Thermodynamic Properties of Oil Droplets Impacting on Chamber Wall in Oil-Injected Screw Compressors

Di Yan, Bo Peng, and Guo Xiao

Abstract As a typical type of positive displacement compressor, screw compressors are widely used in a variety of industrial sectors with a fast-growing trend, especially boosted by the application of oil injection technology. The oil injection process inside the screw compressor is complicated and difficult to observe directly by experiment, as is the accompanying heat transfer process. Since the contact time between the oil and the gas is very short due to the rotation of the rotors, the main object of study remains the heat transfer between the droplet and the chamber wall. In order to investigate the liquid–gas two-phase flow in the compression chamber after oil injection, the Level Set Method is adopted to simulate the impacting process of oil droplet on hot wall with oil film, the influence of oil injection parameters on the heat transfer between oil droplets and wall was analyzed theoretically. The present study contributes to further understanding and accurate prediction of the heat transfer process in oil-injected screw compressors, which is important for improving the energy efficiency of screw compressors. In addition, this research is not only relevant to screw compressor, but also has universal significance for liquid injection technology.

Keywords Oil-injected screw compressor · Oil injection parameters · Oil film · Droplet impact · Heat transfer

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1 Introduction

Screw compressors are one of the most widely used rotary compressors. The most common type of screw compressor is the oil-injected compressor, which accounts for 88% of the total. The first oil-injected screw compressor was developed in 1954 and commercialized in 1957 [1, 2]. Oil-injected machines were preferred over oil-free and water-injected machines because they could reach high pressures in a single stage, are simple in structure, easy to maintain, and were stable and reliable. Therefore, since then, oil-injected twin-screw compressors have occupied an important position in the compressor market at a very fast pace. However, with the gradual improvement of technical requirements such as energy saving and environmental protection, the performance of oil-injected screw compressors is becoming more and more demanding. The energy efficiency has become a key indicator to determine its future development [3–6].

The object of this paper is to investigate the heat transfer in the compression chamber when the oil droplets impact on the chamber wall when the compressor is working. Although there is heat transfer between the gas in the chamber and the oil droplets, it is relatively small, because the contact time between oil and gas is very short due to the rotation of rotors [7]. Therefore, the research object of this paper is mainly about the heat transfer process between the oil droplets and the chamber wall.

In addition to the heat transfer between the droplets and the gas, the heat transfer of the droplets impacting on the chamber wall is an important influence factor in the oil injection cooling process of screw compressors [8]. The heat transfer characteristics during the impacting are closely related to the dynamic characteristics. Therefore, this paper carried out numerical modelling on the impacting process of oil droplets on chamber wall with oil film, analyzed the heat transfer characteristics under different impact parameters, and explored the influence of droplet diameter, droplet velocity, droplet temperature and oil film thickness on heat transfer characteristics. It helps better understanding of heat transfer during the actual working process of oil injection screw compressor.

2 Computational Model

2.1 Model Parameters and Boundary Settings

A two-dimensional model was adopted for numerical simulation, as shown in Fig. 1. The calculation space is a rectangle of 6 mm $\times$ 4 mm, the working medium is gas and oil, and the surface tension coefficient is 0.04 N/m. The boundary conditions of the upper side and the left and right sides were set as open boundary, the bottom was set as constant temperature hot wall boundary and was adiabatic and non-slip, the contact angle of the wall was 60°, and the initial shape of the oil drop was spherical.

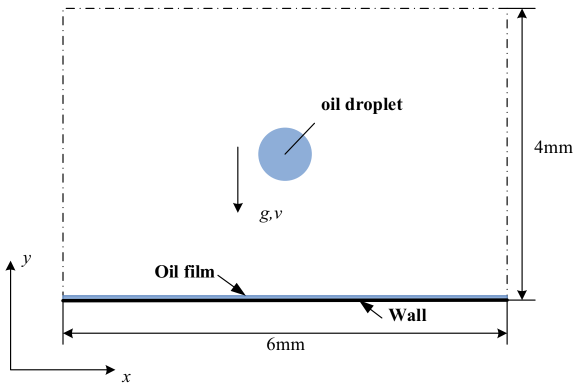


Fig. 1 Geometric model of oil droplet impact on wall

2.2 Governing Equations

The numerical simulation of oil droplets impacting the wall follows three fundamental laws, namely, conservation of mass, momentum and energy. In the meantime, the surface tension and the Marangoni effect between the oil droplets and the hot wall surface should be taken into account. The Level Set Method in COMSOL is used to study the impact of oil droplets on the wall, assuming a gas–liquid two-phase flow as an incompressible flow. The mass and momentum transfer can be described by the incompressible Navier–Stokes equations as follows.

