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Numerical simulation analysis of flow and heat transfer of supercritical LNG in the IFV condenser

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With the development of the technology of storage, transportation and utilization of liquefied natural gas (LNG), the effective and energy-saving gasification equipments had become research hotspot. In order to obtain the characteristics and laws of the flow and heat transfer process of LNG in the intermediate fluid vaporizer (IFV) condenser and provide theoretical basis for optimal design and operation of IFV condenser, Fluent software was used to numerically simulate the flow and heat transfer process of supercritical LNG in IFV condenser. The influences of LNG mass flow rate and operating pressure on the heat transfer process were analyzed emphatically. Simulation results showed that the heat transfer process could be enhanced in the critical region, but it was not conducive to the convective heat transfer in supercritical state. It appeared the phenomenon of heat transfer deterioration in the second half of the heat exchange tube, especially under the condition of low mass flow rate. Increased mass flow rate could enhance heat transfer, which effectively improved the phenomenon of heat transfer deterioration. The average surface heat transfer coefficient was improved by 13. 56%, which was caused by the increase of the average mass flow rate of 0.01 kg/s. Increased operating pressure made the average surface heat transfer coefficient lower, and the average surface heat transfer coefficient was decreased by 1%, which was caused by the increase of the average operating pressure of 0.5 MPa. When the operating pressure was greater than 7.0 MPa, the phenomenon of heat transfer enhancement in the critical region disappeared, and the surface heat transfer coefficient decreased continuously.

Keywords: supercritical fluid; IFV; numerical simulation; LNG

INTRODUCTION

Natural gas (NG), a kind of clean energy, is gradually into the public eyes. The large quantity of NG transportation and storage can be realized by liquefied natural gas (LNG), which means that it is necessary to solve the problem of LNG storage and gasification before large scale applications. Therefore, the effective and energy-saving gasification equipments have become research hotspot. Intermediate fluid vaporizer (IFV), a kind of vaporizer with the intermediate heat transfer medium, is mainly composed of three heat exchangers, namely, evaporator, condenser and thermolator. LNG will transform into supercritical fluid when the temperature of LNG exceeds the critical temperature under supercritical pressure in the IFV condenser. Under the supercritical state, the physical parameters of fluid will change sharply, which will have great effects on the heat transfer process. So, the core heat exchange process of IFV is gasification process of LNG under supercritical pressure, which will directly affects the overall heat transfer efficiency of vaporizer and the transmission efficiency of NG. Therefore, it is very important to analyze the flow and heat transfer process of LNG in the IFV condenser. Pu et al. [1] used different heat transfer correlations to handle three heat transfer processes of IFV, and the influences that mass flow rate of seawater, inlet pressure of LNG and mass flow rate of LNG on the heat transfer process of IFV under various operating conditions were obtained by compiling program and calculation. Liu et al. [2] made the structural optimization design for the existing IFV and proposed a kind of heat exchange tube structure of spiral wound, which contributed to the increase of the compactness and pressure bearing capacity of heat exchange tube bundles. Lee et al. [3] further studied the phase-change heat transfer characteristics of hydrocarbon refrigerants, and the experimental research results of hydrocarbon refrigerants were analyzed comparing with the results of R22. Song et al. [4] carried out the simulation research of the heat transfer process of sub-cooled intermediate fluid by Fluent and studied the influence of different inclination angles of heat exchange tube on the heat transfer process.

Currently, the research on the heat transfer process of supercritical fluid is mainly focused on carbon dioxide and water, but the research on supercritical LNG is relatively few. S. M. Liao and T. S. Zhao [5] studied the flow and heat transfer

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process of supercritical carbon dioxide in vertical micro channel by numerical simulation. The velocity field, temperature field and drag coefficient of fluid in the pipe with four different diameters were analyzed respectively under the condition of gravity, heating and cooling. The results showed that the influence of buoyancy on heat transfer process is very large, and it could not be ignored in the simulation process. Yang et al. [6] studied the convective heat transfer of supercritical carbon dioxide in different inclined angles by numerical simulation. Considering the effects of buoyancy on the heat transfer process, through the analysis of temperature field, secondary flow, surface heat transfer coefficient and other parameters, the conclusion that the surface heat transfer coefficient decreased with the increase of the inclination angles of the heat exchange tubes was drawn. Li et al. [7] used Fluent software to simulate the flow and heat transfer process of supercritical LNG in vertical circular tube and analyzed the heat transfer performance of methane under different heat exchange tubes. The flow and heat transfer correlations of supercritical methane in different structures were obtained.

