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Numerical Study of Evaporation and Motion Characteristics of Liquid Nitrogen Droplet in High-Speed Gas Flow

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Abstract. In the cryogenic wind tunnel, cooling the circulating gas to cryogenic temperature by spraying liquid nitrogen (LN₂) is an efficient way to increase the Reynolds number. The evaporation and motion of LN₂ droplets in the high-speed gas flow is the critical process that determines the cooling rate, cooling capacity and the safe operation of the down-stream compressor. In this study, a numerical model of droplet motion and evaporation in high-speed gas flow is developed and verified against experimental data. The droplet evaporation rate, diameter and velocity are obtained during the evaporation process under different gas temperatures and flow velocities. The results show that the gas temperature has dominant influence on the droplet evaporation rate. High flow speed can increase droplet evaporation effectively at the beginning process. Evaporation of droplets with different diameters follows a similar trend. The absolute evaporation rate increases with the increase of droplet diameter while the relative evaporation amount is highest for the smallest droplet due to its high area-volume ratio. This numerical study provides insight for understanding the evaporation of LN₂ droplets in high-speed gas flow and useful guidelines for the design of LN₂ spray cooling.

1. Introduction

With the development of aerospace technology, the size, height and speed of aircraft increase, and the aircraft construction become more complex, which requires more research on the high quality aerodynamic performance. Numerical simulation and wind tunnel experiment are two approaches to study the aerodynamic performance. However, the model and theory of numerical simulations at high Reynolds number was not mature enough, and the experimental investigation is still required. The cryogenic wind tunnel is the most promising approach to achieve the high Reynolds number. Compared with other methods, lowering the working fluid temperature can be easily realized with relatively small power consumption, and it is easy to adjust the fluid speed, total temperature and total pressure [1].

In the cooling process of cryogenic wind tunnel, the liquid nitrogen spray, droplet mixing, evaporation and heat transfer are the important factors which need careful consideration. The study on the liquid nitrogen spray in the high-speed gas flow can provide the basis for the design of the cryogenic wind tunnel. The evaporation and motion process of a single liquid droplet is the key to understand the spray cooling characteristics including the cooling rate, temperature distribution and droplet distribution.
Many numerical and experimental studies have been reported on the evaporation of droplets composing of conventional fluids such as water and fuel. Spalding [2] studied the evaporation process of fuel droplets in early stage, and assumed that the thermal conductivity of liquid phase was infinite and the physical properties of gas and liquid were constant in the evaporation process. Yuen [3] analyzed the change of the resistance of the droplet among the evaporation process with Reynolds number from 10 to 100. Dombrovsky et al. [4] studied effects of the finite thermal conductivity, assuming that the internal temperature of the droplet was distributed in parabolic, and they proposed an evaporation model which was applicable to the convective heat transfer of liquid droplets. Based on the above model, Abramzon [5] further included the radiation heat transfer of liquid droplets. The experiment of the water droplet evaporation in the superheated steam was carried out, and the correlation to predict the evaporation time of droplet was obtained [6]. The coefficients of Nusselle number correlation proposed by Ranz and Marshall [7] were revised. The temperature distribution of the evaporation droplet was measured by Wong [8], and the influence of Reynolds number and liquid drop viscosity on the temperature distribution and heating mechanism was studied. Sazhin [9] et al. used zero-dimensional heat transfer model to study the evaporation of fuel droplet, and the results showed that the evaporation time of droplet would be significantly reduced when the temperature gradient inside the droplet is considered. Aguilar [10] developed a single-droplet evaporation model to predict droplet diameter and temperature as a function of distance from the nozzle, and found that the velocity had the least influence on the cryogen droplet evolution.

Cryogenic wind tunnel mainly uses liquid nitrogen as working fluid, and the above studies mainly focus on the water and fuel. In this paper, a droplet evaporation model is developed for LN$_2$ droplet in high speed gas flow, and the spray field is analyzed through the evaporation and motion characteristics of a single droplet of liquid nitrogen.

2. Numerical model and method

2.1. Heat and mass transfer equations

Droplet evaporation is a complex physical process that is coupled with flow, heat transfer and mass transfer. This paper mainly considers the process of the steady evaporation and the boiling process. In the subcooling state, the droplet is heated up by the convective heat transfer in high temperature fluid, and the governing equation is

$$m_p c_p \frac{dT_p}{dt} = h A_p \left( T_\infty - T_p \right)$$  \hspace{1cm} (1)

where $c_p$ is the heat capacity of droplet liquid, $T_p$ is the droplet temperature, $A_p$ is the droplet surface area, $T_\infty$ is the temperature of continuous phase, and $h$ is the heat transfer coefficient determined by the following equation.

$$Nu = \frac{h \cdot D}{k_g} = (2 + 0.6 \cdot Re^{1/2} \cdot Pr^{1/3}) \cdot \frac{\ln(1 + B_M)}{B_T}$$  \hspace{1cm} (2)

where Re is the Reynolds number of the continuous phase, Pr is the Prandtl number of the continuous phase, $B_M$ is the mass transfer number, and $B_T$ is the heat transfer number.

