International Science Index, Mechanical and Mechatronics Engineering Vol:11, No:9, 2017 waset.org/Publication/10007936

Numerical Simulation and Analysis on Liquid Nitrogen Spray Heat Exchanger

Wenjing Ding, Weiwei Shan, Zijuan, Wang, Chao He

***Abstract*—**Liquid spray heat exchanger is the critical equipment of temperature regulating system by gaseous nitrogen which realizes the environment temperature in the range of -180 ℃~+180 ℃. Liquid nitrogen is atomized into smaller liquid drops through liquid nitrogen sprayer and then contacts with gaseous nitrogen to be cooled. By adjusting the pressure of liquid nitrogen and gaseous nitrogen, the flowrate of liquid nitrogen is changed to realize the required outlet temperature of heat exchanger. The temperature accuracy of shrouds is ±1 ℃. Liquid nitrogen spray heat exchanger is simulated by CATIA, and the numerical simulation is performed by FLUENT. The comparison between the tests and numerical simulation is conducted. Moreover, the results help to improve the design of liquid nitrogen spray heat exchanger.

***Keywords*—**Liquid nitrogen spray, temperature regulating system, heat exchanger, numerical simulation.

I. Introduction

COLD environment simulation in aerospace is an effective way of forecasting, testing, and demonstrating the performance and reliability of various aircraft. As a cooling medium with high cooling rate and an open development value, liquid nitrogen is widely used in cryogenic environment simulation [1]. Currently, liquid nitrogen is used as the cold source in single phase circulation of the space simulator. However, when the ambient temperature outside the satellite has changed significantly over time, it is necessary to simulate the dynamic orbital thermal environment. Under this condition, gas nitrogen system must be used to adjust the shroud temperature (dynamic thermal environment test). The system with liquid nitrogen spray heat exchanger is shown in Fig. 1.

Liquid nitrogen spray heat exchanger atomizes liquid nitrogen into small droplets using low temperature liquid nitrogen nozzle, and makes them directly contact with the cycling gas nitrogen to transfer heat. The aim is to cool cycling gas nitrogen using latent heat of liquid nitrogen.

By adjusting liquid nitrogen supplying pressure, liquid nitrogen flow is changed, which can achieve dynamically accurate gas nitrogen temperature, and ensure the shroud inlet temperature variation within ±1 ℃. Moreover, after liquid nitrogen's atomization, the total surface area of the liquid is significantly increased since continuous liquid breaks into a large number of discrete droplets, leading to contact area the environmental significantly increase. Hence, heat transfer mass transfer efficiency is so greatly increased so as to reduce the consumption of liquid nitrogen.

Wenjing Ding is with The Beijing Institute of Space Environment Engineering, China (phone: +86-10-68746578-620; fax: +86-10-68746751; e-mail: wjding@163.com).
Weiwei Shan is with The Beijing Institute of Space Environment Engineering, China (phone: +86-10-68746578-623; fax: +86-10-68746751; e-mail: sww_xjtu@163.com).
Zijuan Wang is with The Beijing Institute of Space Environment Engineering, China (phone: +86-10-68746578; fax: +86-10-68746751; e-mail: swwxjtu@163.com).

II. Calculation Model

A. Physical Model

Liquid nitrogen spray heat exchanger calculation model is established by software CATIA, as shown in Fig. 2. The whole model consists of three computing domains from bottom to top, bottom-up, body-net and body-top, respectively. In order to avoid the droplets coming out of the outlet with the airflow in advance, the nozzle penetrates the inside of the heat exchanger. Circulating gas nitrogen goes into the heat exchanger from the inlet, and then stabilizes the pressure when through the metallic wire net, and after that enters into the heat transfer section. In this section, it transfers heat with nozzle (nozzle-inlet) sprayed liquid nitrogen and atomized nitrogen in the form of countercurrent. The cold source is the latent heat of vaporization of liquid nitrogen. Finally, it flows through the outlet.

