

# Influence of different inlet pressures on the flow field and heat transfer characteristics of impinging jets

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**Abstract.** In this paper, the V type slit nozzle in a quick-frozen machine is used as the research object. Under the same air supply conditions, only the pressure entering the impinging jet region is changed. The impact on the flow field and heat transfer characteristics of the impinging jet is observed. The results show that with the increase of the inlet pressure, the velocity of the exit of the V-slit nozzle will change greatly. In this pressure range, the exit velocity of the nozzle is relatively uniform, and frozen products will not be blown off. Therefore, it is beneficial to frozen food safely and effectively. Along the direction of cross flow, the Nusselt number of the steel strip surface of the V slit nozzle will change when the pressure changes, and it will increase with the increase of pressure. Therefore, the heat transfer characteristics of the V type slit nozzle on the surface of the steel strip are stronger and stronger under the increase of the inlet pressure, and the uniformity is also very good.

## 1. Introduction

Nowadays, more and more people use the quick-frozen machine for food freezing, and its efficiency and safety has been recognized by more and more people. Therefore, how to develop a better quick-frozen machine has attracted the attention of the industry. As we all know, the use of impinging jet technology on the quick-frozen machine can enhance heat transfer. Based on the traditional quick-frozen machine, we changed the nozzle shape of the freezer to further optimize the performance of the quick-frozen machine.

Using air as a cooling medium is the most common method at present. Under the condition that the evaporation temperature is constant and the air supply speed is constant, changing the inlet pressure can make the flow field inside the static pressure chamber of the quick-frozen machine change rapidly. As a result, the heat transfer characteristic on the surface of the freezer steel strip changes rapidly, so that the frozen product can be frozen well. Everts *et al* [1] used a smooth circular test section with a diameter of 11.5 mm and a maximum aspect ratio of 872 to study the relationship between the flow field and the pressure in the quick-frozen machine. Pressure drop and heat transfer measurements were made at different heat flux and Reynolds numbers. This method studies the relationship between pressure drop and heat transfer. Results show that Reynolds number is identical to pressure drop and heat transfer at the beginning and the end. Under mixed convection conditions, the heat transfer and pressure drop and the average Nusselt number relation for laminar flow, transition, quasi-turbulent

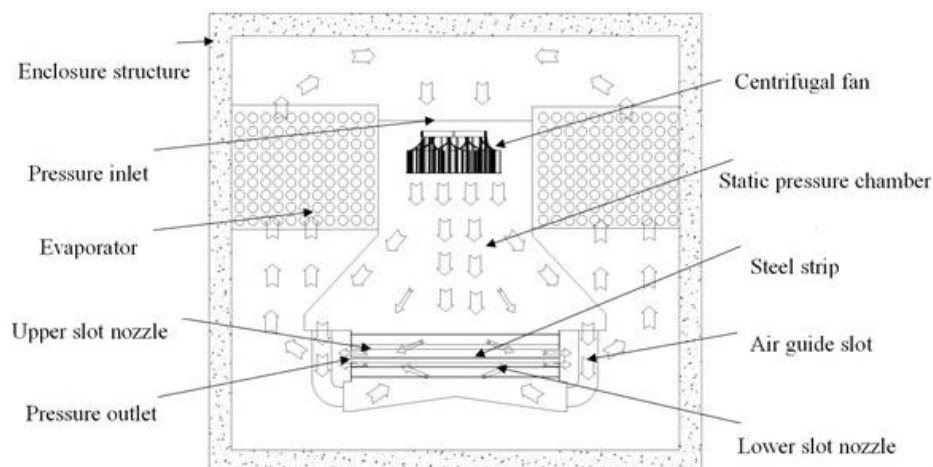


flow, and turbulent flow are established. The results show that the relationship between heat transfer and pressure drop can be used as an additional criterion to distinguish different flow states. Prithvi *et al* [2] used Reynolds averaged Navier Stokes (RANS) and large eddy simulation (LES) to perform numerical simulations of impinging jet arrays. The simulation results are in agreement with the experimental results. To better understand the flow physics of multi-jet impingement array, LES simulations were performed. Simulation results show that the main pressure loss of this system is due to shrinkage and viscosity loss at nozzle entrance. Quan *et al* [3] studied the formation of expansive gas jet under nozzle outlet caused by high jet pressure. Shock structure near nozzle influences jet and mixing characteristics of gas jet. Using schlieren imaging and numerical simulation methods, the gas jet injection process and the shock wave structure evolution law under different nozzle pressure ratios and aperture conditions were studied. The results show that the change of pressure inside the nozzle affects the shock structure near the nozzle, which promotes the spatial distribution and turbulent mixing of the gas jet. Choo *et al* [4] studied the heat transfer characteristics of submerged jets on flat surfaces and developed functional correlations between stagnation point number nozzle pressure and nozzle distance based on experimental results. Giachetti *et al* [5] studied synthetic jets in crossflow that when transverse flow velocity was strong enough to deviate from jet flow and restricted in certain regions the influence of synthetic jet on mainstream region would be minimal.

