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Analysis of Liquid Nitrogen Spray Atomization Characteristics by Internal-Mixing Atomizers

Zhang Lei, Liu Gaotong

***Abstract*—**The atomization effect is an important factor of the heat transfer of liquid nitrogen spray. In this paper, two kinds of internal-mixing twin-fluid atomizers were design. According to the fracture theory and fluid mechanics, the model is established to simulate atomization effect. The results showed that: Internal-mixing atomizers, with the liquid nitrogen atomization size from 20um to 40um, have superior performance. Y-jet atomizer spray speed is greater than Multi-jet atomizer, and it can improve the efficiency of heat transfer between the liquid nitrogen and its spray object. Multi-jet atomizer atomization cone angle is about 30°, Y-jet atomizer atomization cone angle is about 20°. During atomizer selection, the size of the heat transfer area should be considered.

***Keywords*—**Atomization, two-phase flow, atomizer, heat transfer.

I. Introduction

THE spray of liquid nitrogen (LN_2) is a refrigeration method which uses LN_2 latent heat. LN_2 droplets atomized by atomizer transfer heat and mass with the surrounding medium through phase change, to reduce the medium temperature. Accordingly, the atomizer performance is an important factor to affect the heat transfer of LN2 spray. The internal-mixing twin-fluid atomizer has been widely used in recent years for its high quality of atomization and low gas consumption [1], [2]. The internal-mixing twin-fluid atomizer involves complex two-phase flow; therefore previous studies are based on experiment. In addition, the atomizer mainly applied in the field of fuel and water spray, LN2 spray is less involved [3]-[8].

Two kinds of internal-mixing twin-fluid atomizers: Y-jet and Multi-jet atomizer were design. According to breakup theory and fluid mechanics, atomization model was established to simulate two kind of atomizer with different structure with liquid and gas nitrogen (GN_2) as working media. Through the study on the distribution of particle size, velocity field and droplet particle trajectory the characteristics of the atomizers were obtain for the reference of atomizer's design.

II. Atomizer Design

A. Y-jet Atomizer Structure

Fig. 1 shows the structure of Y-jet atomizer. Y-jet atomizer consists of LN_2 injection chamber, GN_2 injection chamber and spray chamber.

Zhang Lei is with the Beijing Institute of Satellite Environment Engineering, Beijing, 100094 China (phone: 86-10-68746578; fax: 86-10-68746751; e-mail: zhangleibuaa@126.com).

Liu Gaotong is with the Beijing Institute of Satellite Environment Engineering, Beijing, 100094 China (e-mail:315267988@qq. com).

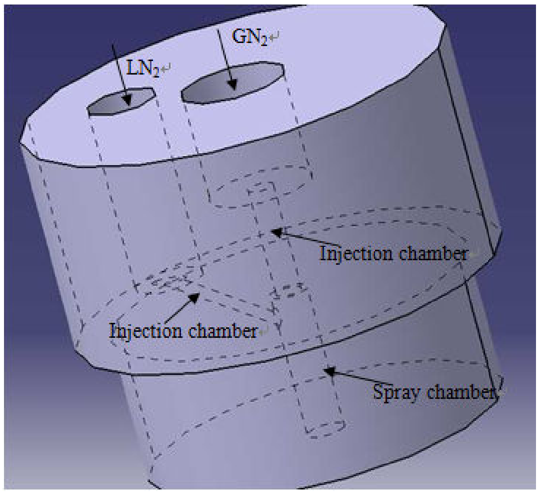

Fig. 1 Y-jet atomizer structure

B. Multi-Jet Atomizer Structure

Fig. 2 shows the structure of Multi-jet atomizer. Multi-jet atomizer consists of LN2 injection chamber, GN2 injection chamber, mixing chamber and nozzles.

