A Comprehensive Study of Dynamic and Heat Transfer Characteristics of Droplet Impact on Micro-Scale Rectangular Grooved Surface

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Abstract: Micro-scale structure of impact surface has a significant effect on the droplet impact. In this study, a three-dimensional numerical model of the droplet impact on micro-scale rectangular grooved surface was established based on coupled level set and volume of fluid (CLSVOF) method. Furthermore, the evolution of droplet morphology was experimentally studied and the validation of numerical model was carried out. The effects of groove width, contact angle, impact velocity and surface temperature on dynamic and heat transfer characteristics of droplet impact at low Weber numbers were numerically investigated. The anisotropy coefficient is defined to investigate the anisotropy of droplet morphology caused by the micro-scale grooved structure. The numerical results show that vertical spreading diameter is less than parallel spreading diameter, and the anisotropy of droplet morphology tends to reduce gradually with increasing contact angle. Both dynamic and heat transfer characteristics of droplet impact are the coupling effect of contact angle and groove width. The analysis of wettability state is utilized to illuminate the heat transfer characteristics of grooved surface. The maximum heat transfer rate of grooved surface increases with increasing impact velocity and surface temperature, and it decreases with increasing contact angle.

Keywords: droplet impact; spreading; groove width; anisotropy; wettability state; heat transfer

1. Introduction

Droplet impact phenomenon widely exists in industrial applications, such as fuel injection of internal-combustion engines, spray cooling, ink-jet printing and so on [1–3]. The study of droplet impact is extremely significant for practical engineering applications. Especially in recent years, the thermal dissipation is more and more severe with the development of electronics industry. Spray cooling has extensive applications in heat removing of electronic components. The process of droplet impact process is a typical free surface flow phenomenon with complex mechanism. It is affected by many factors such as physical parameters of droplet, impact surface characteristics, impact angle and so on. In the last decades, many researchers have conducted the research on the behavior of a droplet impact on flat surface by means of experimental method or numerical method [4–12]. Micro-scale structure of impact surface has a significant effect on the droplet impact. With the development of micro-fabrication technology such as lithography, micro CNC, the studies on the phenomenon of droplet impact on micro-scale textured surface increase gradually in recent years [13].

Malla et al. [14] conducted certain studies on the droplet impact on micro-grooved surface experimentally, and found some parameters are the key factors influencing droplet impact, such as groove pitch and Weber number. Lee et al. [15] experimentally studied droplet impact on hydrophobic textured surfaces. The spreading and dynamic wetting characteristics of droplet were analyzed with different impact velocities and surface properties. Vaikuntanathan et al. [16] experimentally...
investigated the spreading characteristics of droplet impact on textured surfaces with unidirectional parallel grooves at different Weber numbers. Furthermore, a unified model was formulated to predict the maximum spreading of droplet. Kannan and Sivakumar [17,18] investigated the spreading and receding processes of drop impact on different hydrophobic grooved surfaces by means of experimental method, and the comparison of droplet impact on grooved surface and smooth surface was performed. Song et al. [19] reported the experimental investigation on spreading process of droplet impact on partially grooved PDMS surface. The droplet contact angles were analyzed in different directions. Patil et al. [20] performed the experimental study on the impact dynamics of droplet impact on grooved surfaces by using high-speed photography. The wetted diameter and droplet height were discussed with different pillar pitches and impact velocities. Khan et al. [21] experimentally studied the droplet impact on solid surface with V-groove, and the effect of inertia on liquid wicking kinetics was discussed. This study is expected to improve inkjet print quality. Hao et al. [22] conducted the experimental research on water droplet impinging on micro-structured surface. The critical impact velocity and dynamic wetting behavior during impact process were studied. Hu et al. [23] used the high-speed camera system to perform experimental study on droplet impact on grooved surface with different micro-patterns. The dynamic behaviors of drop impact at different Weber numbers were investigated. Moon et al. [24] experimentally investigated the process of droplet impact on heated textured surfaces with different surface temperatures, texture areas and Weber numbers. The correlation between heat transfer characteristics and dynamic wetting state was discussed. Parizi et al. [25] established the three-dimensional numerical modeling of droplet impact on patterned surfaces by using volume of fluid (VOF) method. The Effects of solidification and surface roughness on the final splat shape were studied. Wang et al. [26] applied the many-body dissipative particle dynamics (MDPD) method to simulate the dynamics of droplet impact on textured surfaces in a hybrid state. The validation of numerical method was performed and influence of the microstructure was analyzed. Lee and Son [27] conducted simulation of droplet impact on a rectangular microgroove by employing level set (LS) method. The filling process of droplet was analyzed with different surface properties and impact velocities.