In summary, in the impingement jet quick-frozen machine, the inlet pressure is one of the key factors that affect the flow field distribution and the heat transfer characteristics in the field. The research team takes the V-slit nozzle as the research object and changed the nozzle inlet pressure to study the effect of pressure change on the heat transfer characteristics of the quick-frozen machine. In the development of a new type of impinging jet quick-frozen machine, better inlet pressure was selected to ensure efficient and safe operation of the quick-frozen machine.

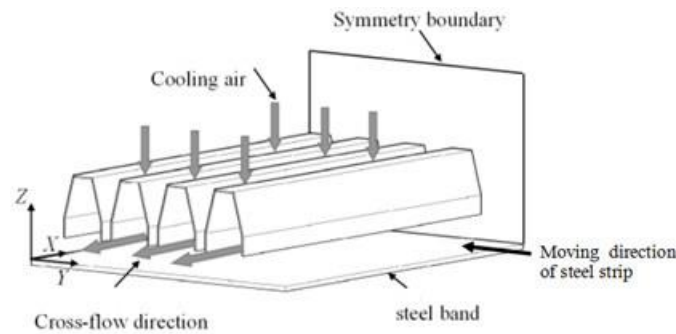
## 2. Physical model

Figure 1 shows the model of the internal flow field circulation in the impinging jet quick-frozen machine [6]. The basic principle of the model is that the quick-frozen machine works through two parts, one of which is to use a centrifugal fan to pump the cold air through the suction into the static pressure chamber. Its static pressure accumulated in cavity can enter from upper surface of steel strip so as to freeze food. The other part of the air enters the induced wind trough, and passes through the lower surface of the steel strip to release the pressure. Convection and heat transfer accelerate the exchange of heat between frozen products and air. The air that inhales the heat will be discharged from both sides of the steel strip under the effect of the circulation pressure difference of the fan, and the temperature will be reduced by the evaporator, and the circulation of the frozen product will always maintain the center temperature at  $-18^{\circ}\text{C}$ .



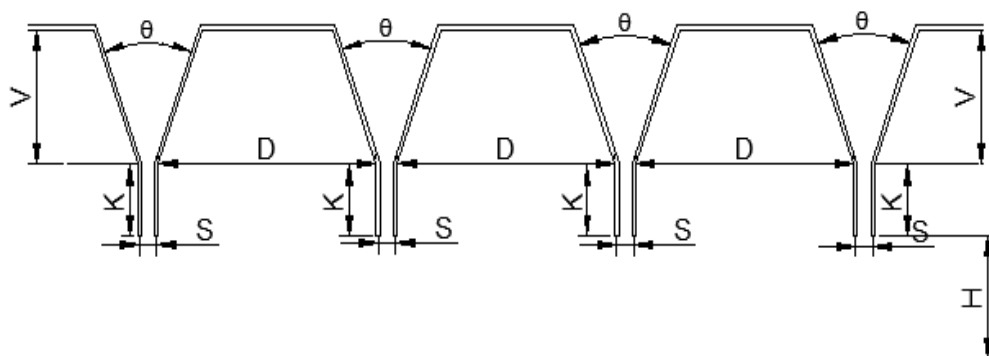
**Figure 1.** Physical model of the internal flow field in the impinging jet quick-frozen machine.

As shown in figure 2, the V-slit nozzle structure was used as the research object [6], and the inlet pressure was continuously changed to study the effect of the pressure change on the heat transfer characteristics. Because the model is completely symmetric, 1/40 of the model is used to reduce the computational strength., and adjacent areas are treated as symmetric boundaries.



**Figure 2.** Structure of type V slit nozzle.

The width of the slot of the V slit nozzle is  $S$ , the length of the slit is  $X_L$ , the steel band is  $Y_w$ , the distance between the steel strip and the strip is  $H$ , the distance between the steel strip and the slit exit is  $H$ , the height of the nozzle extension is  $K$ , and the upper surface of the nozzle is  $V$  from the shrinking section. The distance between the nozzles is  $D$ , the nozzle opening angle is  $\theta$ , and the nozzle structure is shown in figure 3, and the nozzle structure parameters are shown in table 1 [6].



