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A NUMERICAL STUDY ON THE EFFECTS OF OIL CONTAMINATION ON FALLING FILM HEAT TRANSFER OVER HORIZONTAL TUBE IN A HEAT PUMP

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ABSTRACT

In the late period of oilfield exploit, the oilfield production water contains large amount of high temperature water the thermal energy of which should be recovered. The sewage source heat pump system (SSHP) has been widely used for this energy recovery, improving the energy utilization efficiency. However, the heat transfer and flow characteristics of oily wastewater spraying in the heat exchanger are different from the ordinary sewage heat pump system. In this paper, a three-dimensional numerical model was established for a spraying heat exchanger in the oily sewage source heat pump system, and a mixture of water and glycerin was used to simulate the oily wastewater. The VOF model was used to simulate the gas-liquid flow of the spray falling film of oily wastewater over a horizontal tube in the heat exchanger, and the effects of different glycerin content and spray density on heat transfer.

Keywords: Falling film, Heat transfer coefficient, Oily wastewater, Oil content, Sewage source heat pump

NONMENCLATURE

Abbreviations

α_v	Gas phase volume fraction
C_p	Specific heat at constant pressure
ρ_l	Liquid phase density
ρ_v	Gas phase density
Γ	Spray density (mass flow rate per unit length)

1. INTRODUCTION

In the late period of oilfield exploit, the oilfield production water contains large amount of water which should be dehydrated. During this dehydration procedure, a huge amount of wastewater with temperature of 30 ℃ – 70 ℃ is drained, resulting to pollution and waste of thermal energy [1]. Therefore, in recent years, the sewage source heat pump system (SSHP) has been used to recover the heat energy in the oily wastewater, which improves the energy utilization efficiency and has good environmental protection benefits. The sewage heat exchanger is the key equipment of the oily sewage source heat pump system (OSSHP). Among various heat exchangers, the spray heat exchanger is more suitable for OSSHP because of its high heat transfer efficiency, simple structure and anti-blocking properties. In the heat exchanger, sewage is evenly sprayed on the heat, and exchanges heat with the refrigerant inside the heat exchange tubes.

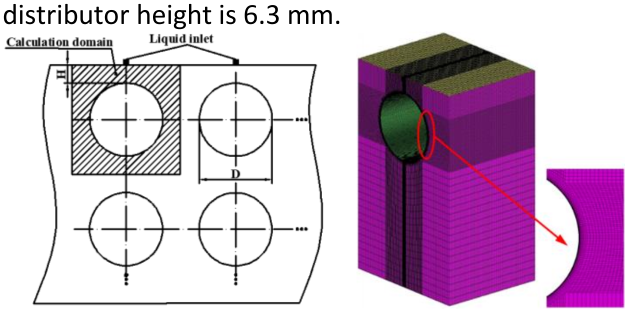
The spray falling heat transfer is the critical problem of the OSSHP, the influencing factors of which have been investigated in a number of previous studies. The physical properties also had obvious effects on the spray falling film heat transfer. Shahzad et al. [2] noted that the heat transfer efficiency during seawater desalination was affected by the salinity of seawater. Gong et al. [3] established a three-dimensional numerical model, analyzed the heat transfer coefficient of falling film of horizontal tube decreased with the increase of salinity of feed seawater. In addition, many scholars have previously studied the process of falling film heat transfer between different refrigerants. The experimental results of Liu et al. [4] explained that the average heat transfer coefficient of R-11 falling film flow in rolled tube rows was not affected by flow rate, heat flux and geometric parameters of tube rows, but only by the physical properties of fluids. Zhao et al. [5, 6] found that under the same conditions, the heat transfer efficiency of R134a is 2-3 times that of R123, and it tends to decrease rapidly after the first film changes smoothly with the decrease of the liquid film flow rate.

The numerical research carried out by Zhao et al. [7] indicated significant effects of surface tension on falling film heat transfer. Mou [8] found that the both heat transfer coefficient of water and seawater falling film increased with *Re*. However, the critical Re were significantly different. These indicate that the viscosity, surface tension, thermal conduction etc., which are determined by different fluid, have obvious effects on the falling film heat transfer. Hence, the specific fluid properties of oily wastewater will definitely lead to different falling film heat transfer characteristics. However, there are few studies on oily wastewater spray falling film heat transfer and the influential factors. Therefore, in this paper, a three-dimensional numerical model was established for the oil wastewater falling flow and heat transfer over a horizontal tube, and the oily wastewater was simulated using water-glycerin mixture. The falling film flow of oily wastewater in horizontal tube under different working conditions is simulated using VOF model.