Based on the above research, this paper took the single heat exchange tube in IFV condenser as the research object. The numerical simulation and analysis of the flow and heat transfer process of LNG were carried out by Fluent. Taking into account the effects of gravity and buoyancy, the influences of mass flow rate of LNG and operating pressure on the heat transfer process of IFV condenser were studied respectively, and the characteristics and laws of the flow and heat transfer process of LNG were obtained, which provided theoretical basis for optimal design and operation of IFV condenser.

ESTABLISHMENT OF ANALYSIS MODEL

Physical model

To get the physical model of the IFV condenser, this paper made the following assumptions and simplifications:

(1) The flow of the fluid in the heat exchange tube was stable, and the pressure loss was ignored.

(2) The number of heat exchange tubes in the condenser is numerous, but the flow and heat transfer process of the fluid in each tube is basically similar. Therefore, this paper took single heat exchange tube of the condenser as the research object.

(3) The saturated propane steam of condenser releases latent heat of condensation to heat the LNG in the heat exchange tubes. Therefore, it can be considered that the outer wall of the heat exchange tube is a uniform wall temperature boundary condition [8].

The simplified physical model is shown in Fig. 1. The design parameters of IFV were chosen in the literature [9]. The length of the heat exchange tube is 6000 mm. The outside diameter is 19 mm, and the inside diameter is 15 mm, and the straight tube spacing is 38 mm.

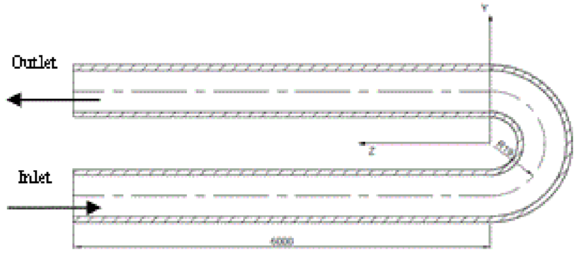


Fig. 1. Sketch map of physical model.

Physical property setting

LNG is a multicomponent mixture, mainly composed of methane, ethane, propane and nitrogen, and methane has the highest percentage of the total [10]. Therefore, this paper used methane to replace LNG in numerical simulation, and the error was within the allowable range of the project [7]. The change of the physical properties of methane under the supercritical pressure was described by linear interpolation function (piecewise-linear) of Fluent. The concrete expression formula of linear interpolation function is as follows:

$$\phi(T) = \phi_n + \frac{\phi_{n+1} - \phi_n}{T_{n+1} - T_n}(T - T_n) \quad (1)$$

Contrast the calculation results of the physical properties of methane by linear interpolation functions with the calculation results by RefProp software. The relative error of the calculated value was less than 2% [11], which can satisfy the engineering precision.

Mathematical model

According to the basic governing equations of fluid flow and heat transfer [12, 13, 14], the RNG k-ε turbulence model with high numerical accuracy for supercritical fluid was adopted in the numerical simulation [15]. For the near wall region, enhanced wall function was used to solve the problem of the computational error due to the high Reynolds number model [16].

In the boundary condition, in order to avoid the influence of the temperature change of LNG at the entrance on the inlet velocity, mass flow inlet was selected as inlet boundary condition, and the inlet temperature was 111.15 K [9]. Because the pressure and temperature at the outlet were unknown, the boundary condition of outlet was set to be free flow condition. The outer surface of the heat exchange tube was set to be the uniform wall temperature boundary condition, and the inner wall of the heat exchange tube was set to be the non slip and fixed wall surface. The annular walls between the inner and outer diameter of the heat exchange tube at the inlet and outlet were set to be adiabatic walls.

