The Mass and Heat Transfer Characteristics Study of the Natural Convection Evaporation of an LNG Droplet in BOG

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Abstract: The evaporation process of LNG droplets in BOG is closely related to the cooling down process of the LNG tank, but there isn't an available droplet evaporation model at present. Been prepared based on the conservation of mass, momentum, and energy, a CFD model of natural convection evaporation of a single LNG saturated droplet in the BOG was developed and applied. The results show that:①There are two distinguished zones around the droplet surface, where the local temperature boundary layer of the droplet gradually thickens and rapidly thickens with the increase of the angle of inflow from 0 ° to 90 ° and from 90 ° to 180 °, respectively; ②With the increase of droplet size, the average thickness of temperature boundary layer increases gradually, which leads to the decrease of relative evaporation rate;③"blowing effect" remains almost unchanged with the increase of droplet size.

1. Introduction
LNG carrier is a special ship for long-distance mass transportation of LNG (Liquefied Natural Gas). The temperature of LNG is -163°C. The LNG tank must be cooling down before loading. For large LNG tanks, LNG is widely used for spray cooling down. To prevent safety accidents caused by condensation of high freezing point gas when injecting LNG, it is required to replace the gas in the cabin with Boiling Off Gas (BOG). Elevated incidence of accidents during cooling down due to the large temperature difference. LNG droplets evaporate violently in their vapor, and there is a high-speed vapor jet on the surface of the droplet, so the "blowing effect" can not be ignored. It is noted that the traditional Lee model[1] is not suitable for this larger temperature difference condition. The value of the time coefficient of the Lee model varies greatly under different application conditions, and the "blowing effect" is not taken into account.

A lot of research work on the evaporation of various types of droplets has been done. In 1989, Haywood[2] found that the evaporation process of droplets was affected by the vapor flow on the droplet surface. Zhou[3] found that in the case of severe evaporation, Stefan flow makes the calculation results of the model deviate greatly. Wang Fang[4, 5] found that there is a large deviation between the droplet evaporation model and the experimental data. The influence of natural convection in the static environment does not take into account in the model, and the droplet evaporation model of the thick exchange layer under natural convection was established. A summary of previous studies found that most of the studies were based on droplet evaporation in a diverse vapor atmosphere, using component gradient and diffusion coefficient to establish droplet evaporation model[6]. The essence of LNG tank spray cooling down is that LNG droplets evaporate and remove heat from BOG which has the same content as LNG. At present, there is not any calculation model suitable for the evaporation of such
droplets in their vapor. Some researchers tried to develop a suitable model, the heat transfer characteristics of natural convection evaporation of LNG droplets in the BOG with distinct temperature differences were studied [7]. However, the effect of particle size does not participate.

A computational fluid dynamics (CFD) simulation model for natural convection evaporation of an LNG saturated single droplet with different particle sizes in BOG was established. Based on the mass conservation, momentum conservation, and energy conservation at the gas-liquid interface [8]. The natural convection evaporation process of a single droplet with different particle sizes was simulated by the model, and the evaporation heat transfer characteristics were analyzed. Further, the "blowing effect" was quantitatively separated by the comparison between the evaporation characteristics of droplets and the heat transfer characteristics of the hypothetical non-evaporation cryogenic ball.

2. Modeling and Verification

2.1 Model Hypothesis

（1）The temperature field and the gas flow field around the droplet are symmetrical and the model was simplified as a two-dimensional axisymmetric model. The droplet shape remains spherical.

（2）Take the methane as model material. Ignoring internal circulation and heat radiation transfer.

（3）The droplet temperature was set as the saturated temperature, and the phase transition occurs only at the gas-liquid interface and conforms to the quasi-steady-state assumption.

![Fig. 1 Physical model diagram](image)

(a) Schematic diagram of the natural convective evaporated droplet (b) Model Setting Diagram

2.2 Modeling Setting

The symmetry axis was taken as the X coordinate, and the droplet size ranged from 0.1 mm to 2.5 mm. The origin of the coordinate axis was the center of the droplet and the cryogenic ball. Setting Gravity Acceleration $g = 9.81 \text{ m/s}^2$ in the positive direction of the X-axis. The pressure of the atmosphere was defined as 0.1 MPa and the droplet surface temperature was set to 110 K which is the saturated temperature of LNG at 0.1 MPa. The droplet surface was set as the Velocity Inlet, which was compiled by the user-defined functions (UDFs). The surface of the cryogenic ball was set as the Wall boundary. The flow angle $\phi = 0^\circ$ was defined as the upstream stagnation point of the droplet or the ball, as illustrated in Fig. 1.