In the saturated state, the heat from the surrounding gas to the droplet is used for vaporization, while the surface temperature of the droplet remains constant. The evaporation rate of the steady evaporation is determined by the following equation.

$$\dot{m}_e = 2 \pi D \left( \frac{k_g}{c_{pg}} \right) \ln(1 + B_T)$$ \hspace{1cm} (3)

where $\dot{m}_e$ is droplet evaporation rate; D is diameter of droplet; $k_g$ is thermal conductivity of gas; $c_{pg}$ is gas specific heat; $B_T$ is heat transfer number.

Evaporation rate is equal to the change rate of droplet mass
\[ \dot{m}_l = 2\pi D \left( \frac{k_l}{c_{p_l}} \right) \ln(1 + B_r) = -\frac{d}{dt} \left( \frac{\pi}{6} \rho_p D^3 \right) \]  
\hspace{1cm} (4) 

where \( \rho_p \) is liquid nitrogen density.

For the boiling of the droplet, the change rate of droplet diameter is determined by the following equation.

\[ \frac{dD}{dt} = \frac{4k_g}{\rho_p c_{p_v}} D \left( 1 + 0.23 \sqrt{Re_d} \right) \ln \left[ 1 + \frac{c_{p_v} (T_v - T_p)}{L_v} \right] \]  
\hspace{1cm} (5) 

where \( Re_d \) is Reynolds number of droplet, and \( L_v \) is latent heat.

### 2.2. Droplet momentum equation

When the droplet is moving in the fluid, the velocity of the droplet is obtained through the solution of the droplet momentum equation. According to the gas-particle interaction in the two phase flow theory, the forces acting on the particle of relative velocity compared with the continuum phase include the viscous, gravity, virtual mass force, thermophoresis force, etc. For tiny droplets, forces except for the viscous and gravity forces can be ignored. According to Newton’s second law, the momentum equation of the droplet is as follows.

\[ \frac{du_p}{dt} = F_D \left( \mathbf{u} - \mathbf{u}_p \right) + \frac{g \left( \rho_l - \rho_g \right)}{\rho_l} \]  
\hspace{1cm} (6) 

The first item at the right hand side is the viscous force, the second term is the gravity force, and \( F_D \) is calculated according to the following equation.

\[ F_D = \frac{18 \mu_l C_D Re_d}{\rho_l D^2} \]  
\hspace{1cm} (7) 

where \( \mathbf{u} \) is fluid velocity, \( \mathbf{u}_p \) is the droplet velocity, \( \rho_l \) is the droplet density, \( \rho_g \) is the gas density, \( \mu_l \) is the viscosity of droplet liquid, \( D \) is the droplet diameter, \( C_D \) is the viscous coefficient, and \( Re_d \) is the droplet Reynolds number.

### 3. Results and Discussions

Based on heat and momentum governing equations, a zero-dimension model is established to predict the \( \text{LN}_2 \) droplet evaporation and motion, which includes the effects of the boiling heat transfer between droplet and gas but ignores the droplet deformation, the internal heat transfer and the radiation heat transfer. A 10 meters long computational domain is selected with air velocity direction parallel to the length direction and gravity direction perpendicular to the direction of the airflow. The time step in all the simulations is 0.01 second.

### 3.1. Model validation

The model is validate against to the experiment of the free fall of liquid nitrogen droplet in the air by Awonorin [11]. The simulation parameters are shown in Table 1. The comparison between the numerical simulation and the experimental results is shown in Figure 1, which shows that the simulation results are in good agreement with the experimental data. The evaporation process is affected by several different factors, including the gas temperature, the airflow speed and the gas pressure. This paper numerically investigates the \( \text{LN}_2 \) droplet evaporation process flow by changing these factors and presents a comprehensive analysis on the influence of these factors on the \( \text{LN}_2 \) droplet evaporation process.
Table 1. Working condition for model validation

| Ambient pressure $p_\infty$/atm | Ambient temperature $T_\infty$/℃ | Droplet diameter $D_0$/mm |
|---------------------------------|---------------------------------|---------------------------|
| 1.0                             | 30                              | 2.00                      |
|                                 | -50                             | 1.22                      |
|                                 | -100                            | 1.11                      |

Figure 1. The comparison between the simulation results and the experimental data by Awonorin [11]

