Structure optimization of nozzle in quick-freezer based on Response Surface Methodology

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Abstract. The structural parameters of nozzle in quick freezer have great influence on the nozzle outlet velocity, and the nozzle outlet velocity directly affects the freezing efficiency of the quick freezer. A V type slot nozzle was simulated with CFD software. The effect of the V type slot nozzle structure parameters variation on nozzle outlet velocity was studied by using Response Surface Methodology. Finally, the optimal structural parameters of the nozzle were obtained: the nozzle outlet height was 3.97 mm, the nozzle outlet width was 8 mm, the V type diversion trench height was 71.63 mm and the V type diversion trench angle was 29.57°. The conclusion provided a theoretical basis for optimal design of nozzle structure of quick freezer.

1. Introduction

In the field of heat and mass transfer, the high heat transfer coefficient is produced by the nozzle impingement jet on the target area, and the main factor affecting the heat transfer intensity below the nozzle is the velocity along the axial direction from the nozzle to the impact plate. This efficient heat transfer mechanism is mainly used in papermaking, drying, metallurgy, food quick freezing and other fields [1-4].

The axial velocity of the nozzle is mainly related to the nozzle inlet and outlet shape. Liang *et al* [5] combined the CFD numerical simulation method with the BP neural network to realize the effective prediction of the nozzle jet. It was found that the increase of the outlet angle of theta and the depth h of the cone hole was helpful to enhance the jet kinetic energy of the nozzle. Zhang *et al* [6] employed the Large Eddy Simulation based on the FLUENT to simulate both the two phase and single phase flow models of the jet flow field of three dimensional nozzle. The rationality of the simulation results of the two phase and single phase flow models of jet flow field of three dimensional nozzles was demonstrated by the diffusion angle and volume flux of jet oil measured by the method of high speed visualization and weighting jet oil, respectively. The result indicated that the volume flux of jet oil increased as the orifice diameter, the angle between orifice axis and upstream axis increased and as the orifice axial length decreased. When the fluid flowed through the nozzle, the energy loss was related to the nozzle structure. Gong *et al* [7] captured the surface structures of the jet with three nozzles with high-speed and microscopy photography. The experimental results show that the nozzle contraction ratios have a significant influence on the jet periodic ripple section. When the contraction ratio is 8/2, the dimensionless wavelength is proportional to the Reynolds number. When the shrinkage ratio is 8/4, the wavelength is inversely proportional to the Reynolds number. While the dimensionless wavelength is insensitive to the Reynolds number when the nozzle with a shrinkage ratio of 8/3. Li *et al* [8] designed the multiple swirling jet nozzles with simple structure. The outflow field of nozzle was simulated by SIMPLEC algorithm firstly, and then the outflow field feature was analyzed. The rock-breaking mechanism was studied by indoor rock-breaking experiment and the structural parameters of nozzle were optimized. The results show: the impacting area of the multiple swirling jet nozzle increases with setting circle radius and decreases with extended angle, and the impacting area firstly increases and then decreases with the increase of torsion angle. Yang *et al* [9] carried out the experiments to study the flow characteristics of cylinder nozzles, cone nozzles and cosine nozzles. The results show that the inlet conditions greatly influence the cavitation energy loss. The cavitation energy loss coefficient of the cylindrical nozzle is the largest, the conical nozzle is the second, and the cosine nozzle is the least. When the inner surface is closed to streamline, the nozzle features significantly affected both kinds of energy losses and they tend to be smaller. Li *et al* [10] used the VOF model and the standard $k-\varepsilon$ model in FLUENT software to simulate and analyze the water-jet flow fields with different nozzles. The results show that the different nozzle structures have great influence on the water-jet performance. When the convergence angle is 14^o and length diameter ratio was 2-4, the performance of the water-jet is the best. Przemysław Młynarczy *et al* [11] observed that the key issue is the selection of nozzles of appropriate shapes and dimensions in order to achieve pressure pulsation reduction without significantly increasing the flow resistance. At the same time, it was found that the twin hyperboloidal nozzle with a 33% reduced cross-section area has the optimal damping properties. Ozgur Oguz Taskiran [12] investigated the effect of nozzle inlet rounding on diesel spray formation and combustion. Results showed that inlet rounding increases discharge coefficient and sharp inlet nozzle produces smaller droplets that shorten spray tip penetration and autoignition delay period due to low discharge coefficient and rounded inlet nozzle has lower combustion temperature, less NO and soot concentration than sharp inlet nozzle. In the laminar flow regime, Barak Kashi *et al* [13] studied the influence of nozzle length in submerged jet impingement heat transfer by validated direct numerical simulations. It is found that the maximal jet velocity first decreases with increasing effective nozzle length, Z=L/(D・Re), to a minimum at Z*≈0:0015,beyond which it increases as in developing pipe-flow. Using transparent nozzles, Cui *et al* [14] investigated the diameter error, conical and inclined that embody common deviations in nozzle geometry. The results indicate that very small differences in geometric structure still have consequences for the obviously different characteristics of cavitating flow. Huang *et al* [15] investigated the effects of the necking circular nozzle and the twisted triangular nozzle on the bubble size distribution, the average gas holdup, liquid mixing time and gas-liquid mass transfer coefficient in the jet bubbling reactor. The experimental results showed that the bubble size was smaller, the average gas holdup was higher and the mixing time was shorter in the case with twisted triangular nozzle, compared with the case with necking circular nozzle. Based on the nozzle shape, Tang *et al* [16] carried out the numerical simulation for the flow field and energy separation effect of the helical nozzles and straight nozzles vortex tube with 4 channels. The result was that a vortex tube with helical nozzles can achieve greater tangential and axial velocity. Compared with the straight nozzle, the vortex tube with helical nozzles can obtain energy separation better.

