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Study on Heat and Mass Transfer Performance during Heating, Pressurization and Expansion Stage in Explosion Puffing at Low Temperature and High-Pressure

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Abstract: China is a large agricultural country that is leading worldwide in the annual number of agricultural products and exports. However, the growth and harvest of fruits and vegetables are greatly affected by geographical conditions, climate and other factors, which will lead to their rotting in peak season and shortages in the off-season. Therefore, it is necessary to vigorously promote the development of drying technology. The explosion puffing technology at low temperature and high pressure is a kind of compound drying technology which can enable the puffed product to obtain the advantages of honeycomb, good rehydration, a short running time, etc. With the guidance of the theory of heat and mass transfer and relevant thermodynamics laws, this study has established high-pressure extruding technology in low-temperature heating; expanded the two-phase theoretical model, using mass conservation and the law of the conservation of energy to analyze the coupled heat and mass transfer process and influencing factors; and researched the influence of the operation temperature, pressure and time on the properties of dried fruit.

Keywords: heating pressure; puffing drying; heat and mass transfer

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1. Introduction

China is a large agricultural country [1,2] with the leading volume of agricultural products and annual exports worldwide. However, the growth and harvest of fruits and vegetables are greatly affected by geographical conditions, the climate and other factors, which lead to the phenomena of fruits and vegetables rotting in peak season and shortages in the off-season [3–5]. Therefore, it is necessary to actively promote the development of fruit and vegetable storages and the processing industry. At present, there are various methods for the storage and processing of fruits and vegetables, such as processing fresh fruits and vegetables into dried ones. The essence of fruit and vegetable dehydration is to reduce the water content of the fresh fruit and vegetables, so as to decrease the breeding of microorganisms by reducing the activity of biological enzymes and taper off the decay rate of fruits and vegetables so as to prolong the storage time. However, the long drying time and poor quality of dried products limits the development of this field [6]. Therefore, it is critical to further the research on the drying mechanism of fruits and vegetables to replace the empirical or semi-empirical formula [7], improve the quality of fruits and vegetables and reduce the production costs.

At present, fruit- and vegetable-drying technologies mainly include hot-air drying, heat-pump drying, vacuum drying, freeze drying, explosion puffing at low temperature and high pressure, microwave drying and far-infrared drying [8,9]. Explosion puffing at low temperature and high pressure is a form of composite drying technology, which can offer the advantages of honeycomb, good rehydration and a short operation time. Ma et al. [10] studied the effects of expansion temperature and pressure on the quality of apple slices. It was found that the expansion temperature and pressure had little effect on the moisture

content, specific volume, hardness and brittleness of the product. The optimum expansion temperature was 105 °C and the pressure was 0.3 Mpa. Song et al. [11] reported on how expansion pressure differences, temperature and evacuation time affect the expansion degree and hard brittleness of kiwifruit chips. The results showed that the ideal evacuation time of kiwifruit's low-temperature and high-pressure osmotic expansion was 2.95 h, the ideal expansion pressure difference was 1.82 MPa and the ideal expansion temperature was 70 °C. Zhu et al. [12] used the thermodynamic theory to establish the energy and exergy balance equation of explosion puffing using a low-temperature and high-pressure process and carried out a relative theoretical analysis, which revealed that the effective utilization rate of energy in the heating and pressurization stage was only about 8%; most of the energy was wasted while heating the tank. In addition, Zhu et al. [13] also analyzed water migration using the law of thermodynamics. The analysis showed that, under the process parameters of heating and a pressurization section with a temperature of 105 °C and pressure of 0.3 MPa, the vapor moisture of 30 kg material in the expansion tank was 0.446 kg. Using the principle of heat transfer, Hu et al. [14] constructed the heat conduction equation for three stages, including heating and pressurization and vacuum drying and cooling, and solved the time-dependent relationship of material temperature. Afterward, the mathematical model of the pressure relief expansion process was established by their team using thermodynamic theory and the relationship between material temperature and expansion temperature and pressure in a steady state was obtained. Lixia Hou et al. [15] established a 3D multiphase porous model to describe heat and mass transfer within kiwifruit slices. The temperature distribution of kiwifruit slices from both the simulation and experiment indicated that the sample temperature at the corners and edges was higher than that at the center of the container, and the sample temperature at the center was the lowest for a single kiwifruit slice. Fengying Xu et al. [16] established a heat and mass transfer model on the shell membrane and solved flesh-stone drying for litchi under the liquid–vapor interface moving and the temperature equation under shrinkage with the interface moving numerically, based on the spherical character of litchi.

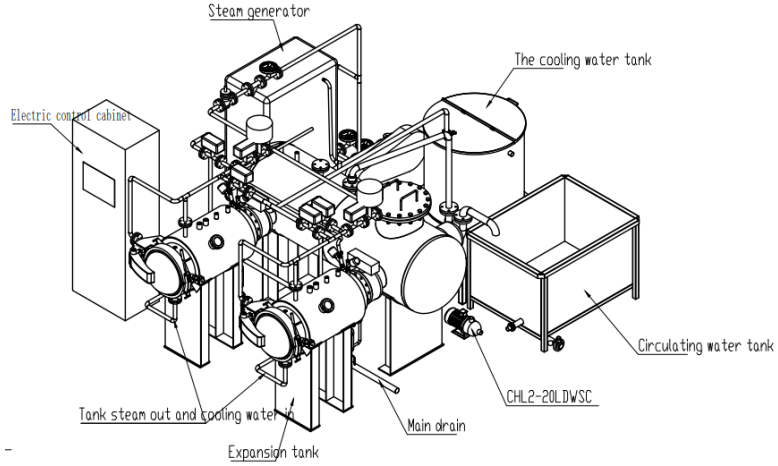
At present, scholars mostly employ experimental research to obtain semi-empirical formulas that could fit the correlation between the characteristics of moisture content and temperature and pressure and running time. Other scholars used the theory of heat transfer and thermodynamics to establish a simple heat transfer model or simulate the process of heat and mass transfer through software. However, the model was too simple to reveal the coupling mechanism of heat and mass transfer in the process of drying fruit in enough depth.