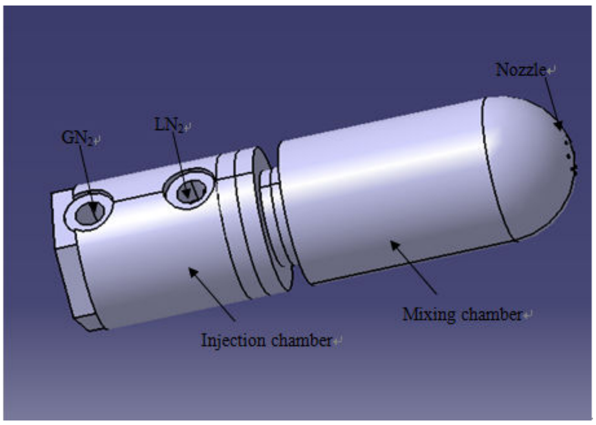

Fig. 2 Multi-jet atomizer structure

III. Simulation Model and Simulation Settings

A. Mathematical Model

1. Continuous phase control equation

Continuous phase control equations including the continuity equation, momentum equation, energy equation and the Reynolds averaged three-dimensional N-S equation. RNG $k-\varepsilon$ model was employed to simulate turbulent [9].

$$\begin{aligned}
&\frac{\partial Q}{\partial t}+\frac{\partial F_j}{\partial x_j}+\frac{1}{\mathrm{Re}}\frac{\partial F_{vj}}{\partial x_j}=S \\
&Q=[\rho,\rho u_i,\rho E]^T \\
&F_j=[\rho u_j,\rho u_i u_j+p\delta_{ij},(\rho E+p)u_j]^T \\
&F_{vj}=[0,-\tau_{ij},-\tau_{ij}u_i+q_i]^T \\
&S=[S_m,S_u,S_h]^T
\end{aligned} \tag{1}$$

where Q is the conservation variable flux; F_j is the inviscid flux; F_{vj} is the viscid flux; S_m, S_u, S_h is the quality source, momentum source and energy source.

$$\frac{\partial}{\partial \tau}(\rho k)+\frac{\partial}{\partial x_i}(\rho k U_i)=\frac{\partial}{\partial x_i}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_i}\right)+G_k-\rho\varepsilon+S_k \tag{2}$$

$$\frac{\partial}{\partial \tau}(\rho \varepsilon)+\frac{\partial}{\partial x_i}(\rho \varepsilon U_i)=\frac{\partial}{\partial x_i}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_i}\right)+G_{1\varepsilon}G_k\frac{\varepsilon}{k}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \tag{3}$$

where G_k is the generation of turbulence kinetic energy due to the mean velocity gradients; $G_{1\varepsilon}, G_{2\varepsilon}$ is the model constants; $\alpha_k, \alpha_\varepsilon$ is the Turbulent Prandtl number of k equation and ε equation; S_k, S_ε is defined according to the specific conditions.

2. Discrete Phase Control Equation

The discrete phase model is based on the Lagrangian method. Using random orbital model, particle trajectory was simulated. The orbital equation is shown in (4).

$$\begin{aligned}
&\frac{du_P}{dt}=F_D(u-u_P)+\frac{g_x(\rho_P-\rho)}{\rho_P}+F_x \\
&F_D=\frac{18\mu C_D R_e}{\rho_P d_P^2 24} \\
&R_e=\frac{\rho d_P|u_p-u|}{\mu} \\
&C_D=a_1+\frac{a_2}{\mathrm{Re}}+\frac{a_3}{\mathrm{Re}}
\end{aligned} \tag{4}$$

where F_D is the drag force per unit mass; C_D is the drag force coefficient; u, u_p is the particle velocity of continuous phase and discrete phase; ρ, ρ_p is the particle density of continuous phase and discrete phase; dp is the droplet diameter; a_1, a_2, a_3 is the constant.

3. Atomization Model

Air-assisted atomization model was adopted. Liquid form a liquid film through the atomizer, and auxiliary air directly impact the liquid film in order to speed up the film broken. The smaller droplets can be obtained with the role of auxiliary air, and to prevent collisions between droplets.

4. Droplet Collision and Breakup Model

Droplet collision model selection O'Rourke and crushing select fluctuations model. We get the initial diameter of the liquid droplets by the jet stability analysis. After the crushing of the liquid droplets to form small droplets, and the r1 calculated by (5).

$$\begin{aligned}
&\frac{dr_1}{dt}=-\frac{r_1-r}{\tau} \\
&r=0.61\Lambda \\
&\tau=\frac{3.726B_1 r_1}{\Lambda\Omega}
\end{aligned} \tag{5}$$

where r is the broken droplet radius; Λ is the wavelength; τ is the crushing time; Ω is the maximum growth rate; B_1 is the crushing time constant.