In this paper, the object was the V type slot nozzle of the impact freezer. By changing the structural parameters of the nozzle, a larger nozzle outlet velocity could be obtained.

2. Numerical simulation

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

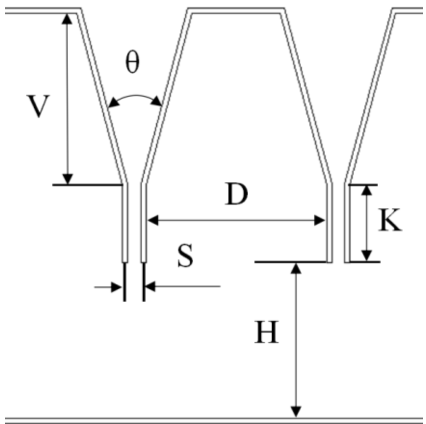

Figure 1. V type slot nozzle structure

Table 1. Nozzle structure parameters

Nozzle type	D	K	S	V	θ
V type slot nozzle	73 mm	30 mm	5 mm	66 mm	30°

The flow medium was air, and the simulation process assumed:

- Air was an incompressible, homogeneous viscous fluid.
- The wall of the nozzle was considered as no slip wall, that was, the air velocity at the wall was U=0.
- The wall of nozzle was adiabatic, that was, heat flux q=0 W/m^2.

The continuity equation, momentum equation and energy equation were combined to solve the numerical simulation. Pressure inlet was selected as inlet boundary, Pressure outlet was as outlet boundary, and P_{in}=220 Pa, T_{in}=228 K, P_{out}=0 Pa, T_{out}=233 K. The calculation model and the adjacent parts of the V type nozzle were set as symmetry boundary, which were Symmetry1 and Symmetry2 which were shown in the figure 2. A solution method was based on k-εturbulence model, the SIMPLE algorithm with second order upwind [17] for all spatial discretization.

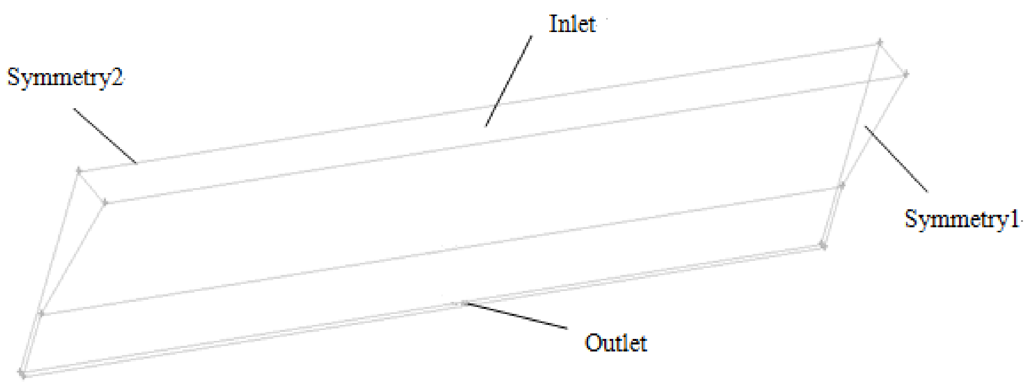

Figure 2. Numerical model and boundary condition setting

3. Experiment design of Response Surface Methodology

With the advantages of modulating one factor at a time in determining experimental-response relationship, the response surface methodology (RSM) is one of the most commonly used multivariate techniques [18]. By establishing a mathematical model, RSM could evaluate variable parameters and interactions using quantitative data, effectively optimizing processing technology based on statistical results, thus reducing the number of experimental trials required [19]. RSM has been successfully used for developing, improving, and optimizing processes in many fields, e.g. food, herbal medicine, and microbiology.

