Effects of Different Orifice Structure on Heat Transfer Characteristics of Steel Strip Surface in an Air Impinging Freezer

Yu-yan LIU, Jin-feng WANG and Jing XIE*
Shanghai Ocean University, Shanghai, China
Shanghai Engineering Research Center of Aquatic Product Processing & Preservation, Shanghai
Shanghai Professional Technology Service Platform on Cold Chain Equipment Performance and Energy Saving Evaluation, China
Quality Supervision, Inspection and Testing Center for Cold Storage and Refrigeration Equipment(Shanghai), Ministry of Agriculture, China
*Corresponding author

Keywords: Orifice plate, Impinging jet, Numerical simulation, Heat transfer characteristics, Air impinging freezer.

Abstract. In this paper, the fluid field in an air impinging freezing experimental table was studied by computational fluid dynamics (CFD) numerical simulation technology. The influence of the different diameter D and orifice spacing distance S on the heat transfer characteristics on the steel strip surface were analyzed, and the difference of the heat transfer effect between the orifice and slit nozzle were compared. The results show that when the orifice diameter is less, the heat transfer coefficient on the steel strip surface is less due to the effect of cross-flow. With the orifice diameter is increased, the effect of the resistance along the upstream is increased. The average Nusselt number on the steel strip surface is the highest at D=10mm. When the spacing distance is less, the distance between the first row of orifice nozzle in the upstream and the adhering wall is less and the velocity of flow is less. With the increased of spacing distance, the distance between the first row of orifice nozzle in the upstream and the last in the downstream is increased, and the effect of cross-flow is increased. The average Nusselt number on the steel strip surface is the highest at S=34mm. The effect of cross-flow under the slit nozzles is weak and the food can be better protected. The average Nusselt number on the steel strip surface under the orifice nozzles is 9.7% higher than that of the slit nozzle.

Introduction

Jet impingement is a commonly technique used in heating, cooling or drying the surface[1, 2]. The boundary layer on the food surface is destroyed by high-speed air and the heat transfer is greatly enhanced. It is one of the most effective and flexible local cooling technologies[3, 4]. Cross flow is defined as the fluid flow in the direction perpendicular to the impinging jet. It can be formed by external flow or accumulating spent flow. The cross-flow has an adverse effect on the heat transfer on the impinging surface. The cross-flow effect must be minimized in order to achieve effective heat transfer[5-7]. Nuntadusit C and Sarkar A et al[8, 9] used oil film technique to visualize the impinging surface flow. They found that the cross-flow effect became more notified along the axial direction. In the downstream area, the center of an impingement jet was shifted and the shapes of fluid flow on the impinging surface become irregular. Dano et al[10]determined the flow behavior of impinging surfaces by digital particle image velocimetry(DPIV) and flow visualization techniques. The results show that the heat transfer rate was maximum at the stagnation point, and the peak of the heat transfer coefficient was decayed along the cross-flow direction. According to the previously published works, the heat transfer characteristics on the impinging surface is significantly affected by the cross flow.

In order to simplify the model of the air impinging freezer, the impinging freezing experiment table is as object of study in this paper. When the pressure difference between the inlet and the outlet of the cold air is constant, the influence of different orifice diameter and orifice spacing distance on the heat
transfer characteristics of the steel strip surface will be analyzed. And the different of the heat transfer effect between the orifice and slit nozzle will be compared.

**Numerical Simulation**

**Physical Model**

The model of impinging freezing experiment table is in Figure 1. The size of static pressure tank is 300mm × 300mm × 500mm, and the size of orifice plate is 300mm × 300mm × 5mm. The structure of model is symmetrical, so the model is calculated by only 1/2. The model of jets impingement is in Figure 2. Cold air is directly sprayed onto the steel strip surface through the orifice plate and is flowed through the confined rectangular channel. The area away from the pressure outlet is called the upstream area and the area near the pressure outlet is called the downstream area. The jet-to-plate distance (H) is fixed at 20mm. The model of orifice and slit nozzles are in Fig3. Both of two nozzles have the same exit area. The cross-flow direction from left to right. For orifice nozzles, there are 8 rows of nozzles in the X-direction.

