Structure optimization of nozzle in quick-freezer based on CFD

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Abstract. A V type slot nozzle in an impact type quick freezer was selected as the research object, the influence of nozzle structure parameters on nozzle outlet velocity was studied with CFD software. The results showed that the optimal height range of the V type diversion trench was 70-74mm. When the angle of V type diversion trench was 15°, the nozzle outlet velocity reached the maximum value. As the angle increased, the outlet velocity of the nozzle increased obviously and then decreased slowly. With the increasing of nozzle width, the outlet velocity of nozzle was obviously different, and it showed the overall upward trend. The nozzle exit height had little influence on the nozzle outlet velocity, when nozzle exit height changed from 0mm to 40mm, the nozzle outlet velocity was between 13.00-14.50m/s. This study provided a theoretical basis for optimal design of impact freezer nozzle structures.

1. Introduction
The quick-frozen food which uses appropriate quick-frozen processing, rapid freezing and cold storage, generally requires continuous low temperature (usually under -18°C - 20°C and different food need different temperature). And its biggest advantages is based solely on low temperature to preserve food original quality by reducing the heat which is inside the food or the energy which support a variety of chemical activity, and freezing parts of the cell free water at the same time which would reduce the activity of water. This kind food does not use any preservatives and additives, which preserves the maximum food nutrition. Therefore, the freezing speed of quick-freezing machine is the
key to determine the quality of food quick-freezing.

The axial velocity of the nozzle is mainly related to the nozzle inlet and outlet shape. Chong Zhang et al. [1] conducted a simulation about the external flow field of conical long straight pipe nozzle by ANSYS FLUENT and Eulerian multiphase flow model. Results in different parameters were compared and indicated that: The water jet velocity core region was promoted a little with the increase of the nozzle diameter, and in different nozzle diameter the velocity attenuation rate was almost the same. Xuyong Zong et al. [2] made the optimization analysis on the numerical simulation of ejector structure of gravel delivery device based on the ejector principle by employing numerical simulation software Fluent based on computational fluid dynamics in this paper. The analysis results show that the diameter of the nozzle has great influence on the performance of the ejector and the injection coefficients of ejector decrease with the increase of ejector nozzle diameter, but the smaller nozzle diameter will lead to the increase of pump pressure load of mud pump. Jing Zhang et al. [3] established the numerical model of internal flow field characteristics of ultrasonic atomization nozzle and simulated the different nozzle jet pressure inside the distribution of velocity field by fluid simulation software CFD. The numerical calculation results show that the ultrasonic velocity obviously enhances the nozzle turbulence effect, thus improves the atomization of liquid. With the increase of droplet jet pressure, the internal velocity and turbulence effect is strengthened. Jin Wang et al. [4] simulated the fluid flow behavior of internal flow filed in swirl nozzle by using CFD software. The results show that the swirl nozzle with four entrances is much better than others in absence of outlet section, which can be used as a reference to the desulfurization tower. Yanling Liu et al. [5] established the mathematics models on fluid fields distribution in cold store. The results showed the mathematics models proposed by ourselves could be simulated the fluid fields distribution in cold store, and when the fruits and vegetables in cold store were arranged both sides of the passage, the fluid fields distribution was better.

Xiaojian Li et al. [6] simulated the internal flow fields of micro-oscillating cavity nozzles with different structures by grid independence test and SIMPLEC algorithm. The simulated results show that both nozzles are gradually increasing along the axial direction, resulting in maximum velocity in the throat section. Hongxi Li et al. [7] theoretically analyzed and numerically simulated with CFD software for design optimization of the ultrasonic vibration nozzle. The simulated results show that the jetting velocity strongly depends on the inlet pressure and jetting distance but weakly on the collision wall angle.

L.Sushma et al. [8] investigated and understood the performance of conical and scarfed nozzle by using commercially available software FLUENT. CFD Studies carried out for selecting a suitable mesh and selection of suitable turbulence model for computing nozzle jet flow field. Parham Babakhani Dehkordi et al. [9] extracted two phase pressure drop, instantaneous radial velocity and holdup profile, cross-sectional time-averaged holdup and slip ratio from CFD simulations. In terms of concentrated pressure drop and mean water holdup, the results of CFD simulations are consistent with the experimental data. Mazzelli Federico et al. [10] represent the metastable behaviour of the flow with reasonable accuracy. The scheme is based on a single-fluid approach and solves the transport equation for a homogeneous mixture flow coupled with conservation equations for the number of droplets and liquid mass fraction. C. H. Lee. [11] investigated the effects of nozzle orifice size and
ambient gas density combinations on the spray penetration. A total of 20 cases in the CFD simulations were considered with combinations of the 4 nozzle orifice diameters and 5 ambient gas densities. CFD simulations with the NGJBL spray model were more accurate than those with either the standard KIVA3V or gas jet spray models as the nozzle orifice diameter and ambient gas density was increased.