As mentioned above, there are numerous studies on dynamic characteristics of droplet impact on micro-scale textured surface. However, there are few studies on heat transfer characteristics of droplet impact on micro-scale textured surface. The study on the effect of micro-scale structure on heat transfer characteristics of droplet impact process is significant to the optimization of thermal control. Moreover, most studies on the droplet impact on micro-scale textured surface have focused on the experimental method, which rarely involve the numerical method. The cost of numerical study is lower than experimental study, and the research content of numerical study is more flexible.

In this work, a three-dimensional numerical model of the droplet impact on micro-scale rectangular grooved surface was established based on coupled level set and volume of fluid (CLSVOF) method. Furthermore, the evolution of droplet morphology was experimentally studied and the validation of numerical model was carried out. The effects of groove width, contact angle, impact velocity and surface temperature on dynamic and heat transfer characteristics of droplet impact at low Weber numbers were numerically investigated. The anisotropy coefficient is defined to investigate the anisotropy of droplet morphology caused by the micro-scale grooved structure. The analysis of wettability state is utilized to illuminate the heat transfer characteristics of grooved surface. This work has reference values for the thermal control with micro-scale grooved structure and the optimization of spray cooling system.
2. Numerical Model and Experimental Study

2.1. Numerical Method

The coupled level set and volume of fluid (CLSVOF) method is utilized to perform numerical study, and it is more accurate than both the standalone level set method and volume of fluid method [28]. The governing equations of coupled level set and volume of fluid method are [29]:

\[ \nabla \cdot U = 0 \quad (1) \]

\[ \frac{\rho(\phi)\partial U}{\partial t} + \rho(\phi) \cdot \nabla (U \cdot U) = -\nabla P + \nabla \cdot [\mu(\phi)\nabla U + (\nabla U)^T] - \sigma \kappa \delta(\phi) \nabla \phi + \rho(\phi)g \quad (2) \]

\[ \frac{\partial}{\partial t} [\rho(\phi)C_p T] + \nabla \cdot [\rho(\phi)C_p UT] = \nabla \cdot (\lambda \cdot \Delta T) \quad (3) \]

where \( U, T, P, t, \lambda, \mu, \rho, C_p, \sigma, g \) and \( \kappa \) represent velocity vector, temperature, pressure, time, thermal conductivity, viscosity, density, specific heat capacity, surface tension coefficient, gravity acceleration and boundary curvature, respectively. Boundary curvature \( \kappa \) is expressed as [30]:

\[ \kappa = \nabla \cdot \frac{\nabla \phi}{|\nabla \phi|} \quad (4) \]

where \( \phi \) is a symbol distance function. Bringing in the smoothed Heaviside function, it can be established that [31]:

\[ H(\phi) = \begin{cases} 
0 & \phi < -\alpha \\
\frac{1}{2} \left[ 1 + \frac{\phi}{\alpha} - \frac{1}{\pi} \sin \left( \frac{\pi \phi}{\alpha} \right) \right] & |\phi| \leq \alpha \\
1 & \phi > \alpha 
\end{cases} \quad (5) \]

where \( \alpha = 1.5 \text{ m} \) and \( m \) represents the minimum size of the grid, then the smoothed density and viscosity can be calculated by:

\[ \rho(\phi) = \rho_g(1 - H(\phi)) + \rho_lH(\phi) \quad (6) \]

\[ \mu(\phi) = \mu_g(1 - H(\phi)) + \mu_lH(\phi) \quad (7) \]