![Figure 1. Model of impinging freezing experiment table.](image)

![Figure 2. Model of jets impingement.](image)

![Figure 3. Model of orifice and slit nozzle (a. orifice nozzle, b. slit nozzle).](image)
Condition setting of numerical model

The fluid of the model is air, the following assumptions were made: (1) Air is regard as incompressible fluid. (2) During the normal operation of the model, the internal flow field is regarded as steady state. (3) The walls of static pressure tank are adiabatic.

The model is k-ε turbulence model. Due to the temperature of the frozen zone changes during the impacting, the energy equation is opened. Pressure inlet boundary is defined as $P_{in} = 250\text{Pa}$ and pressure outlet boundary is defined as $P_{out}=0\text{Pa}$. For the frozen zone, the inlet temperature at 230K and the outlet temperature at 235K. Conveyor belt is defined as a steel strip, which the thermal conductivity is 16.3W/(m*℃).

Results and Discussion

Effect of Orifice Diameter

When the orifice spacing distance (S) is constant for 34mm, the difference of the heat transfer characteristics on the steel strip surface under different orifice diameters are shown in Figure 4 (a-f). It can be found that the heat transfer below the orifice is the highest. The heat transfer coefficient in the upstream area is higher when the orifice diameter is less. As the orifice diameter is increased, the heat transfer coefficient in upstream area is gradually decayed and the peak of heat transfer is moved to downstream. Figure 5 is shown that cross-flow velocity distribution on the steel strip surface under different diameters. With the X-direction, the cross-flow velocity is increased. As the orifice diameter is increased, the cross-flow velocity is increased rapidly. The cross-flow velocity is high especially in the downstream area. When the orifice diameter is less, the mass flow of cool air through the orifice is less and the direction of jet flow is easy to be interfered by the cross flow. In the upstream area, the effect of cross-flow is not obvious and the velocity of impinging jet on the steel strip surface is higher, so the heat transfer on the surface is greater. In the downstream area, the cross-flow is gradually accumulated, resulting in an increase of the velocity in the cross-flow direction. So the velocity of impinging jet on an impinged surface and the heat transfer coefficient in the upstream zone are decreased. When the orifice diameter is larger, the mass flow of cool air through the orifice is heavier. The direction of flow is not easy to be interfered by the cross flow and the effect of cross-flow is weak.

Figure 6 is shown that Z-velocity distribution at orifice nozzle outlet on streamwise row. In the upstream area, the Z-velocity distribution at orifice nozzle outlet is lower. As the X-direction, Z-velocity is gradually increased. At the last row of orifice nozzle, the Z-velocity of nozzle outlet tends to be consistent for all orifice diameters. Because the resistance along the upstream area is larger, resulting in the flow resistance at the nozzle outlet is increased. Therefore, the flow velocity at the nozzle outlet in the upstream area is lower. With the X-direction, the distance between nozzles and the pressure outlet is closer, the resistance along the way is lower. So the velocity at the nozzle outlet in the downstream area is increased greatly. Therefore, the heat transfer coefficient on the steel strip surface is increased.

When the orifice diameter is less, the heat transfer coefficient in the downstream area is lower. Because the velocity of impinging jet on the steel strip surface is decreased due to the effect of cross-flow. With the orifice diameter is increased, the flow of nozzle outlet is increased and the effect of cross-flow on impinging jet is reduced. However, the resistance along the upstream is larger, resulting in the velocity of nozzle outlet in the upstream area is decreased and the heat transfer coefficient on the steel strip surface is decreased. Therefore, with the increase of orifice diameter, the heat transfer coefficient of the upstream area is gradually decayed, and the heat transfer peak of jet center is gradually moved to the downstream area.
Figure 4. Nusselt number distribution of steel strip under different diameters (a. D=8mm, b. D=9mm, c. D=10mm, d. D=11mm, e. D=12mm, f. D=13mm).

Figure 5. Cross-flow velocity distribution on the steel strip surface under different diameters.

Figure 6. Z-velocity distribution at orifice nozzle outlet on streamwise row.