This paper derives from a horizontal project, based on the parameters of the fruit and vegetable drying process provided by the company, analyzing the performance of heat and mass transfer. In addition, using the theory of heat and mass transfer and the relevant laws of thermodynamics, a theoretical model was established for the two stages of high-pressure heating and expansion in the low-temperature, high-pressure expansion process. We also carry out a coupling analysis and examine the influential mechanism through the law of conservation of mass and energy. Furthermore, we study the influence of process operation temperature, pressure and time on the fruit drying performance. The final results are consistent with the actual process, which can reflect the heat and mass transfer characteristics of the drying process.

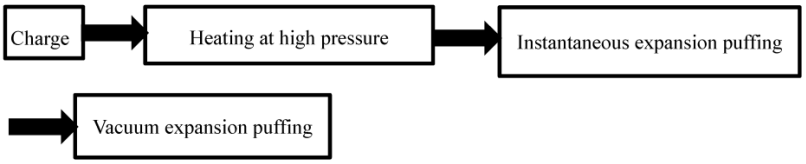
2. Brief Introduction to the Explosion-Puffing Technology at Low Temperature and High Pressure for Semi-Dried Apple Products

The system of explosion puffing at a low temperature and high pressure for semi-dried apple products consists of an air-compressor, vacuum tank, expansion tank, steam-generator and steam-heating pipe rack. The drying process is as follows: First, load the expansion tank. The initial moisture content of dried fruit is 25%, with a total weight of 15 kg; the inner diameter of the expansion tank is 1.5 m and the length is 2 m. After this, the air compressor will blow air into the tank to increase the pressure in the tank from normal pressure to an absolute pressure of 0.3 MPa. At that time, it is necessary to open

the steam inlet valve to inject saturated steam at a temperature of 150 °C into the jacket of the expansion tank and the heating pipe rack to raise the temperature in the tank up to 100 °C. Meanwhile, this pressure and temperature should be maintained for 10 min. During operation, if the temperature in the tank exceeds 100 °C, the steam supply should be stopped. However, when the temperature is lower than 100 °C, the steam inlet valve should be reopened. After operating for 10 min in the heating and pressurization phase, the butterfly valve connecting the expansion tank and the vacuum tank should be opened, instantly relieving the pressure in the expansion tank, and the pressure in the tank will suddenly drop from 0.3 to −0.07 MPa. Then, the vacuum pump will continue to evacuate the expansion tank, so that the vacuum in the tank can continue to rise to −0.098 MPa, which generally takes 10 min. Figure 1 shows the puffing-drying system and the structure of the fruit- and vegetable-drying equipment that was actually applied by the company.



(**a**)



(**b**)

Figure 1. (**a**). Puffing-drying system entity diagram. (**b**). Process flow chart.

3. Construction of Theoretical Model of Technology on Heating Explosion Puffing at High Pressure

In this paper, a theoretical model of heat and mass transfer was established for the high-pressure heating puffing stage and the expansion puffing stage in the heating explosion puffing using a high-pressure process.

3.1. Theoretical Model of Heating and Pressure-Drying Stage

While being heated and dried under high pressure, the temperature and pressure in the tank are maintained at the rated process parameters. During operation, the heat transfer from the heat source to the air in the tank through the pipe rack and jacket wall is equal to that of the transfer from the inner air to the dried fruit, which is equal to the heat required by the rise in the temperature of the dried fruit itself and the water precipitation. The heat balance equation is as follows:

$$\int_0^{\tau_h} Q_h d\tau = \int_0^{\tau_a} Q_a d\tau = \int_{t_{p0}}^{t_{p1}} c_p m dT + \int_0^{\tau_a} M_w A_f \gamma d\tau \quad (1)$$

3.1.1. Heat Transfer Model from Heat Source to Air in Tank

The heat transfer from the source to the air in the tank includes three processes: condensation and heat release of saturated steam in the expansion tank jacket and heating pipe rack, heat conduction of the pipe wall, and natural convection heat transfer between the pipe wall (or tank wall) and the air in the tank. The calculation method of heat transfer power is as follows:

$$Q_h = \left(k_{hj}A_{hj} + k_{hg}A_{hg}\right)\left(t_h - t_a\right) \tag{2}$$

$$\frac{1}{k_{hi}} = \frac{1}{h_{hi}} + \frac{\delta_{hi}}{\lambda_{hi}} + \frac{1}{h_{ai}} \tag{3}$$

The heat transfer coefficient of steam condensation in the expansion tank jacket is as follows [17]:

$$h_{hj} = 0.729\left[\frac{rg\lambda_\iota^3\rho_\iota^2}{\eta_\iota d\left(t_h - t_{hj}\right)}\right]^{\frac{1}{4}} \tag{4}$$

The heat transfer coefficient of steam condensation in the heating pipe is as follows [18]:

$$h_{hg} = 0.555\left[\frac{\lambda_\iota^3\left(\rho_\iota - \rho_g\right)gr}{\mu_\iota D\left(t_h - t_{hg}\right)}\right]^{0.25} \tag{5}$$

The heat transfer coefficient of natural convection with a large space in the tank is as follows [19,20]:

$$Nu_m = 0.48(GrPr)^{0.25} \tag{6}$$

$$h_{aj} = h_{ag} = Nu_m\lambda_a/\iota_g \tag{7}$$

3.1.2. Model of Heat Transfer from Air to Dried in Pot

The heat transfer from the air in the tank to the dried fruit adopts the large space natural convection heat transfer equation, in which the natural convection heat transfer equations of the horizontal cold surface downward and the cold surface upward are used to determine the heat transfer coefficient on the lower and upper surfaces of the dried fruit, respectively.