B. Boundary Conditions and Calculation Method

The Simple pressure-velocity coupling algorithm is adopted in this paper. First, numerical continuous phase was calculated, after the continuous phase convergence, the discrete phase was loaded. In this paper, the RNG k-epsilon turbulence model was applied to simulate turbulence. Considering the fragmentation and merging of droplets in the discrete phase, Wave broken model were adopted. Inert particles were selected in particle type; Dynamic Drag Model Theory was applied in calculation. Inlet pressure was defined as 0.8 *MPa*; outlet pressure was defined as 0.2 *MPa*.

IV. Results and Analysis

A. Radial Particle Size Distribution of the Spray Field

The purpose of atomization is to evaporate for the heat exchanging, and the smaller particle size of the jet out droplets, the better of the evaporating heat transfer effect. The radial particle size distribution of the Spray field is an important indicator to judge the atomization effect, and then select Sauter mean diameter (SMD) expressing the droplet size[10]. Fig. 3 shows the radial particle size distribution of the Y-jet atomizer and Multi-jet atomizer spray field. It can be seen that when the LN_2 atomizing size of the internal-mixing atomizer is between 20*um* and 40*um*, the atomizing performance will be superior. In which that the droplet size (20*um*-25*um*) of the Multi-jet atomizer is less than the Y-jet atomizer (35*um*-40*um*).

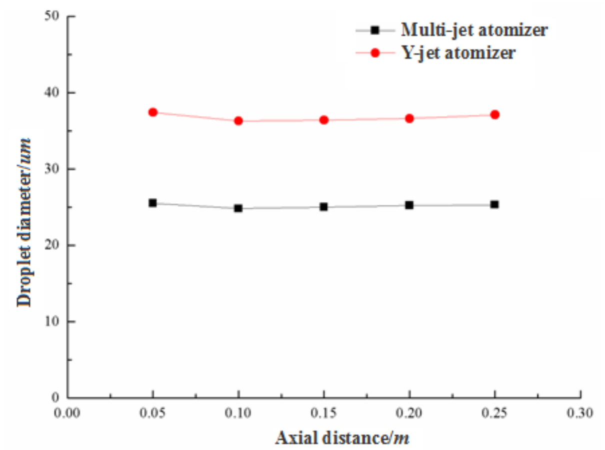

Fig. 3 The curve of droplet diameter with the spray distance

B. The Nozzle Velocity Field Distribution

Fig. 4 shows the velocity field distribution at the outlet of the Y-jet atomizer, and Fig. 5 shows the velocity field distribution at the outlet of the Multi-jet atomizer. As can be seen, the velocity at the outlet of the Y-jet atomizer is greater than the Multi-jet atomizer. The greater velocity at the outlet, the greater the formed spoiler intensity will be, and then it will enhance the droplet crushing, and exacerbate collision degree between the gas and liquid, thereby increasing the heat transfer effect.