2.3 Verification

To evaluate the model, this model was employed to simulate the test natural convection evaporation process of the normal heptane droplets with initial particle size $d_0=1.18\text{ mm}$ and temperature of 290K in an atmosphere temperature of 297K[9]. The calculated results were compared with the experimental data. As showing in Fig. 2, the calculated results of the model agreed well with the experimental data.
3. Result & Discussion

"Blowing effect" refers to the fact that when the droplet is evaporated, there is vapor on the surface that is ejected outward. Therefore, the ejected vapor absorbs part of the heat that should be transferred to the droplet, and has a certain "blowing effect" on superheated vapor, reducing the heat transferred to the droplet by superheated vapor. Owing to the "blowing effect", the natural convective heat transfer characteristics of droplets are different from those of cryogenic balls. Therefore, the definition of "blowing effect" is equal to the ratio of the difference between the value of droplet and the corresponding value of cryogenic ball [7]:

$$\beta = \frac{\varphi_d - \varphi_c}{\varphi_c} \times 100\%$$

Where, $\varphi_d$ - the value of droplets, $\varphi_c$ - the value of the cryogenic ball. By the comparison analysis of natural convection heat transfer characteristics of the cryogenic ball and the evaporated droplet, the "blowing effect" of droplet natural convection was quantified.

3.1 Temperature boundary layer

3.1.1 The cryogenic ball

The distribution of the outer boundary line of the temperature boundary layer of the cryogenic ball with different particle sizes at the temperature difference $\Delta T = 190 \text{ K}$ was presented in Fig. 3, and the corresponding temperature boundary layer thickness $\delta_c$ changes with the flow angle $\phi$ were shown in Fig. 4.

Combined with Figs. 3 and 4, it was found that the shape of the outer boundary line of the cryogenic ball temperature boundary layer with different particle sizes is similar, and the $\delta_c$ gradually increases with the increase of $\phi$, which makes the thermal resistance of convective heat transfer gradually increases with the increase of $\phi$. The temperature boundary layer thickness of the cryogenic ball increases slightly with the increase of $\phi$ from 0° to 90° and increases exponentially with the increase of $\phi$ from 90° to 180°. And under the same conditions $\delta_c$ increases with the increase of cryogenic ball particle size. When $\Delta T = 190 \text{ K}$, the relationship between the average temperature boundary layer thickness of the cryogenic ball $\delta_c$ and the particle size $d_0$ was shown in Fig. 5. It was found from the
figure that there is a quadratic polynomial relationship between $\delta_c$ and $d_0$, and $\delta_c$ increases with the increase of $d_0$. When $d_0 = 0.1 \text{ mm}$, $\delta_c = 2.1 \text{ mm}$. When $d_0 = 2.5 \text{ mm}$, $\delta_c = 44.4 \text{ mm}$, increased by 95.3%. That is to say, with the increase of particle size, $\delta_c$ will gradually increase, which will enhance convective heat transfer resistance.

3.1.2 The droplet and the "blowing effect"

The comparison of the outer boundary line of the temperature boundary layer with different sizes was shown in figure 3, and the comparison of the thickness $\delta_d$ and $\delta_c$ of the droplet temperature boundary layer with the angle $\varphi$ of the incoming flow was shown in figure 4. From figures 3 and 4, it could be observed that the trend of the temperature boundary layer along the flow direction is similar. However, due to the "blowing effect", under the same working condition, the temperature boundary layer thickness of the droplet is greater than that of the cryogenic ball. Fig. 5 showed that the average thickness of the droplet temperature boundary layer $\delta_d$ also increases with the increase of $d_0$. When $d_0 = 0.1 \text{ mm}$, $\delta_d = 2.7 \text{ mm}$. When $d_0 = 2.5 \text{ mm}$, $\delta_d = 57.5 \text{ mm}$, the thickness increased by 95.3 %. But under the same conditions, the "blowing effect" makes $\delta_d$ greater than $\delta_c$. The "blowing effect" $\beta$ of the droplet temperature boundary layer varies with $d_0$ as shown in Figure 6. It can be noted from the figures, under different temperature conditions, $\beta$ almost unchanged. When $\Delta T = 190 \text{K}$, the average $\beta$ is about 29.0 %. When $\Delta T = 10 \text{K}$, the average $\beta$ is about 1.6 %.

3.2 Analysis of droplet natural convection evaporation characteristics

3.2.1 Evaporation velocity

Fig. 7 showed that when the temperature difference is 190 K, the change of evaporation velocity $V$ on the surface of droplets with different particle sizes with the incoming flow angle $\varphi$, and the change of average evaporation velocity $V$ on the surface of droplets with particle size was shown in Fig. 7. It can be observed in Fig. 7 that $V$ gradually decreases with the increase of $\varphi$ under different particle sizes. From 0° to 90°, $V$ decreases slowly. $\varphi$ decreases rapidly from 90° to 180°. From Figure 8, it can be seen that the power function relationship decreases with $\bar{\nu}$ the increase of $d_0$. The $d_0$ increases from 0.1mm to 2.5mm, $\Delta T = 190 \text{K}$, $\bar{\nu}$ decreases from 62.9mm/s to 4.8mm/s, reduced by 92.3 %. $\Delta T = 90 \text{K}$, $\bar{\nu}$ = 2.3mm/s, decreased by 92.2 %. $\Delta T = 10 \text{K}$, $\bar{\nu}$ = 0.2 mm/s decreased by 91.5 %. It can be seen that with the change of temperature difference, the influence of particle size on the vapor emission rate is almost consistent.

