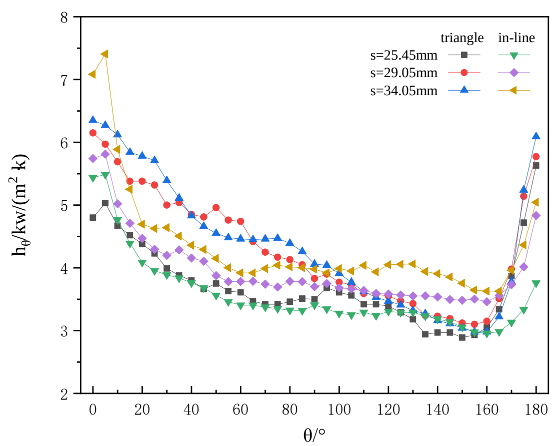


Γ=0.119 *kg*/(*m·s*), *D*=19.05 *mm*, T_i=46 *ºC*, Glycerin 10%
Fig. 4 Local heat transfer coefficient around tube under different tube spacing in triangle arrangement

Fig.5 is a comparison between the triangular arrangement and the one-character arrangement. It can be seen that the two arrangements have little effect on the top row of tubes, but the effect is more obvious below the top row. Under the same tube distance, the local heat transfer coefficient of the triangular arrangement is better than the local heat transfer coefficient of the in-line arrangement. This is because the tube bundles below the top row in the triangular arrangement will be affected by the tube bundles of other rows. For example, the liquid film on the third row will not only fall from the liquid film of the first row, but also receive splashes from the falling film of the second row. The bottom pipes arranged in line will only be affected by the upper pipe bundle. Due to the staggered splashing of the liquid film, the occurrence of the triangular arrangement will cause the unstable change of the heat transfer coefficient.



(a)upper tube



(b) down tube

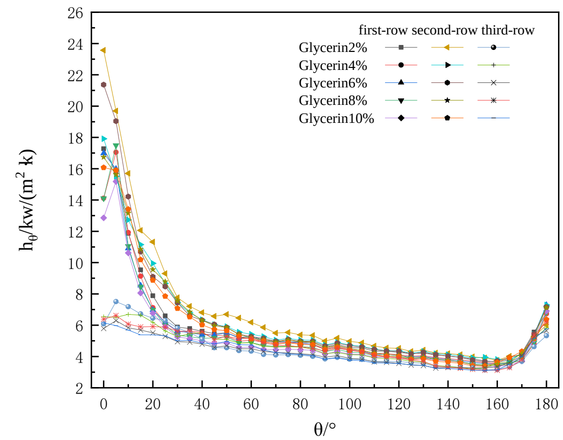
Γ=0.119 *kg*/(*m·s*), *D*=19.05 *mm*, T_i=46 ºC, Glycerin 10%

Fig. 5 Local heat transfer coefficients of two arrangements of different tube spacing at each circumferential angle outside the horizontal tube

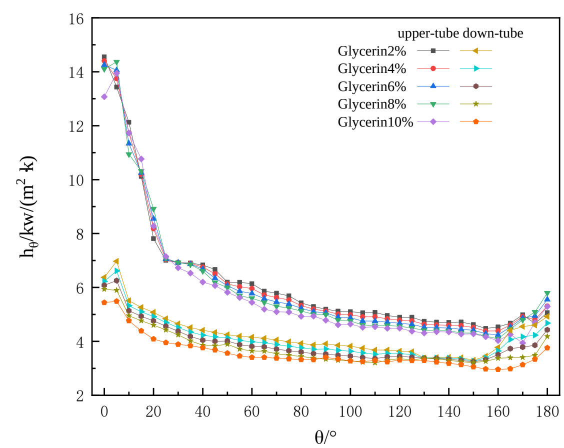
3.2.2 <u>local heat transfer coefficient under different glycerin content</u>

It can be seen from the above that when the tube spacing of the triangular tube row is 29.05*mm*, the local heat transfer coefficient is optimal. Therefore, this section adopts the tube row method with a tube spacing of 29.05*mm* to simulate the influence of different oil content.

Fig.6 shows the local heat transfer coefficients at different circumferential angles when oily sewage with different oil content flows outside the three rows of horizontal pipes in a triangular tube bundle arrangement as a falling film. It can be seen that when the liquid film flow is stable, the local heat transfer coefficient gradually decreases as the oil content of the fluid increases. This point is consistent with the change of the local heat transfer coefficient under the in-line arrangement. This is because as the oil content increases, the speed of the liquid film flowing outside the tube wall decreases, which increases the thickness of the liquid film, weakens the convective heat transfer strength between the liquid film and the tube wall, and reduces the local heat transfer coefficient.