**Figure 3.** V type slot nozzle structure.

**Table 1.** Nozzle structure parameters [6].

Nozzle type	D	K	$X_L$	$Y_w$	S	V	$\theta$
V -slit nozzle	73mm	30mm	750mm	600mm	5mm	66mm	30°

### 3. Conditional setting of numerical models and selection of computational models

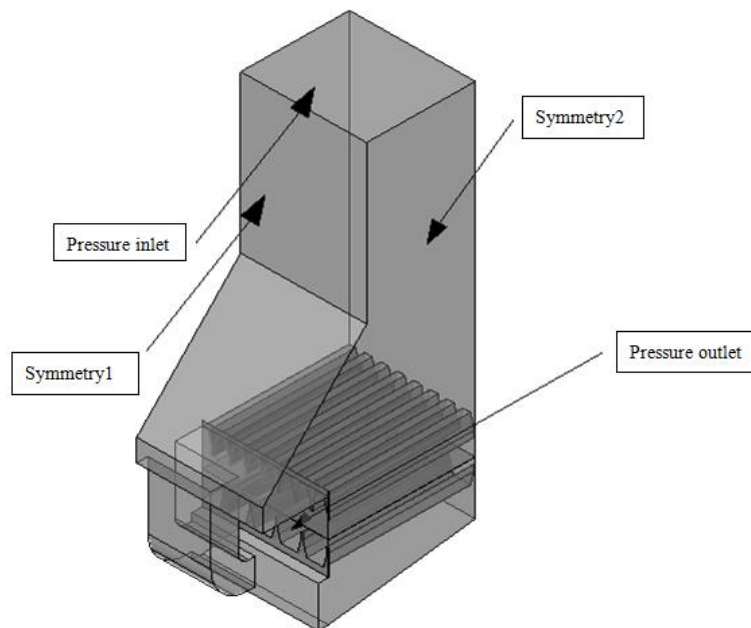
V-shaped Slitting nozzle is selected as the object of study to set the calculation conditions and model.

The flowing medium of the simulated object is air, and during the simulation, it is assumed that:

- Air is incompressible and uniform viscous fluid;
- The wall of the static pressure chamber and the wall of the nozzle wall are regarded as non slip wall, that is, the gas velocity at the wall is  $U=0$ ;
- The static pressure chamber is insulated from the nozzle wall, that is, the heat flux density is  $q=0 \text{ W/m}^2$ ;

In the process of numerical simulation [7], the continuity equation, energy equation and momentum equation need to be calculated.

- Pressure inlet is used as the entrance boundary condition, Pressure outlet is the exit boundary condition, and  $P_{in}$  is the entrance pressure, which are 100 Pa, 120 Pa, 140 Pa, 160 Pa, 180 Pa, 200 Pa, 220 Pa, 230 Pa, 240 Pa, 250 Pa, 260 Pa, 270 Pa, 280 Pa, etc. Temperature:  $T_{in}=230$  K,  $P_{out}=0$  Pa,  $T_{out}=235$  K;
- The calculation model is set as a mirror boundary with the integral part of the quick-frozen machine, that is, Symmetry1 and Symmetry2, as shown in figure 4 [6].
- The  $k-\varepsilon$  turbulence model, SIMPLE algorithm and two order upwind scheme [8] are used to calculate the model.



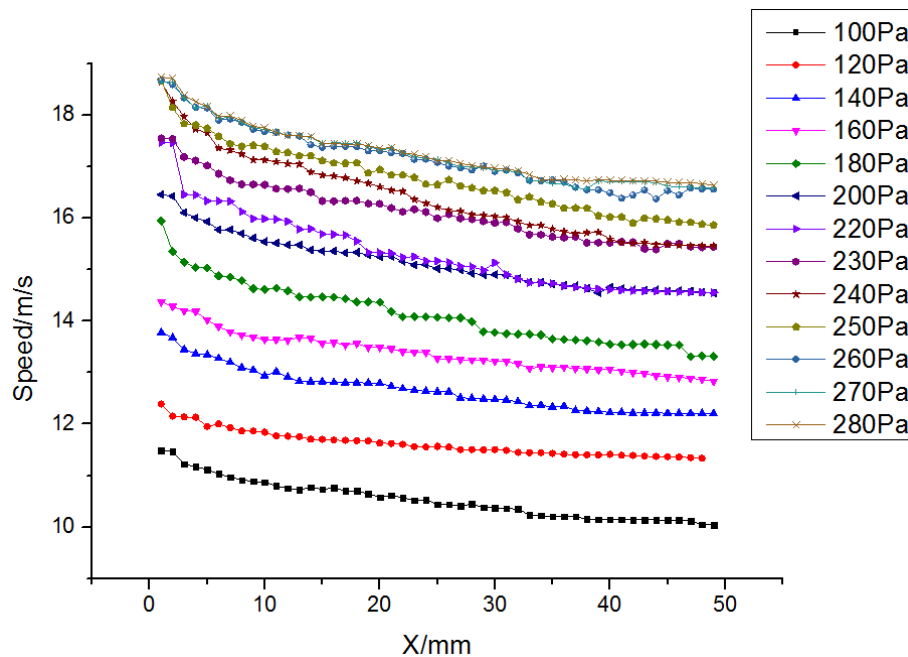
**Figure 4.** Numerical model and boundary condition setting.

