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ANALYSIS OF CFD HEAT TRANSFER OF VACUUM FREEZE-DRYING SHELF

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ABSTRACT

The vacuum freeze-drying technology is extensively used in biochemical technology industry, especially applicable to materials that are sensitive to temperature, easily deteriorate, and need to remain the original taste. The main defect of this process is long process time. This study used commercial computational fluid dynamics (CFD) software Fluent to research the impact of the shelf inside the vacuum freeze-drying machine on the heat transfer performance of the object being dried in the course of heating, and used different shelving arrangements and inlet velocities for numerical simulation of flow field and heat transfer properties. The fluid flowing inside the shelf was 50% glycol water, the inlet velocity was 5m/s, 9.4m/s and 20m/s, and the shelf were stainless steel. Assuming that the shelf surface was a low temperature material layer 233K, and the shelf and materials were in a vacuum and heat insulated environment, the results showed that the temperature difference between the inlet and outlet reached was the smallest when the shelf inlet velocity was 20m/s, and was the highest when the shelf inlet velocity was 5m/s. Although the heat exchange between the fluid and the low temperature layer was better when the inlet velocity was low, the large shelf surface temperature difference was likely to cause unstable material quality. The inlet velocity could be set as 9.4m/s in consideration of saving the energy of pumps.

INTRODUCTION

Vacuum freeze-drying has been extensively used in biochemical technology industry and food processing industry, especially applicable to the temperature sensitive and deteriorative foodstuff, in order to keep the primary taste of the ingredients. The entire drying process is carried out at a low temperature. The moisture is sublimed from the solid state into the vapor state directly, and removed by vacuum pumping and heating. The foodstuff is heated on the shelf, and the heating must by uniform in order to improve the quality and avoid the foodstuff collapsing in the freeze-drying process.

In the studies related to the heat and mass transfer mechanism of primary drying, it is very important to keep the article drying temperature below the eutectic or collapse temperature in the primary drying process [1] [2], so as to avoid the melting of the articles being dried. Generally, the temperature of articles is not controlled directly, but to control the temperature of shelves and the pressure of vacuum process chamber to control the temperature of articles [3] [4]. At this point, the balance between the heat supplied by shelves and the heat taken away by the moisture sublimation inside the articles determines the temperature of the articles [5] [6]. The ice line goes down when the foodstuff is being heated, and the drying layer forms a barrier layer that makes the moisture unlikely to sublime, therefore, the products cannot be too thick, so as to avoid an overlong drying period [7].

The studies related to secondary drying are described below. The secondary drying follows the primary drying closely. It desorbs moisture or volatile matter out of the porous structure of drying layer at a higher temperature in a vacuum environment. It is generally agreed that this process starts until the ice line of the article being dried reaches the heating plane [8], and the time spent is approximately 30~50% of primary drying [9]. Besides water, other substances in medicine, biotechnology and other domains are required to be desorbed at this stage [10,11]. It is found in the shelf temperature parameter control during primary and secondary drying that the sublimation rate can be controlled effectively by drying at about the melting temperature of the article being dried. The process time can be shortened effectively by implementing primary and secondary drying at the melting temperature and scorch temperature. The temperature of vacuum chamber should be controlled at a level slightly higher than the melting temperature in the primary drying process, and the temperature of vacuum chamber should not be lower than the scorch temperature in the secondary drying process [12] [13]. The shelves designed with flat edges and without protrusions are advantageous to the drying process [14].

Therefore, this study discussed the effect of shelves inside the vacuum freeze-drying machine on the heat transfer performance of the articles being dried in the heating process, and used different plies of shelves and inlet velocities for numerical simulation of flow field and heat transfer properties.

NUMERICAL MODELS

This study used the CFD business software FLUENT 6.3 to analyze the heat transfer inside and outside shelves, in order to determine a preferable shelf design. The most efficient shelf heat transfer was obtained to save the energy required by vacuum freeze-drying equipments for freezing and heating, and to improve the drying quality of articles being dried. The shelf vacuum freeze-drying machine designed by this laboratory was used as the research carrier to studying the heat transfer and flow channel design for shelves, as shown in Fig. 1.

The vacuum process chamber contains three plies of shelves, and the article being dried is placed on the shelf. Fig. 2. shows the three-dimensional graph and flow channel of shelves.