$$\rho\frac{\delta \mathrm{u}}{\delta \mathrm{t}} + \rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -p\nabla\cdot\boldsymbol{I} + \nabla\cdot\mu\big((\nabla\boldsymbol{u})^T + \nabla\boldsymbol{u}\big) + \rho g + F_{st} \tag{1}$$

$$\nabla\cdot\boldsymbol{u} = 0 \tag{2}$$

In the above equations, ρ is density, u is speed, t is time, p is the pressure, μ is viscosity. Momentum equation contains gravity ρg and the surface tension component represented by F_{st}.

Surface tension is defined by the following formula.

$$F_{st} = \nabla\cdot\mathbf{T} = \nabla\cdot\left[\sigma\left\{\mathbf{I} + \left(-\mathbf{nn}^{\mathrm{T}}\right)\right\}\delta\right] \tag{3}$$

where σ is the surface tension coefficient, **I** is the identity matrix, **n** is the interface unit normal, δ is the Dirac delta function. This function is non-zero only at the fluid interface.

The energy conservation equation is

$$\frac{\delta\left(c_p PT\right)}{\delta t} + \rho\nabla\cdot\left(\boldsymbol{u}c_pT\right) = \nabla\cdot(\lambda\nabla T) \tag{4}$$

where T is temperature, c_p is the specific heat capacity, λ is the heat transfer coefficient.

In addition, considering that the oil droplet is heated by the hot wall surface during the impact process, which leads to the change of temperature inside the droplet. The temperature at the contact point with the wall is higher, and the temperature at the center of the oil droplet is the lowest. The uneven temperature distribution will lead to the formation of temperature gradient. The temperature gradient creates a surface tension gradient on the surface of the oil drop, resulting in the Marangoni effect, which can be expressed as follows,

$$\tau = \frac{\delta\sigma}{\delta T}\nabla T \tag{5}$$

2.3 Grid Independence Verification

Taking the numerical model of oil droplet impact on dry wall as an example, the numerical simulation results under different mesh numbers were compared and analyzed to test the grid independence. In this case, three kinds of mesh quantities, 17,817, 31,750 and 89,886, are adopted respectively. The initial diameter of the oil droplet D_0 is 1 mm, the velocity of the oil droplet v_0 is 1 m/s, the initial temperature of the oil droplet T_o is 313 K, and the wall temperature T_w is 373 K. The spreading diameter D of the oil droplet after impacting the wall under different grid division is calculated. The results are shown in Fig. 2.

It can be found that when the number of grids is 31,750 and 89,886, the variation of oil droplet spreading diameter with time is very close. However, when the grid

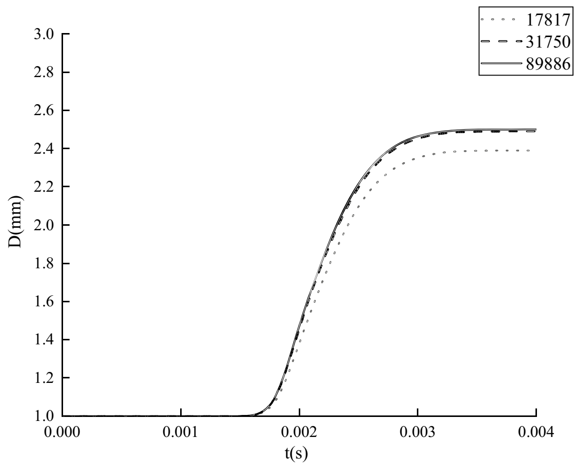


Fig. 2 Grid independence verification

number is 17,817, there is an obvious difference in the spread diameter of oil droplets. Therefore, the numerical model adopts the division method of the grid number of oil droplets is 31,750, which can ensure the calculation accuracy and save the calculation time and cost. All the subsequent simulation calculations of oil droplets against the wall adopt the grid number of 31,750. Therefore, the numerical model adopts the grid division method with the mesh number of 31,750, which can ensure the calculation accuracy and save the calculation time and cost. The grid number of 31,750 is adopted in all subsequent simulations of droplet impacting.