B. Mathematical Model

In liquid nitrogen spray heat exchanger, the processes of liquid nitrogen atomization by going through the nozzle and the droplet evaporation in the heat exchanger heat transfer are two-phase flow problem. At present, the two-phase flow numerical methods can be divided into two categories: one is the Euler-Euler method, the fluid and particles are co-existence of mutual penetration of the continuous medium, the size of the particles according to the size of multiple groups. Each group is considered as a quasi-fluid or continuous medium, and there is a continuous velocity and temperature distribution and equivalent transport properties (viscosity, diffusion, thermal conductivity, etc.). The other is to consider the fluid as a continuous medium and particles as discrete, which is the Euler-Lagrangian method. The particle dynamics and the particle orbit are discussed. The model is based on the Monte-Carlo method, considering a representative sample of discrete droplets, using the Lagrangian method to track these droplet samples movements, i.e. to solve a description of its trajectory and heat transfer mass transfer process of a group of ordinary differential equations [2], [3].

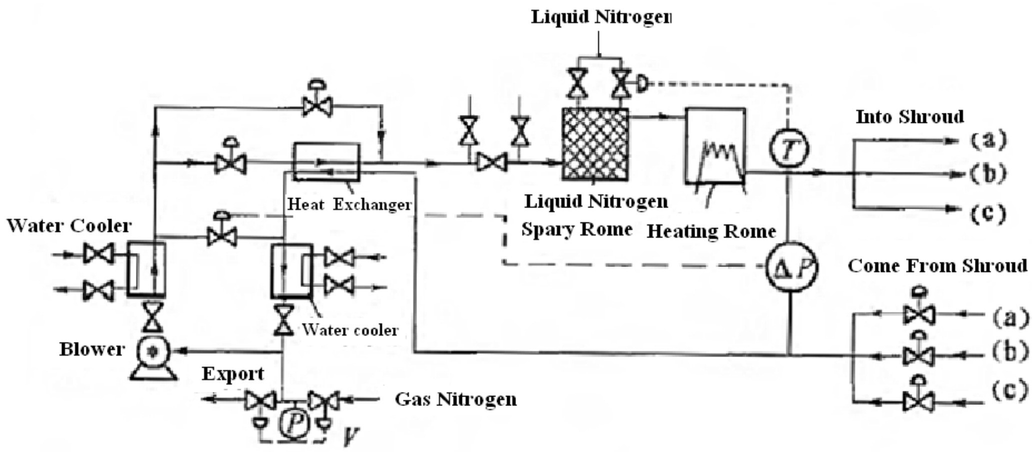

Fig. 1 Gas nitrogen thermostat equipment flow chart

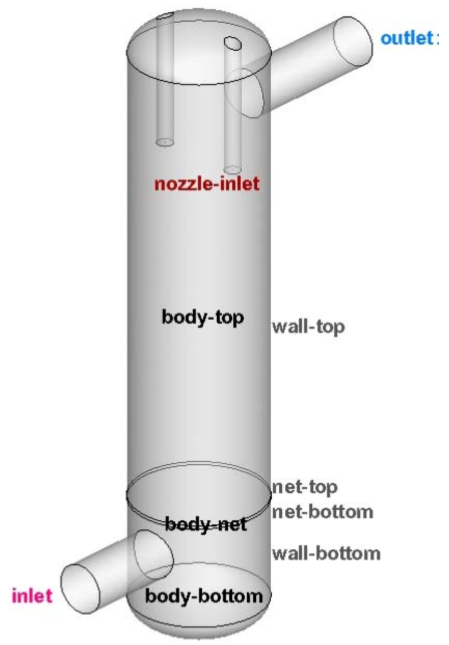

Fig. 2 Liquid nitrogen spray heat exchanger model

In this paper, Euler-Lagrangian method is used by utilising software FLUENT Discrete Particle Model (DPM) model simulation. According to the continuous phase flow field, the discrete phase motion is simulated under the pull coordinate to calculate the heat and mass transfer process of the discrete phase particle orbit, the phase and the coupling result and the coupling result on the continuous phase flow of the discrete phase track box [4]-[6].