The optimum outlet velocity of V nozzle was determined by Response Surface Methodology optimization. Using Box-Behnken designed Experiment, and the four structural parameters of the nozzle outlet width S, the nozzle outlet height K, the V type diversion trench height V and the V type diversion trench angle θ were taken as the investigation factors, with the outlet velocity of the V nozzle as the response value, and the factor level of the four structural parameters were shown as table 2.

Table 2. Response Surface Methodology factor level table.

	Level	-1	0	1
Factors	K (mm)	0	20	40
	V (mm)	40	65	90
	S (mm)	2	5	8
	Θ (°)	0	22.5	45

4. Analysis of Response Surface Methodology

It was shown the Response Surface Methodology test plan and result of outlet velocity of V type nozzle under different structural parameters in table 3. There was 29 test points, which met the requirements of experimental design.

Table 3. Response Surface Methodology experimental schemes and results for V type nozzle outlet velocity under different structural parameters.

Experimental number	K	V	S	Θ	U
1	0	40	5	22.5	13.84507
2	0	65	2	22.5	13.8254
3	0	65	5	45	13.81316
4	0	65	5	0	7.5649905
5	0	65	8	22.5	14.92598
6	0	90	5	22.5	15.01413
7	20	40	2	22.5	11.80583
8	20	40	5	45	12.867069
9	20	40	5	0	7.634309
10	20	40	8	22.5	13.90371
11	20	65	2	0	7.731772
12	20	65	2	45	10.410857
13	20	65	5	22.5	14.09999
14	20	65	5	22.5	14.09999
15	20	65	5	22.5	14.09999
16	20	65	5	22.5	14.09999
17	20	65	5	22.5	14.09999
18	20	65	8	45	13.3453
19	20	65	8	0	11.64252
20	20	90	2	22.5	12.14446
21	20	90	5	45	12.31009
22	20	90	5	0	7.074209
23	20	90	8	22.5	14.42242
24	40	40	5	22.5	12.86933

25	40	65	2	22.5	11.03425
26	40	65	5	0	7.120394
27	40	65	5	45	11.99354
28	40	65	8	22.5	14.06344
29	40	90	5	22.5	13.77314

Regression analysis of the data in table 3 could obtain the multiple regression equation:

$$U=2.51867-0.028237*K+0.10398*V+0.61208*S+0.43987*\Theta-1.32625E-004*K*V+8.03587E-003*K*S-7.63902E-004*K*\Theta+6.00267E-004*V*S+1.38711E-006*V*\Theta-3.61594E-003*S*\Theta-5.00706E-004*K2-7.56263E-004*V2-0.030405*S2-6.89799E-003*\Theta \quad (1)$$

The U was the outlet velocity of the nozzle, and the K, S, V, and Θ were nozzle outlet height, nozzle outlet width, V type diversion trench height and V type diversion trench angle respectively.

Table 4 showed the results of variance analysis of regression equation. The correlation coefficient R^2=93.13% of the model showed that the correlation degree of the model was better. The coefficient of variation (C.V.) was 7.59%; the result indicated that the reliability of the model was high. The predicted value of the model was in good agreement with the actual value, and it was suitable for the prediction and analysis of the outlet velocity of the V type slot nozzle. From table 4, we could see that the whole model had a significant impact on the response value（P＜0.001), and there was no significant interaction among the parameters (P < 0.01). It was known from the f value that the influence of each factor on the nozzle outlet speed was D (V type diversion trench opening angle) > C (nozzle outlet width S) > A (nozzle outlet height K) > B (V type diversion trench height V).