3 Oil Film Heat Transfer with Droplet Impacting on the Wall

The phenomenon of oil droplet impacting the wall is a continuous process in the actual working process of oil-injected screw compressor. When oil droplets impact the dry wall surface, some of the droplets break and splash, and the residual oil droplets adhere to the wall surface. After a period of time, the oil droplet will form an oil film on the wall surface, and then the subsequent oil droplet will impact oil film on the wall. Therefore, the heat flux of the wall can be written as:

$$q = h \times \left(T_w - T_f\right) \tag{6}$$

where h is surface convective heat transfer coefficient; T_w is wall temperature; T_f is the average temperature of the oil film in contact with the wall.

In this paper, a numerical study is carried out to reveal the heat transfer characteristics of the droplets impacting on the chamber wall under the action of the oil film. The relationship between dynamic characteristics of oil droplets and heat transfer characteristics is analyzed, and the effects of oil film thickness, oil drop temperature, initial velocity and diameter on heat transfer are obtained, which helps to understand the actual cooling process inside oil-injected screw compressor from the oil droplet's point of view.

3.1 The Influence of Oil Film Thickness

Oil film thickness is an important parameter that influences the heat transfer characteristics when oil droplets impact on the wall. The impacting process was analyzed numerically under different thickness of oil film, among which, the initial diameter of droplet is set as 1 mm and initial temperature 313 K. The thickness of the oil film is 0.1, 0.15 and 0.2 mm, the velocity of the oil drop is 1 m/s, and the temperature of the wall and the oil film is 373 K.

Figure 3 shows the temperature changes after the oil droplets impact the film with thicknesses of 0.1 mm, 0.15 mm and 0.2 mm, respectively. It can be seen that, in the initial stage of impact, the maximum splashing height of jet generated when the oil droplet hits the oil film of 0.2 mm; the oil film of 0.15 mm follows behind; the lowest splash height is produced on the oil film of 0.1 mm. After the impact, the oil droplet disturbs the oil film under the action of force, which is the main reason for the generation of jet. For 0.1 mm oil film, the disturbance is the largest, so the jet flow is higher. On the contrary, the disturbance for 0.2 mm film is the smallest, so the jet flow is the lowest. On the other hand, the smaller the thickness of the oil film, the larger the spreading diameter of the oil droplet. This is because when the oil droplets hit the thinner oil film, they are less affected by the surface tension of the oil film. It can also be found from the figure that the smaller the thickness of the oil film, the faster the heat transfer between the droplet and the oil film, so the faster the internal temperature of the oil droplet rises.

As shown in Fig. 4, the wall heat flux generally presents similar changes under different oil film thicknesses. The smaller the oil film thickness is, the larger the wall heat flux is, and the faster the increase is, the shorter the time it takes to reach the

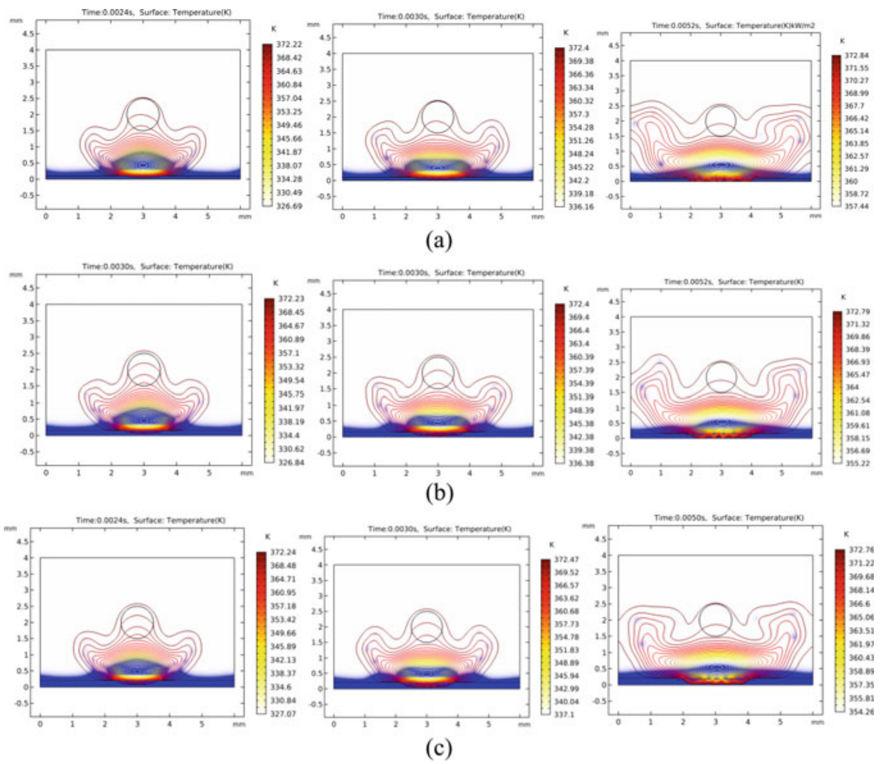


Fig. 3 Temperature distribution diagram of oil droplet impacting oil film with different thickness **a** h = 0.1 mm; **b** h = 0.15 mm; **c** h = 0.2 mm