In this paper, the object was the V type slit nozzle of the impact freezer. By changing the structural parameters of the nozzle, a larger nozzle outlet velocity could be obtained. Lili Zhang et al. [12] built a blast atomizer by CFD technology. The simulated profiles of flow fields and particle locus, local temperature and humidity of the air phase in the drying chamber were presented and the drying progress of particle with different initial diameter was analyzed.

2. Numerical simulation

The physical model of the V type slit nozzle structure was shown in figure 1[13], and the nozzle structural parameters were shown in table 1. The width between the two nozzles D was 73mm, the nozzle outlet width S was 5mm, the nozzle exit height K was 30mm, the V type diversion trench height V was 66mm, the V type diversion channel angle theta was 30°. This paper studied the effect of parameters changed on the outlet velocity of V nozzle during quick freezing.

![Figure 1. V type slot nozzle structure](image)

| Nozzle type         | D     | K     | XL    | S     | V     | θ   |
|---------------------|-------|-------|-------|-------|-------|-----|
| V type slit nozzle  | 73mm  | 30mm  | 750mm | 5mm   | 66mm  | 30° |

The flow medium is air, and the simulation process assumes:

a. Air is an incompressible, homogeneous viscous fluid.
b. The wall of the nozzle is considered as no slip wall, that is, the air velocity at the wall is U=0.
c. The wall of nozzle is adiabatic, that is, heat flux q=0W/m².

The continuity equation, momentum equation and energy equation are combined to solve the numerical simulation. Pressure inlet is selected as inlet boundary condition, Pressure outlet is as exit boundary condition, and \( P_{in}=220\text{Pa} \), \( T_{in}=228K \), \( P_{out}=0\text{Pa} \), \( T_{out}=233K \). The calculation model and the adjacent parts of the V type nozzle are set as symmetry boundary, that is Symmetry1 and Symmetry2 which is shown in the figure 2. A solution method was based on k-\( \varepsilon \) turbulence model, the SIMPLE algorithm with second order upwind for all spatial discretization.
Figure 2. Numerical model and boundary condition setting

Continuity equation:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_x}{\partial y} + \frac{\partial v_z}{\partial z} = 0$$  \hspace{1cm} (2-1)

Momentum conservation equation:

$$\frac{\partial (\rho u)}{\partial t} + div(\rho u) = div(\mu grad u) - \frac{\partial p}{\partial x} + S_u$$  \hspace{1cm} (2-2)

$$\frac{\partial (\rho v)}{\partial t} + div(\rho u) = div(\mu grad v) - \frac{\partial p}{\partial y} + S_v$$  \hspace{1cm} (2-3)

$$\frac{\partial (\rho w)}{\partial t} + div(\rho u) = div(\mu grad w) - \frac{\partial p}{\partial z} + S_w$$  \hspace{1cm} (2-4)

Energy conservation equation:

$$\frac{\partial}{\partial t} (\rho T) + div(\rho u T) = div \left( \frac{k}{c_p} grad T \right) + S_T$$  \hspace{1cm} (2-5)

Component mass conservation equation:

$$\frac{\partial (\rho e_2)}{\partial t} + div(D_e \cdot grad(\rho e_2)) + S_e$$  \hspace{1cm} (2-6)
k-ε turbulence model:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_j} \right] + \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho \varepsilon \tag{2-7}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{2\varepsilon} \varepsilon) - C_{3\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{2-8}
\]

\[
G_k = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \tag{2-9}
\]

\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \tag{2-10}
\]

3. Analysis on the influence of structural parameters of v-shaped slot nozzle on nozzle outlet velocity

3.1. The influence of the height of V type diversion trench on the nozzle exit speed

When the opening angle of the V type diversion trench was 30°, the nozzle exit height was 66mm and the nozzle outlet width was 5mm, the simulation results were shown in figure 3. With the increase of the height of the V type diversion trench, the outlet velocity of the nozzle increased first and then decreased. When the nozzle exit height was V=40-72mm, the nozzle outlet velocity increased with the increase of V, which increased from 13.18232m/s to 13.51516m/s. When the nozzle outlet height V=72-90mm, the nozzle outlet velocity presented a decreasing trend, from 13.51516m/s to 13.31995m/s. As a whole, the speed of the exit was concentrated between 13.00-13.50m/s and the maximum deviation was 2.46%. It could be concluded that the influence of the height change of the V type diversion trench on the nozzle exit speed was not very big, but the nozzle exit speed was more larger between V=65-75mm, which meant that the energy loss of the jet under this structural dimension was smaller than that of other structures. For the internal flow of the nozzle, the longer nozzle would make the airflow produce the frictional resistance loss within the nozzle and reduce the nozzle exit speed\(^{[14]}\).