Table 4. Variance Analysis of Response Surface Methodology regression model

Source of variation	Quadratic sum	Degree of freedom	Mean Square	f value	p value	significance
Model	164.55	14	11.75	13.56	< 0.0001	significant
A-K	5.51	1	5.51	6.36	0.0244	
B-V	0.27	1	0.27	0.32	0.5829	
C-S	19.64	1	19.64	22.65	0.0003	
D-Θ	56.21	1	56.21	64.85	< 0.0001	
AB	0.018	1	0.018	0.020	0.8888	
AC	0.93	1	0.93	1.07	0.3179	
AD	0.47	1	0.47	0.55	0.4724	
BC	8.107E-003	1	8.107E-003	9.353E-003	0.9243	
BD	2.435E-006	1	2.435E-006	2.809E-006	0.9987	
CD	0.24	1	0.24	0.27	0.6083	
A2	0.26	1	0.26	0.30	0.5924	
B2	1.45	1	1.45	1.67	0.2169	
C2	0.49	1	0.49	0.56	0.4665	
D2	79.10	1	79.10	91.25	< 0.0001	
Residual	12.14	14	0.87			
Lack of fit	12.14	10	1.21			insignificant
Pure error	0.000	4	0.000			
Total error	176.68	28				
		R^2=93.13%		C.V.%=7.59		

According to the results of variance analysis in table 4, the relationship model between the regression equation of the nozzle outlet velocity and the response face value was significant ($p<0.05$), and the test for lack of fit was not significant ($p>0.05$). It showed that the experimental model fully fitted the test data, and the regression equation of the nozzle outlet velocity was a suitable mathematical model to show the relationship between the nozzle outlet velocity and the parameters of the structure of the V type slot nozzle structure.

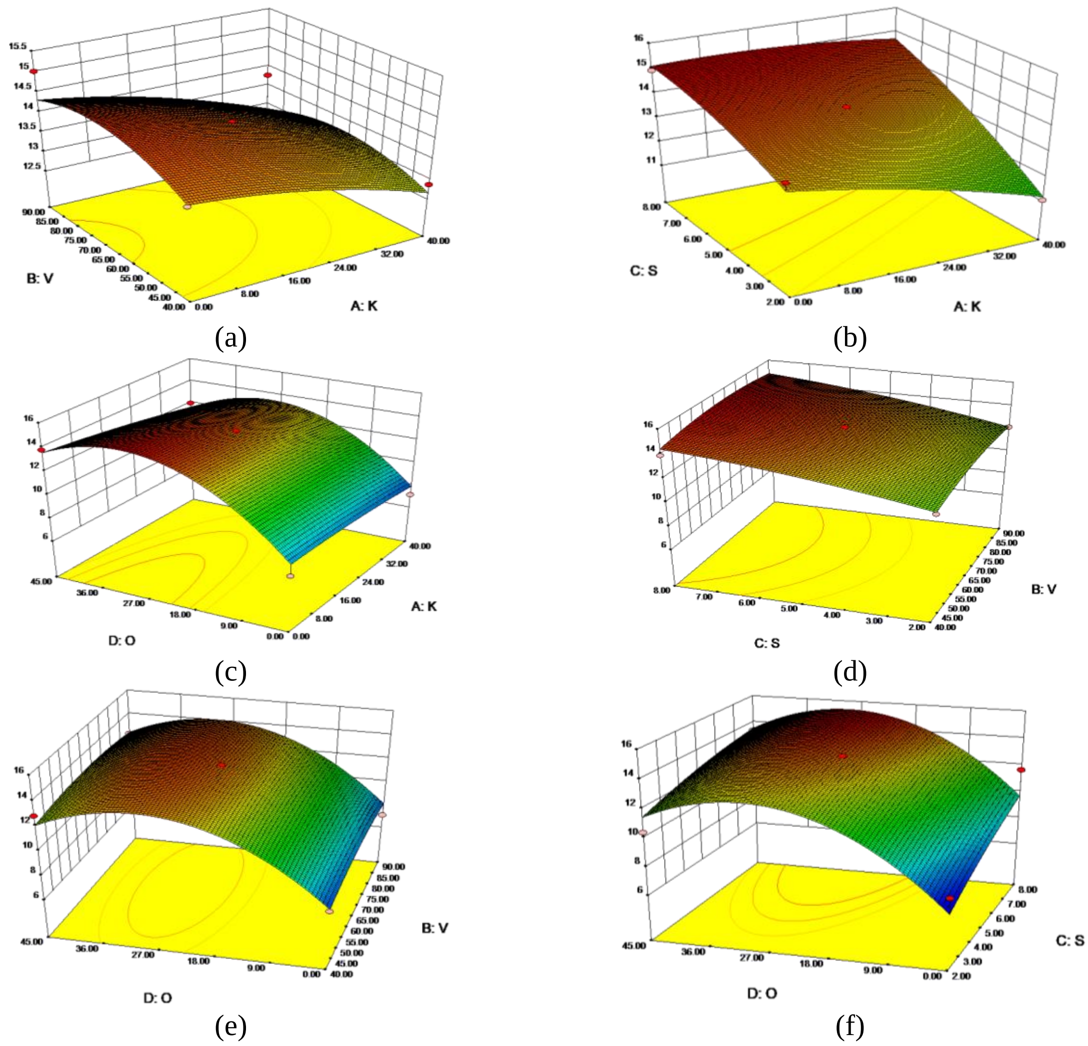

Figure 3. Response Surface Methodology diagram of interaction between various factors on nozzle outlet velocity.