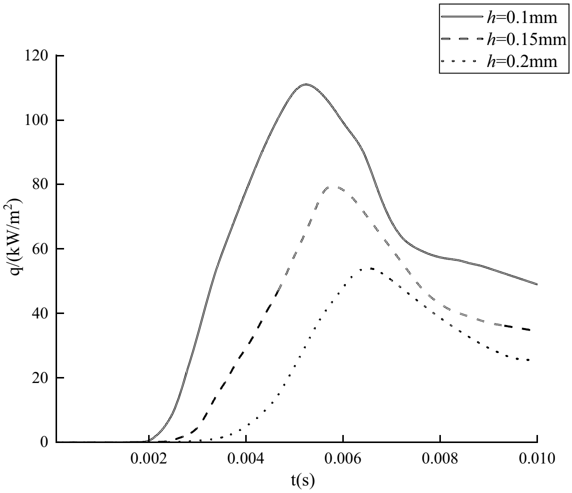


Fig. 4 Influence of oil film thickness on wall heat flux

maximum wall heat flux is. When h is 0.1 mm, 0.15 mm and 0.2 mm respectively, the corresponding maximum wall heat flux is 111.45, 79.81 and 54.02 kW/m^2. It can be seen that the wall heat flux is closely related to the oil film thickness. The smaller the oil film thickness is, the faster the wall heat flux increases, and the easier the heat transfer between the oil droplet and the wall surface is. According to the analysis, this is because the oil droplet impacts the oil film wall with a small thickness, the viscous resistance of the oil film is small, and the disturbance of the oil droplet to the wall is large. Therefore, the heat transfer capacity between the oil droplets and the wall is large, which increases the heat flux of the wall in the impact area of the oil droplet. In addition, the smaller the thickness of the oil film, the more obvious the spreading feature of the oil droplet. The greater the pressure at the interface between the impact zone and the non-impact zone of the oil droplet spreading edge, the greater the disturbance to the wall surface, so as to improve the wall heat flux at the interface of the spread edge.

3.2 *The Influence of Oil Drop Temperature*

The heat transfer characteristic of droplet impacting on oil film is simulated by changing the initial temperature of oil droplets. The initial temperature of the oil droplet is 293 K, 313 K and 333 K respectively, and the temperature of the wall and oil film is set to 373 K. The oil droplet with diameter of 1 mm falls down at a speed of 1 m/s to impact the oil film with a thickness of 0.1 mm. The temperature distribution during the process of oil droplets impacting the oil film at different temperatures are as Fig. 5a–c. Because the time of oil droplets reaching the maximum spreading width

