Effect of surface micromorphology and hydrophobicity on condensation efficiency of droplets using the lattice Boltzmann method

Lijun LIU a,b, Gaojie LIANG b,*, Haiqian ZHAO b,*, Xiaoyan LIU b

a School of Electronic and Information Engineering, Changshu Institute of Technology, Changshu, Jiangsu, China

b School of Civil Engineering and Architecture, Northeast Petroleum University, Daqing, Heilongjiang, China

* Corresponding authors, E-mail: a1062378608@163.com, dqzhaohaiqian@163.com

In the present study, the effects of the surface morphology and surface hydrophobicity on droplet dynamics and condensation efficiency are investigated using the lattice Boltzmann method (LBM). Different surface morphologies may have different condensation heat transfer efficiencies, resulting in diverse condensation rates under the same conditions. The obtained results show that among the studied morphologies, the highest condensation rate can be achieved for conical microstructures followed by the triangle microstructure, and the columnar microstructure has the lowest condensation rate. Moreover, it is found that when the surface microstructure spacing is smaller and the surface microstructure is denser, the condensation heat transfer between the surface structure and water vapor facilitates, thereby increasing the condensation efficiency of droplets. Furthermore, the condensation process of droplets is associated with the surface hydrophobicity. The more hydrophobic the surface, the more difficult the condensation heat transfer and the longer the required time for droplet nucleation. Meanwhile, a more hydrophobic surface means that it is harder for droplets to gather and merge, and the corresponding droplet condensation rate is also lower.

Key words: lattice Boltzmann method, droplet, microstructure, condensation rate

1. Introduction

Studies show that dropwise condensation has a higher heat transfer coefficient than film condensation so that it is widely applied in diverse applications, including steam power generation, seawater desalination, thermal power plant, petrochemical plants and other industrial applications [1, 2]. With the increasing escalation of the energy crisis, dropwise condensation heat transfer technology has attracted many scholars in recent years [3]. The performed investigations show that the vapor-solid contact surface can significantly improve the condensation phase transformation efficiency in the vapor-liquid phase transformation process. Therefore, it is of great significance to study the movement of droplets on the microstructure surface and the condensation heat transfer mechanism.
Recently, researchers have carried numerous experiments about the influence of droplet condensation on the heat transfer and dynamic characteristics of the droplet condensation, mainly focusing on the effects of surface wettability [4, 5], surface morphology [6, 7] and subcooling [8, 9]. Xie et al. [10] carried out dropwise condensation experiments on different surfaces and found that the wettability of superhydrophobic surfaces decreases as the temperature increases, while the smooth hydrophobic surfaces could maintain stable heat transfer. Chen et al. [11] found that surface roughness significantly affects the number and frequency of the droplet jump. However, the specific effect of the surface microstructure on the droplet condensation heat transfer efficiency is still unclear.

It should be indicated that simulating the droplet condensation in the microscopic state is an enormous challenge for numerical methods. The conventional CFD method can hardly quantify the interface transfer of mass and heat [12]. It is worth noting that high computational costs and low efficiency limit the application of molecular dynamics in this area [13]. In the past two decades, LBM has developed into an effective method widely used to simulate multiphase flows and phase change processes [14, 15]. Studies show that the surface microstructure plays an important role in enhancing condensation heat transfer and condensation kinetics [16, 17]. Therefore, numerous investigations have been carried out on the condensation heat transfer of droplets with the surface morphology as the object. Moreover, the effects of different morphologies such as columnar [18], triangle [19], on strengthening the condensation heat transfer of droplets have been studied. In this regard, Zhang et al. [20] studied the droplet condensation kinetics on the superhydrophobic surfaces and found that the density of the surface microstructure has an important influence on the droplet condensation efficiency. Recently, condensation heat transfer research on the surface wettability has become a research hotspot [21, 22]. Li et al. [23] simulated the droplet condensation on different hydrophobic surfaces using a phase transition model. The results show that the condensation efficiency on a hydrophilic surface is higher than that on a hydrophobic surface.

However, the majority of studies in the field of the surface micro-morphology, hydrophobicity and the droplet condensation heat transfer have focused on the influence of a single influencing factor on the droplet condensation process in isolation, ignoring the influence of multiple factors on droplet condensation kinetics. The real condensation process is the result of the interaction between various influencing factors. It should be indicated that a comprehensive study on the influence of the surface morphology and hydrophobicity on droplet condensation can result in a conclusion closest to the real condensation process, which has guiding significance for strengthening the condensation heat transfer process of droplets on the hydrophobic surface.