$$Q_1 = \left(h_{fu} + h_{fd}\right)A_f\left(t_a - t_f\right) \tag{8}$$

$$h_{fu} = h_{fd} = Nu_m\lambda_f/\iota_f \tag{9}$$

The natural convection heat transfer in a large space on the upper surface of dried fruit (cold surface upward) Nu is as follows [19,20]:

$$Nu = 0.27(Gr{\cdot}Pr)^{1/4}, 10^5 \le Gr{\cdot}Pr \le 10^{10} \tag{10}$$

The large space natural convection heat transfer model of the lower surface of dried fruit (cold surface downward) is as follows [21]:

$$Nu = 0.54(Gr{\cdot}Pr)^{1/4}, 10^4 \le Gr{\cdot}Pr \le 10^7 \tag{11}$$

$$Nu = 0.15(Gr{\cdot}Pr)^{1/4}, 10^7 \le Gr{\cdot}Pr \le 10^{11} \tag{12}$$

3.1.3. Dried Fruit Temperature

The surface temperature of dried fruit is used in the heat transfer model. Its value needs to be assumed first; after this, the heat and mass transfer and energy conservation equations are used for heat calculation and heat balance checks. If the heat is unbalanced, the temperature of dried fruit will be assumed until Formula (1) is met.

3.1.4. Mass Transfer Model of Dried Fruit Drying

The mass transfer process of dried fruit drying in the heating stage under high pressure is a one-way diffusion process in which the water in dried fruit is precipitated and vaporized under constant pressure and temperature; in that way, a one-way mass diffusion model is selected. The dried fruit needs to absorb enough heat for heating and water precipitation and vaporization, all of which comes from the heat transfer from the air in tank to the dried fruit.

The mass diffusion rate equation of the dried fruit water is as follows [22]:

$$\frac{dp_a}{p_a} = \frac{R_w T}{D p_0} M_w dx \tag{13}$$

$$m_{w0} = \int_0^{\tau_0} M_{w0} A_f d\tau \tag{14}$$

$$\omega = \frac{m_{w0}}{m_{fo}} \cdot 100\% \tag{15}$$

3.2. Theoretical Model of Expansion Stage

Expansion uses the principle of phase change and the hot-pressing effect of gas to rapidly vaporize and expand the liquid within the processed material, as well as to drive the structural denaturation of high-molecular substances in the components by relying on the expansion force of gas, to make it a finalized porous substance with the characteristics of a network structure.

3.2.1. Instantaneous Expansion Drying Model

The instantaneous expansion process is an adiabatic process. After expansion, the moisture in dried fruit is emitted into the air in the expansion tank as steam. The energy and mass conservation equation of the instantaneous expansion process is as follows:

$$m_{f1} c_p (t_1 - t_2) + m_{fw1} h'_{fw1} = m_{aw2} h''_{aw2} + \left(m_{fw1} - m_{fw2}\right) h'_{fw2} \tag{16}$$

The conservation of mass is as follows:

$$m_{f1} = m_{f2} + \Delta m_{fw} \tag{17}$$

After instant expansion, the temperature of dried fruit is 70 °C. The reason for this is that the pressure in the tank suddenly drops to −0.07 MPa during instant expansion, and the original temperature of dried fruit is about 77 °C, which is higher than the corresponding surface saturation temperature of 70 °C. Under this pressure, the temperature of the dried fruit will decrease.

3.2.2. Model of Puffing Drying

Since the air was pumped outward during evacuation and expansion, the evacuation process of the expansion tank is the adiabatic process of the opening system. According to the energy conservation, the difference in the thermodynamic energy of the substances (air and dried fruit) in the tank before and after the 10 min evacuation is equal to the enthalpy of the extracted gas.

$$U_3 - U_2 = H \tag{18}$$

$$U_3 = m_{a3} U_{a3} + m_{aw3} U_{aw3} + m_{g3} U_{g3} + m_{fw3} U_{fw3} \tag{19}$$

$$U_2 = m_{a2} U_{a2} + m_{aw2} U_{aw2} + m_{g2} U_{g2} + m_{fw2} U_{fw2} \tag{20}$$

$$H = (m_{a1} - m_{a2}) C p_a \left(\frac{T_3 + T_2}{2}\right) + (m_{aw3} - m_{aw2}) C p_w \left(\frac{T_3 + T_2}{2}\right) + \left(m_{fw3} - m_{fw2}\right) C p_f \left(\frac{T_3 + T_2}{2}\right) \tag{21}$$

3.3. Mass Transfer Equation

The air in the tank is constantly evacuated, so that there are always differences in the pressure concentration between the dried fruit and the environment. Therefore, in this tank, the reason that dried fruit is always overheated is that it is affected by the total dynamic difference and pressure difference in the gas, rather than the differential pressure difference in the water vapor in the gas. Therefore:

$$\Delta m = m_{fw3} - m_{fw2} = N_w A_f \tau \rho_w = \frac{D(c_3 - c_2)}{\Delta x} A_f \rho_w \quad (22)$$

4. Analysis of Heat and Mass Transfer Performance

In this paper, the theoretical model and calculation program were established using MATLAB. We analyzed the characteristics of the changes in the process parameters (such as temperature, pressure and operation time in tank) and the high-pressure heating stage and the process parameters (such as vacuum degree and evacuation time) during expansion that influence the heat and mass transfer rate, heat transfer, water content and moisture content of the fruit-drying process. Table 1 shows the influencing factors of the two processes, as well as the reference and analysis values of the process parameters.

Table 1. Change value of process parameters at each stage.