The form in the Cartesian coordinate system (X) is:

$$\frac{du_P}{dt} = F_D(u - u_P) + \frac{g_X(\rho_P - \rho)}{\rho_P} + F_X \tag{1}$$

where FD (u-up) is the unit mass of the droplets:

$$F_D = \frac{18\mu C_D R_e}{\rho_P d_P^2 24} \tag{2}$$

where u is the continuous phase velocity, u_P is the velocity of the discrete phase particles; ρ is the continuous phase density, ρ_P is the density of the discrete phase particles; dp is the droplet diameter, Re is the Reynolds number of the droplet.

$$\mathrm{Re} = \frac{\rho d_P |u_P - u|}{\mu} \tag{3}$$

CD is the pull force coefficient, expressed as:

$$C_D = a_1 + \frac{a_2}{\mathrm{Re}} + \frac{a_3}{\mathrm{Re}} \tag{4}$$

For spherical particles, in a certain Reynolds number range, the above formula α1, α2, α3 is constant. CD can also use:

$$C_D = \frac{24}{\mathrm{Re}}\left(1 + b_1 \mathrm{Re}^{b2}\right) + \frac{b_3 \mathrm{Re}}{b_4 + \mathrm{Re}} \tag{5}$$

$$b_1 = \exp\left(2.3288 - 6.4581\phi + 2.4486\phi^2\right) \tag{6}$$

$$b_2 = 0.0964 + 0.5565\phi \tag{7}$$

$$b_3 = \exp\left(4.9 - 13.9\phi + 18.4\phi^2 - 0.26\phi^3\right) \tag{8}$$

$$b_4 = \exp\left(1.5 - 2.26\phi + 20.7\phi^2 - 15.9\phi^3\right) \tag{9}$$

The shape factor φ is defined as:

$$\phi = \frac{s}{S} \tag{10}$$

where s is the surface area of the spherical particles having the same volume as the actual particles, and S is the surface area of the actual particles.

The integral of the force balance equation yields the particle velocity at each position on the particle orbit, and the droplet trajectory can be obtained by:

$$u_P = \frac{dx}{dt} \tag{11}$$

C. Calculation Grid

The meshing software is ICEM and the unstructured grid is adopted. The simulating target is heat transfer of 30 Nm^3/min, shown in Figs. 3 and 4.

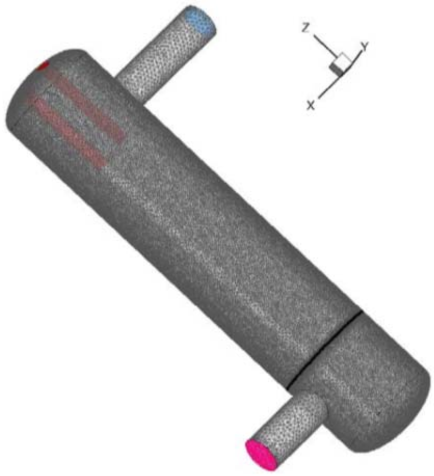

Fig. 3 Calculated domain grid

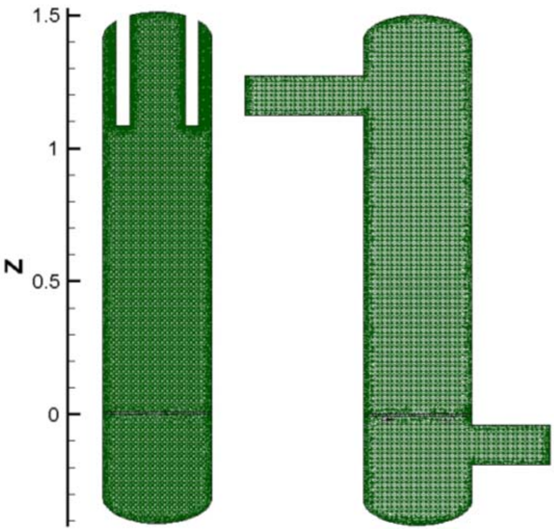

Fig. 4 Heat exchanger x = 0, y = 0 section grid

III. Calculation Results and Analysis

The simulation conditions are as follows:

a) Nitrogen flow rate: 30 Nm^3 / min;
b) Nitrogen pressure: 0.5 MPa;
c) Inlet temperature: 113 K.

In order to characterize the simulation results, a series of analytical auxiliary surfaces are taken, including x = 0, y = 0, the interface of the nozzle and the section of gravity direction, the cross section is marked with z coordinate value, Z = 875 mm, z = 675 mm, z = 775 mm, z = 875 mm, z = 975 mm and z = 1075 mm, see Fig. 5, z = 75 mm, z = 175 mm, z = 275 mm, z = 375 mm, z = 475 mm, z = 575 mm, z = 675 mm. The internal flow field is shown in Figs. 6 and 7.