In the present study, the multi-component multiphase SC model [24] is used to simulate the droplet condensation on the microstructure surface. In the simulation process, the effects of different surface microstructures, including columnar surface, triangle surface and conical surface, and microstructure spacing and hydrophobicity on the condensation quality and efficiency of droplets are comprehensively considered. The main objective of this article is to reveal the influence of the surface microstructures and wettability on the condensation and growth of droplets.

2. Simulation Method

In this study, the BGK collision operator used in pseudo-potential models is adopted commonly, and the two-dimension, nine-velocity (D2Q9) model is used to simulate the density distribution in the
process of water vapor condensation. The density distribution formula describing the evolution of particles is expressed as following [20]:

\[
f_i^\lambda(x + e_i \partial x, t + \partial t) - f_i^\lambda(x, t) = -\frac{1}{\tau^\lambda}\left[f_i^\lambda(x, t) - f_i^\lambda(eq)(x, t)\right]
\]  

(1)

where \( f_i^\lambda(x, t) \) is the density distribution function of the \( \lambda \)th component in the \( i \)th velocity direction, \( \tau^\lambda \) stands for relaxation time, and the relation between it and viscosity coefficient is \( \nu^\lambda = c_s^\lambda (\tau^\lambda)^{-0.5} \delta t \). The equilibrium distribution function is:

\[
f_i^\lambda(eq) = \omega_i \rho^\lambda(x, t) \left[ 1 + \frac{3(e_i \cdot u^\lambda(x, t))}{c_s^2} + \frac{4.5(e_i u^\lambda(x, t))^2}{c_s^4} - \frac{1.5(u^\lambda(x, t))^2}{2c_s^2} \right]
\]  

(2)

where \( u^\lambda \) represents the macroscopic velocity of the fluid, \( \rho^\lambda \) represents the density of the fluid of different components. \( \omega_i \) represents the weight coefficient and \( e_i \) represents the discrete velocity, which provided by:

\[
\omega_i = \begin{cases} 
4/9, & i = 0 \\
1/9, & i = 1-4 \\
1/36, & i = 5-8 
\end{cases}
\]  

(3)

\[
e_i = \begin{cases} 
(0,0), & i = 0 \\
(\pm1,0), (0, \pm1), & i = 1-4 \\
(\pm1,\pm1), & i = 5-8 
\end{cases}
\]  

(4)

The density and macroscopic velocity of fluid can be expressed as:

\[
\rho^\lambda = \sum_{i=0}^{8} f_i
\]  

(5)

\[
u^\lambda(x, t) = u^\lambda(x, t) + \frac{\tau^\lambda \partial \rho^\lambda(x, t)}{\rho^\lambda}
\]  

(6)

where \( F^\lambda \) is the force acting on the \( \lambda \)th component, which includes the interaction between different fluids \( F_{\text{in}}^\lambda(x, t) \) and the interaction between fluid and solid wall \( F_{\text{ads}}^\lambda(x) \):

\[
F^\lambda = F_{\text{in}}^\lambda(x) + F_{\text{ads}}^\lambda(x)
\]  

(7)

The interaction force between fluids of different components can be indicated as:

\[
F_{\text{in}}^\lambda(x, t) = -\psi^\lambda(x, t) \sum G(x, x') \sum_{i=0}^{8} \psi^\lambda(x', t) e_i
\]  

(8)

where \( \lambda \) and \( \bar{\lambda} \) indicate two different fluid components, \( \psi^\lambda(x, t) \) and \( \psi(x', t) \) as effective densities can be expressed as follows [25]:

\[
\psi^\lambda(x, t) = \rho^\lambda(x, t)
\]  

(9)
\[ \psi^L(x,t) = \rho^L(x,t) \] (10)

The pressure value at position \( x \) is determined by the following equation:

\[ P(x,t) = \frac{1}{3} \sum_i \frac{\rho^L(x,t)}{\psi^L(x,t)} + \frac{G^L(x,t) \psi^L(x,t)}{3} \] (11)

The interaction force between fluid and solid is expressed as:

\[ F_{ads}^L(x,t) = -\rho^L(x,t) \sum_{i=0}^{8} \delta_i G_{ads}^L s(x + e_i \delta) \] (12)

where \( s \) is the wall index. When the lattice is solid or liquid, its values are 1 or 0 respectively. The strength of the wall force of fluid and solid is controlled by \( G_{ads}^k \). Therefore, the droplet contact angle can be controlled by controlling the size of \( G_{ads}^k \). In this work, the model system includes two components: water vapor and non-condensing gases [20]. The relationship between \( G_{ads}^1 \) (H\(_2\)O/solid) and \( G_{ads}^2 \) (non-H\(_2\)O/solid) is \( G_{ads}^1 = -G_{ads}^2 \).