#### 4. Influence of inlet pressure variation on nozzle outflow velocity and cross flow

Figure 5(a) shows the velocity distribution of the V type slit nozzle at the outlet of the nozzle along with the change of the inlet pressure of the quick-frozen machine nozzle. The results show that, on the one hand, the change of nozzle inlet pressure is inversely proportional to the velocity change along the cross flow direction (the outlet of the quick-frozen machine extends to the center of the quick-frozen machine). With the change of the transverse flow distance, the velocity of the transverse flow gradually decreases, which indicates that the change of the inlet pressure leads to the change of the internal flow field, and it has a obvious rule to follow. The reason for the above rules lies in that in the same speed quick-frozen machine, all the sizes and air supply conditions of the nozzle do not change, which means that the nozzle outlet wind velocity varies with the change of the transverse flow direction only under the same inlet pressure, but because the drag in the pressure exit region is very small and negligible. As a result, the outlet wind velocity of the nozzle at the pressure outlet is the largest, and then the resistance of the nozzle increases gradually along the transverse flow direction, making the nozzle exit wind velocity smaller and smaller. On the other hand, when the nozzle inlet pressure increases, the outlet wind velocity of the nozzle increases gradually. The reason is, the greater the pressure, the greater the velocity of the wind in the same direction. Finally, it can be seen from the figure that there is no rapid rise or rapid drop in the exit wind velocity of the nozzle, and the overall wind velocity exhibits a smooth change. According to the formula (1), the variation rate of the nozzle outlet wind velocity under different inlet pressures is within 15%, which means that the higher uniformity of the air flow is beneficial to the freezing of the food.

$$\phi = \frac{u_{x=0} - u_{x=50}}{u_{x=0}} \times 100\% \quad (1)$$

Where  $u_{x=0}$  is the nozzle outlet flow rate at the pressure outlet and  $u_{x=50}$  is Nozzle outlet flow velocity at the center of the freezer in the width direction.



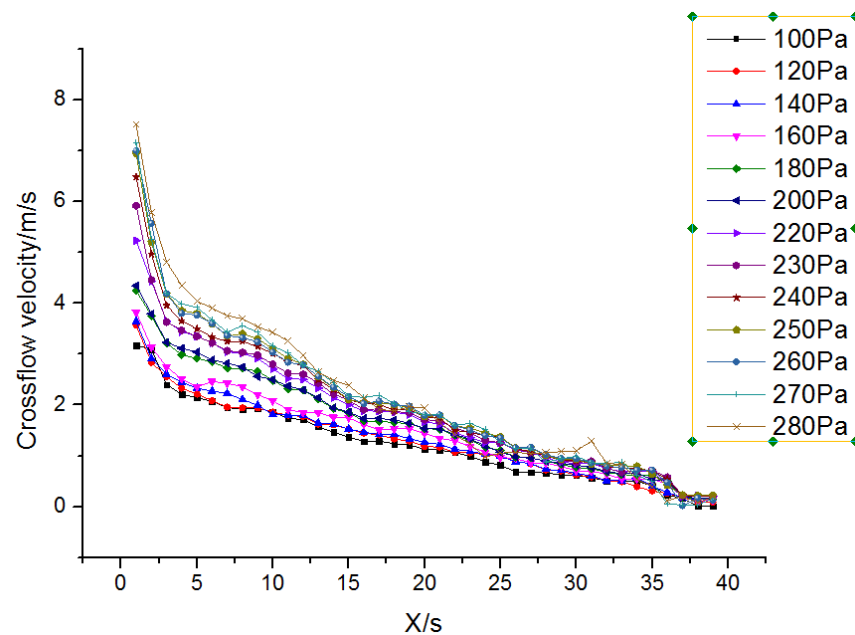
**Figure 5.** Velocity distribution of nozzle exit.

When the quick-frozen machine is running, the frozen product on the surface of the steel strip will be affected by the airflow organization force. When the cross-flow velocity reaches a certain value, the frozen product will be blown away from the frozen area, which is unfavorable for the safe and effective operation of the equipment. To determine the safe freezing wind velocity of different frozen products, it is necessary to carry out the blow-off experiment on frozen products placed on the steel strip. To determine the safe freezing wind velocity of different frozen products, it is necessary to blow off the frozen products on the steel strip Experiment. Therefore, in this study, shrimp is selected as the experimental object, and multi-point anemometer SYSTEM MODEL 1560 and 0965-00/01 wind velocity probes are selected as testing tools. The final experimental test results show that the speed of shrimp movement is positively correlated with the cross-flow wind velocity. When the cross-flow wind velocity is greater than or equal to 11.5 m/s, the frozen product is blown off.