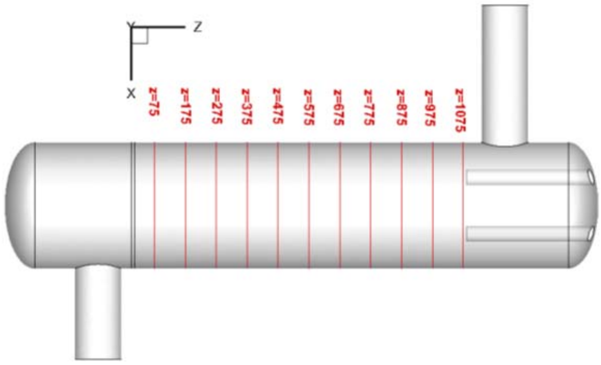

Fig. 5 Liquid nitrogen spray heat exchanger (along the gravity direction of the auxiliary surface)

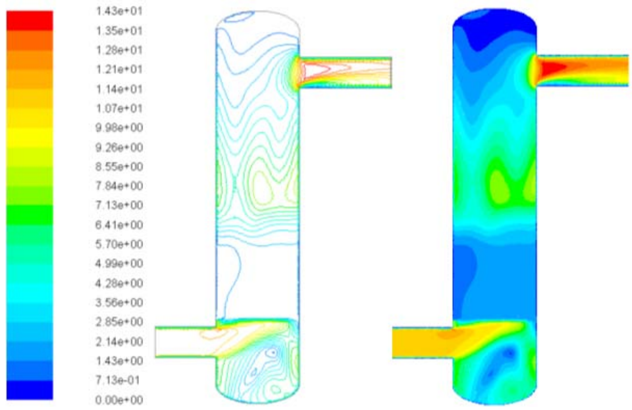

Fig. 6 Liquid nitrogen spray heat exchanger speed cloud surface

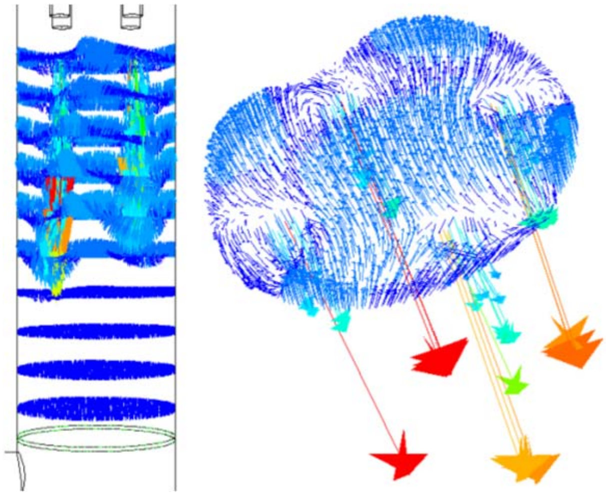

Fig. 7 Cross-section of the heat exchanger and z = 975 cross-section velocity vector

As a temperature control device, the export temperature and internal temperature distribution in liquid nitrogen spray heat exchanger is essentially important. The outlet temperature is around 97 K (-175 ℃), as shown in Fig. 8, lower than -170 ℃, and the entire outlet temperature is uniformly distributed, with temperature uniformity ±1 ℃.