3. Results and Discussions

3.1. Model Validation

Firstly, the correctness of the above model is verified by verifying the Laplace law. The pressure difference inside and outside the droplet is proportional to the reciprocal of the droplet radius according to the Laplace law, which can be expressed by the following formula:

\[ \Delta p = \sigma / r \] (13)

where \( \Delta p \) represents the pressure difference between inside and outside the droplet, and \( \sigma \) represents the surface tension of the droplet. The simulation calculation locale is set to 101×101 lu (lattice unit) and the center of the droplet is set in the center of the calculation region (50,50). Periodic boundary conditions is applied to the surrounding boundaries of the calculation region and neglect the effect of gravity. The radius of droplet is taken as 14, 15, 17, 20, 22, 25, and 28 lattice units, respectively. The variation of the internal and external pressure difference of the droplet with the reciprocal of the droplet radius is recorded after the droplet state remained stable. It is found that \( \Delta p \) and \( 1/r \) have a linear fitting relationship through the analysis of each data point, as shown in figure 1(a), which is consistent with previous report [26]. The slope of the fitting line is the surface tension of the droplet which is calculated to be about 0.2763.

The contact angle can be verified by adjusting \( G_{ads}^k \) in the SC model. Similarly, set the calculation area to 101×101 lu, the left and right boundaries are set as periodic boundary and standard bounce-back boundary is adopted at the upper and bottom boundaries. The droplet with a radius of 14 lu is lay at the bottom, then adjust the intensity coefficient \( G_{ads}^i \). The contact angle between the droplet and the solid surface is recorded after the droplet state remained stable. The linear relationship between contact angle and \( G_{ads}^i \) as shown in figure 1(b), which is consistent with previous studies [27, 28].
Figure 1. Model verification: (a) relationship between the pressure difference inside and outside the droplet and the reciprocal of droplet radius; (b) relationship between contact angle and solid-liquid contact coefficient $G^l_{ads}$.

3.2. System Parameters and Boundary Conditions

The computational region is set at $211 \times 101 \text{ lu}$ in this study as shown in figure 3. The initial density parameters of water vapor($\text{H}_2\text{O}$) and non condensable gases($\text{non-H}_2\text{O}$) in the calculation area are saved as $\rho_{\text{H}_2\text{O}} = 0.035 \text{ mu·lu}^{-2}$ (mass units per square lattice unit) and $\rho_{\text{non-H}_2\text{O}} = 0.965 \text{ mu·lu}^{-2}$. Standard bounce-back boundary scheme is employed at the bottom boundary and the left and right boundaries are set as periodic boundary. Zou-He pressure boundary is adopted at the upper boundary to provide water vapor to the system continuously [29]. The gases densities at the inlet of the upper boundary are remained at $\rho_{\text{H}_2\text{O}} = 0.08 \text{ mu·lu}^{-2}$ and $\rho_{\text{non-H}_2\text{O}} = 0.92 \text{ mu·lu}^{-2}$. As shown in the enlarged figure on the right side of figure 2, the bottom structure of the system adopts columnar microstructure, conical microstructure and triangle microstructure. The letters $W$, $D$, $H$ and $F$ symbolizes the base width, spacing, height and top width of the microstructure, respectively [30].

Figure 2. Model and simulation parameters.
3.3 Effect of Surface Micromorphology on Droplet Condensation