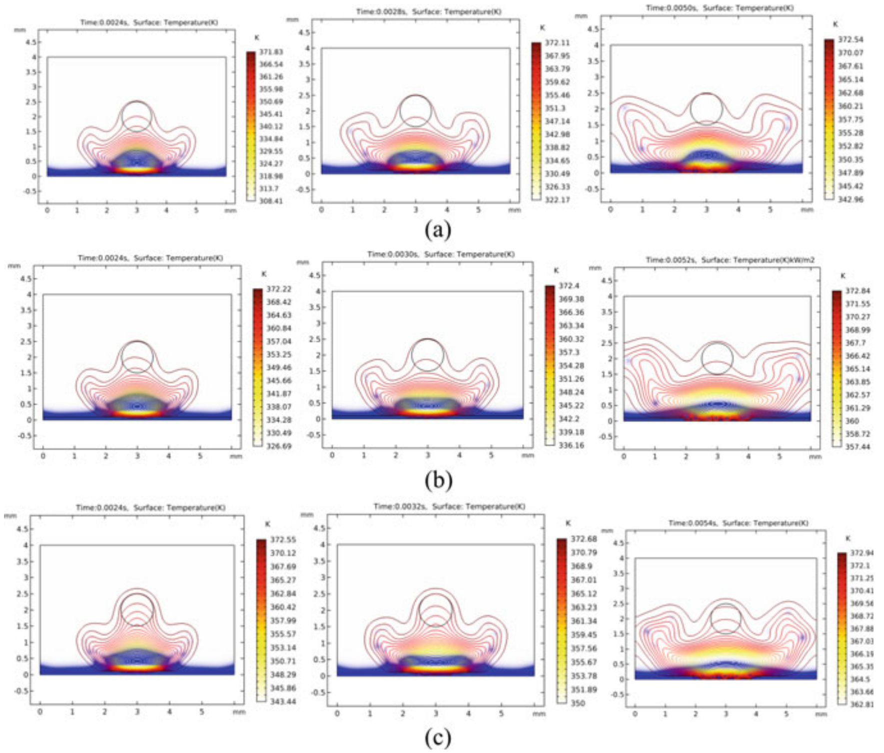


Fig. 5 Temperature distribution diagram of oil droplet impacting oil film at different temperatures. **a** $T_o = 293$ K; **b** $T_o = 313$ K; **c** $T_o = 333$ K

after impacting the wall at different temperatures are different, sampling time of the three figures are inconsistent.

It can be seen from the simulation results that the jet splashing heights generated by the oil droplet impacting the oil film at different temperatures are very close, which indicates that the correlation between the jet height and the temperature of the oil droplet is small, it also means that the Marangoni effect caused by heat transfer has negligible influence on the jet height during the process of droplet impacting.

In addition, as the temperature of the oil droplet decreases gradually, the time for the oil droplet to reach the maximum spreading diameter becomes faster, reaching the maximum spreading diameter at 0.0032 s, 0.0030 s and 0.0028 s, respectively. From the perspective of heat transfer, with the impacting process of the oil droplet, the lower the temperature of the droplet, which also means the greater the temperature difference, the faster the heat transfer in contact area with the oil film. Moreover, with the decrease of the temperature of oil droplet, the temperature variation range of the oil film is also larger, so the heat transfer ability between the oil film and the wall is also larger.

Fig. 6 Influence of oil drop temperature on wall heat flux

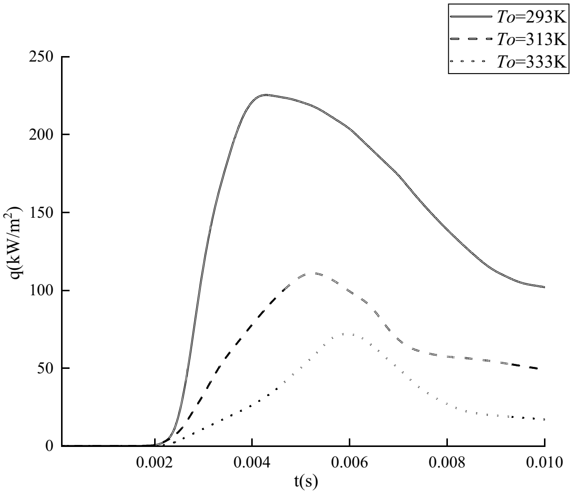


Figure 6 shows the change of wall heat flux with time under different oil drop temperatures. On the whole, when oil droplets with different initial temperatures impact the oil film, the wall heat flux changes in the same trend with time, showing a trend of firstly increasing and then decreasing.

The higher the oil droplet temperature is, the smaller the maximum wall heat flux value is. This is because the higher temperature of the oil droplets means the smaller the temperature difference. When the oil droplet contacts with the oil film, the oil droplet in the impact center has less disturbance to the wall surface, and the wall heat flux changes less. Specifically, at the initial stage when the oil droplets contact the wall, the temperature difference between the oil droplets and the wall surface is large. With the spread of the oil droplets, the heat flux of the wall surface gradually increases until it reaches a certain peak value. The corresponding maximum heat flux is 225.88 kW/m^2, 111.45 kW/m^2 and 72.05 kW/m^2 respectively. After that, because the oil droplet stays on the oil film, its temperature rises, which leads to the decrease of heat transfer, and the maximum heat flux under the temperature of the three oil drops decreases to a relatively small value.

3.3 The Influence of Oil Droplet Velocity

In order to study the influence of the oil droplet velocity on the heat transfer characteristics of the oil droplet impacting the wall with oil film, the oil droplets with diameter of 1 mm and temperature of 313 K impact the oil film with thickness of 0.1 mm on the wall at the velocity of 0.8 m/s, 1.0 m/s and 1.2 m/s, respectively, and the impact process was studied by numerical simulation. Where, the wall contact angle is 60°, and the oil film temperature and wall temperature are both 373 K.