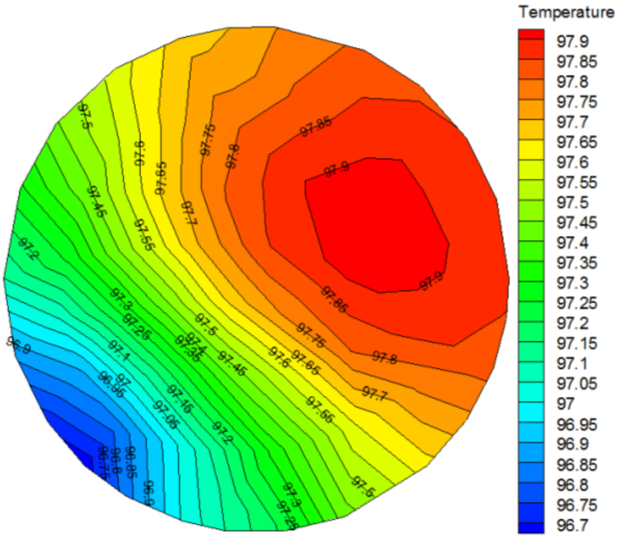

Fig. 8 Outlet temperature distribution

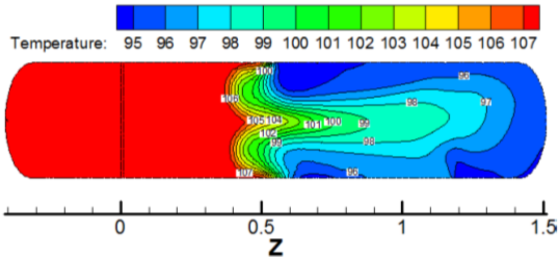

Fig. 9 The temperature contour (X=0)

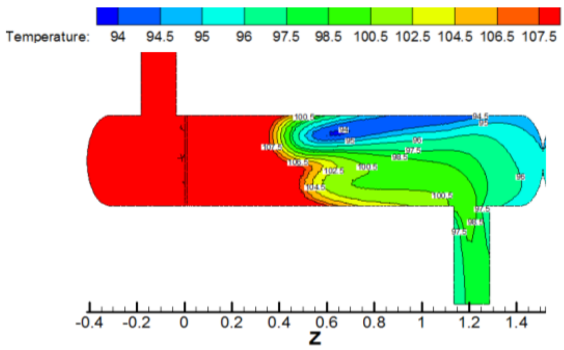

Fig. 10 The temperature contour (y=0)

Figs. 9-11 show the temperature profile at the section x=0, y=0, and at the nozzle section. In these profiles, there is a peak indicating that the liquid nitrogen spray heat exchanger internal center temperature is higher, but reduces along the radial axis, where the nozzle is in the same position. When gas is rising, it keeps transferring heat in low temperature zone at the bottom of the nozzle (liquid nitrogen spray area), and makes the temperature gradually go down. Due to the higher temperature of the atomized nitrogen, the low temperature zone has a certain distance from the nozzle. The outlet position also affects the temperature distribution, and the temperature near the outlet side is higher because the gas flows out through the outlet, forming a low pressure, and the circulating gaseous nitrogen is large at the outlet side, so the temperature is high. The temperature distribution indicates that the practical heat transfer length is less than the design length of the heat transfer in the heat exchanger design and it can meet the requirements.

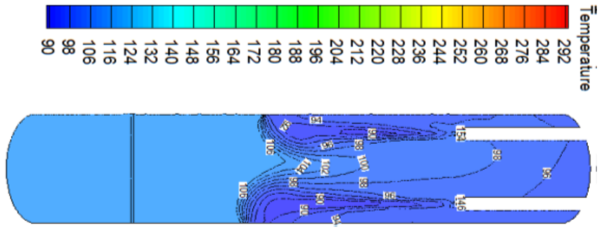

Fig. 11 The temperature contour (nozzle section)

IV. Conclusion

The numerical simulation of the internal heat transfer process of the nozzle atomization process and the liquid nitrogen spray heat exchanger was carried out by using the commercial CFD software FLUENT. The results show that when the nozzle fluid is nitrogen and liquid nitrogen, the outlet temperature of the heat exchanger is as low as 97K (-175 ℃), and the whole outlet temperature distribution is uniform and the temperature variation is less than ±1 ℃.

References

[1] Huang Bencheng, Ma Youli. Spacecraft space environment experimental technology (M). Beijing: National Defense Industry Press, 2002.
[2] Yang Shiming, Tao Wenquan. Heat transfer (M). Beijing: Higher Education Press, 1998.
[3] Tao Wenquan. Numerical heat transfer (M). Xi'an: Xi'an Jiaotong University Press, 1998.
[4] Zhou Junjie. Fluent engineering technology and examples of analysis (M). Beijing: China Water Resources and Hydropower Press, 2010.
[5] Yu Yong. Fluent entry and advanced tutorial (M). Beijing: China University of Technology Press, 2008.
[6] J. Kim. Spray cooling heat transfer. The state of the art (J). International Jounal Heat and Fluid Flow, 2007, 28 (4): 753-767.

Wenjing Ding: born in P.R. China, 1978, and achieved Doctor Degree of Heat Transfer in Xi’an Jitaotong University, China in 2006. He is working in BISEE in Beijing as a senior engineer.