Mesh generation and numerical methods

The structured grid was used to divide the whole computation domain. According to the flow field characteristics of the research object, the computation domain was divided into solid and fluid domains, and the fluid-solid coupling treatment was carried out on the contact surface of the solid and fluid domains, so as to realize the fluid-solid coupled heat transfer. The axial and radial grid distributions of the heat exchange tube are shown in Fig. 2 and Fig. 3 respectively. Grid distribution was uniform, and there was no grid distortion. Besides, the grid connection was tight at the junction of the straight pipe and the elbow. The total number of meshes was 3460000, and the worst mesh quality was 0.625.

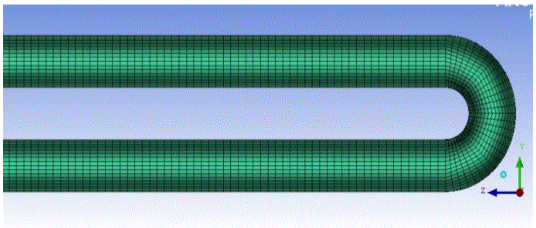


Fig. 2. The axial grid distribution.

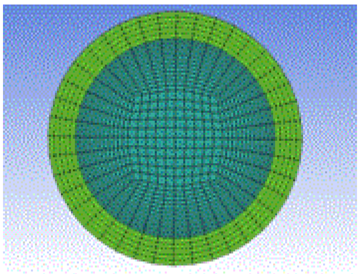


Fig. 3. The radial grid distribution.

The separation algorithm based on pressure of Fluent was chosen to solve the three-dimensional steady flow. The governing equations were discretized by the finite volume method, and the first order upwind scheme was adopted in the discretization scheme. Implicit method was used for the linearization of the equation. The standard pressure interpolation scheme was used, and the SIMPLE algorithm was used for the pressure-velocity coupling algorithm.

CALCULATION RESULTS

Influence of mass flow rate on the heat transfer process

Under the operating pressure of 6.0 MPa, the influences of four kinds of inlet mass flow rate (0.02 kg/s, 0.03 kg/s, 0.04 kg/s and 0.05 kg/s) on the heat transfer process of methane in the tube were studied respectively, and 0.02 kg/s was the actual working conditions. According to the calculation results of physical properties of methane by the REFPROP software, the results show that the specific heat of methane increased with the increase of temperature under supercritical pressure and appeared maximum value near the critical point, and then decreased with increasing temperature, and finally tended to be stable [11]. In order to facilitate the research and description, the region near the critical point was referred to as critical region, and the region between the critical point and the extreme point of specific heat was defined as critical region.

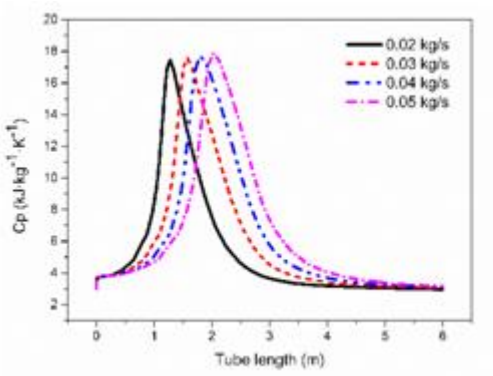


Fig. 4. Curves of specific heat of the fluid near the wall.

Fig. 4 shows the curves of the specific heat of the fluid near the wall inside the tube under four different inlet mass flow rate. As it can be seen, with the increase of mass flow rate, the position of extreme point of specific heat went backwards along the length direction of the tube, but the extreme value did not change. That is because the change of mass flow rate does not affect the physical parameters of methane and only affect the distribution of the physical parameters. It also shows the position of the critical region of methane went backwards with the increase of mass flow rate.