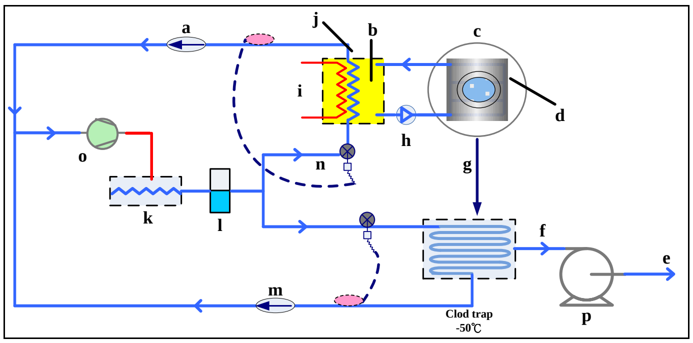

Fig. 1. Schematics of shelf freeze drying system: (a) check valve; (b) secondary refrigerant; (c) vacuum cavity; (d) shelf; (e) air; (f) dry-air; (g) wet-air; (h) pump; (i) heater; (j) heat exchangers; (k) condensers; (l) receivers; (m) check valve; (n) expansion valve; (o) compressors; (p) vacuum pump

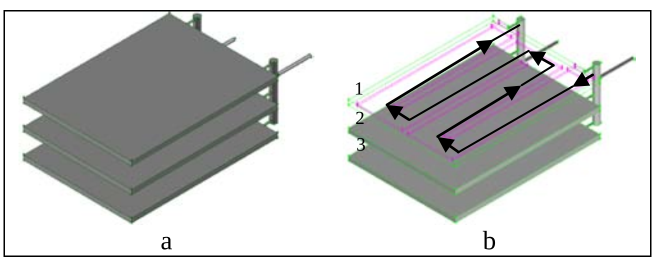

Fig. 2 Three-dimensional graph and flow channel of shelves

Fundamental assumptions:

The following assumptions were made before the analytical simulation of shelf heat transfer

(1) Steady-state flow field
(2) Viscous Model is Laminar
(3) Pressure-Velocity Coupling is SIMPLE
(4) Convection-Diffusion terms use First Order Upwind
(5) The foodstuff is kept at constant temperature 233K in the computational process
(6) The shelves are in adiabatic condition in vacuum environment

Governing equation:

FLUENT 6.3 uses the control volume finite difference method (CVFDM) for discretization of governing equations, the governing equations include continuity, momentum, energy and turbulent model equations. The turbulent model adopts standard k-ε turbulent model equation, and all the equations are listed as follows:

Continuity

$$\frac{\partial u_j}{\partial x_i} = 0 \tag{1}$$

Momentum

$$\frac{\partial}{\partial x_j}\left[\left(\mu_l + \mu_t\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j} - \delta\frac{2}{3}\frac{\partial u_k}{\partial x_k}\right) - \rho u_j u_i - \delta_{ij} p\right] = 0 \tag{2}$$

Energy

$$\frac{\partial}{\partial x_j}\left[\left(\Gamma_1 + \frac{\mu_t C_p}{\sigma_\tau}\right)\frac{\partial T}{\partial x_j} - pu_j C_p T\right] + \mu_l \Phi_v + \rho\varepsilon = 0 \tag{3}$$

Turbulent kinetic energy

$$\frac{\partial}{\partial x_j}\left[\left(\mu_l + \frac{\mu_t}{\sigma_\tau}\right)\frac{\partial k}{\partial x_j} - \rho u_j k\right] + \rho P - \rho\varepsilon = 0 \tag{4}$$

Turbulent dissipation energy

$$\frac{\partial}{\partial x_j}\left[\left(\mu_l + \frac{\mu_t}{\sigma_\tau}\right)\frac{\partial \varepsilon}{\partial x_j} + \rho u_j \varepsilon\right] + C_{\varepsilon 1}\frac{\rho\varepsilon P}{k} + C_{\varepsilon 2}\frac{\rho\varepsilon^2}{k} = 0 \tag{5}$$

NUMERICAL SIMULATION SETTINGS

This study carried out numerical simulation of flow field and heat transfer properties of internal flow channel of shelves, including different plies of shelves and inlet velocities. There are three cases, the shelf flow channel model is shown in Fig. 3.

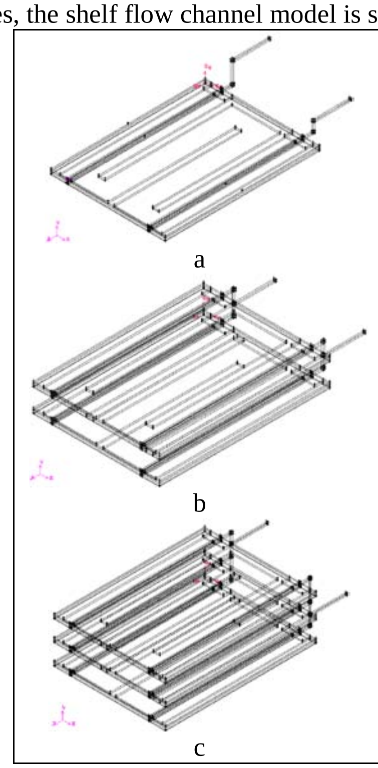

Fig. 3 Shelf flow channel model

The shelves are made of 304 stainless steel, and the shelves and foodstuff are assumed to be in a vacuum insulation environment. The number of grids is shown in Table 1. In hypothetical simulation conditions, the involved computing domain has one inlet, one outlet, one in-shelf liquid, the others are solid boundaries. The cases are respectively described below.