	Influential factor	Reference value of process parameters	Change value of process parameters
High- pressure heating phase	Temperature in tank, °C	100	90, 95, 100, 105, 110
	Pressure in tank, MPa	0.4	0.35, 0.375, 0.4, 0.425, 0.45
	Running time, min	10	9, 9.5, 10, 10.5, 11
Expansion stage	Instantaneous expansion pressure, Mpa	−0.078	/
	Evacuation and expansion pressure, Mpa	−0.098	/

4.1. Analysis of Heat and Mass Transfer Performance at High-Pressure Heating Stage

4.1.1. Effect of Temperature in Tank on Heat and Mass Transfer Performance

It was ensured that the pressure and operation time in the tank were taken as the benchmark process parameters. The temperature in the tank was increased from 90 °C to 110 °C. Based on the above, this paper analyzed the characteristics of heat and mass transfer rate, heating time, heat transfer, precipitation water and moisture content of dried fruit with the temperature in the tank during the drying process, as shown in Figure 2.

Figure 2a shows that when the heat source temperature remains unchanged, the temperature of dried fruit tends to increase with the temperature in the tank but its temperature increase is less than that in the tank, which means that when the temperature in the tank rises from 90 °C to 110 °C, the dried fruit temperature rises from 71.8 °C to 82.8 °C, with an increase of 11 °C. Figure 1b shows that, as the temperature in the tank increases, the heat transfer power from the heat source to the air in the tank significantly decreases, while the heat transfer power from the air in the tank to the dried fruit significantly increases. The reason for this is that, when the temperature of the heat source remains unchanged, with the increase in the temperature in the tank, the heat transfer temperature difference between the heat source and the air in the tank decreases, reducing its heat transfer power. At the same time, with the rise in the temperature of the dried fruit, which is less than that of the air in the tank, the heat transfer temperature difference between the air in the tank and the dried fruit increases, which greatly increases the heat transfer power from the air in the tank to the dried fruit. With the increase in the temperature in the tank, the water analysis rate in the dried fruit, that is, the mass transfer rate of the dried fruit, increases. The reason for this is that the mass flux density increases with the increase in the temperature in the tank, so the mass transfer rate increases. It is clearly shown in Figure 2c that, during the 10 min operation, with the increase in the temperature in the tank, although the heat

transfer power from the heat source to the air in the tank decreases, the total heat transfer increases from 3051 kJ to 4096 kJ. About two-thirds of the heat comes from the expansion tank jacket, while the remaining heat comes from the heating pipe rack. This shows that, as the temperature in the tank increases, the heat source needs to transfer more heat to the tank. Figure 2e indicates that, with the increase in the temperature in the tank, the amount of water released from dried fruit significantly increases, as more than 85% of the water is stored in the air in the tank as steam, and a small amount of steam condenses into condensate at the bottom of the expansion tank cover. When the temperature in the tank rises by 20 °C, the amount of water released from dried fruit increases by 0.4 kg, including 0.38 kg of gaseous water, because the heat source provides more heat to the dried fruit. A small portion of this is used to heat the dried fruit, while most is used to provide the vaporization that this heat required for the analysis of the dried fruit water. Figure 2f implies that the moisture content of dried fruit decreases from 21.66% to 19.35% with the increase in the temperature in the tank, as the increase in the temperature in the tank will increase the water analysis rate of dried fruit. Under the same operation time, the yield of water from the dried fruit will increase, thus reducing the moisture content of dried fruit. When the temperature in the tank rises by 1 °C, water precipitates will increase by 0.02 kg. Figure 2d represents that, as the temperature in the tank rises, the working time of the heat source (steam inlet time) increases from 3 min to 7.3 min due to the increase in the temperature in the tank—the heat transfer from the heat source to the air in the tank increases but the heat transfer power tends to decrease, which prolongs the working time of the heat source, though not to less than the operation time of the process (10 min).

In summary, increasing the temperature in the tank can strengthen the heat transfer performance, develop the water evaporation rate of the air in the tank to the dried fruit and reduce the moisture content of the dried fruit. However, the heat transfer performance of the heat source to the air in the tank decreases and the heating time of the heat source increases.

4.1.2. Effect of Tank Pressure on Heat and Mass Transfer Performance

This paper ensures that the temperature and operation time in the tank are taken as the benchmark process parameters. The pressure in the tank was increased from 0.35 MPa to 0.45 MPa and the characteristics of the heat and mass transfer rate, heating time, heat transfer, precipitation water volume and moisture content of dried fruit were analyzed as a function of the pressure in the tank, as shown in Figure 3.

Figure 3a shows that when the heat source temperature remains unchanged, the dried fruit temperature increases with the increase in pressure in the tank. When the pressure in the tank rises from 0.35 MPa to 0.45 MPa, the dry fruit temperature increases from 74.8 °C to 79.7 °C, with a rise of 4.9 °C in Figure 3b. This vividly demonstrates that, as the pressure in the tank increases, the heat transfer rate from the heat source to the air in the tank significantly increases and the heat transfer power from the air in the tank to the dried fruit also increases to a certain extent. This is because, as the pressure in the tank increases, the air volume in the tank increases and the physical parameters of the gas clearly change, resulting in an increase in the convective heat transfer coefficient and heat transfer rate between the heat source and the gas in the tank. At the same time, the convection heat transfer coefficient between the air in the tank and the dried fruit also increases but the temperature difference between the air in the tank and the dried fruit decreases due to the increase in the causal dry temperature; the heat transfer rate under the combined effect slightly increased. In addition, when the pressure in the tank increases, the water analysis rate in the dried fruit, that is, the mass transfer rate of the dried fruit, slightly decreases because changing the pressure in the tank has little effect on the mass transfer parameters; thus, the change is not obvious. Figure 3c shows that the total heat transfer from the heat source to the air in the tank increases from 3606 kJ to 3663 kJ with the increase in the pressure in the tank during the 10 min operation time. This conveys the message that, with the increase in pressure in the tank, the heat that the heat source needs to provide to the dried fruit only slightly increases. From Figure 3e we can see that,

with the increase in the pressure in the tank, the amount of water released from dried fruit slightly decreases. That is to say, when the pressure in the tank increases by 0.1 MPa, the average amount of water released from dried fruit decreases by 0.035 kg, including 0.041 kg of gaseous water and 0.006 kg of condensate. What led to this phenomenon is that the pressure change in the tank has little effect on the mass transfer rate of dried fruit and the pressure rise is not conducive to the precipitation of dried fruit moisture. Figure 3f shows that the moisture content of dried fruit increases from 20.53% to 20.72% with the increase in pressure in the tank; this change is not obvious. Figure 3d shows that the working time of the heat source decreases with the increase in pressure in the tank, from 4.91 min to 4.33 min. This is because the temperature of dried fruit increases but the amount of water that is released slightly decreases, which slightly increases the heat transfer of the heat source. In addition, the heat transfer rate from the heat source to the air in the tank significantly increases, which reduces the working time of the heat source.