Surface tension adopts the continuum surface force model [32]:

\[ F_s = \sigma \kappa \delta(\phi) \nabla \phi \quad (8) \]

\[ \delta(\phi) = \frac{\partial H(\phi)}{\partial \phi} = \begin{cases} 
1 + \cos \left( \frac{\pi \phi}{2\alpha} \right) & |\phi| < \alpha \\
\frac{2\alpha}{\pi} & |\phi| \geq \alpha 
\end{cases} \quad (9) \]

The model of Lee [33] is adopted to the mass and heat transfer of droplet:

\[ S_m = \begin{cases} 
\rho_l k (T - T_{sat})/T_{sat} & T \geq T_{sat} \\
\rho_g k (T_{sat} - T)/T_{sat} & T < T_{sat} 
\end{cases} \quad (10) \]

where \( S_m \) is the interphase mass transfer source and its unit is kg/(m$^3$·s). \( r \) is the liquid and air mass transfer time coefficient, and it is specified at 100 s$^{-1}$ [34]. \( k \) is the volume fraction.

2.2. Physical Model

Figure 1 shows the physical model of droplet impact on micro-scale rectangular grooved surface. The size of computational domain is 10 mm, 10 mm and 5 mm. The boundary condition of grooved surface is wall. The boundary condition of surroundings is pressure inlet, whose pressure value is the standard atmospheric pressure. The temperatures of air and grooved surface are the same.
Figure 1. Physical model of droplet impact on micro-scale rectangular grooved surface.

Figure 2 shows the schematic of groove geometry. In the numerical investigations on dynamic and heat transfer characteristics of droplet impact, the groove depth \( D \) of rectangular groove is 0.1 mm, and the groove space \( S \) is also 0.05 mm. The groove width \( W \) is a variable, which ranges from 0.05 mm to 0.2 mm.

The property of droplet is water, and the shape of droplet is sphere. The initial droplet diameter \( d_0 \) is 2 mm in this paper. At the initial time, the bottom of the droplet is tangent to the grooved surface.

The physical parameters of droplet are shown in Table 1.

| Physical Parameters | Values |
|---------------------|--------|
| \( d_0 \) (mm)      | 2      |
| \( T \) (K)         | 293.15 |
| \( \rho \) (kg/m\(^3\)) | 998.2  |
| \( \mu \) (Pa·s)    | 0.001  |
| \( \sigma \) (N/m)  | 0.073  |
| \( C_p \) (kJ/(kg·K)) | 4.187 |
| \( \lambda \) (W/(m·K)) | 0.599 |
| \( L \) (kJ/kg)     | 2257   |

The contact angle \( (CA) \) is the angle between a droplet’s edge and the surface underneath it, which is an important parameter to measure the wettability of the impact surface. The contact angle refers to
the eigen contact angle of the impact surface in this work. Furthermore, the Weber number ($We$) is used in this paper, which is defined as follows [35]:

$$We = \frac{\rho v^2 d_0}{\sigma}$$

(11)

The spreading diameter of droplet impact on flat surface is $d_{flat}$. Figure 3 shows the spreading of droplet on grooved surface. The vertical spreading diameter is the spreading diameter perpendicular to the groove direction, and it is called $d_{vertical}$. The parallel spreading diameter is the spreading diameter parallel to the groove direction, and it is called $d_{parallel}$. Dimensionless treatment is performed and the flat spreading factor $\beta_{flat}$, vertical spreading factor $\beta_{vertical}$ and parallel spreading factor $\beta_{parallel}$ are as follows:

$$\beta_{flat} = \frac{d_{flat}}{d_0}$$

(12)

$$\beta_{vertical} = \frac{d_{vertical}}{d_0}$$

(13)

$$\beta_{parallel} = \frac{d_{parallel}}{d_0}$$

(14)

Figure 3. Schematic of droplet spreading.

To investigate the anisotropy of droplet morphology caused by the micro-scale grooved structure, the anisotropy coefficient $\varepsilon$ is defined as:

$$\varepsilon = \frac{\beta_{parallel, max}}{\beta_{vertical, max}}$$

(15)

With the increase of anisotropy coefficient, the effect of grooved structure on dynamic characteristics of droplet is stronger. When the droplet impact on the flat surface, the value of anisotropy coefficient is 1.