Table 1 Number of grids in cases

	Case1	Case2	Case3
Number of grids	888348	1768092	2108658

The boundary conditions of Case 1 to Case 3 are set as follows.

(1) Inlet/outlet boundary

The boundary condition of inlet is set as velocity-inlet.

The inlet velocities are 5m/s, 9.4m/s and 20m/s respectively.

The inlet temperature is fixed temperature 253K.

The outlet boundary is set as outflow.

(2) In-shelf liquid

The fluid boundary condition settings adopt 50% ethylene glycol solution, the fluid properties are density of 1085kg/m^3, specific heat of 3490J/kg-K, thermal conductivity of 0.42w/m-k and viscosity coefficient of 0.029kg/m-s

(3) Solid boundary

This solid boundary is set as wall and the material is set for steel.

Wall surface has no temperature heat flux=0.

The top is assumed to contact low temperature material at preset temperature of 233K.

SIMULATION RESULTS ANALYSIS

The internal flow channel of the shelf of the frozen vacuum dryer uses the fluid to provide heat to the shelf. The shelf temperature should be considerably even to avoid excessive temperature difference that may result in uneven drying quality. The numerical simulation results use different inlet velocities and shelf plies to analyze the temperature changes between the secondary coolant and the shelf as well as the heat transfer effects after the addition of low temperature materials. The temperature field cross sections in the direction of Z at the shelf outlet, centre and end are used to check the temperature changes in outlet and top of the shelf. The cross section location is as represented by the red dotted line.

Case 1:

Figure 4 illustrates the sectional drawing of the single-ply shelf temperature field in Z direction. The sectional location as shown in the figure is represented by the red dotted line. The high temperature region on the left of Figure 4a is the inlet and the high temperature on the right is the outlet. At the topmost of Figure 4a, it is the single-ply shelf of inlet velocity at 5m/s. When the inlet velocity is assumed as 5m/s, the fluid velocity is slower and the heat exchange effect is relatively better. As a result, the temperature in the outlet direction is relatively lower. In the middle of Figure 4a, it is the shelf with inlet velocity at 9.4m/s. Since the inlet velocity is relatively fast, the outlet temperature will be higher than the single-ply shelf with velocity at 5m/s. The bottom of Figure 4a is the shelf with inlet velocity at 20m/s, which is the single-ply shelf with fastest fluid speed. Hence, the outlet temperature will be the highest, which is only lower than the inlet temperature by 1.45K. It also applies to the smallest temperature difference in case of others flow velocity.

Figure 4b illustrates the section of the temperature field in the middle of the flow channel. The sectional location is represented by the red dotted line as shown in the Figure 4b. According to the temperature colours as shown in the figure, the flow velocity is proportional to the stability of heat provided by the fluid. When the fluid flows in the centre of the flow channel, the heat exchange effect with the low temperature layer reaches certain level. If the heat is not sufficient, it will result in relatively lower temperature of the metal between the shelf and the flow channel. At the bottom of Figure 4b is the shelf with inlet velocity at 20m/s. As the flow velocity is fast, it can provide relatively more heat or higher stability. Hence, in terms of temperature distribution, the flow channel central temperature in the inlet direction of the left and the temperature in the outlet direction are relatively close.

Figure 4c illustrates the farthest end of the shelf in the longest distance from the inlet, and the sectional location is represented by the red dotted line on the right as shown in Figure 4c. At this sectional location, there is no fluid but only solid steel. According to the performance in case of various flow velocities, when the flow velocity is faster, the deep blue representing low temperature will be less. When it is at the frozen vacuum drying state, the single-ply shelf uses the inlet velocity at 20m/s. It can provide more stable heat even at the end of the shelf as compared with other flow velocities, and the shelf temperature difference will be relatively smaller.