2. RESEARCH METHODOLOGY

2.1 Physical model

The oily wastewater is sprayed from the liquid distributor to the top of the horizontal heat exchange tube with spray density Γ, as shown in Fig. 1. The oily wastewater was simulated using glycerin-water liquid mixture, and different content of glycerin was investigated. The tube diameter is 25.4 mm, and the distributor height is 6.3 mm.



(a) Calculation domain (b) Mesh

Fig. 1 Spray heat exchanger geometry and mesh

2.2 CFD model

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

In this paper, the VOF model is used to dynamically track the flow of the free boundary of the gas-liquid phase. In the VOF model, the gas phase is set to the primary phase and the liquid phase is the second phase. The equations of the VOF model are as follows [9]:

$$\frac{\partial(\alpha_v\rho_v)}{\partial t}+div(\alpha_v\rho_v V_v)=S_{\partial_v}+\dot{m}_c \tag{1}$$

$$\alpha_l+\alpha_v=1 \tag{2}$$

$$\rho=\alpha_v\rho_v+(1-\alpha_v)\rho_l \tag{3}$$

Where $\dot{m}_c$ is the mass transport in the phase transition process, the source term S_{∂_v} is zero by default; α_l and α_v are the volume fractions of the liquid phase and the gas phase respectively; ρ_l and ρ_v are the density of the liquid phase and the gas phase; ρ is the volume fraction weighted average of phase density.

2.3 Simulation cases

The oily wastewater was simulated using water-glycerin mixture. Six different ratios of glycerin content in the oily wastewater were investigated, as shown in Table 1. The spray density was set at 0.084, 0.168 and 0.262 kg/m·s.

Table 1 Physical properties of oily wastewater

Glycerin content %	Density kg/m^3	Viscosity 10^6kg/m·s	C_p J/kg·k	Surface tension N/m
0	991.3	583.4	4224	0.06844
2%	986.9	657.4	4192	0.06842
4%	982.5	693.4	4159	0.06840
6%	978.2	732.0	4127	0.06838
8%	973.9	773.4	4095	0.06836
10%	969.9	817.9	4063	0.06834

3. RESULTS AND ANALYSIS

3.1 Discussion

The local heat transfer coefficient is the value of the heat transfer coefficient at various angles around the tube, which is determined by the heat flux, the local wall temperature and the fluid inlet spray temperature.

$$h_\theta = \frac{q}{T_{w,\theta} - T_i} \quad (4)$$

The average heat transfer coefficient is the average value of the local heat transfer coefficient at each point outside the pipe wall. The calculation formula is:

$$h_{ave} = \frac{1}{\pi}\int_0^\pi h_\theta d\theta \quad (5)$$

Where q is the heat flux, θ is the circumferential angle, $T_{w,\theta}$ is the temperature of tube wall, and T_i is the wastewater spray temperature.

Fig. 2 shows the local heat transfer coefficients of the oily wastewater with different glycerin contents at different spray density around the tube. As seen, at the top of the tube, there was a significant variation of local heat transfer coefficient; at the middle part of the tube, the local heat transfer coefficient underwent a slight variation; and at the bottom of the tube, the local heat transfer coefficient was increased sharply. Therefore, the heat transfer characteristic can be divided into three regions according to the variation of local heat transfer coefficient.

(1) Impingement region (0°-30°). In this region, the local heat transfer coefficient varied obviously and decreased sharply. Firstly, the oily wastewater was directly sprayed to the top of the tube surface and leaded to stagnation and fully impingement on the top region of the tube surface, enhancing the heat exchange effect. Thereafter, when the liquid film gradually flowed around the tube, the disturbance inside the liquid film was weakened, so that the local heat transfer coefficient was drastically decreased.

(2) Thermal developing region (30°-160°). In this region, the liquid film spread along the tube surface under the force of gravity, viscosity and surface tension. At this time, the disturbance inside the liquid film was small, and the local heat transfer coefficient was gradually lowered with the increase in circumferential angle.

(3) Departure region (160°-180°). The local heat transfer coefficient appeared to increase again. In this region, the liquid accumulated, and vortex formed leading to an increase in local heat transfer.

According to the three regions, the influence of spray density and glycerin content on the heat transfer was investigated. Fig. 2 shows the local heat transfer coefficients of the oily wastewater with different glycerin contents at different spray density around the tube. As seen, the local heat transfer coefficient was increased when the spray density was increased from 0.084 to 0.262 kg/m·s, due to that the increasing spray density raised the film flow velocity leading to advanced heat transfer. On the other hand, significant difference between the different glycerin contents was also shown in Fig. 2. In the impingement region, at lower spray density, the local heat transfer coefficient was much lower for oily wastewater with glycerin of 10% than pure water, due to the higher viscosity. When the spray density was raised to a higher level, the local heat transfer coefficient for the oily wastewater was higher than pure water, due to the strengthened mixing flow in this region. In the thermal developing region, the wastewater with glycerin content of 10% had the slightly lower local heat transfer coefficient, due to the slower flow.