The curves of surface heat transfer coefficient under different mass flow rate are shown in Fig. 5. The comparison of Fig. 4 and Fig. 5 shows that the position of extreme point of specific heat was very close to the position of extreme point of surface heat transfer coefficient under the same mass flow rate. In the monotonically decreasing region of specific heat, methane was completely transformed into supercritical fluid, and the surface heat transfer coefficient decreased sharply. Even in the second half of the heat exchange tube, it appeared the phenomenon of heat transfer deterioration, especially under conditions of low mass flow rate. With the increase of the inlet mass flow rate, surface heat transfer coefficient at the same position of the tube was significantly improved. The position of heat transfer deterioration went backwards, and the range of heat transfer deterioration became smaller.

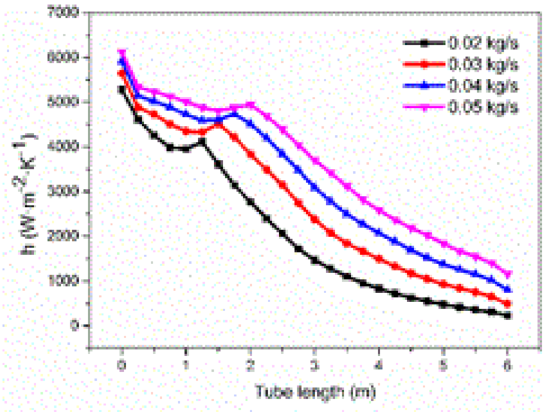


Fig. 5. Curves of surface heat transfer coefficient.

Influence of operating pressure on the heat transfer process

Under the inlet mass flow rate of 0.05 kg/s, the influences of four kinds of operating pressures（6.0 MPa, 6.5 MPa, 7.0 MPa and 7.5 MPa）on the heat transfer process of methane in the tube were studied respectively.

Fig. 6 shows the curves of the specific heat of the fluid near the wall inside the tube under four different operating pressures. It is known that the extreme value of specific heat of methane decreased with the increase of operation pressure. The position of extreme point of specific heat went backwards along the length direction of the tube, and the peak range became larger. This indicates that the critical region of methane went backwards with the increase of the operating pressure.

The curves of surface heat transfer coefficient under different operating pressures are shown in Fig. 7. The comparison of Fig. 6 and Fig. 7 shows that the extreme point of surface heat transfer coefficient was very close to the extreme point of specific heat under the same operating pressure when the operating pressure was less than 7.0 MPa. In the monotonically decreasing region of specific heat, the surface heat transfer coefficient was decreased continuously, which was not conducive to the convective heat transfer. When the operating pressure was greater than 7.0 MPa, the surface heat transfer coefficient decreased along the tube, and there was no extreme value in the curve of surface heat transfer coefficient.

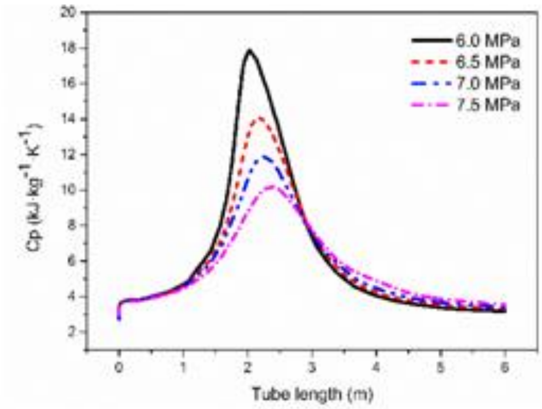


Fig. 6. Curves of specific heat of the fluid near the wall.

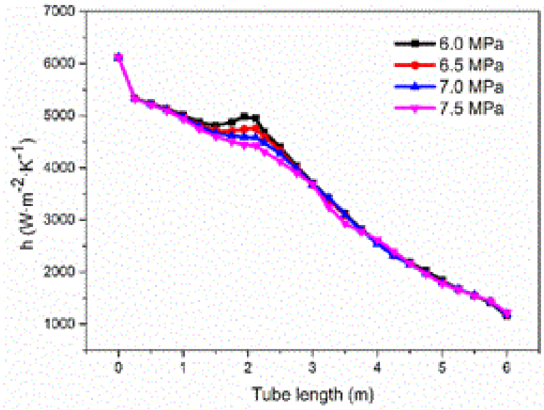


Fig. 7. Curves of surface heat transfer coefficient.