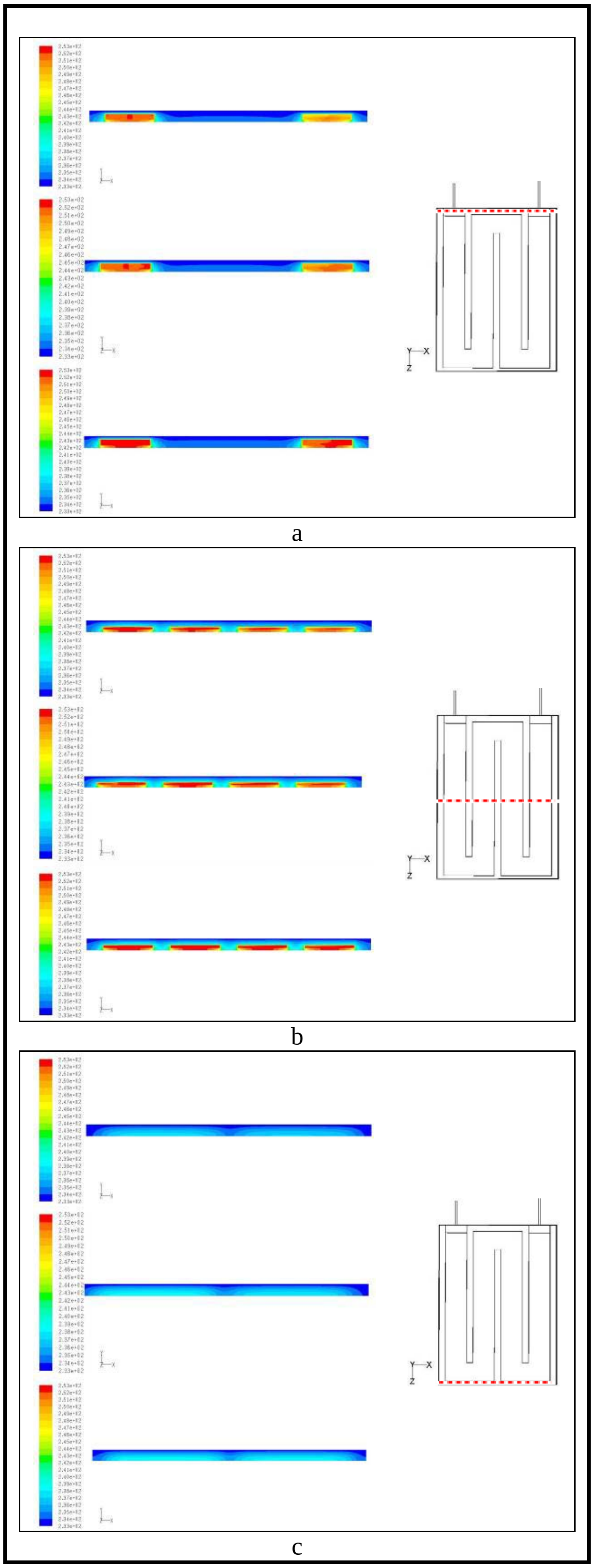

Figure 4 Temperature field of Z-direction section of shelf in Case 1

To explore the impact of the flow channel quantity of heat and the low temperature layer, in the middle of the shelf in Y direction as shown in Figure 5a, 200 points at an interval of 1.345mm from left to right are selected to analyze the temperature distribution after heat exchange. The red dotted line of the section of the Z direction represents the corresponding location of the section. The green block on the left is the inlet flow channel and the blue block on the right is the outlet flow channel as shown in Figure 5b. The curves illustrate the temperature distribution of the shelf flow channel and the surface low temperature layer in case of different flow velocities. When the flow velocity is 20m/s, as the green triangular curve as shown in Figure 5c, the temperature distribution from the inlet flow channel at the left to the outflow channel on the right is relatively even with very small temperature difference. When the flow velocity is reduced to 9.4m/s, as the red quadrilateral curve as shown in Figure 5c has suggested, temperature difference occurs after the heat exchange of fluids, and the temperature is the lowest at the flow channel at the far right. The temperature difference with the flow channel in the inlet direction is 0.3K. When the flow velocity is 5m/s, after the continuous heat exchange of the fluid, the flow velocity will be slower and the temperature will be highest when the quantity of heat is fixed. As the blue diamond curve as shown in Figure 5c has suggested, the flow channel temperature difference is 0.7K, which is the poorest in terms of shelf surface temperature uniformity in case of different inlet flow velocities.

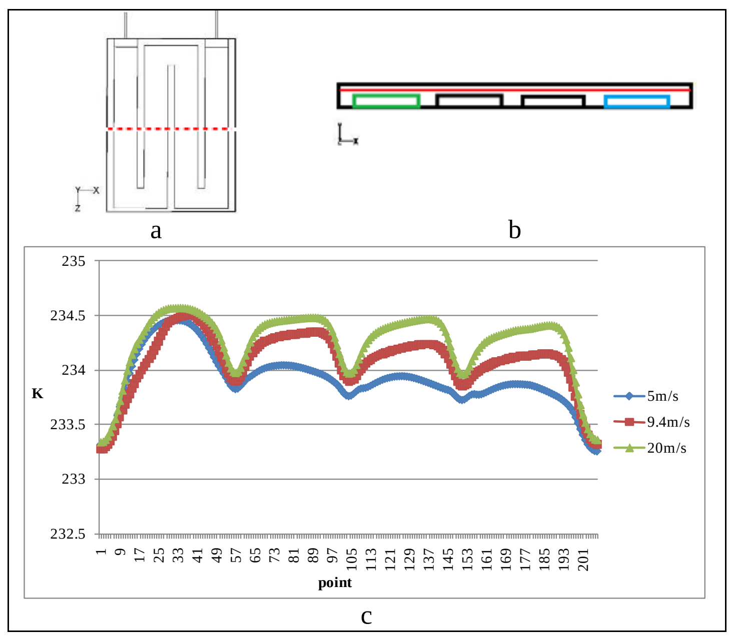

Figure 5 Shelf surface temperature curve in Case 1

Case 2:

In the frozen vacuum drying technology, it may require shelf of more than one ply. Figure 6 illustrates the two-ply shelf used in Case 2. In Case 2, the main inlet and outlet are located between two shelves as shown in Figure 3b. Figure 6a illustrates the temperature field section in Z direction and the sectional location is represented by the red dotted line on the right of Figure 6a. As shown in Figure 6a, the inlet velocity is assumed as 5m/s. When the number of shelf is increased to two plies, the low temperature material will increase. Hence, when the inlet velocity is 5m/s, the upper and lower plies will exchange heat with the low temperature material. Therefore, the outlet temperature will be lower than the temperature section of the same location in Case 1. As shown in the figure, the metal part in the middle of the flow channel will be at a low temperature due to the slow flow velocity, providing almost no heat. Figure 6a illustrates the two-ply shelf with inlet velocity at 9.4m/s. Due to faster inlet speed and the gravitational force, the inlet temperature of the upper layer shelf will be lower than the temperature of lower level, but the inlet temperature is almost the same. At the bottom of Figure 6a, it is assumed that the inlet velocity is 20m/s, it increases the upper layer flow channel inlet temperature, and the increasing flow velocity can increase outlet temperature more significantly than the other two velocities.

Figure 6b illustrates the section of the temperature field in Z direction in the middle of the flow channel, and the sectional location is represented by the red dotted lines as shown in Figure 6b. At the topmost part of Figure 6b, it is the temperature field section in Z direction of the shelf with inlet velocity at 5m/s. As shown, the flow channel temperature distribution is lower at the location closer to the outlet. However, the temperature distribution is almost the same in case of the upper ply and the lower ply shelf. As the flow velocity is relatively slow, the temperature between flow channels is lower than the shelf in case of velocities with greater temperature difference. In the middle of Figure 6b, it is the shelf of inlet velocity at 9.4m/s. In Case 1, the temperature distribution of the upper and bottom plies of shelves is similar, however, the temperature between flow channels is higher than that of the inlet velocity at 5m/s, and evener. The temperature at locations close to the outlet is similar to those in other cases as they are relatively lower. In the bottom of the Figure 6b, it is the shelf of inlet velocity at 20m/s, the trend of temperature of the upper ply and the lower ply is similar to the temperature of the location close to the shelf outlet flow channel, being higher than 9.4m/s by about 0.3K. When the flow velocity is different, the flow channel outlet temperature will change due to changing flow velocity. However, the same temperature gradient will be produced in temperatures of the upper ply and the lower ply as the temperature changes of the two plies are almost the same.

Figure 6c illustrates the temperature field section in the Z direction of the two plies shelf end, and the sectional location is represented by the red dotted line. The temperature at this location indicates whether the heat provided by the flow channel can reach the extreme of the shelf end. At the topmost of Figure 6c, it is 5m/s followed by 9.4m/s, and it is 20m/s at the bottom. As seen, the temperature at the shelf end is relatively low. The temperature of the metal between the shelf corner and the flow channel shows that the temperature distribution in case of shelves with inlet velocity at 9.4m/s and 20m/s is more uniform. The place in the furthest distance can provide sufficient heat for the low temperature layer for heat exchange without much impact from the lower temperature layer.

Figures 6a to 6c illustrate the temperature change from the inlet to the furthest end of the shelf. When the velocity is slow, the temperature channel in the inlet direction will be higher and the temperature will significantly reduce in the outlet direction. Meanwhile, the temperature of the metal layer between the shelf and the flow channel will be gradiently decreasing. However, the temperature gradient of flow channel of faster inlet velocity is smaller. During the freeze-drying process, greater shelf temperature gradient can more easily lead to poor quality.

In addition to the temperature analysis of the flow channel, this study discusses the part between flow channel and low temperature layer. In places including the central part of the shelf, the middle of the flow channel and the lower temperature layer in the Y direction, this study analyzes the temperature distributions of the flow channel heat transfer as shown in Figures 7a and 7b. As shown in Figure 7b, the green block represents the inlet and the blue block represents the outlet. As shown in Figure 7c, the diamond curve represents the inlet velocity at 5m/s, the blue line represents the first ply and the red line represents the second ply. The first ply shelf outlet pressure is 7.34 kPa and the second ply shelf outlet pressure is 7.23 kPa, the outlet pressure difference is only 1.5% between two plies. Hence, the flow difference is not significant and the heat quantity is close. Therefore, the temperature curves of the first ply and the second ply almost overlap; however, the temperature difference of the flow channel is 0.6K. The triangular curve represents the inlet velocity at 9.4m/s, the green line represents the first ply, and the purple line represents the second ply. The first ply shelf outlet pressure is 15.29kPa, the second ply shelf outlet pressure is 14.37kPa, and the differential pressure is 6%. However, it is similar to 5m/s in terms of temperature display as the temperature of the two shelves is identical. However, the temperature difference of the flow channel in the inlet direction is 0.5K. The circular curve represents the inlet velocity at 20m/s, the light blue line represents the first ply shelf, the orange line represents the second ply shelf, the surface temperature distribution is almost identical in case of the upper ply shelf and the lower ply shelf. The temperature difference of the maximum temperature and the lowest temperature of the flow channel is the minimal at about 0.3K.