As for grid partition, the type of computational mesh is hexahedron. Figure 4 depicts the mesh independence verification of computational domain. The eigen contact angle of grooved surface is $105^\circ$ and the surface temperature is 353.15 K. The groove width is 0.05 mm. The impact velocity of droplet is 0.3 m/s. $N$ presents the total number of computational meshes. The vertical spreading factor $\beta_{vertical}$ is utilized as the criterion of mesh independent analysis. It can be observed in the figure that, when the total number of computational meshes reaches 3,980,400, the vertical spreading factor of droplet changes little at the same time as the number of meshes increases. To ensure the efficiency of numerical calculation, we choose the total number of meshes as 3,980,400 in this numerical study.
2.3. Experimental Study and Validation of Numerical Model

In this work, the experimental study of droplet impact on solid surface with rectangular microgrooves was conducted. Figure 5 shows the schematic of the experimental apparatus. The main components of the experimental apparatus are droplet generator, grooved surface, light source, high speed camera and computer. The type of high speed camera is Optronis CP80-3M/C-540 with macro lens (Tamron, 28–300 mm f/3.5–6.3). The droplet is generated by droplet generator. The initial droplet diameter \(d_0\) is controlled by the droplet volume \(V_0\):

\[
V_0 = \frac{4}{3} \pi \left(\frac{d_0}{2}\right)^3
\]  

(16)

The initial droplet diameter is 2 mm in this study. Thus, the value of \(V_0\) is set as 4.189 \(\mu\)L. The impact velocity of droplet is adjusted by the height of droplet generator. The temperature of experimental environment is 293.15 K, which is measured by the K-type thermocouple system. Uncertainty analysis of the experimental measurements are presented in Table 2.

![Figure 5. Schematic of the experimental apparatus.](image-url)
The region of deeper color corresponds to the region of groove bottom. There exists transitional region in the edge of groove. According to statistics, the groove width (contains transitional region) is approximately 46 µm and the groove space is approximately 52 µm. Furthermore, the groove depth is approximately 98 µm. As for the eigen contact angle of SU-8 surface, the measured value is approximately 84.2°.

Figure 6 shows the images of micro-scale rectangular grooved surface in experimental study. The micro-scale rectangular grooved surface is fabricated by using ultraviolet lithography of SU-8 on silicon substrate. Figure 6b shows the SEM image of micro-scale rectangular grooved surface. The region of deeper color corresponds to the region of groove bottom. There exists transitional region in the edge of groove. According to statistics, the groove width (contains transitional region) is approximately 46 µm and the groove space is approximately 52 µm. Furthermore, the groove depth is approximately 98 µm. As for the eigen contact angle of SU-8 surface, the measured value is approximately 84.2°.

Table 2. Uncertainty analysis of the experimental measurements.

| Measurement Quantity | Measuring Equipment | Uncertainty |
|-----------------------|---------------------|-------------|
| Temperature           | K-type thermocouple, A/D converter | $\frac{\delta L}{L} = 0.757\%$ |
| Droplet volume        | Droplet generator    | $\frac{\delta (AV)}{AV} = 0.898\%$ |
| Dripping height       | Vernier caliper      | $\frac{\delta (AH)}{H} = 0.2\%$ |

Figure 7 shows the evolution of droplet morphology on grooved surface. The impact velocity is set as 0.3 m/s and the Weber number of droplet is 2.46. The acquisition frame rate of high speed camera is 4000 frames per second with the relation pixel of 512 × 512. The time of 0 ms refers to the time when droplet touches the grooved surface. It is observed that the spreading diameter of droplet gradually becomes larger as time goes by. The kinetic energy of the droplet is converted to surface tension energy, potential energy and viscous dissipation energy. The change of spreading factor is presented in Figure 8. It can be seen in the figure that the vertical spreading factor is less than the parallel spreading factor. In the later stage of the impact process, the anisotropy of droplet morphology becomes more significant. In addition, the period of droplet spreading in vertical and parallel direction is not synchronous owing to the existence of microgrooves. In the parallel direction of groove, the droplet is always spreading. In the vertical direction of groove, the vertical spreading factor reaches the maximum value at the time of 3 ms. Thereafter, the droplet begins to retract under the action of surface tension, and the vertical spreading factor gradually decreases.
Furthermore, the numerical simulation was performed with the same impact velocity, temperature and surface morphology. The comparison of spreading factor of numerical results with experimental results is shown in Figure 8. The numerical results agree well with the experimental results. It follows that this numerical model is capable of simulating the process of droplet impact on micro-scale rectangular grooved surface.