The model Response Surface Methodology diagram drawn by the software design-expert 8.0.6 could directly reflect the interaction among four nozzle structural parameters on nozzle outlet velocity. Their influence on the response value could be determined by the inclination of the surface: high inclination indicated that the interaction between the two parameters was significant. The circular contour showed that the interaction between factors was not significant, while the ellipse was significant. According to the regression equation of nozzle outlet velocity, the Response Surface Methodology analysis results of different factors were shown in figure 3. There was no interaction between K and S from figure 3(b) the contour map of the nozzle outlet height K and the nozzle outlet width S of the nozzle. Because the contour lines in figure 3(b) were parallel, and the whole response faced a relatively flat plane shape. From figure 3(e), the contour map of the opening angle of the V type diversion trench and the height of the V type diversion trench was elliptical, and the interaction was remarkable. It could be seen from the three-dimensional image that the surface was convex. Along the direction of D axis, the color of 3D surface became deep and then shallower. It showed that with the change of the angle of the V type diversion trench, the change trend of the nozzle outlet velocity was first severe and then slowly. The effect of interaction of various factors on the outlet velocity of the nozzle could be seen intuitively from figure 3. It could be seen that the factor D (the opening angle of the V type diversion trench) had the greatest influence on the nozzle outlet velocity, and the factor C (nozzle outlet width) was the second, which coincided with the results of table 4 variance analysis.

The optimum structure parameters of the V slot nozzle were determined by software analysis. That was, the maximum outlet speed of the V slot nozzle was 15.5119 m/s. The optimum combination scheme of the structural parameters was the nozzle outlet height 3.97 mm, the nozzle outlet width 8 mm, V type diversion trench height 71.63 mm and V type diversion trench angle 29.57°.

Table 5. Error analysis of Response Surface Methodology regression model and actual calculation.

	K	V	S	θ	U1	U2	deviation
1	30	80	5	30	13.35918	13.12791396	1.73%
2	30	66	5	30	13.56634	13.23109676	2.47%
3	0	66	5	30	14.44290	14.27357096	1.17%
4	10	66	5	30	14.01249	14.02622076	-0.10%
5	15	66	5	30	13.81926	13.86499271	-0.33%
6	25	66	5	30	13.55905	13.46743071	0.68%
7	35	66	5	30	13.31748	12.96972751	2.61%
8	30	66	4	30	13.13122	12.99409124	1.04%
9	30	66	6	30	13.67814	13.34648228	2.42%
10	30	66	7	30	13.87802	13.3402478	3.87%
11	30	66	8	30	14.00329	13.21239333	5.65%
12	30	40	5	30	13.18232	12.63620843	4.14%
13	30	50	5	30	13.29395	12.98601372	2.32%
14	30	60	5	30	13.39778	13.1845664	1.59%
15	30	70	5	30	13.51355	13.23186648	2.08%

The error analysis of Response Surface Methodology regression model and actual calculation was shown in Table 5. Compared with the results of formula (1) calculation and numerical simulation, the deviation of both of them was less than 10%, and the deviation was small. It was proved that the result was reasonable and reliable, and it was an acceptable deviation range. Therefore, the formula (1) obtained by the Response Surface Methodology method could be applied to the calculation of the outlet velocity of the V type slot nozzle.

5. Conclusion

Taking V type slot nozzle as the research object and using control variable method, this paper studied the influence of different nozzle parameters on the outlet velocity of V type slot nozzle during quick-freezing process, including the nozzle outlet width S, the nozzle outlet height K, and V type diversion trench height V and V type diversion trench angle θ. The conclusion was obtained: on the basis of single factor experiment, the structural parameters of nozzle were optimized by Response Surface methodology. The structural factors affecting the nozzle outlet speed were arranged in the order of main and secondary: the opening angle of the V type diversion trench, the width of the nozzle outlet, the height of the V type diversion trench and the height of the nozzle outlet. Finally, the optimum structural parameters were as follows: nozzle height was 3.97 mm, nozzle outlet width was 8mm, V type diversion trench height was 71.63 mm and V type diversion trench angle was 29.57°.

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