Figure 7 shows the temperature distribution after oil droplets impact the oil film with different speeds. It can be seen that when the initial velocity of the oil drop is 1.2 m/s, the splash height is the highest; when the velocity decreases to 1 m/s, the splash height decreases slightly. This is because the kinetic energy of the droplet during impact decreases and the disturbance to the oil film decreases as a result of the decreased velocity, so the splash height decreases. When the velocity decreases to 0.8 m/s, there is no obvious splash. This is because at this time, the surface tension of the oil film is slightly stronger than the inertial force, and the oil droplets spread on the surface of the oil film, so only a "crown" shaped jet is generated. In addition, the larger the velocity of oil droplets, the larger the spreading diameter of oil droplets on the oil film. With the gradual increase of the velocity of oil droplets, the time for droplets to reach the maximum spreading diameter is faster, and the maximum spreading diameter is reached at 0.0034 s, 0.0030 s and 0.0028 s respectively. Based on the above two factors, it can be concluded that the larger the velocity of the oil droplet, the faster the temperature rise at the contact area of the wall. The oil droplet with a larger initial velocity has a larger impact kinetic energy and a larger heat transfer capacity between it and the wall.

Figure 8 shows the changes of heat flux on the wall after the oil droplets hit the oil film at different speeds. As can be seen from the figure, wall heat flux changes with different initial velocities of oil droplets are similar. At the initial moment of wall collision, due to the effect of the surface tension of the oil film, the spread diameter of the oil droplets is relatively small, and the heat transfer between the oil droplets and the oil film is large, while the heat transfer between the oil droplets and the wall surface is small, so the wall heat flux is also relatively small. The maximum heat flux from small to large velocity is 85.20 kW/m^2, 111.45 kW/m^2 and 156.77 kW/m^2, respectively.

With the gradual increase of the spread diameter of the oil droplet, the disturbance between the oil droplet and the oil film also increases correspondingly, and the wall heat flux increases gradually. However, when the wall heat flux reaches the maximum, it gradually decreases and becomes stable. It can be seen that increasing the droplet velocity can promote the heat transfer between the oil droplet and the wall surface. Meanwhile, the larger the initial velocity of the oil droplet is, the larger the heat transfer coefficient is. Therefore, the total heat flow corresponding to the oil droplet with a higher velocity rises faster and the heat flux also rises rapidly.

3.4 The Influence of Oil Droplet Diameter

The change of oil droplet diameter directly affects its contact area with the wall surface, which is also closely related to the change of heat transfer characteristics. In order to analyze the influence of oil droplet diameter on heat transfer characteristics, t simulation was carried out for the impact of 0.6 mm, 0.8 mm and 1 mm oil droplets on 0.1 mm oil film with an initial temperature of 313 K and a velocity of 1 m/s. The

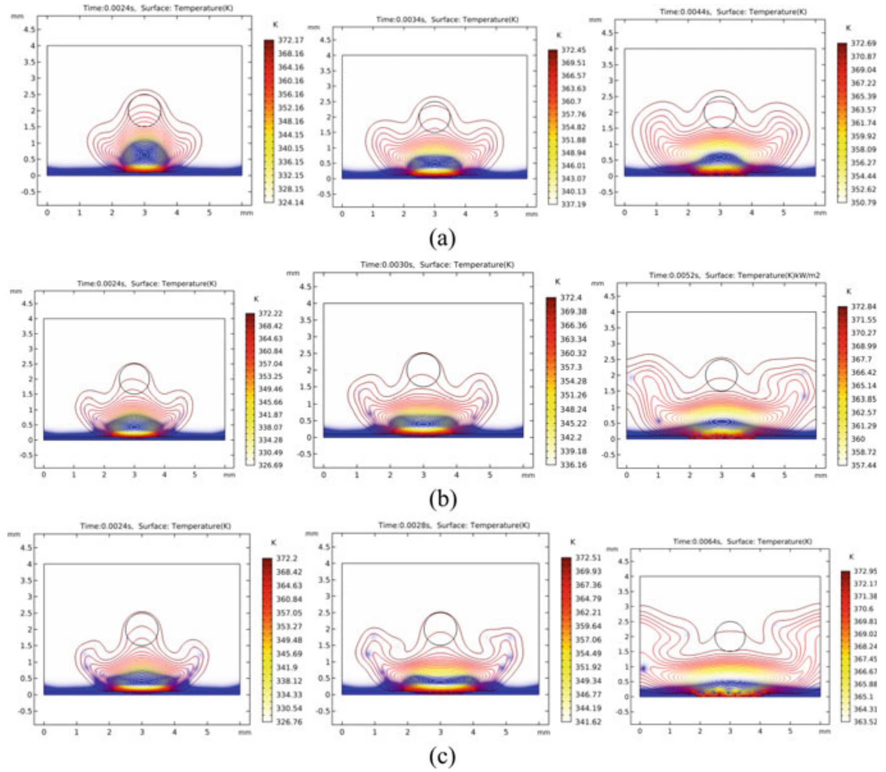
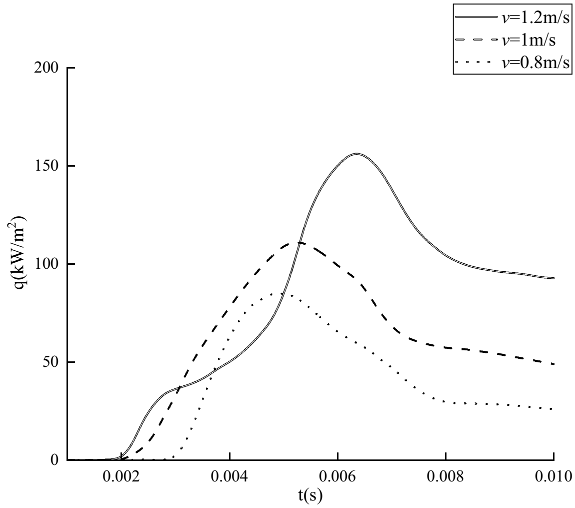