3. Numerical Results and Discussion

3.1. Dynamic Characteristics of Droplet

Figure 9 shows the effects of contact angle and groove width on dynamic characteristics of droplet with the impact velocity of 0.4 m/s. The Weber number of droplet is 4.38. The eigen contact angle of impact surface ranges from 90° to 135°, and the groove width ranges from 0.05 mm to 0.2 mm. The temperature of grooved surface is 353.15 K. Moreover, the comparison of droplet impact on grooved surface and flat surface under the same condition was performed.

It is observed that the dynamic characteristics of droplet is the coupling effect of contact angle and groove width. The dynamic characteristics of droplet have a variation between vertical direction and parallel direction due to the existence of micro-scale grooved structure. The numerical results show that the vertical spreading factor of droplet impact on grooved surface is less than parallel spreading.
factor with different contact angles and groove widths. The anisotropy of droplet morphology becomes significantly as time goes on. With the increase of contact angle, the maximum vertical spreading factor, maximum parallel spreading factor and maximum flat spreading factor all decrease, and the anisotropy of droplet morphology tends to reduce. Besides, the time needed to arrive at the maximum spreading factor becomes less with increasing contact angle.

Figure 9. Dynamic characteristics of droplet, influences of eigen contact angle and groove width: (a) \( \text{CA} = 90^\circ \); (b) \( \text{CA} = 105^\circ \); (c) \( \text{CA} = 120^\circ \); and (d) \( \text{CA} = 135^\circ \).

When the eigen contact angle of grooved surface is 90°, the groove width plays an important role in the evolution of droplet morphology. The vertical spreading factor is less than flat spreading factor, and the parallel spreading factor is greater than flat spreading factor. With the increase of groove width, the vertical spreading factor decreases and the parallel spreading factor increases. It indicates that the anisotropy of droplet morphology becomes significant. At the time of 8 ms, the droplet movement has experienced the first oscillation period in vertical direction and it is still spreading in parallel direction.

When the eigen contact angle of grooved surface is 105°, the numerical results show that the maximum parallel spreading factors of droplet impact on grooved surface with groove width of 0.05 mm and 0.1 mm are less than the maximum flat spreading factor. It can be observed that the anisotropy of droplet morphology on the grooved surface with groove width of 0.05 mm is smallest. Its anisotropy coefficient is 1.06. At the time of 8 ms, only the droplet on grooved surface with groove width of 0.2 mm has experienced the first oscillation period in vertical direction.

When the eigen contact angle of grooved surface is 120°, the parallel spreading factor of droplet impact on grooved surface with groove width of 0.1 mm is less than the parallel spreading factor of droplet impact on grooved surface with groove width of 0.05 mm. It can be observed that the
anisotropy of droplet morphology on the grooved surface with groove width of 0.1 mm is smallest. Furthermore, the vertical spreading factor of droplet decreases with increasing groove width.

When the eigen contact angle of grooved surface is 135°, the hydrophobicity of the impact surface is significant. The grooved structures bring the resistance on the movement of droplet in both vertical and parallel directions. Both the vertical spreading factor and parallel spreading factor are less than the flat spreading factor. At the time of 8 ms, the droplet impact on grooved surface and flat surface are in retracting process.