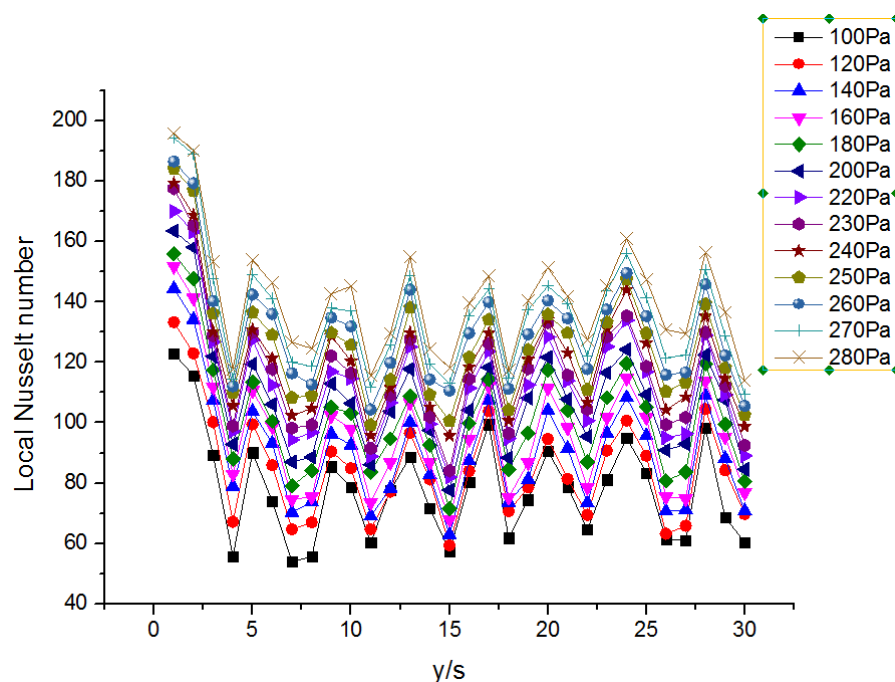
In order to further study the state of the frozen product on the surface of the steel strip, the shrimp is also the research object. Since the general placement height of the shrimp during the freezing process is about 10 mm, the upper surface of the steel strip is taken for 10 mm for analysis. As shown in figure 6. Obviously it can be seen from the figure: (1) As the distance in the direction of the cross flow increases, the cross-flow wind velocity at the same inlet pressure gradually decreases. (2) At the same cross-flow direction, the cross-flow wind velocity increases with the increase of pressure. The cause of the (1) phenomenon is that the closer to the center of the freezer, the stronger the capacity of the air flow directly impact the surface of the steel strip, the smaller the turbulence is, the smaller the velocity of the flow is. When the air flow approaches the exit point, as the accumulation of exhaust gas gradually increases, the disturbance caused by the air flow is strengthened, and a large lateral wind velocity is generated. The reason for the (2) phenomenon is that at the same position, when the inlet pressure is increased, the power given to the airflow will be increased, which will accelerate the

accumulation of lateral exhaust gas and increase the cross-flow wind velocity. However, according to the experimental test results, for the V-slit nozzle, under the condition that  $H/S$  is less than 14, the inlet pressure of the nozzle is not greater than 11.5 m/s at 10 mm above the steel strip between 100 Pa and 280 Pa. In other words, frozen products will not be directly blown off due to the increase of cross-flow wind velocity. This shows that the safe and stable operation of the quick-frozen machine within the above inlet pressure range is guaranteed.

However, the cross-flow effect of impinging jets is where we have to think carefully.



**Figure 6.** Cross-flow velocity distribution at 10mm above the surface of steel strip.



**Figure 7.** The local Nusselt number distribution of steel strip surface.



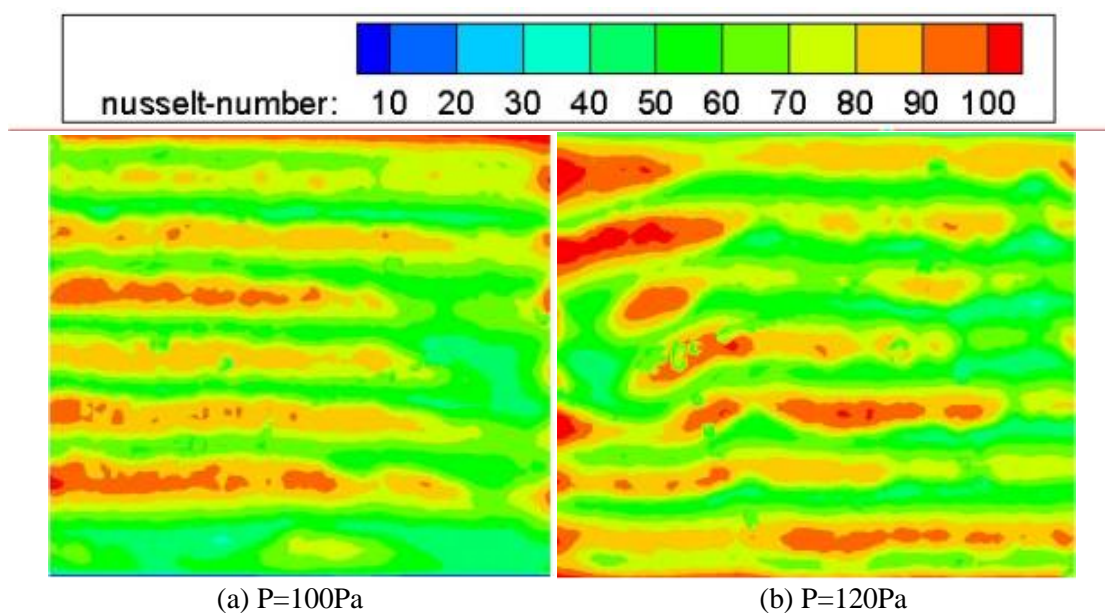
### 5. Heat transfer characteristics of steel strip surface