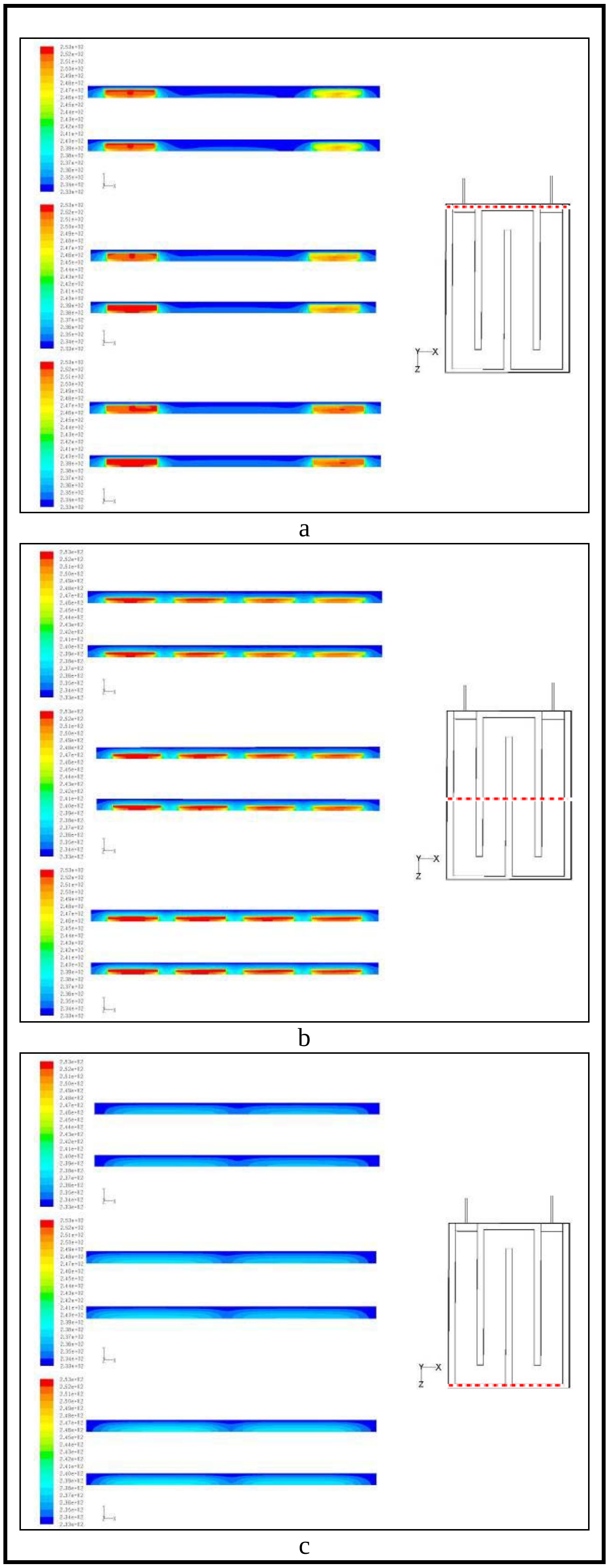

Figure 6 Temperature field of Z-direction section of shelf in Case 2

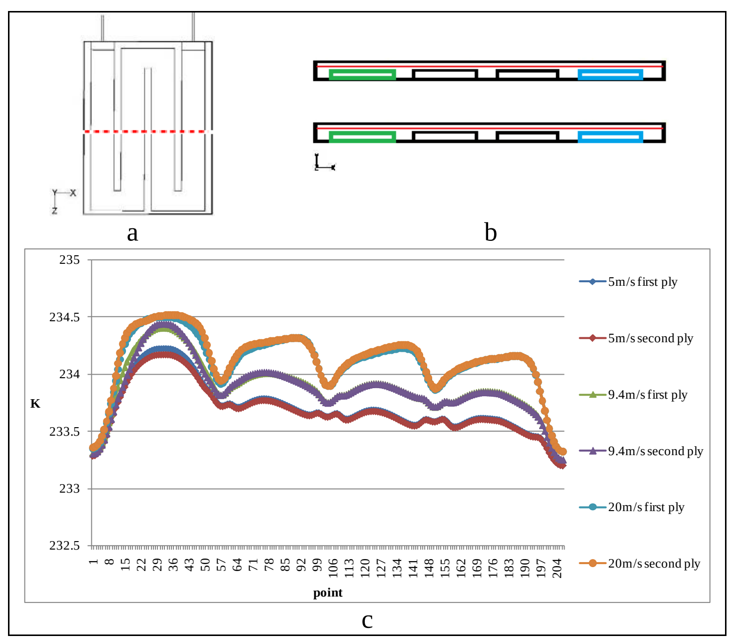

Figure 7 Shelf surface temperature curve in Case 2

Case3

The general small type frozen vacuum dryer usually uses three-ply shelves. In case of the three-ply shelves, in addition to analysis of the flow channel heat provision uniformity, whether the flow channel temperatures of the three shelves are stable and close to each other should also be discussed. In Case 3, the inlet is located between the second ply and the third ply of shelf. Due to the gravitational force, the outlet is located between the first ply shelf and the second ply shelf as shown in Figure 3c. Figure 8 illustrates the temperature field section in Z direction of the three-ply shelves in Case 3. As shown in Figure 8a, when the inlet velocity is 5m/s, the temperature will drop to 251K after the fluids enter the flow channel for heat exchange with the low temperature layer. However, the temperature at the inlet pipe is 253K. At the outlet, the temperature of the second ply shelf is slightly lower than the rest plies of shelf. In case of the shelf with inlet velocity at 9.4m/s, the inlet temperature is similar to that of the inlet velocity at 5m/s. However, the temperature will be higher in the outlet parts. The temperature of the outlet of the middle shelf will be lower than the other two shelves. When the inlet velocity is 20m/s, the outlet temperature is higher than the shelves of other inlet velocities. The temperature difference is the lowest among three cases of different inlet velocities. However, the temperature of the inlet in the middle shelf reduces significantly, and the outlet temperature is lower than the upper and lower plies of shelves.

Figure 8b illustrates the temperature field section in Z direction in the middle of the flow channel, and the sectional location is represented by the red dotted line as shown in Figure 8b. In case of the three-ply shelf, the temperature filed distribution in the middle of the flow channel tends to be close in case of inlet velocity at 20m/s and 9.4m/s. When the inlet velocity is 5m/s, the temperature of the flow channel in the outlet direction is apparently lower.

Figure 8c illustrates the furthest end of the shelf. In case of the shelf with inlet velocity at 5m/s, the low temperature region in the middle of the two flow channels of the first ply shelf and the third ply shelf is relatively large. The flow channel provision of temperature and heat is apparently insufficient. At the same location of the second ply, almost no temperature or heat is provided. The temperature distribution is almost the same in case of inlet velocity at 9.4m/s and at 20m/s. The high temperature provided by the flow channel of the second ply shelf has a relatively significant depression.