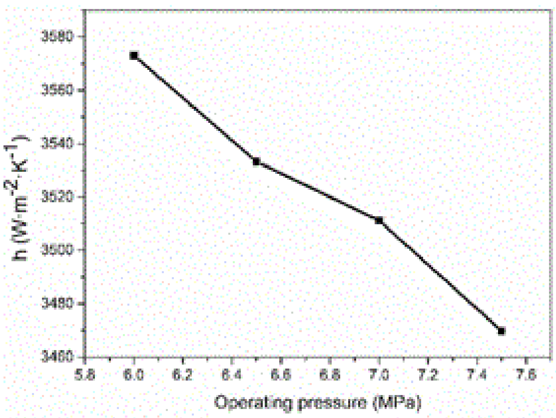


Fig. 8. The curve of average surface heat transfer coefficient.

The comparison of Fig. 6 and Fig. 7 also shows that the surface heat transfer coefficient near the extreme point of specific heat decreased with the increase of operating pressure, and the surface heat transfer coefficient was little affected by the operating pressure in the region away from the extreme point of specific heat. Because of the differences of the surface heat transfer coefficient under different operating pressures near the extreme point of specific heat, the average surface heat transfer coefficient was decreased with the increase of the operating pressure, as shown in Fig. 8.

DISCUSSION AND ANALYSIS

Main results and findings

In order to obtain the characteristics and laws of the flow and heat transfer process of LNG in the intermediate fluid vaporizer (IFV) condenser, this paper took the single heat exchange tube in IFV condenser as the research object, and Fluent software was used to numerically simulate the flow and heat transfer process of LNG in the three dimensional heat transfer tube. The following main results and findings are obtained:

1) The maximum point of surface heat transfer coefficient was near the extreme point of specific heat of methane. In the monotonically decreasing region of specific heat, the surface heat transfer coefficient was decreased continuously. It appeared the phenomenon of heat transfer deterioration in the second half of the heat exchange tube, especially under conditions of low mass flow rate.

2) Increasing the inlet mass flow rate of LNG made the surface heat transfer coefficient at the same position of the tube significantly improved. The position of heat transfer deterioration went backwards, and the range of heat transfer deterioration became smaller.

3) There was no maximum point in the curve of surface heat transfer coefficient when the operating pressure was greater than 7.0 MPa. The surface heat transfer coefficient near the extreme point of specific heat decreased with the increase of operating pressure, and the operating pressure had little effect on the surface heat transfer coefficient in the region away from the extreme point of specific heat.

Analysis and comparison of the results

According to the Heat Transfer [8], the calculation formulas of Reynolds number, Nusselt number, Prandtl number and mass flow rate are as follows:

$$Re = \rho u d / \mu \tag{2}$$

$$Nu = hd / \lambda \tag{3}$$

$$Pr = \mu c_p / \lambda \tag{4}$$

$$q_m = \rho A u \tag{5}$$

According to the Dittus-Boelter formula, the heat transfer correlation of forced convection heat transfer is as follows when the LNG is heated in tube:

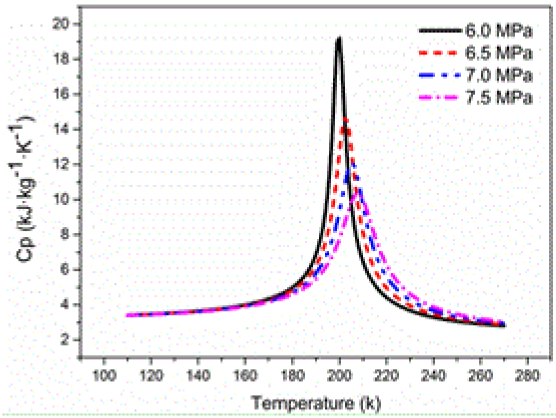
$$Nu = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \tag{6}$$

Formula (2), (3), (4), (5) and (6) formed the simultaneous equations, which can obtain the relation between surface heat transfer coefficient and physical property parameters of fluid, and the relation is expressed as:

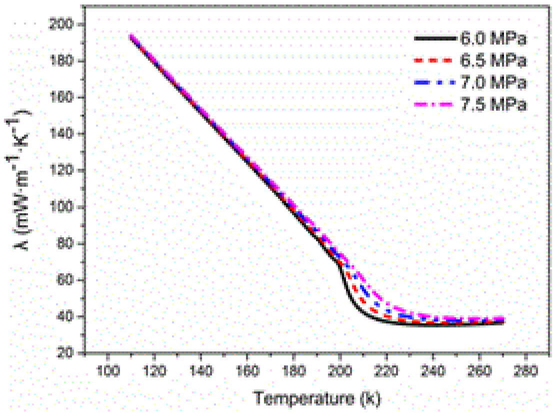
$$\mathrm{h} = 0.0279 \lambda^{0.6} \cdot d^{-1.8} \cdot \mu^{-0.4} c_p{}^{0.4} \cdot q_m{}^{0.8} \tag{7}$$

It was known that the surface heat transfer coefficient was affected by thermal conductivity, pipe diameter, viscosity, specific heat and mass flow rate by formula (7). However, the surface heat transfer coefficient was only affected by thermal conductivity, viscosity and specific heat when the pipe diameter and mass flow rate were constant. Fig. 9 shows the curves of specific heat, thermal conductivity and viscosity of methane under four kinds of operating pressures. Thermal conductivity and viscosity of methane decreased sharply in the critical region but the specific heat increased sharply in the critical region, as shown in Fig. 9. When the operating pressure was less than 7.0 MPa, the specific heat in the critical region increased by an order of magnitude, however, the viscosity and thermal conductivity decreased within the same order of magnitude. According to the formula (7), in the critical region, specific heat was the main factors that affected the surface heat transfer coefficient under the same mass flow rate. Because of the changing trends and characteristics of specific heat near the extreme point, the surface heat transfer coefficient increased in the critical region and appeared the maximum point near the conductivity of the extreme point of specific heat, which indicated that the heat transfer coefficient increased and the heat transfer process was enhanced in the critical region. In the monotonically decreasing region of specific heat, methane was completely transformed into supercritical fluid. The specific heat and thermal methane were both reduced and the viscosity tended to be stable, which made the surface heat transfer coefficient decreased continuously. Especially under the condition of low mass flow rate, the surface heat transfer coefficient was further reduced. Therefore, the phenomenon of heat transfer deterioration occurred when the methane was completely transformed into supercritical fluid in the second half of the heat exchange tube. When the pressure was greater than 7.0 MPa, the increase of specific heat in the critical region decreased significantly, which made the increasing trend of surface heat transfer coefficient unobvious near the extreme point of specific heat and the extreme point of surface heat transfer coefficient disappeared. Zhou [17] studied the influences of mass flow rate on the heat transfer of supercritical LNG in the horizontal pipe and found that the maximum point of surface heat transfer coefficient occurred in the critical region, but the phenomenon of heat transfer deterioration in the second half of the heat exchange tube was not found under the condition of low mass flow rate. Li et al. [7] studied the characteristics of the flow and heat transfer process of the supercritical LNG in tube. The result that the maximum point of surface heat transfer coefficient occurred in the critical region was successfully predicted by numerical simulation and Dittus-Boelter formula, however, the phenomenon of heat transfer deterioration in the second half of the heat exchange tube was still not found under the condition of low mass flow rate. The above analysis and research showed that the heat transfer process in the tube can be enhanced in the critical region when the operating pressure was less than 7.0 MPa. The flow velocity increased with increase of the mass flow rate, which resulted in the increase of the disturbance of fluid. The thermal boundary layer of the fluid and the velocity boundary layer became thin, which was conducive to the convective heat transfer. Therefore, increasing the inlet mass flow rate of LNG made the surface heat transfer coefficient at the same position of the tube significantly improved. The position of heat transfer deterioration went backwards, and the range of heat transfer deterioration became smaller. Wang et al. [18] found that the increase of mass flow rate of LNG can make the surface heat transfer coefficient increased by analyzing the heat transfer process of supercritical LNG in the IFV. Du et al. [19] obtained the same conclusion as Wang by the numerical simulation of cooling heat transfer to supercritical methane in vertical circular tube. Therefore, it was suggested that the mass flow rate should be improved appropriately to increase the surface heat transfer coefficient and enhance the heat transfer process. Meanwhile, the range of heat transfer deterioration became smaller, and the phenomenon of heat transfer deterioration was improve.