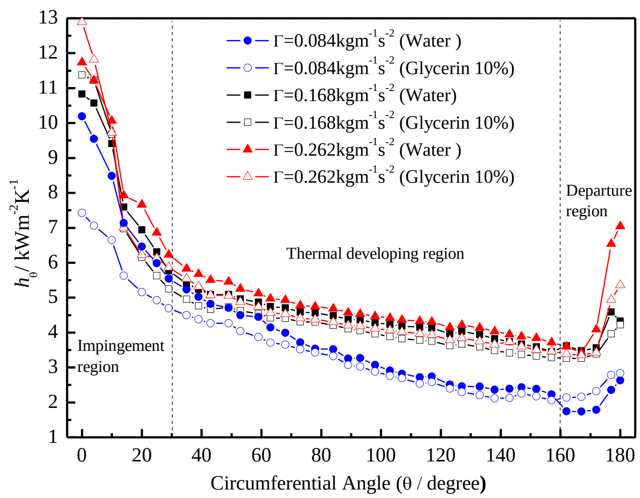


Fig. 2 Local heat transfer coefficient around tube under different glycerin content

The temperature distribution around the horizontal tube is shown in Fig. 3(a) and (b). The high-temperature region is the spray falling film which spreads on the surface of the tube from the top to the bottom with a significant temperature decrease. Fig. 3(a) shows the pure water while Fig. 3(b) shows the oily wastewater with Glycerin of 10%. As seen, there seems no significant difference in temperature distribution. To understand the detailed reason for the different heat transfer performance, the temperature versus the dimensionless location inside the falling film was obtained, as shown in Fig. 3(c). Firstly, the temperature inside the liquid film gradually increased from the tube surface to the film-air interface, due to the heat flux from the pure water or wastewater. Secondly, the temperature gradient near the tube surface decreased with the increase in circumferential angle, suggesting weakened heat transfer at the lower part of tube. Thirdly, the overall temperature differences were different for pure water and oily wastewater. The temperature difference with 10% glycerin content was higher than pure water, which indicates a lower heat transfer performance. The is due to that the oily content increased the viscosity of the wastewater, led to a slower flow velocity, and weakened the heat transfer performance.

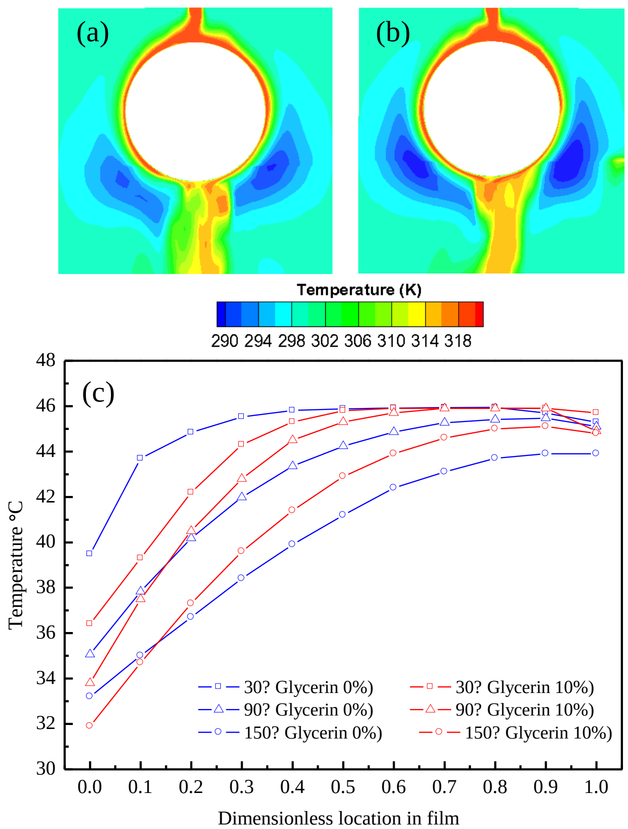


Fig. 3 Temperature field around the tube
a: Temperature distribution around the tube for pure water, b: Temperature distribution around the tube for Glycerin=10%, c: Variation of temperature inside the film versus the dimensionless location

4. CONCLUSIONS

In this paper, a gas-liquid two phase numerical study was carried out on the oily wastewater spray falling film over a horizontal tube. The local heat transfer coefficient and the temperature distribution were analyzed. It can be concluded that the glycerin in the wastewater weakened the heat transfer. The heat transfer characteristic of falling film can be divided into three regions along the tube surface. The negative effect of oily content in wastewater has been reported.

ACKNOWLEDGEMENT

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