Fig. 7 Temperature distribution of oil droplet impacting oil film at different speeds. **a** v = 0.8 m/s; **b** v = 1 m/s; **c** v = 1.2 m/s

Fig. 8 Influence of oil drop velocity on wall heat flux



wall contact angle was 60°, and the oil film temperature was the same as the wall temperature, both being 373 K.

Figure 9 shows the temperature distribution diagram during the impact of three oil droplets with different diameters on the oil film. It can be found that the larger the initial diameter of the oil droplets is, the higher the splash height will be. There is no obvious jet flow. This is because the diameter is small and the surface tension of the oil film is stronger than the inertial force, so the oil drops spread on the surface of the oil film. In addition, the increase of the diameter also increases the maximum spreading diameter of the oil droplet, and the spreading diameter of the oil droplet with a diameter of 1 mm is the largest when it hits the oil film. The spreading diameter of 0.6 mm oil drop is the smallest after hitting the oil film. From the perspective of heat transfer, at the same time (0.0024 s), the smaller the diameter of the oil droplet, its overall temperature is more affected by the oil film and wall surface, and the smaller the diameter of the oil droplet into the oil film faster, so the internal temperature of the oil droplet rises faster.

As can be seen from Fig. 10, increasing the diameter of the oil droplet significantly increases the wall heat flux, among which the maximum heat flux reached by the