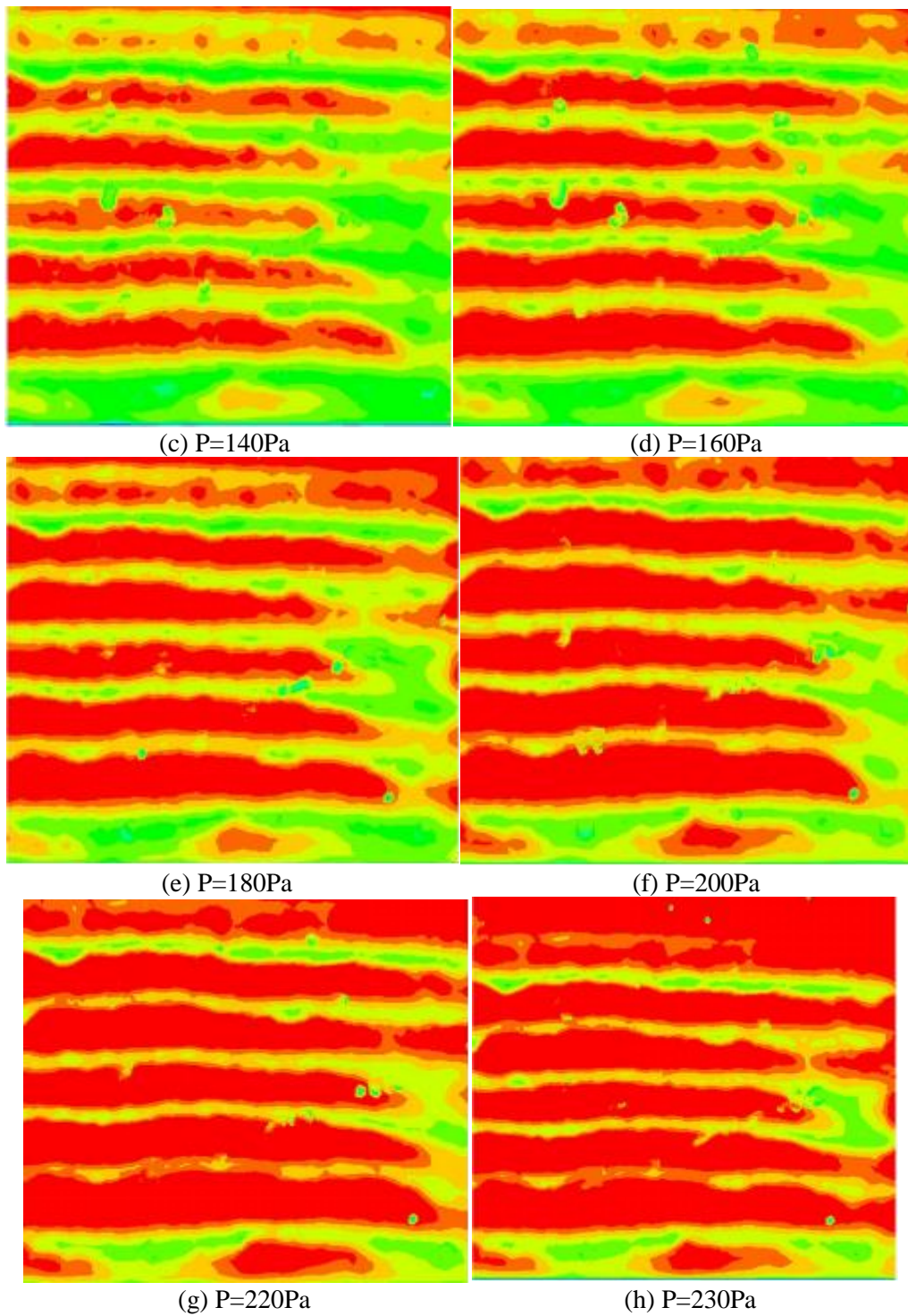
Figure 7 shows the local Nusselt number distribution on the surface of the V type joint nozzle under different inlet pressure (100 Pa-280 Pa), from top to bottom, it represents the exit direction of the slit. As shown in the figure, the difference in inlet pressure causes a difference in the Nusselt number on the surface of the steel strip, that is, it has a great influence on the heat transfer characteristics of the surface of the steel strip. In addition, it is worth noting that the V-slit nozzle will have a peak at the stagnation point on the surface of the steel strip, and the Nusselt number near the peak gradually decreases, and the change is very obvious, showing a wave-like distribution. The reason for the wave-like distribution is that at the center of the jet, the jet of air is faster, which enhances the heat transfer on the surface of the strip. On both sides of the jet center, the disturbance of the airflow is increased, which greatly weakens the heat exchange between the airflow and the steel strip. In addition, near the airflow outlet, the resistance along the way is small and the airflow will show the largest Nusselt number at the location.