Figure 7 is shown the local area-averaged row Nusselt number under different diameters. When the orifice diameter is varied from 8mm to 10mm, the Nusselt number becomes decreased at the sixth row of nozzles. Because the effect of cross-flow becomes notified, and the velocity of impinging jet
on the steel strip surface is decreased. Therefore the heat transfer coefficient on the steel strip is decreased. When the orifice diameter is varied from 11mm to 13mm, the heat transfer coefficient in the upstream area is low. The heat transfer coefficient in the downstream area is increased along the X-direction. The reason is that the resistance along the upstream is larger, resulting in the velocity at nozzle outlet in the upstream area is lower. So the heat transfer coefficient in the upstream area is lower. The resistance along the downstream is decreased and the velocity at orifice outlet is increased, resulting in the heat transfer coefficient in the downstream area is rapidly increased. When D=10mm, the fluctuation of the local area-averaged row Nusselt number is most flat, and the uniformity of heat transfer is the greatest. Figure 8 is shown the average Nusselt distribution on the steel strip surface under different diameters. When D=10mm, the Nusselt number on the steel strip surface is the highest. Therefore, it can be concluded that when the spacing distance is constant, the Nusselt number on the steel strip surface has the maximum and the heat transfer is most uniform at D=10mm.

![Figure 7. Local area-averaged row Nusselt number under different diameters.](image)

![Figure 8. Average Nusselt number distribution on the steel strip surface under different diameters.](image)

**Effect of Spacing Distance**

When the orifice diameter (D) is constant for 10mm, the differences of the heat transfer characteristics of the steel strip surface under different orifice spacing distance is shown in Figure 9 (a-f). Compared with Figure 4 (c), it is indicated that when the spacing distance S is less, the heat transfer coefficient at the adherent wall is lower. The heat transfer coefficient at the adherent wall is gradually increased as the spacing distance increased. Figure 10 is shown the Z-direction velocity distribution on the steel strip surface for three spacing distance. With the increase of S, the Z-direction velocity is rapidly increased in the range of X=0-15mm. But the growth rates of the three
spacing distance are different, of which S = 31mm is the slowest and S = 37mm is the fastest. It can be speculated that Z-velocity of other spacing distance on the steel strip surface are fluctuated in this range. Because the spacing distance is increased, the distance between the center of the jet and the adherent wall is decreased. So the airflow velocity at the adherent wall is increased and the heat transfer coefficient on the steel strip surface is increased. Along the X-direction, with the increase of spacing distance, the peak of Z-direction velocity is gradually decreased because cross-flow is formed in the downstream area. When the spacing distance is larger, the range of cross-flow is increased. So the flow in downstream area is disrupted and the Z-direction velocity in the downstream is weak. Thus the heat transfer coefficient is reduced.

Figure 9. Nusselt number distribution of steel under different spacing distance (a. S=31mm, b. S=32mm, c. S=33mm, d. S=35mm, e. S=36mm, f. S=37mm).

Figure 10. Z-velocity distribution on the steel strip surface.

Figure 11 is shown the Local Nusselt number distribution on the steel strip surface under different spacing distance. The local Nusselt number on the steel strip surface at S=31mm is lower than S=34mm in the range of X=0-15mm. It can be inferred that the local Nusselt number on the steel strip surface is fluctuated in this range when S=31-34mm. With the increased of S, the distance between the first row of orifices in the upstream and the adhering wall is reduced and the velocity of flow is increased. So the heat transfer coefficient is increased and the average Nusselt number on the steel strip surface is increased. When S is in the range of 34-37mm, the distance between the first row of orifice nozzle in the upstream and the last in the downstream is increased, and the effect of cross-flow is increased. The jets in the downstream area are interfered by the cross-flow and the Z-velocity is
decreased. Therefore, the heat transfer coefficient is reduced and the average Nusselt number on the steel strip surface is decreased. Figure 12 is shown the Average Nusselt number distribution on the steel strip under different spacing distance. The average Nusselt number on the steel strip surface is the highest at S=34mm.

Figure 11. Local Nusselt number distribution on the steel strip under different spacing distance.

Figure 12. Average Nusselt number distribution on the steel strip under different spacing distance.