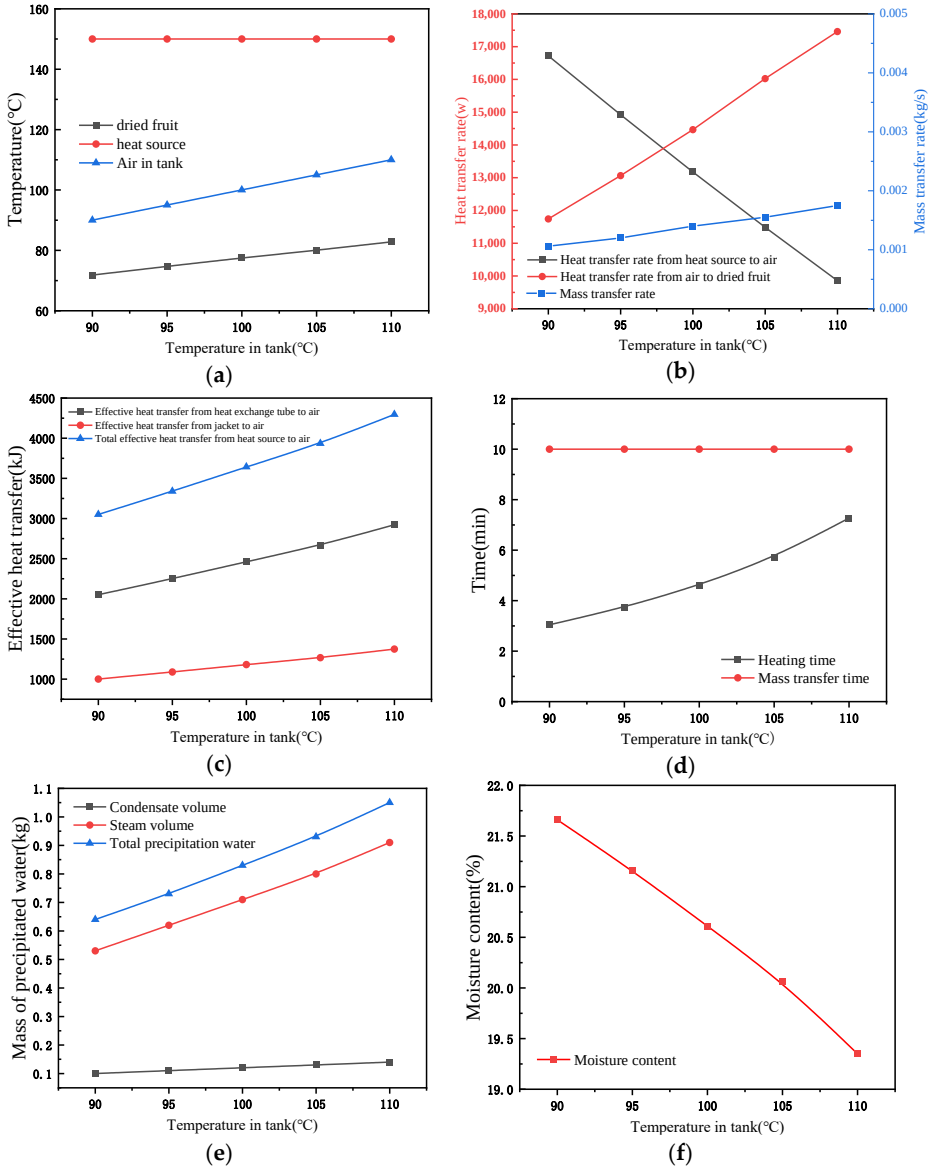


Figure 2. Effect of temperature in tank on heat and mass transfer performance. (**a**) Temperature changes in the tank; (**b**) Influence of temperature in tank on heat and mass transfer power; (**c**) Effect of temperature in tank on heat transfer; (**d**) Effect of tank temperature on heating time; (**e**) Influence of temperature in tank on precipitation and condensation water; (**f**) Effect of temperature in tank on moisture content of dried fruit.