Figure 10 shows the effect of impact velocity on maximum spreading factor with different groove widths. The impact velocity ranges from 0.3 m/s to 0.5 m/s and the Weber number ranges from 2.46 to 6.48. The groove width ranges from 0.05 mm to 0.2 mm. The eigen contact angle of grooved surface is 105°. The temperature of grooved surface is 353.15 K. Simulation results show that the maximum vertical spreading factor and maximum parallel spreading factor all increase with increasing impact velocity. Besides, the vertical spreading factor is always minimal with different impact velocities. The effect of impact velocity on anisotropy coefficient was studied, which is shown in Table 3. As can be seen from the table, the anisotropy coefficient of droplet impact on grooved surface with the groove width of 0.2 mm is largest with different impact velocities. With the increase of impact velocity, the anisotropy coefficients of droplet impact on different grooved surface all increase. It indicates that the grooved structure has a more significant influence on the dynamic characteristics of droplet.

Table 3. Effect of impact velocity on anisotropy coefficient.

| Velocity | $\varepsilon$ (W = 0.05 mm) | $\varepsilon$ (W = 0.1 mm) | $\varepsilon$ (W = 0.2 mm) |
|----------|-----------------------------|-----------------------------|-----------------------------|
| 0.3 m/s  | 1.0491                      | 1.2159                      | 1.4551                      |
| 0.4 m/s  | 1.0554                      | 1.2288                      | 1.4748                      |
| 0.5 m/s  | 1.0632                      | 1.2430                      | 1.5138                      |

Figure 10. Effect of impact velocity on maximum spreading factor with different groove widths.

Table 4 shows the effect of surface temperature on the dynamic characteristics. The temperature of grooved surface ranges from 323.15 K to 353.15 K. The groove width is 0.05 mm. The impact velocity of droplet is 0.4 m/s and the Weber number of droplet is 4.38. The eigen contact angle of grooved surface is 105°. As can be seen in Table 4, the effect of surface temperature on the maximum spreading factor of droplet is relatively small. Both the maximum vertical spreading factor and parallel
spreading factor increase with increasing surface temperature. When the surface temperature increases from 323.15 K to 353.15 K, the growth rates of vertical spreading factor and parallel spreading factor are, respectively, 1.05% and 1.47%. The variation of surface tension could be employed to explain this phenomenon. Heat transfer phenomenon occurs after the droplet impact on grooved surface. The water temperature near the region of triple-phase contact line increases rapidly. The surface tension coefficient decreases with increasing temperature, and it improves the process of droplet spreading. The time of droplet reaching to the maximum spreading factor is transient, which is usually less than 6 ms. Thus, the evaporation volume of droplet is tiny. Furthermore, it is observed that the anisotropy coefficient also increases with increasing surface temperature.

### Table 4. Effect of surface temperature on dynamic characteristics of droplet.

| Temperature | $\beta_{\text{vertical, max}}$ | $\beta_{\text{parallel, max}}$ | $\varepsilon$ |
|------------|-------------------------------|-------------------------------|-------|
| 323.15 K  | 1.3398                        | 1.4082                        | 1.0511 |
| 333.15 K  | 1.3442                        | 1.4142                        | 1.0521 |
| 343.15 K  | 1.3506                        | 1.4225                        | 1.0532 |
| 353.15 K  | 1.3539                        | 1.4289                        | 1.0554 |

### 3.2. Heat Transfer Characteristics of Grooved Surface

Figure 11 shows the heat transfer rate of grooved surface with the Weber number of 4.38. The impact velocity of droplet is 0.4 m/s. The eigen contact angle of grooved surface ranges from 90° to 135°. The groove width ranges from 0.05 mm to 0.2 mm. The temperature of grooved surface is 353.15 K. Besides, the numerical simulation of droplet impact on flat surface was performed under the same condition. It can be concluded from the figure the heat transfer characteristics of grooved surface is the coupling effect of contact angle and groove width. The heat transfer rate of grooved surface increases firstly and then decreases, and the maximum heat transfer rate of grooved surface decreases with increasing contact angle.

The analysis of wettability state is utilized to illuminate the heat transfer characteristics of grooved surface. The wettability state of the droplet which is analyzed refers to the time that the heat transfer rate of grooved surface reaches maximum value. The main factor affecting the heat transfer characteristics is the contact area between grooved surface and droplet. The contact area between grooved surface and droplet can be composed of three parts: the contact area of groove space, the contact area of groove side, and the contact area of groove bottom. The contact areas of groove side and groove bottom are affected by the wettability state of droplet.