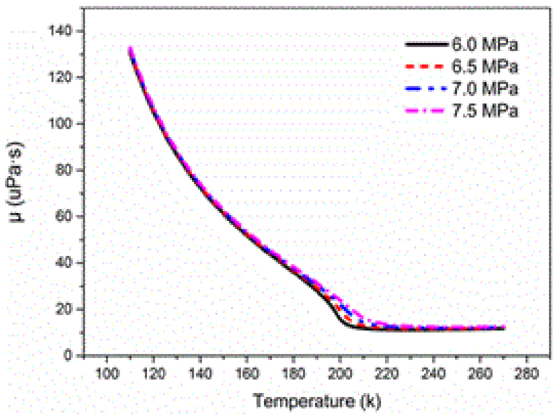
The change of the specific heat under different operating pressures was the most significant near the extreme point of specific heat of methane, as shown in Fig. 9. Thus, near the extreme point of specific heat, surface heat transfer coefficient was mainly affected by specific heat. The specific heat near the extreme point decreased sharply with the increase of operating pressure, which led to the decrease of surface heat transfer coefficient. In the region away from the extreme point of specific heat, the physical properties of methane under different operating pressures were very close, as shown in Fig. 9(a-c).



(a) Specific heat



(b) Thermal conductivity



(c) Viscosity

Fig. 9. Physical properties of methane under different pressures.

Therefore, the change of the operating pressure had little effect on the surface heat transfer coefficient under the same mass flow rate. Because of the differences of the surface heat transfer coefficient under different operating pressures near the extreme point of specific heat, the average surface heat transfer coefficient was decreased with the increase of operating pressure. Pu [1] also found that the surface heat transfer coefficient decreased with the increase of operating pressure by the thermal performance analysis of IFV for LNG. However, Jin [11] obtained the opposite conclusion that the surface heat transfer coefficient increased with the increase of operating pressure. The reason why Jin got the opposite conclusion might be because of the difference of the heat exchange environment outside the heat exchange tube. Jin studied the flow and heat transfer process of the supercritical LNG in the submerged-combustion vaporizer, whose heat exchange environment outside the heat exchange tube is water bath environment, but the heat exchange environment in this paper is saturated propane steam. Thus, the difference of the heat exchange environment outside the heat exchange tube resulted in the different change laws of surface heat transfer coefficient inside the heat exchange tube.

Due to the limitation of the length of this paper, only the part of straight tube of the heat exchange tube was studied. The flow and heat transfer process of LNG in the elbow part will be further analyzed in the follow-up work.

CONCLUSIONS

In this paper, the flow and heat transfer process of LNG in the IFV condenser was analysed by numerical simulation. The effects of inlet mass flow rate and operating pressure on the flow and heat transfer process were studied respectively. The following conclusions are obtained:

1) The heat transfer process of LNG can be enhanced in the critical region when the operating pressure was less than 7.0 MPa, but it was not conducive for LNG to convective heat transfer in supercritical state. It appeared the phenomenon of heat transfer deterioration in the second half of the heat exchange tube especially under the condition of low mass flow rate.

2) Increased mass flow rate can enhance heat transfer, which effectively improved the phenomenon of heat transfer deterioration. The average surface heat transfer coefficient was improved by 13.56%, which was caused by the increase of the average mass flow rate of 0. 01kg/s.

3) Increased operating pressure made the average surface heat transfer coefficient lower, and the average surface heat transfer coefficient was decreased by 1%, which was caused by the increase of the average operating pressure of 0.5 MPa.

4) When the operating pressure was greater than 7.0 MPa, the phenomenon of heat transfer enhancement in the critical region disappeared, and the surface heat transfer coefficient decreased continuously. It was suggested that the IFV condenser should be operated under the pressure of less than 7.0 MPa.

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