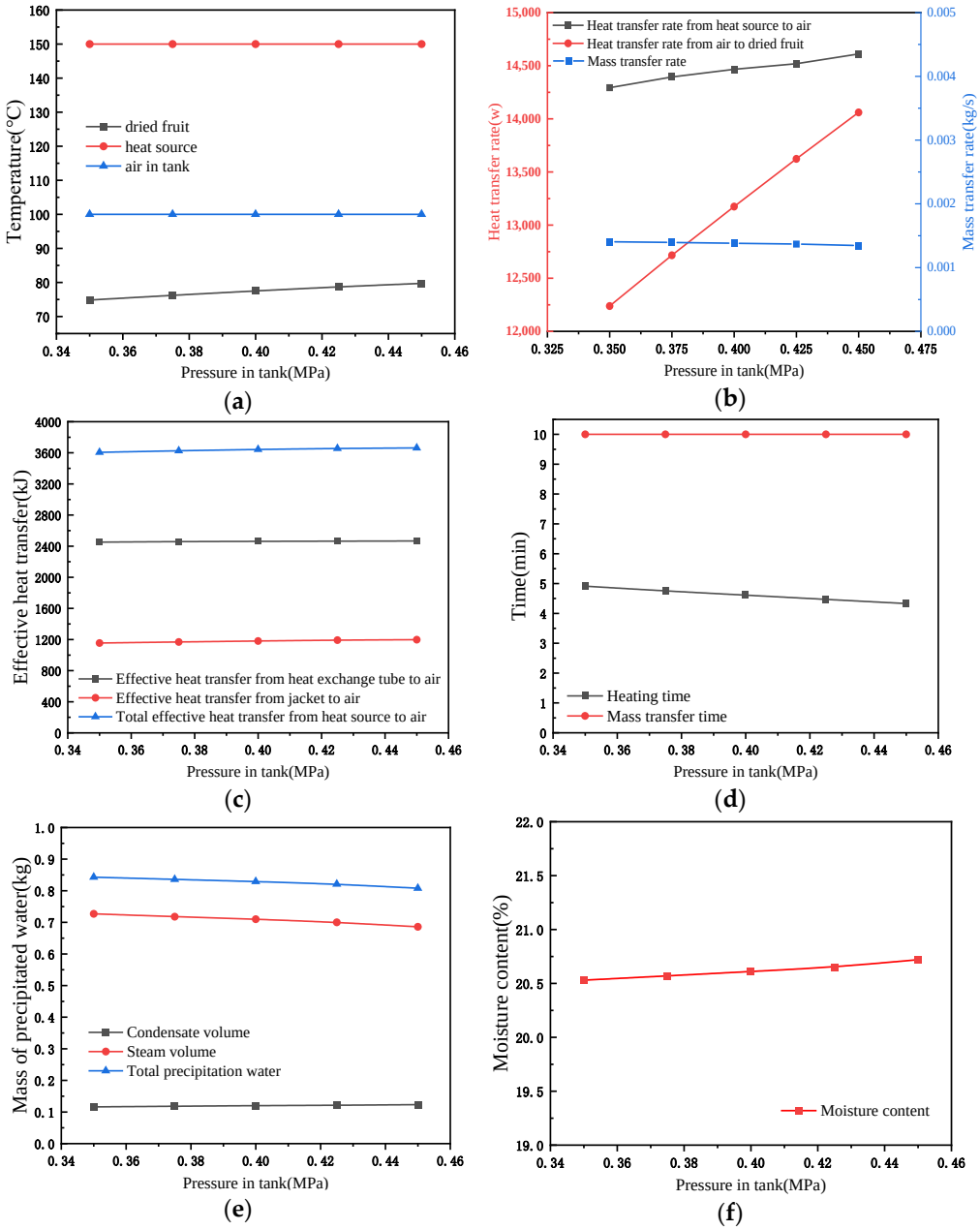


Figure 3. Effect of tank pressure on heat and mass transfer performance. (**a**) Effect of pressure in tank on temperature. (**b**) Influence of pressure in tank on heat and mass transfer power. (**c**) Effect of pressure in tank on heat transfer. (**d**) Effect of tank pressure on heating time. (**e**) Influence of pressure in tank on precipitation and condensation water. (**f**) Effect of pressure in tank on moisture content of dried fruit.

In a word, the pressure change in the tank has little effect on the mass transfer performance. When the pressure is reduced, the drying performance of the fruit will be slightly increased. When the pressure goes down by 0.04 MPa, the water content of dried fruit also decreases by 0.06% at the same time.

4.1.3. Effect of Running Time on Heat and Mass Transfer Performance

Ensuring that the pressure and temperature in the tank are taken as the benchmark process parameters, this paper changes the operation time from 9 min to 11 min and analyzes the characteristics of heat and mass transfer rate, heating time, heat transfer,

precipitation water volume and moisture content with the operation time; the result of which is shown in Figure 4.