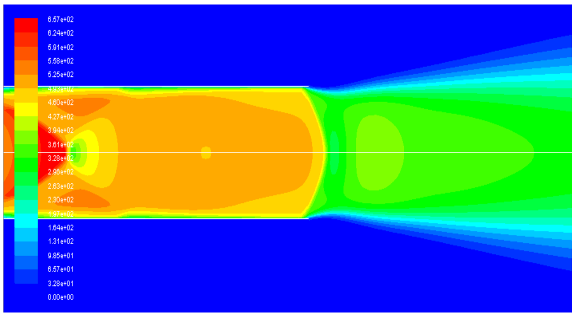

Fig. 4 Y-jet atomizer spray speed distribution

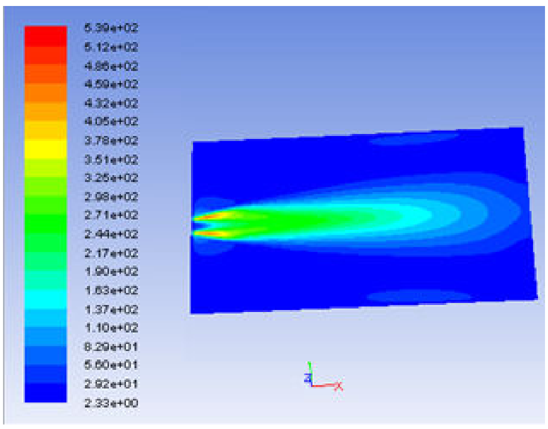

Fig. 5 Multi-jet atomizer spray speed distribution

C. The Droplet Discrete Particle Trajectory

Fig. 6 shows the droplet discrete particle trajectory at the outlet of the Y-jet atomizer, and Fig. 7 shows the droplet discrete particle trajectory at the outlet of the Multi-jet atomizer. As can be seen, the Y-jet atomizer atomization cone angle is approximately 20°, and the Multi-jet atomizer atomization cone angle cone angle is approximately 30°. The atomization cone angle has a great influence on the heat transfer, if the atomization cone angle is too large, the droplets may pass through the strongest turbulence area to be poor mixed. In addition, it also because that LN_2 sprayed onto wall surface of the heat exchanging area then causes effusion. If the atomization cone angle is too small, the droplets cannot be effectively distributed in the entire heat exchanging area to be poor mixed. During atomizer selection, the influence of the heat exchanging area size needs to be considered.

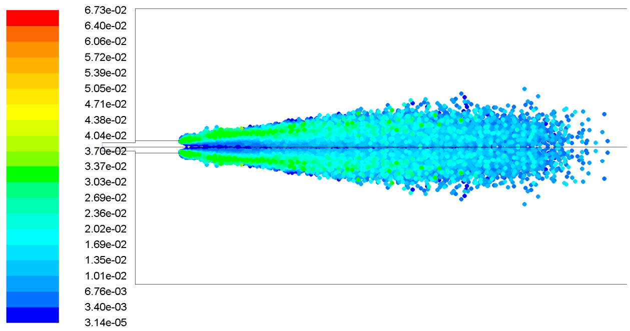

Fig. 6 The discrete phase distribution of Y-jet atomizer

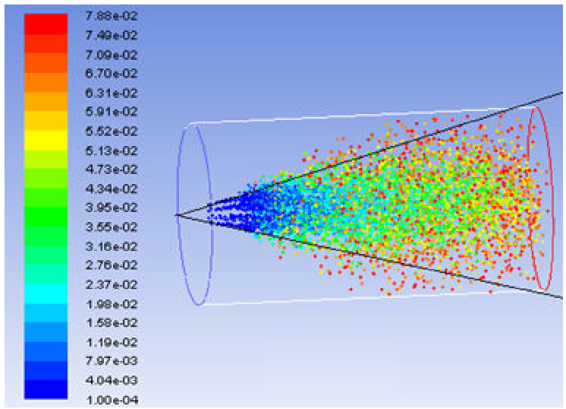

Fig. 7 The discrete phase distribution of Multi-jet atomizer

V. Conclusion

Based on the simulation calculation of Y-jet atomizer and Multi-jet atomizer atomization effect, the conclusions are as following:

1) Internal-mixing atomizers, with the liquid nitrogen atomization size from 20um to 40um, have superior performance. Y-jet atomizer's atomization size is 35um-40um, and Multi-jet atomizer's atomization size is 20um-25um.
2) Y-jet atomizer spray speed is greater than Multi-jet atomizer, and it can improve the efficiency of heat transfer between the liquid nitrogen and its spray object.
3) Multi-jet atomizer atomization cone angle is greater than

Y-jet atomizer. During atomizer selection, the size of the heat transfer area should be considered.

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Zhang lei, Born in Hebei, China, 1983 and get the Ph.D. degree from Beijing University of Aeronautics and Astronautics in 2010. He is now working in Beijing Institute of Satellite Environment Engineering. The current and previous research interest is the refrigeration and cryogenic technology.

Liu Gaotong, Born in Shangdong, China, 1986 and get the Master's degree from Tianjin University in 2010. She is now working in Beijing Institute of Satellite Environment Engineering as an engineer. The current and previous research interest is the space environment control technology.