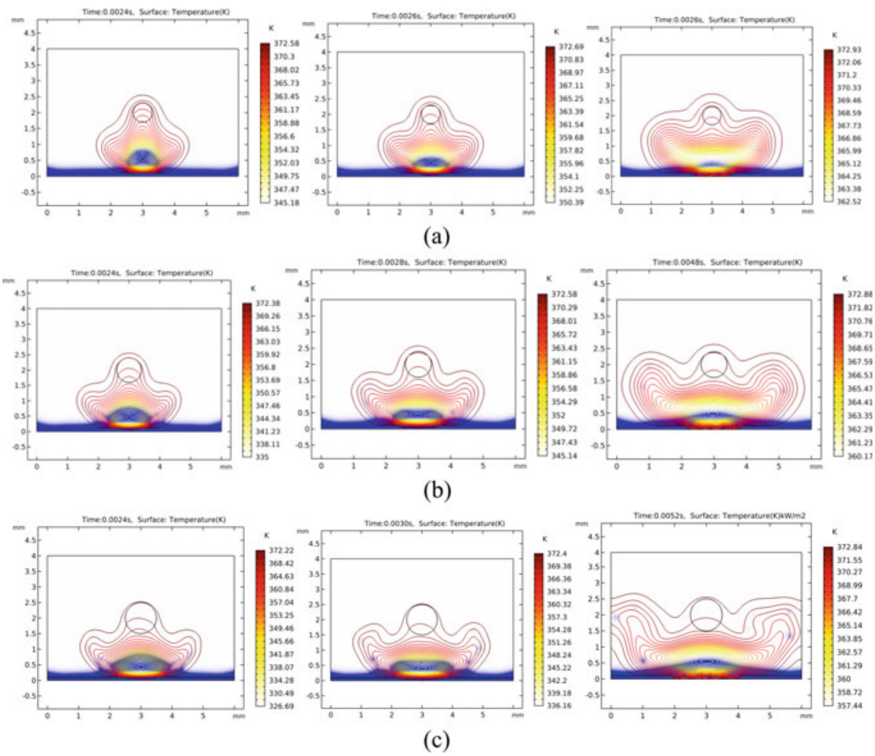


Fig. 9 Temperature distribution of oil droplet impacting oil film with different droplet diameters. **a** $D_o = 0.6$ mm; **b** $D_o = 0.8$ mm; **c** $D_o = 1$ mm

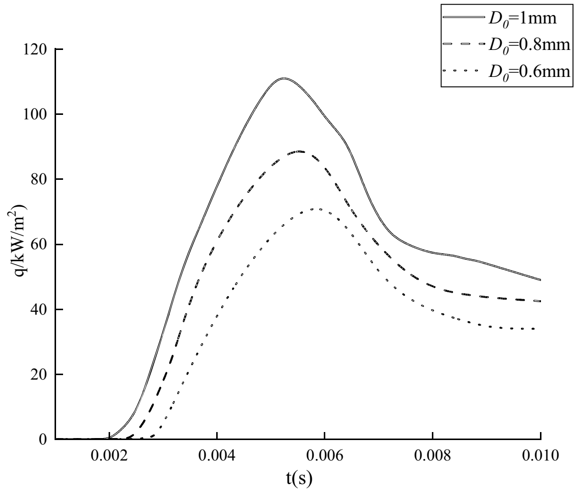


Fig. 10 Influence of oil drop diameter on wall heat flux

oil droplet with diameter of 0.6 mm, 0.8 mm and 1 mm after impacting the wall is 111.45 kW/m^2, 90.45 kW/m^2 and 68.03 kW/m^2, respectively. The increase in the diameter of the oil drop brings more oil into contact with the wall, and thus more heat is exchanged. The reason for this situation is that the oil droplet with a large diameter has a larger inertia and is easy to form a larger spreading area on the oil film, which promotes heat transfer between the oil film and the oil film. The temperature rise of the oil film is higher, the temperature difference between the oil film and the wall decreases, and the heat flux of the wall is smaller. In the subsequent stage, due to the gradual integration of the oil droplets into the oil film over time, the temperature difference between the oil and the wall decreases, so that the corresponding wall heat flow of the oil droplets of these three diameters gradually decreases and eventually tends to be similar.

4 Conclusions

In this paper, the heat transfer characteristics of the oil droplet impacting on the oil film wall under different conditions were numerically studied by the Level Set Method. The influence of oil droplet temperature, oil droplet velocity, oil droplet diameter and oil film thickness on heat transfer during the impact process was explored, and the variation law of the droplet morphology, temperature field and wall heat flux were analyzed.

Similar to the process of oil droplet impacting the dry wall surface, under different conditions, after oil droplet impacting the wall with oil film, the heat flux of the wall surface changes with time in the same trend, showing a trend of firstly increasing and then decreasing. However, the difference is that the “crown” shaped jet splashing motion will be generated after the oil droplet hits the oil film. The shape and size of the splashing motion will also change with the change of the impact conditions.

It is found that the thinner the oil film thickness is, the higher the relative jet height is, the more obvious the jet splash is, and the greater the impact disturbance of the oil droplet on the wall oil film is. Therefore, the greater the heat transfer capacity between the oil droplet and the wall surface is, and the greater the maximum heat flux of the wall surface is.

The higher the temperature of the oil droplet is, that is, the smaller the temperature difference between the oil droplet and the oil film. When the oil droplet impacts the oil film, the smaller the splash height is generated. The disturbance of oil droplets in the impact center to the oil film on the wall is relatively small, so is the maximum wall heat flux.

However, when the diameter and initial velocity of the oil droplet increase, the higher the height of the jet generated after the droplet impinging on the oil film of the same thickness, the larger the spreading area on the oil film, and the larger the disturbance to the oil film. This helps to promote the heat transfer between the oil film and the wall surface, and the peak value of the wall heat flux also increases.

This research provides reference for the optimization of oil injection parameters and the improvement of energy efficiency of screw compressors.

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