### 6. The average number distribution of the Nusselt number on the steel strip surface

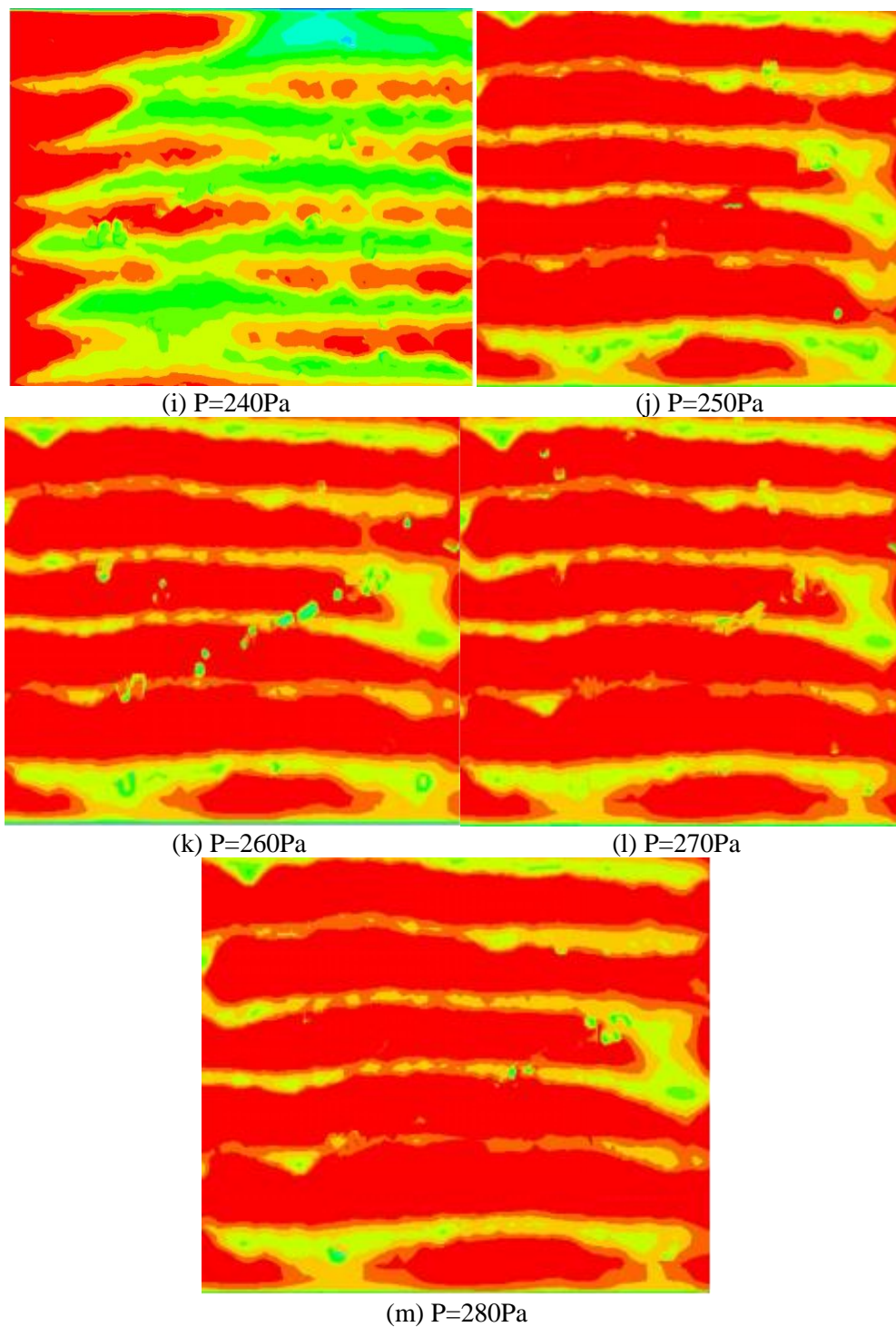
The average Nusselt number on the surface of the steel strip shows the overall heat transfer status of the steel strip surface [9]. Figure 8 is the average Nusselt distribution of the V-slit nozzle along the cross-flow direction. The cross-flow direction is from left to right, where the pressure are respectively 100 pa, 120 pa, 140 pa, 160 pa, 180 pa, 200 pa, 220 pa, 230 pa, 240 pa, 250 pa, 260 pa, 270 pa, 280 pa, etc.