![Figure 11. Cont.](image-url)
When the eigen contact angle of grooved surface is 90°, the wettability states of droplet on grooved surface with different groove widths are all Wenzel state, which are shown in Figure 12. The view angle of wettability state is along the direction of Z axis. The contact area of groove side for grooved surface with groove width of 0.05 mm is larger than 0.1 mm and 0.2 mm, and its maximum heat transfer rate is largest with the value of 22.97 W. The maximum heat transfer rate of flat surface is smallest with the value of 11.89 W. All of micro-scale grooved structures can enhance the heat transfer with the eigen contact angle of 90°.

When the eigen contact angle of grooved surface is 105°, the surface property is hydrophobic. As is shown in the figure, the maximum heat transfer rate of grooved surface with a groove width of 0.1 mm is largest. The maximum heat transfer rate of flat surface is smallest. The wettability state of droplet on grooved surface with a groove width of 0.05 mm is the combination of Wenzel state and Cassie state. The wettability states of droplet on grooved surface with the groove width of 0.1 mm and 0.2 mm are both Wenzel state. The contact area of groove side with groove width of 0.1 mm is larger than 0.2 mm, and its contact area is largest. All micro-scale grooved structures can enhance the heat transfer with the eigen contact angle of 105°.

When the eigen contact angle of grooved surface is 120°, the maximum heat transfer rate of grooved surface with a groove width of 0.2 mm is largest. The effect of groove width on wettability state of droplet is investigated, which is shown in Figure 13.
As can be seen in Figure 13, the transition of wettability state tends to occur with the increase of groove width. When the groove width is 0.2 mm, the wettability state of droplet is Wenzel state and its contact area is largest. When the groove width is 0.05 mm, the wettability state of droplet is Cassie state and its contact area is smallest. The wettability state of droplet on grooved surface with the groove width of 0.1 mm is the combination of Wenzel state and Cassie state. Only the micro-scale grooved structure with a groove width of 0.2 mm can enhance the heat transfer with the eigen contact angle of 120°.

When the eigen contact angle of grooved surface is 135°, the maximum heat transfer rate of grooved surfaces with different groove widths are all less than flat surface. The wettability state of droplet on grooved surface with a groove width of 0.2 mm is the combination of Wenzel state and Cassie state. The wettability states of droplet on grooved surface with the groove width of 0.05 mm and 0.1 mm are Cassie state. Furthermore, it is observed that the maximum heat transfer rate of grooved surface with a groove width of 0.05 mm is larger than the grooved surface with a groove width of 0.1 mm. Its wettability state is the same. It can be explained by the spreading of droplet. In Figure 9d, both the vertical spreading diameter and parallel spreading diameter of droplet on grooved surface with a groove width of 0.05 mm are larger than 0.1 mm. Thus, its contact area of groove space is larger. Overall, the contact areas between droplet and grooved surface with different groove widths are less than flat surface. All the micro-scale grooved structures with different groove widths cannot enhance the heat transfer with the eigen contact angle of 135°.

Figure 14 shows the effect of impact velocity on maximum heat transfer rate with different groove widths. The temperature of grooved surface is 353.15 K. The eigen contact angle of grooved surface is 105°. The impact velocity ranges from 0.3 m/s to 0.5 m/s, and the Weber number ranges from 2.46 to 6.48. The groove width ranges from 0.05 mm to 0.2 mm. It can be concluded from figure that the maximum heat transfer rate of grooved surface increases with increasing impact velocity. The maximum heat transfer rate of grooved surface with the groove width of 0.1 mm is always biggest at different impact velocities, and the maximum heat transfer rate of grooved surface with a groove width of 0.05 mm is always smallest. When the impact velocity increases from 0.3 m/s to 0.5 m/s, the variation of maximum heat transfer rate of grooved surface with a groove width of 0.05 mm is largest with the rate of 125.5%. The variation of maximum heat transfer rate of grooved surface with a groove width of 0.2 mm is smallest with the rate of 40.9%.