3.3.1 Effect of Different Morphologies on Droplet Condensation

Studies show that the surface morphology has a significant effect on the condensation heat transfer of droplets [27]. Accordingly, three types of the surface microstructures, including the triangle microstructure, conical microstructure and columnar microstructure, are designed to simulate the condensation heat transfer of droplets. Figure 3 shows these microstructures. The size of the simulation area is $211 \times 101$ lu, and the geometric size of the microstructure is set to $W = 20$ lu, $F = 10$ lu, $D = 15$ lu and $H = 10$ lu. Boundary conditions will be discussed in section 3.2. In figure 3, the color change in the diagram represents the density change of water vapor, the change in the density of water vapor from 0.05 to 0.9 indicates that the water vapor condenses into droplets. Figure 3 illustrates that the water vapor begins to accumulate on the microstructure surface after the simulation. When $t=5000$, the droplet nucleation appears on the triangle and conical microstructure surfaces, while no droplet nucleation occurs on the columnar microstructure surface. Meanwhile, the nucleation droplet on the triangle surface is significantly larger than that on the conical microstructure surface. It is found that under the same condensation conditions, the triangle surface has the shortest nucleation time, while the columnar surface has the lowest nucleation time and the nucleation time of the conical microstructure surface is in the middle. At $t=15000$, the droplets on the triangle microstructure surface coalescence, while the droplets on other surfaces still exist in a single form. Then, the droplets absorb the water vapor in the surrounding liquid phase and continue to grow. At $t=22000$, it is observed that the droplet radius generated on the triangle and conical microstructure surface is significantly larger than that on the columnar microstructure surface. It is concluded that the droplet condensation efficiency on the triangle and conical microstructure surfaces is greater than that on the columnar microstructure surface.

In order to confirm the condensation efficiency of droplets on different types of microstructure surfaces, distributions of the condensation mass and condensation rate on different types of microstructure surfaces over time are compared. It is observed that the surface morphology significantly affects the condensation quality and condensation efficiency of droplets. Figure 4(a) illustrates that the condensation mass and condensation velocity of the columnar microstructure surface are lower than those of the other microstructure surfaces at the same time step. Moreover, it is found that the upward trend of the condensation mass curve on the surface of the triangle structure is relatively smooth and uniform, that on the surface of the conical microstructure is relatively rapid. Before $t=15000$, the condensation mass of droplets on the triangle microstructure surface is larger than that on the conical microstructure surface. However, after $t=15000$, the condensation mass of droplets on the conical microstructure surface exceeds that on the triangle microstructure surface, and the gap widens as time progresses. Compared with the condensation velocity curve in figure 4(b), it is observed that the condensation velocity of droplets on the conical microstructure surface increases continuously, while the condensation velocity on the triangle microstructure surface remains in a relatively stable state. Although the condensation velocity on the columnar microstructure surface increases, the increment is extremely limited.

Figures 3 and 4 reveal that under the same simulation conditions, the condensation efficiency of studied microstructures in an ascending order includes the columnar microstructure surface, triangle microstructure surface and the conical microstructure surface. Accordingly, the conical microstructure
is utilized to investigate the influence of the surface topography geometric parameters on the condensation efficiency of droplets.

![Figure 3. Condensation process of droplets on different types of bottom micromorphology.](image)

![Figure 4. Condensation mass and rate diagrams of droplets with different morphologies: (a) the relationship between condensation mass and time step \( t \); (b) the relationship between condensation rate and time step \( t \).](image)

### 3.3.2 Effect of Surface Morphology Spacing on Droplet Condensation

The spacing of the surface microstructure has a significant influence on the dropwise condensation heat transfer. Therefore, the conical microstructure surfaces with different spacing are simulated in this study. Figure 5 shows the simulation results of the condensation process on the surface of the conical microstructure with different spacing. Except for the structural spacing \( D \), the size of the simulation area is \( 211 \times 101 \) lu and the geometric size parameters of the conical microstructure are consistent with those mentioned in section 3.3. Figures 5(a), 5(b) and 5(c) show that the spacing of conical microstructures is \( D = 22, 15 \) and 10, respectively. It is observed that the
condensation process of droplets on the conical microstructure surface is similar to that shown in figure 3(b). Water vapor initially gathers at the bottom of the conical microstructure surface, then nucleates at the top of the conical microstructure and absorbs water molecules in the surrounding liquid phase. Moreover, it is found that the nucleation time of droplets on the microstructure surface with different spacing is roughly the same, indicating that the spacing of the surface microstructure does not affect the overall trend of the droplet condensation.

In this section, the effect of the microstructure spacing on the condensation heat transfer performance of droplets is investigated. Figure 6 illustrates the variations of the condensation mass and condensation rate at the same time steps on the surface of three conical microstructures with different spacing. It is found that at the initial stage of the condensation, the surface structure spacing has a negligible impact on the condensation quality and condensation rate of droplets. However, as the condensation process progresses, the difference in the condensation quality of droplets on the surface of different spacing microstructures increases. Figure 6(b) presents the variation of the condensation rate against time, which shows the condensation rate of droplets. Accordingly, it is found that the microstructure surface with a smaller spacing size has a faster condensation rate.