As shown in figure 9, the peak value of Nusselt number is mainly concentrated at the return air outlet. With the increase of pressure, the Nusselt number peak and the cross flow upstream area show a great difference. When the pressure is 120 Pa, the power of gas flow is smaller, and the farther away from the return air, the greater the resistance along the cross-flow direction. As the pressure increases, the power of gas flow increases, and the Nusselt number increases accordingly. In addition, because of the special construction of the V-slit nozzle, the Nusselt number of the jet center is much larger than the Nusselt number of the surroundings. This is because the cross-sectional area of the V-slit nozzle is larger, impeding the injection of ambient gas, and the change in Nusselt number along the cross-flow direction is more gradual. It can be seen from figure 9 that with the increase of inlet pressure, the Nusselt number on the surface of the steel strip is getting larger and larger, indicating that the heat exchange between the air stream and the strip surface is very good.

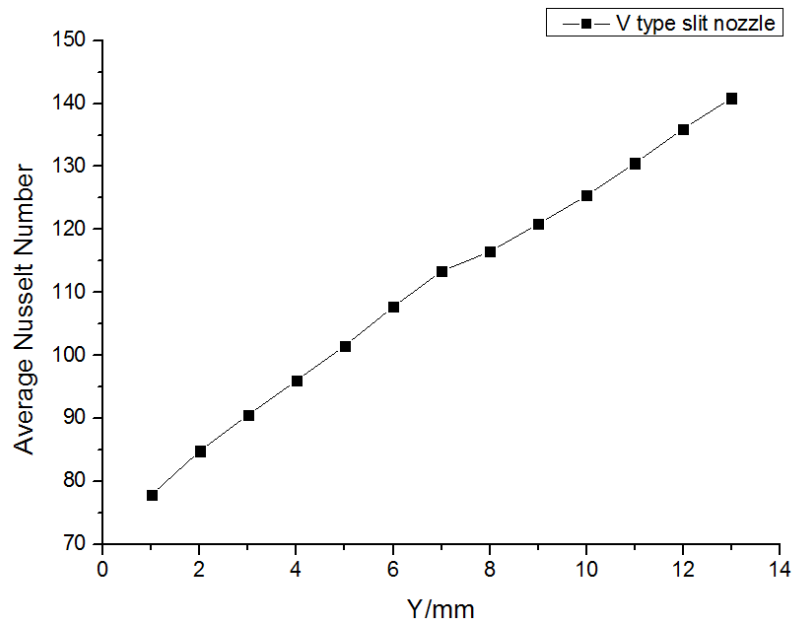








**Figure 8.** Distribution of Average Nusselt number on the surface of different pressure steel strips.



**Figure 9.** Distribution of Average Nusselt number on the surface of different pressure steel strips.

Compared with the conventional nozzle shape, the V-slot nozzle is very advantageous in terms of affecting its heat transfer characteristics. The cross-flow effect is the mutual disturbance of the lateral flow of the gas generated by the jet impacting the surface of the steel strip, and the slit nozzle has continuity, so the influence of the cross-flow effect on it is very weak, so there will be no significant influence between the upstream and downstream nozzles [10]. Moreover, when the inlet pressure is changed, the heat transfer can be optimized and the frozen product will not be blown off.

## 7. Conclusions

In this paper, the V slit nozzle is used to replace the other shape nozzles, and the inlet pressure of the static pressure chamber is constantly changed to explore the change of the heat transfer characteristics of the flow field and the steel strip surface under the same air supply conditions and different inlet pressure. The following conclusions are drawn:

- The cross flow direction and nozzle inlet pressure have great influence on the internal flow field and heat transfer characteristics of the quick freezing machine. In the cross flow direction, from the pressure exit position to the central position of the quick freezing machine, the velocity of the nozzle outlet of the quick freezing machine decreases gradually. At the same location: with the increase of nozzle inlet pressure, the outlet wind speed of the nozzle is higher. However, the overall trend of the air flow is relatively smooth, and the uniformity of the air flow is high, which is conducive to the freezing of food.
- The transverse flow effect is one of the important factors affecting the freezing efficiency of the freezer [11,12]. The transverse flow effect is determined by the cross flow wind speed. The transverse flow wind velocity produced by the pressure of 100 Pa, 120 Pa, 140 Pa, 160 Pa, 180 Pa, 200 Pa, 220 Pa, 230 Pa, 240 Pa, 250 Pa, 260 Pa, 270 Pa, 280 Pa, and nozzle is adopted in this paper. But in order to achieve the goal of making the frozen products blow up, it can maintain the effective operation of the quick freezing machine.
- Nusselt number can well reflect the heat transfer of frozen goods on steel strip. With the increase of the inlet pressure of the nozzle, the average number of Nusselt on the surface of the steel strip is increased obviously, which indicates that the heat transfer effect of the steel strip is obviously improved. There is a peak value of the local Nusselt number on the surface of the steel strip, which indicates that the heat transfer effect is best below the nozzle, and the

number of local Nusselt increases as the inlet pressure increases. The overall trend is smooth, indicating that the heat transfer uniformity of the steel strip surface is good.

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