![Figure 14](image_url)

**Figure 14.** Effect of impact velocity on maximum heat transfer rate with different groove widths.
Figure 15 shows the heat transfer rate of grooved surface with different surface temperatures. The temperature of grooved surface ranges from 323.15 K to 353.15 K. The impact velocity of droplet is 0.4 m/s, and the Weber number of droplet is 4.38. The groove width is 0.05 mm. The eigen contact angle of grooved surface is 105°. With the increase of surface temperature, the heat transfer rate of grooved surface increases. The differences of heat transfer rate with different surface temperatures increase firstly and then decrease. Furthermore, it is observed that the time needed to arrive at the maximum heat transfer rate is not synchronous with different surface temperatures. It could be explained by the variation of droplet surface tension. The surface tension coefficient decreases with increasing temperature. It exerts an influence on the wettability state and spreading of droplet. Thus, the time needed to arrive at the maximum heat transfer rate is not synchronous with different surface temperatures.

4. Conclusions

In this work, a comprehensive study of dynamic and heat transfer characteristics of droplet impact on micro-scale rectangular grooved surface was performed at low Weber numbers. This paper has reference values for the thermal control with micro-scale grooved structure and the optimization of spray cooling system. The following conclusions are obtained:

1. When the droplet impacts on grooved surface, the vertical spreading diameter of droplet is less than the parallel spreading diameter. The period of droplet spreading in vertical and parallel direction is not synchronous owing to the existence of microgrooves. In the later stage of the impact process, the anisotropy of droplet morphology becomes more significant.

2. The dynamic characteristics of droplet is the coupling effect of contact angle and groove width. With the increase of contact angle, the maximum vertical spreading factor and maximum parallel spreading factor all decrease, and the anisotropy of droplet morphology tends to reduce. The transition of wettability state tends to occur with the increase of groove width. Besides, the time needed to arrive at the maximum spreading factor becomes less with increasing contact angle.

3. With the increase of impact velocity, the maximum vertical spreading factor and maximum parallel spreading factor all increase, and the anisotropy coefficient of droplet increases. Moreover, the maximum heat transfer rate of grooved surface increases with increasing impact velocity.

4. The effect of surface temperature on the maximum spreading factor of droplet is relatively small. With the increase of surface temperature, the heat transfer rate of grooved surface increases. Furthermore, it is observed that the time needed to arrive at the maximum heat transfer rate is not synchronous with different surface temperatures.
5. The heat transfer characteristics of grooved surface is the coupling effect of contact angle and groove width. The maximum heat transfer rate of grooved surface decreases with increasing contact angle. Furthermore, all these micro-scale grooved structures with different groove widths cannot enhance the heat transfer with the eigen contact angle of 135°.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

| Symbol | Definition                          |
|--------|------------------------------------|
| U      | Velocity vector                    |
| T      | Temperature                         |
| P      | Pressure                            |
| t      | Time                                |
| λ      | Thermal conductivity               |
| µ      | Viscosity                           |
| ρ      | Density                             |
| \(C_p\) | Specific heat capacity             |
| σ      | Surface tension coefficient         |
| κ      | Boundary curvature                  |
| \(\Phi\) | Symbol distance function            |
| \(S_m\) | Interphase mass transfer source     |
| r      | Mass transfer time coefficient      |
| k      | Volume fraction                     |
| D      | Groove depth                        |
| S      | Groove space                        |
| W      | Groove width                        |
| L      | Latent heat of evaporation          |
| CA     | Contact angle                       |
| We     | Weber number                        |
| d      | Diameter                            |
| β      | Spreading factor                    |
| ε      | Anisotropy coefficient              |
| N      | Total number of computational meshes|
| \(V_0\) | Initial droplet volume             |
| H      | Dripping height                     |

Subscript

| Subscript | Definition                           |
|-----------|--------------------------------------|
| 0         | Initial                              |
| Flat      | Droplet impact on flat surface       |
| vertical  | Droplet impact on grooved surface, vertical direction |
| parallel  | Droplet impact on grooved surface, parallel direction |
| max       | Maximum value                        |

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