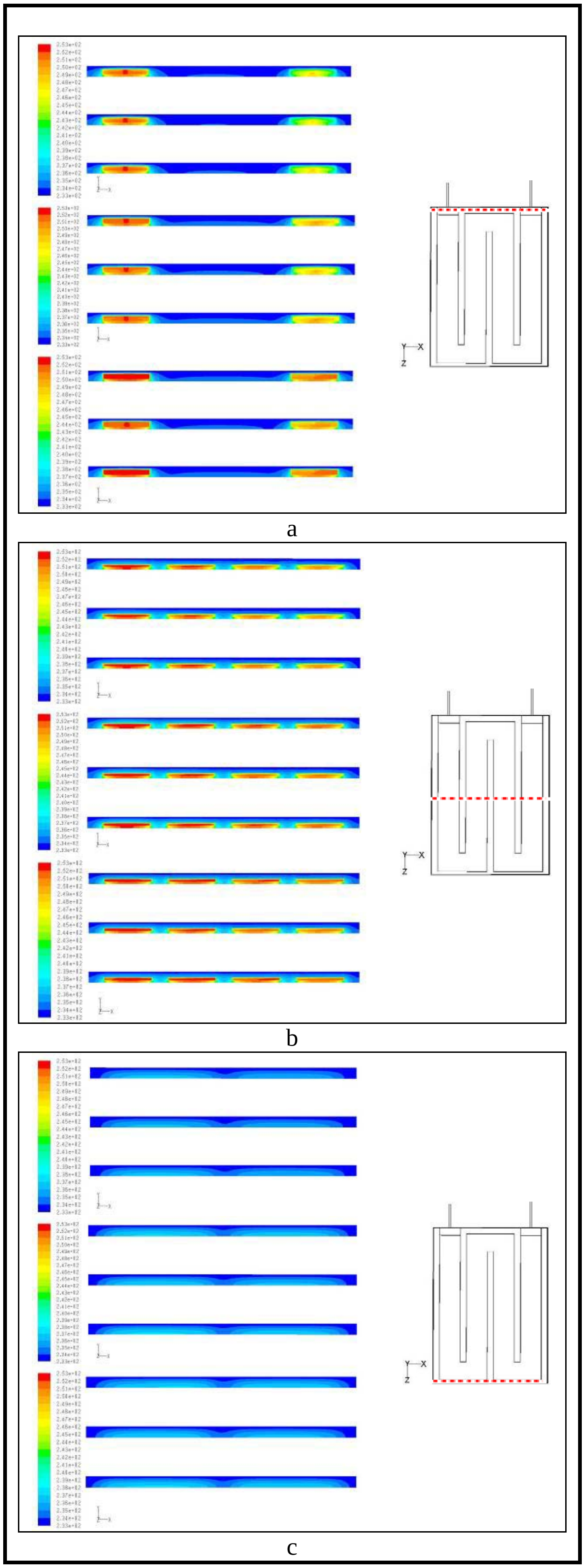

Figure 8 Temperature field of Z-direction section of shelf in Case 3

Figure 9 illustrates the temperature curves of the shelf and the middle of the flow channel. When the inlet velocity is 5m/s, the surface temperature distribution of the first ply shelf is almost identical with the surface temperature distribution of the third ply shelf. However, the temperature of the second ply is relatively lower as the second ply shelf outlet pressure is 2.27kPa and third ply pressure is 5.23kPa with a difference by 56%. As a result, the temperature outlet temperature will be relatively lower. However, when the inlet velocity is 9.4m/s, the difference of pressure between the second ply shelf outlet pressure and the first ply shelf is 53%, and the difference is 46% in case of inlet velocity at 20m/s. The cause of such pressure differences is the different heights of inlet/outlet positions.

Although the outlet temperature of the shelf with inlet velocity at 20m/s is the highest, the temperature difference of the second ply shelf and the rest two plies of shelves is the minimum when the inlet velocity is 5m/s. However, the heat quantity may be insufficient and it may prolong the entire processing time.

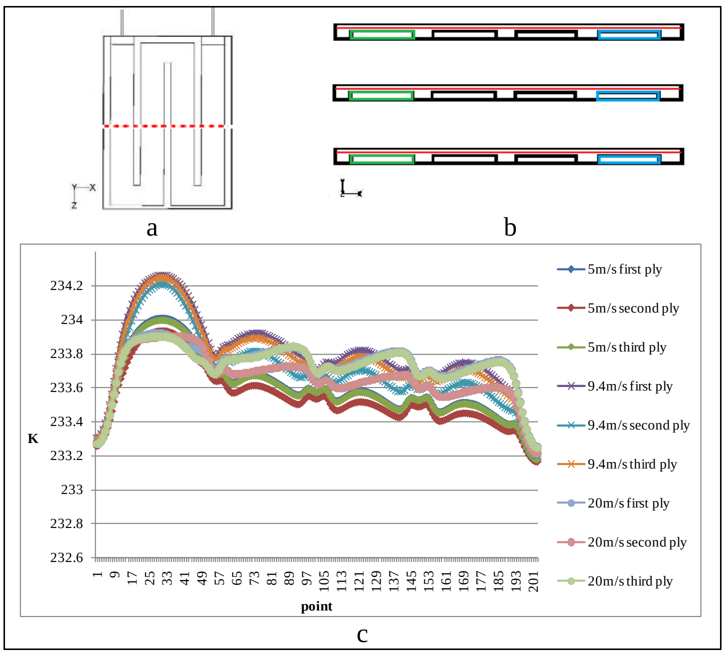

Figure 9 Shelf surface temperature curve in Case 3

CONCLUSION

This study uses the commercial CFD software FLUENT 6.3 to simulate the heat transfer analysis in case of different flow velocities and number of shelves with the following conclusions:

1. The single-ply shelf's inlet velocity will affect the temperature distribution of the entire shelf. For example, in case of 20m/s inlet velocity, it can be found that the self flow channel temperature is the most uniform. The maximum temperature difference occurs in case of flow velocity at 5m/s. In the two-ply shelf simulation the increase in low temperature layer will reduce to the outlet temperature. Even in case of the flow channel of inlet velocity at 20m/s, the temperature difference is more significant than the single-ply shelf. When the number of shelves increases to 3, the temperature difference will be the minimal when the flow velocity is 5m/s. However, the temperature difference between the inlet and the outlet will be the maximal. When the flow velocity is 9.4m/s, the temperature difference of the second ply is lower than other by 0.1K, and the inlet/outlet temperature difference is relatively smaller. When the inlet flow velocity is 20m/s, the inlet and outlet temperature difference is minimal. The temperature difference of the second ply is smaller than other two plies by 0.3K.
2. The positions of the inlet and outlet are the major cause of temperature difference between shelves. Regarding the pressure difference caused by positions of different heights, in case of two-ply shelf, the outlet pressure and temperature of the two plies are close. However, in case of the three-ply shelf, the inlet/outlet cannot be located in the middle, resulting in lower outlet pressure and temperature of the second ply.
3. When the shelf inlet velocity is 20m/s, the inlet/outlet temperature is minimal. When the shelf inlet velocity is 5m/s, the inlet/outlet temperature difference is maximal. Although slower inlet velocity leads to better heat exchange with the low temperature layer, the surface temperature difference will be larger. As a result, the material quality will be more unstable. For consideration of the saving energy of the pump, we can choose the inlet velocity at 9.4m/s.

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