**Effect of Orifice and Slit Nozzles**

Figure 13 is shown Nusselt number distribution on the steel strip surface under slit nozzle. There is an obviously difference between the Nusselt number distribution in the upstream area and downstream area. The peak of Nusselt number is mainly concentrated in the downstream area. Figure 14 is shown the Z-velocity distribution at the orifice and slit nozzle outlet. The Z-velocity at the slit nozzle outlet is gradually increased along the X-direction. Because the resistance along the upstream is larger, resulting in the flow resistance at the nozzle outlet is increased. Therefore, the flow velocity at the nozzle outlet in the upstream area is reduced. With the X-direction, the distance between nozzles and the pressure outlet is closer, and the resistance along the way is lower. So the velocity at the nozzle outlet in the downstream area is great increased. When the velocity of the orifice outlet is increased, the velocity of impinging jet on the steel strip surface is increased. Therefore, the heat transfer coefficient on the steel strip surface is increased. The difference between the maximum and the minimum (range) of the Z-velocity at the slit nozzle outlet is 7m/s. For the orifice nozzle, the Z-velocity range is 5 m/s. It can be seen that the Z-velocity distribution at the orifice nozzle outlet is more uniformly, so the heat transfer coefficient on the steel strip surface is more uniform.
Figure 13. Nusselt number distribution of steel strip under slit nozzle.

Figure 14. Z-velocity distribution at the orifice and slit nozzle outlet.

Figure 15 is shown the cross-flow velocity distribution on the steel strip surface under circular and strip nozzle. For both of the orifice and slit nozzle, the cross-flow velocity is increased in the X-direction. However, the cross-flow velocity under the slit nozzle is obviously lower than that of the orifice nozzle. Because the slit nozzle is continuous and the flow in the downstream is not effect by the upstream spent air. So the effect of cross-flow on the steel strip surface is weaker. The strong cross-flow effect can make the frozen food to be blown off, so that the frozen food can be better protected under the slit nozzles.

Figure 15. Cross-flow velocity distribution on the steel strip surface under circular and slit nozzle.
Figure 16 is shown that the Local Nusselt number distribution on the steel strip surface under orifice and slit nozzle. For the orifice nozzle, the local Nusselt number distribution on the steel strip surface is similar to the sinusoidal distribution. There is a maximum of local Nusselt number near the stagnation point and a minimum near the midpoint between two adjacent stagnation points. For the slit nozzle, the local Nusselt number distribution on the steel strip surface is a linear upward trend. The average Nusselt number on the steel strip surface is 254.91 under the orifice nozzle. For the slit nozzle, the average Nusselt number is 232.37. The average Nusselt number on the steel strip surface under the orifice nozzle is 9.7% higher than that of the slit nozzle.

![Figure 16. Local Nusselt number distribution on the steel strip surface under orifice and slit nozzle.](image)

**Conclusion**

In the present study, the impinging freezing experiment table is as object of study. The influence of different orifice diameter and orifice spacing distance on the heat transfer characteristics of the steel strip surface were analyzed. And the different of the heat transfer effect between the orifice and the slit nozzles were compared. The main findings are shown as follows:

1. When the orifice diameter is less, the heat transfer coefficient in the downstream area is lower. Because the velocity of impinging jet on the steel strip surface is decreased due to the effect of cross-flow. With the orifice diameter is increased, the flow of nozzle outlet is increased and the effect of cross-flow on impinging jet is reduced. However, the resistance along the upstream is larger, resulting in the velocity of nozzle outlet in the upstream area is decreased and the heat transfer coefficient on the steel strip surface is decreased. Therefore, with the increase of orifice diameter, the heat transfer coefficient of the upstream area is gradually decayed, and the heat transfer peak of jet center is gradually moved to the downstream area. The average Nusselt number on the steel strip surface is the highest at D=10mm.

2. With the increased of S, the distance between the first row of orifices in the upstream and the adhering wall is reduced and the velocity of flow is increased. So the heat transfer coefficient is increased and the average Nusselt number on the steel strip surface is increased. When S>34mm, the distance between the first row of orifice nozzle in the upstream and the last in the downstream is increased, and the effect of cross-flow is increased. The jets in the downstream area are interfered by the cross-flow and the Z-velocity is decreased. Therefore, the heat transfer coefficient is reduced and the average Nusselt number on the steel strip surface is decreased. The average Nusselt number on the steel strip surface is the highest at S=34mm.

3. The slit nozzles are continuous and the flow in the downstream is not effect by the upstream spent air. So the effect of cross-flow on the steel strip surface is weak and the food can be better protected under the slit nozzle. The average Nusselt number on the steel strip surface under the orifice nozzle is 9.7% higher than that of the slit nozzle.
Acknowledgment

The authors would like to acknowledge the financial supports from National Key R&D Program of China (No. 2016YFD0400303).

References