In summary: (1) The height of the V type diversion trench had the best range, that was, V=70-74mm. (2) The height of the V type diversion trench had little influence on the outlet velocity of the nozzle. Therefore, in the range of 40-90mm, it was more appropriate to choose the height of the V type diversion trench, preferably 65-75mm.
3.2. The influence of the opening angle of V type diversion trench on the nozzle exit speed

When the nozzle exit height was 66mm, the nozzle height was 30mm and the nozzle outlet width was 5mm, the simulation results were shown in figure 4. With the change of angle, there was a significant difference in the outlet velocity of the nozzle, with a maximum deviation of 47.27%. When the angle of the V type diversion trench was θ=0°, the velocity of the nozzle outlet was different from that of θ>0°. When the angle was 0°, the nozzle outlet velocity was 7.39672m/s. When the opening angle was between 0 and 15 degrees, the velocity of nozzle exit varied from 7.39672m/s to 14.02768m/s, showing an obvious increasing trend. At 10°< θ <20°, the nozzle outlet velocity changed little. When the angle is 15°, the outlet velocity of the nozzle reached a maximum value of 14.02768m/s, about two times bigger than the θ=0°. In more than 15°, due to the differential pressure at both ends of the nozzle decreased, the outlet velocity of the nozzle decreased. Analysis of the above phenomena, the reason was that the jet density was poor when the angle of the V channel was very small. With the increase of the angle, the exit boundary layer decreased and the velocity of the jet exits increased. Therefore, for the cutting ability of the jet, the angle of the V type diversion trench had the best value[15].

In summary: (1) There was a great difference between angle and no angle about the opening of V type diversion trench. The outlet velocity of the nozzle was obviously improved by the existence of the V type diversion trench. (2) With the increase of the angle of the V type diversion trench, the outlet velocity of the nozzle increased obviously and then slowly decreased. (3) The angle of the V type diversion trench had the best value that was, θ=15°. Therefore, the outlet velocity of the nozzle could be increased properly by selecting the proper opening angle of the V type diversion trench. We suggested that it should be 15°.
3.3. The influence of the width of nozzle outlet on the nozzle exit speed

When the opening angle of the V type diversion trench was 30°, the nozzle exit height was 66mm and the nozzle height was 30 mm, the simulation results were shown in figure 5. With the increase of nozzle outlet width, the nozzle outlet velocity increased gradually, but the growth rate gradually decreased. When the nozzle outlet width was 2-8mm, the nozzle outlet velocity increased from 11.01347m/s to 14.00329m/s, showing a distinct upward trend. When the nozzle outlet width is 8-30mm, the nozzle exit speed was increased from 14.00329m/s to 15.37663m/s and the growth rate was obviously less than that of the outlet width of 2-8mm. Analysis of the above phenomena, the reason was that: with the increase of nozzle width, the nozzle axle center velocity decreased quickly when the airflow passed through the nozzle with smaller outlet width [14]. The velocity decreasing of the nozzle with larger outlet width was relatively slow and the energy loss was smaller.

In summary: (1) There was no optimal value for the width of the nozzle. (2) With the increase of nozzle width, the outlet velocity of nozzle was obviously different, and the overall trend was to keep up. (3) It was proved that the change of nozzle width had a significant effect on the outlet velocity of the nozzle. To sum up, the nozzle width had a great influence on the nozzle exit speed, but in order to ensure the number of the nozzle in the freezer, the maximum nozzle exit width should be selected in a reasonable condition.
3.4. The influence of the height of nozzle outlet on the nozzle outlet velocity

When the opening angle of the V type diversion trench was 30°, the nozzle exit height was 66mm and the nozzle width was 5 mm, the simulation results were shown in figure 6. The effect of nozzle exit height on nozzle outlet velocity was not significant, concentrating on 13.00-14.50m/s. With the increase of nozzle exit height, the outlet velocity decreased from 14.44290m/s to 13.23400m/s, and the maximum deviation was 8.37%, showing a slow decreasing trend. The reasons for the analysis were as follows: with the increase of nozzle exit height, the length of jet concentration decreased, so the outlet velocity of nozzle decreased.

In summary: When the opening angle of the V type diversion trench was 30°, the nozzle exit height was 66mm and the nozzle width was 5 mm, the nozzle most suitable exit height is 0mm.

4. Conclusion

(1) The height of the V type diversion trench had the best range, that was, V=70-74mm. The height of the V type diversion trench had little influence on the outlet velocity of the nozzle.

(2) The angle of the V type diversion trench had the best value, that was, θ=15°. The outlet velocity of
the nozzle was obviously improved by the existence of the V type diversion trench. With the increase of the angle of the V type diversion trench, the outlet velocity of the nozzle increased obviously and then slowly decreased.

(3) There was no optimal value for the width of the nozzle. With the increase of nozzle width, the outlet velocity of nozzle was obviously different, and the overall trend was to keep up. The outlet width of the nozzle was a criterion to determine the flow of the system. When the flow rate and the rated pressure parameters were determined, the diameter of the nozzle exit was determined. The change of the smaller nozzle diameter was reflected in the pressure of the equipment, so the calculation error of the nozzle exit width couldn’t be too large.

(4) The nozzle exit height had little difference in the overall outlet velocity. With the increase of nozzle height, the outlet velocity of the nozzle decreased slowly.

(5) This nozzle structure is simple and easy to process. And the quick freezer with the nozzle structure is high working efficiency, that is, it has rapid freezing rate and less energy consumption. Therefore, it has a good application prospect.

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