(a)triangle

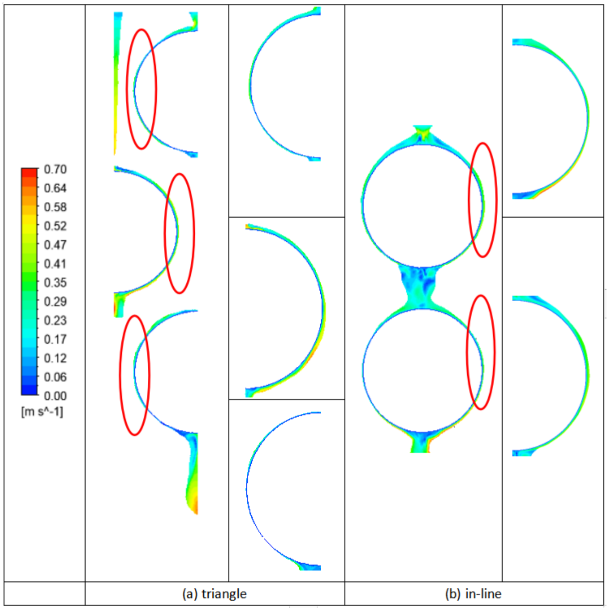


(b)in-line

Fig.6 Local heat transfer coefficients of different glycerin content at each circumferential angle under different tube bundle arrangements

3.3 Influence of tube bundle arrangement on fluid flow velocity

Fig.7 is a cloud diagram of the velocity distribution inside the liquid film in the falling film flow of oily sewage in two arrangements. The falling film flow outside the horizontal tube is the result of gravity, viscous force, and surface tension. It can be seen that no matter which arrangement is used, the flow velocity inside the liquid film closer to the tube wall due to the viscous force is smaller. In the interval that the circumferential angle is less than 90°, the action of the tangential component force in the vertical direction of gravity makes the flow velocity of the liquid film gradually increase. When the circumferential angle is greater than 90°, the viscous force will gradually replace the gravity as the main force, and the liquid film The flow velocity will gradually decrease after reaching the maximum value. And as the number of tube rows increases, the flow rate of the liquid film will gradually decrease. This is because the more tube rows, the speed of fluid flowing to the lower tube wall will gradually decrease, and dry spots may even occur locally.



Γ=0.119 $kg/(m{\cdot}s)$, S=25.45 mm, D=19.05 mm, T_i=46 ºC, Glycerin 10%

Fig. 7 Velocity distribution inside the liquid film in two arrangements

This chapter compares and studies the flow characteristics of oily wastewater in triangular arrangement and in-line arrangement. Two mathematical models of different permutations and combinations were established, and the influence of the distance between the lower pipes and the oil content of the two permutations on the flow pattern and heat transfer effect of the liquid film was explored. Studies have shown that the arrangement of the tube bundles has an effect on the falling film flow. On the whole, the triangular staggered arrangement will enhance heat transfer to a certain extent, but in order to simplify the calculation, the number of tube rows in this paper is only three. It cannot be ruled out that the law will change as the number of tube rows increases. In addition, due to the method of controlled variable method, the working condition data under other thermal parameters is slightly insufficient, so the research on the heat transfer of falling film with different arrangements needs further research.

4. CONCLUSIONS

This paper compares the flow pattern of the falling film outside the horizontal tube, the velocity distribution in the liquid film and the local heat transfer coefficient of each circumferential angle to analyze the influence of different tube bundle arrangement modes on the heat transfer of the horizontal falling film. The conclusions are as follows:

(1) The liquid film flow under the triangular tube bundle arrangement is faster and the unevenness is higher than the in-line arrangement.

(2) The tube bundle arrangement has a greater influence on the heat transfer of the tube bundles below the top row. Under the same working conditions, the local heat transfer coefficient of the triangular arrangement at each circumferential corner is slightly larger than that of the in-line arrangement, and the triangular arrangement with a tube spacing of 29.05*mm* has the best heat transfer.

(3) The local heat transfer coefficient of triangular arrangement and in-line arrangement will decrease with the increase of oil content.

(4) Regardless of the arrangement, the closer to the tube wall, the smaller the flow rate of the liquid film, and as the number of tubes increases, the flow rate will gradually decrease.

ACKNOWLEDGEMENT

The study was supported by Shandong Provincial Natural Science Foundation, China (No.: ZR2020ME170, ZR2016EEQ29).

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