Figures 5 and 6 show that under the same condensation conditions, the smaller the distance between surface microstructures, the faster the condensation rate of droplets, and the higher the condensation heat transfer efficiency of droplets.

![Figure 5](image-url). Condensation process of droplets on the same type and different spacing bottom microtopography.
Figure 6. Condensation mass and rate diagrams of droplets at different spacing bottom microtopography: (a) the relationship between condensation mass and time step $t$; (b) the relationship between condensation rate and time step $t$.

3.4 Effect of Surface Hydrophobic on Droplet Condensation

Figure 7 shows the condensation evolution of droplets on the microstructure surface with different hydrophobicities, including $G_{ads}^l = 0.02$, $G_{ads}^l = 0.03$ and $G_{ads}^l = 0.04$. It should be indicated that the size of the simulated region is 211×101 lu, and the geometric parameters of the conical microstructure are $W = 20$ lu, $F = 10$ lu, $D = 10$ lu and $H = 10$ lu. The remaining boundary conditions were discussed in section 3.2. It is observed that when $t = 4000$, the droplet nucleation occurs on the top of the conical microstructure with $G_{ads}^l = 0.02$. However, only water vapor accumulation occurs on the surface of the microstructure with $G_{ads}^l = 0.03$ and $G_{ads}^l = 0.04$. When $t = 5000$, the droplet nucleation appears on the microstructure surface with $G_{ads}^l = 0.03$, and the droplet nucleation time on the microstructure surface with $G_{ads}^l = 0.04$ occurs at $t = 7000$. Then water molecules grow in the droplet absorption system on three distinct hydrophobic surfaces. At $t = 30000$, the droplets in figure 7(a) coalescence due to the continuous growth breaking through the limitation of the surface spacing of the microstructure. It is worth noting that the droplets in figures 7(b) and 7(c) are still in a single form.

Moreover, the effect of the surface hydrophobicity on the condensation heat transfer performance of droplets is investigated. Figure 8 shows the distribution of the condensation mass and condensation rate of droplets with three surface hydrophobicity conical microstructures over time. Figure 8(a) shows that the more hydrophobic the surface, the later the condensation mass begins to increase. Moreover, figure 8(b) reveals that condensation rates of droplets on the microstructure surface with different hydrophobicity are very different, and the condensation rate of droplets on the surface with stronger hydrophobicity is smaller. Furthermore, it is observed that the condensation kinetic behavior of droplets also affects the condensation rate of droplets. For instance, the rapid increment in the condensation rate of surface droplets with $G_{ads}^l = 0.02$ in figure 8(b) mainly originates from the coalescence of droplets.

Figures 7 and 8 indicate that the condensation efficiency of droplets is also correlated to the surface hydrophobicity. The stronger the hydrophobicity ($G_{ads}^l$), the more difficult the nucleation and
growth of droplets. Moreover, the longer the waiting time for the nucleation, the lower the overall condensation efficiency.

Figure 7. Condensation process of droplets on different hydrophobic surface.

Figure 8. Condensation mass and rate of droplets on different hydrophobic surfaces: (a) the relationship between condensation mass and time step $t$; (b) the relationship between condensation rate and time step $t$.

4. Conclusions

In the present study, a two-dimensional multi-component and multi-phase flow LBM model is proposed to simulate the condensation of droplets on the microstructure hydrophobic surface. Moreover, the influence of the surface microstructure and hydrophobicity on the growth and condensation efficiency of condensation droplets is investigated. Based on the obtained results, the following conclusions are drawn:
(1) The condensation efficiency of the droplet is correlated to the type of the surface micromorphology. The condensation efficiency of the studied surfaces in descending order are the conical surface, the triangle surface, and the column surface.

(2) The condensation efficiency of the droplet is correlated to the geometric parameters of the surface microstructure. The smaller the distance between the surface microstructure, the faster the condensation rate of the droplet and the higher the condensation efficiency of the surface.

(3) The condensation process of droplets is linked to the surface hydrophobicity. The higher the surface hydrophobicity, the longer the nucleation time of droplets, and the lower the corresponding condensation efficiency.

Acknowledgment

This work is supported by the Nature Science Foundation of Heilongjiang Province(YQ2019E008 and LH2020E017), Education Department Project of Heilongjiang Province (2018GPQZ09) and Outstanding Youth Reserve Program of Northeast Petroleum University(SJQHB202003)

References


- **Paper submitted:** 06 May 2021
- **Paper revised:** 15 July 2021
- **Paper accepted:** 17 July 2021