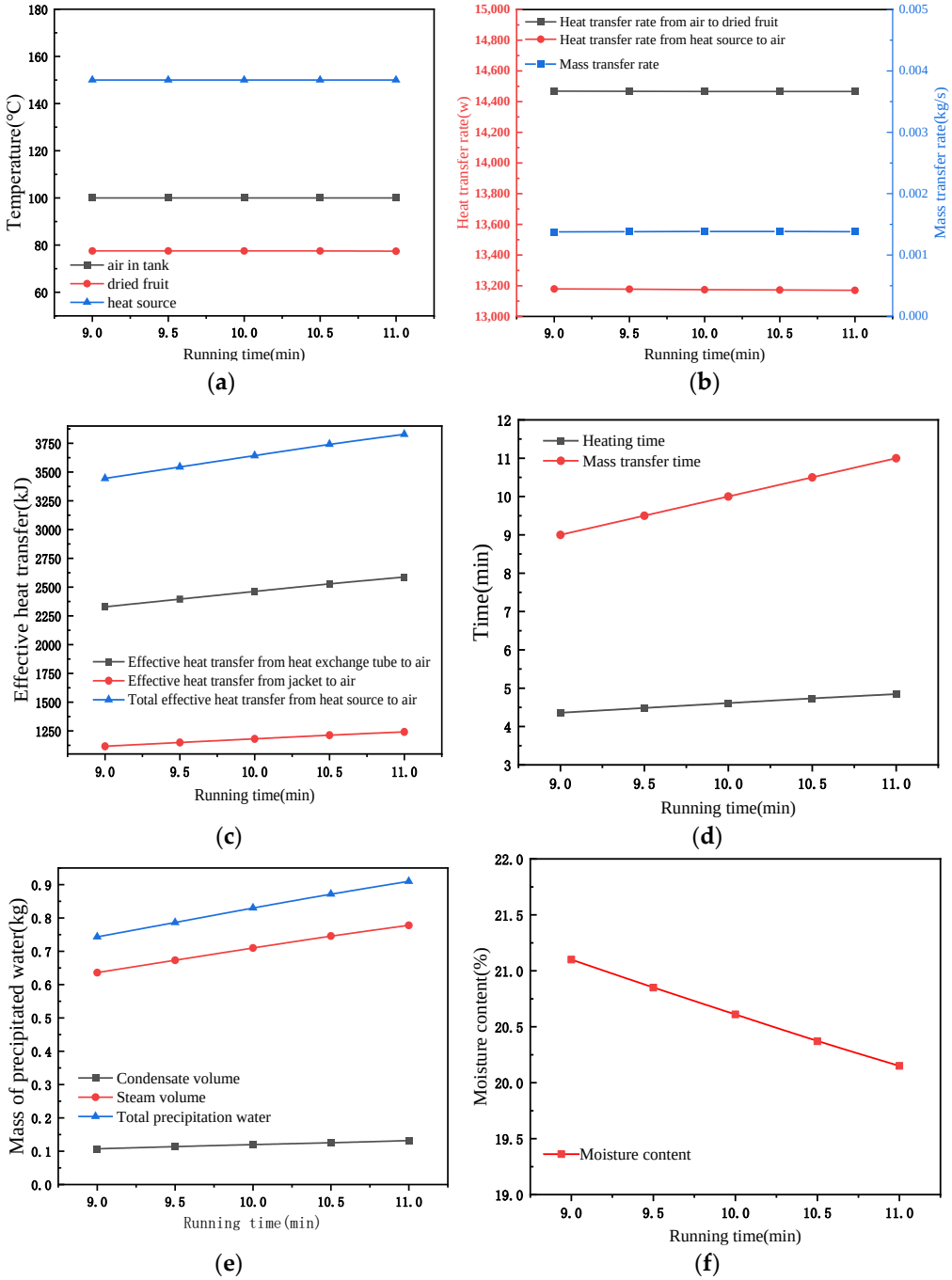


Figure 4. Effect of operation time on heat and mass transfer performance. (**a**) Effect of running time on temperature. (**b**) Effect of running time on heat and mass transfer power. (**c**) Effect of running time on heat transfer. (**d**) Effect of running time on heat transfer. (**e**) Effect of running time on precipitation and condensation water. (**f**) Effect of running time on dry fruit moisture content.

Figure 4a shows that, when the heat source temperature remains unchanged, the dried fruit temperature remains unchanged with the extension of operation time. Figure 4b shows that, as the temperature in the tank increases, the heat transfer rate from the heat source to the air in the tank and the heat transfer power and mass transfer rate from the air in the tank to the dried fruit do not change. The reason for this is that changing the

operation time has no effect on the heat and mass transfer rate per unit time. Figure 4c additionally demonstrates that, with the extension of operation time, the total heat transfer from the heat source to the air in the tank increases from 3444 kJ to 3888 kJ. This shows that the heat source needs to provide more heat to the dried fruit with the extension of operation time. At the same time, Figure 4e shows that, with the extension of operation time, the precipitation water of dried fruit significantly increases. When the running time was extended for two minutes, the water content of dried fruit increased by 0.166 kg, while that of gaseous water increased by 0.142 kg. This is because the mass transfer rate remains unchanged and the running time is prolonged, which increases the total precipitation water. Figure 4f indicates that the moisture content of dried fruit decreases from 21.1% to 20.5% with the extension of operation time, mainly because the water content of dried fruit increases with the extension of operation time, which reduces the moisture content of dried fruit. Finally, Figure 4d shows that the working time of the heat source increases from 4.35 min to 4.86 min with the running time. This is because the amount of water released from the dried fruit increases, the heat required by the dried fruit increases and the heat transferred from the heat source to the air in the tank increases, though the heat transfer rate remains unchanged. Therefore, the working time of the heat source increases.

In sum, prolonging the operation time will not speed up the heat transfer rate between the heat source and the dried fruit, as well as the evaporation rate of the moisture in the dried fruit, but the water precipitation of dried fruit will increase and the moisture content of the dried fruit will be reduced.

4.2. Analysis of Heat and Mass Transfer Performance in Expansion

The effects of temperature, pressure and running time in the pot on the heat and mass transfer performance of the dried fruit during heating at high pressure were analyzed. This mainly includes the fruit dry temperature, water content and moisture content after instant expansion and evacuation expansion.

The changes in temperature, pressure and operation time in the tank during heating and pressurization can also have a certain impact on the heat and mass transfer performance in the expansion stage, as shown in the figures below.

Figures 5a, 6a and 7a show that, after instant expansion and vacuum expansion, if the pressure remains unchanged the corresponding saturation temperature is 70.09 °C; the dried fruit temperature, after 10 min evacuation and expansion, is stable at 65 °C, which does not change with the difference in the three factors in the previous stage (high-pressure heating stage).

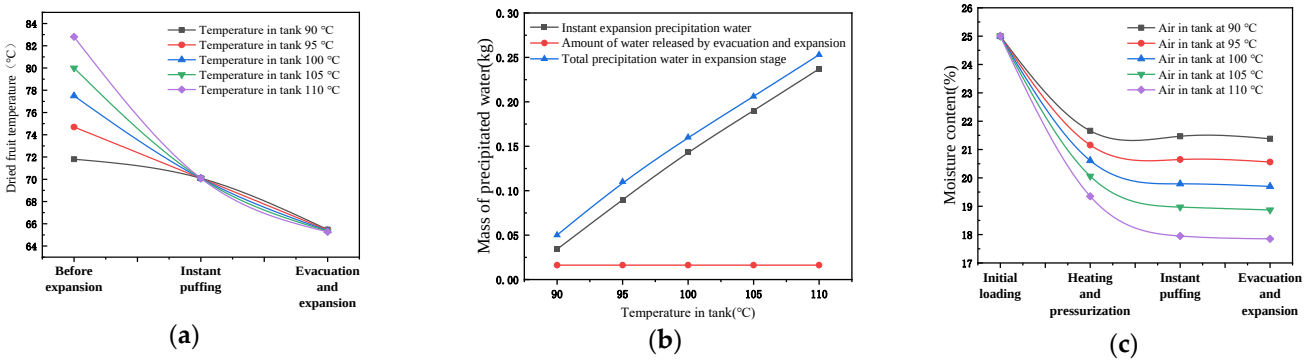


Figure 5. Effect of temperature in tank on mass transfer in expansion stage. (**a**) Effect of the temperature in the pressure section on the drying temperature of expanded fruit. (**b**) Influence of temperature in pressurized section on water precipitation in expanded section. (**c**) Effect of temperature in pressurized tank on moisture content of dried fruit.