3.2. Impact of gas temperature
Figure 2 shows the changes of the droplet diameter, position and evaporation rate of droplet in different gas temperatures. The simulation parameters are as follows: the gas pressure is 0.5 MPa; the airflow speed is 10 m·s$^{-1}$; the droplet speed is 7 m·s$^{-1}$; the direction are along the length direction towards the downstream. The initial diameter of LN$_2$ droplet is 0.4 mm and the initial temperature is the saturation temperature (77.4 K) at 0.1 MPa. Figures 2 (a) and (b) indicate that the gas temperature has a great influence on the droplet evaporation rate. According to the heat transfer and mass transfer equations of droplets, the gas temperature difference is proportional to the droplet heat and mass transfer rate. When the droplet starts to evaporate, the evaporation rate at 300 K is larger than that at 200 K. However, the evaporation rate becomes smaller after 0.3 seconds because the evaporation rate decreases with the decreasing diameter as well as the Reynolds number. At the beginning of simulation, the droplet is in subcooling state and its evaporation rate is zero until the temperature reach boiling point. The gas temperature has little influence on the velocity of the droplet, the distance curves at different gas temperature coincides with each other. In figure 2 (b), it can be easily observed that the LN$_2$ droplet can completely evaporate in the 300 K gas flow, and 99.4% of the droplet evaporates in the 200 K gas flow.
3.3. Impact of gas velocity

The parameters for the simulations in this section are as follows: the gas temperature is 300 K; the gas pressure is 0.5 MPa; the droplet speed is 7 m·s⁻¹; the droplet initial diameter is 0.4 mm; the droplet temperature is 77.4 K which is saturation point at 0.1 MPa. Figure 3 (a) shows that the high flow speed can increase droplet evaporation effectively at the beginning process. At the end of the flow, the droplet evaporation rate becomes similar because the speed difference between airflow and droplet becomes very small. Figure 3 (b) shows that the higher flow speed lead to a shorter evaporation time and a longest evaporation distance. Therefore, in the cryogenic wind tunnel with restricted space, the small fluid velocity has the advantage of a short evaporation distance which can prevent the LN₂ droplet blowing into the compressor.

3.4. Impact of the initial droplet diameter

Figure 4 shows the evaporation rate variations for droplets with different initial diameter. The simulation parameters are as follows: gas temperature is 300K; the gas pressure is 0.5 MPa; the airflow speed is 10 m·s⁻¹; the droplet speed is 7 m·s⁻¹; the direction are all along the length towards the downstream; the droplet temperature is 77.4K. A higher characteristic length means a higher Reynolds number under the same velocity and properties. According to equation (2), we can find a high
Reynolds number can lead to a large coefficient of heat transfer. Therefore the droplets with a diameter of 0.4 mm have the highest evaporation rate. Figure 4 (b) shows that the droplet can completely evaporate when the diameter is smaller than 0.4 mm. The absolute evaporation rate is higher for the bigger droplet, but the relative evaporation amount is highest for the smallest droplet due to its high area-volume ratio.

![Figure 4](image_url)

Figure 4 (a) Impact of initial diameter on the droplet evaporation rate; (b) Impact of initial diameter on the diameter and distance variations.

### 3.5. **Impact of gas pressures**

Figure 5 shows the evaporation process in different gas pressures. The simulations under different gas pressure and same initial temperature actually investigates the influence of subcooling degree on evaporation characteristics. The droplets can be heated up to the saturation state in the first 0.03 seconds of all the three condition. It means the subcooling does not play an important role in droplet evaporation. Figure 5 (b) indicates that the droplets have a quick evaporation in the high pressure gas flow because the higher gas density can lead to a higher Reynolds number as well as a higher coefficient of heat transfer.

![Figure 5](image_url)

Figure 5 (a) Impact of gas pressure on the droplet evaporation rate; (b) Impact of gas pressure on the diameter and distance variations.
4. Conclusions
In this paper, the droplet evaporation model is modified according to the actual working condition in the wind tunnel and the LN$_2$ properties. Simulations on the droplet evaporation process are performed in the high-speed gas flow by changing the parameters including the gas temperature, the gas flow velocity, the initial diameter and the gas pressure. The following conclusions can be drawn from this study.

(1) The gas temperature has a significant influence on the droplet evaporation rate. The LN$_2$ droplet can completely evaporate within 0.37 second in the gas flow with a temperature of 300 K and evaporate 99.4% in the gas flow with a temperature of 200 K. When the gas temperature is down to 100 K, the droplet can only evaporate 1.07% in 10 meters long channel. The moving speed of the droplet remains unaffected under different gas temperature.

(2) The gas pressure has little influence on the evaporation rate. The overall trend is that the higher the environmental pressure, the larger the evaporation rate. The influence of gas pressure on the droplet speed is mainly caused by the change of gas density;

(3) The small gas flow velocity can lead to a short evaporation distance which is desirable for the design of cryogenic wind tunnel. The evaporation distances in gas flow with velocities of 30 m/s, 20 m/s and 10 m/s are 8.1 m, 6.5m and 3.5m, respectively. The other parameters have little influence on the droplet travel distance.

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