![Fig. 5 Variation of mean thickness of temperature boundary layer with particle size](image1)

![Fig. 6 The relationship between "blowing effect" and particle size](image2)
3.2.2 Mass evaporation rate

The variations of droplet mass evaporation rate \( u \) (kg/s) and per unit area of mass evaporation rate \( u^* \) (kg/s·m\(^{-2}\)) with \( d_0 \) were shown in Fig. 9 (a) and Fig. 9 (b). It can be viewed in the fitting image in Fig. 9 (a) that \( u \) increases with the increase of \( d_0 \) and the two show a quadratic polynomial relationship. Fig. 9 (b) shows that \( u^* \) decreases with the increase of \( d_0 \) and the two show a power function relationship. The larger the particle size is, the greater the mass evaporation rate of the droplet is, and the smaller the mass evaporation rate per unit area is. When \( \Delta T = 190 \text{ K} \), \( d_0 \) increased from 0.1 mm to 2.5 mm, \( u \) increased from \( 0.4 \times 10^{-8} \) kg/s to \( 17.0 \times 10^{-8} \) kg/s, increased by 46.8 times. The \( u^* \) decreased from 0.11 kg/s·m\(^{-2}\) to \( 8.6 \times 10^{-3} \) kg/s·m\(^{-2}\), reduced by 92.3%.

4. Conclusions

The numerical simulation model of a single droplet on the spray cooling down process of the LNG tank was developed. The natural convection evaporation processes of an LNG droplet with different particle sizes and distinct temperature differences in BOG were simulated, and the evaporation characteristics were analyzed. The "blowing effect" was distinguished by comparing with the natural convection heat transfer process of the cryogenic ball and the droplet was obtained:

(1) There are two separate zones around the droplet surface. With the increase of the flow angle \( \phi \) from 0° to 90°, the temperature boundary layer slightly thickened which will increase the thermal resistance slowly, then the vapor evaporation velocity slowly decreased. With the increase of the flow angle \( \phi \) from 90° to 180°, the temperature boundary layer thickens rapidly, so the thermal resistance is rapidly increased, then the vapor evaporation velocity is rapidly reduced.

(2) The average thickness of the temperature boundary layer and mass evaporation rate increase with the increase of particle size, so the average vapor evaporation velocity and per unit area of mass evaporation rate decrease with the increase of particle size.

(3) The "blowing effect" leads to the thickening of the temperature boundary layer and the weakening of the convective heat transfer intensity. But the "blowing effect" is independent of the particle size.
Acknowledgments
This work was supported by a Project supported the Zhejiang basic public welfare research project (Grant No.Q18E090007), Zhoushan City Technology Bureau Project Funding (Grant No.2017C41002, 2018C12044).

References
[1] LEE W H. PRESSURE ITERATION SCHEME FOR TWO-PHASE FLOW MODELING [J]. 1980,
[2] HAYWOOD R J, NAFZIGER R, & RENKSIZBULUT M. A Detailed Examination of Gas and
Liquid Phase Transient Processes in Convective Droplet Evaporation. [J]. Journal of Heat
Transfer, 1989, 111(2): 495.
[3] ZHIFU Z, GUOXIANG W, BIN C, et al. Evaluation of Evaporation Models for Single Moving
Droplet with a High Evaporation Rate [J]. Powder Technology, 2013, 240(95-102).
[4] WANG F, YANG S F, ZHANG S F, ZHANG X Z, et al. Droplet evaporation model in thick
exchange layer considering natural convection and its verification [J]. Propulsion technology,
2017, 38(03): 620-9.
[5] WANG F, LIU R, LI M, et al. Evaporation model of multicomponent droplet natural convection in
thick exchange layer and its verification [J]. Propulsion technology, 2019, 40(06): 1300-13.
[6] SAZHIN S S. Modelling of fuel droplet heating and evaporation: Recent results and unsolved
problems [J]. Fuel, 2017, 196(69-101.
[7] DENG J J, HUU YW, LU J S, et al. Heat transfer characteristics of natural convection of methane
droplet in its vapor [J]. Natural gas industry, 2019, 39(12): 116-23.
[8] DENG J J, XU J, LU J S, et al. Evaporation model of saturated single droplet of liquefied natural
gas and its influence on blowing effect [J]. Journal of Shanghai Jiaotong University, 2019,
53(08): 1010-6.
[9] DAiF A, BOUAZIZ M, CHESNEAU X, et al. Comparison of multicomponent fuel droplet
vaporization experiments in forced convection with the Sirignano model [J]. Experimental
Thermal and Fluid Science, 1998, 18(4): 282-90.