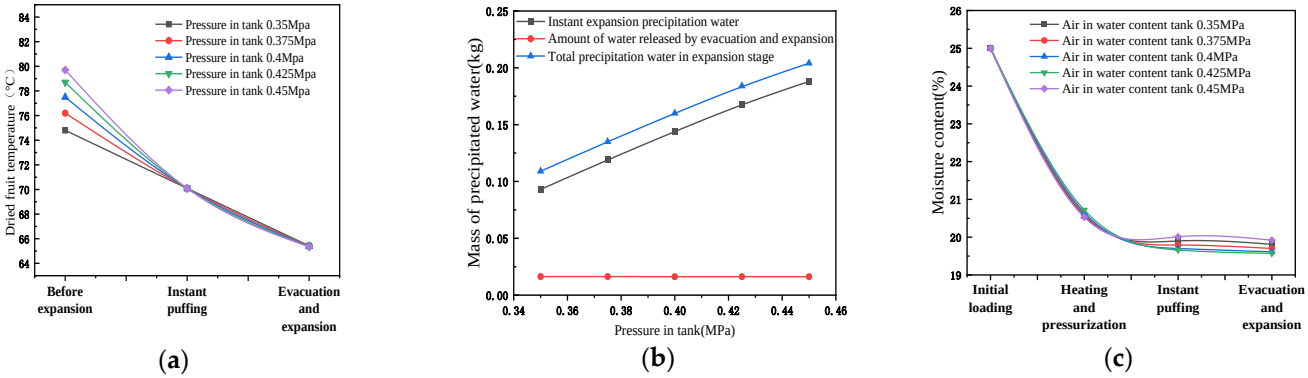


Figure 6. Effect of tank pressure on mass transfer in expansion stage. (**a**) Effect of pressure in the pressure section on drying temperature of expanded fruit. (**b**) Influence of the pressure in the pressure section on the water release in the expansion section. (**c**) Effect of pressure in the pressure section on dry fruit moisture content.

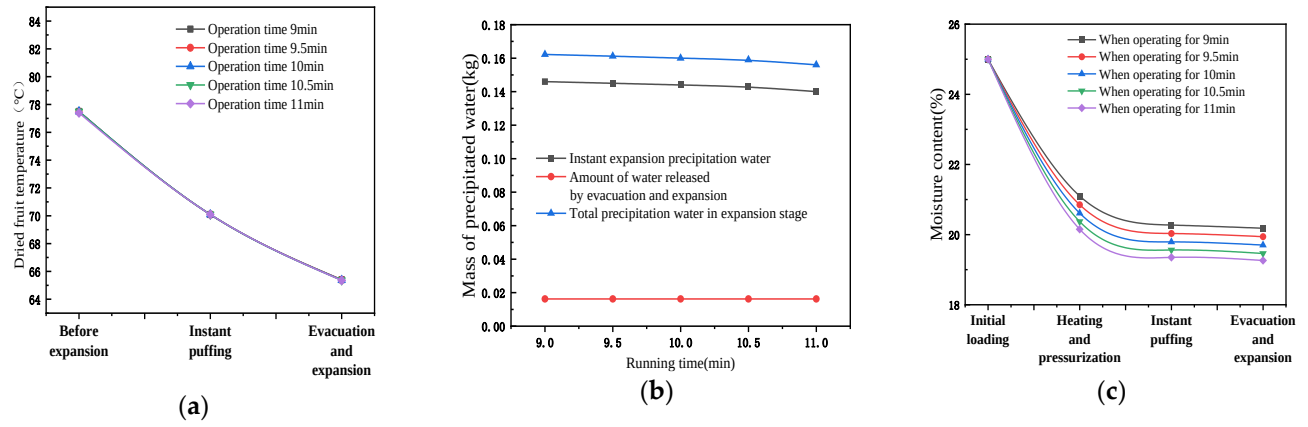


Figure 7. Effect of operation time on mass transfer in expansion stage. (**a**) Effect of operation time in pressurized section on dried fruit temperature in expanded section. (**b**) Effect of operation time in pressurized section on water precipitation in expanded section. (**c**) Effect of operation time in pressurized section on moisture content of dried fruit.

Besides what is discussed above, Figures 5b, 6b and 7b demonstrate that the temperature and pressure in the high-pressure heating section mainly change the temperature and pressure of the dried fruit before expansion, thus forming different instantaneous expansion temperature differences and pressure differences. The larger the temperature difference and pressure difference, the greater the amount of water released by the instantaneous expansion and the lower the moisture content of the dried fruit. This is because the increase in the pressure difference will also lead to an increase in the temperature difference of the dried fruit and the increase in the temperature difference of the dried fruit will lead to more energy being contained in the dried fruit itself during the cooling process. This energy will be released into the air in the form of water while increasing the water precipitation from the dried fruit. Due to the fixed difference in temperature pressure before and after evacuation and expansion, the volume of precipitated water is not affected by the changes in the three process parameters in the previous stage—all the water volumes within a 10 min evacuation and expansion were 0.01623 kg. The change in operation time in the high-pressure heating stage will not change the temperature of the dried fruit before the instant expansion, so the temperature difference in the expansion of the dried fruit is the same but the quality of the dried fruit itself decreases with the increase in time due to evaporation. Therefore, the precipitation water in the instant and evacuation expansion will decrease along with the time added during the high-pressure heating process, while

the increase in temperature in the tank has the greatest impact on the precipitation water in the expansion stage (the precipitation water increases from 0.05 kg to 0.253 kg); this is followed by the increase in pressure in the tank (the precipitation water increases from 0.109 kg to 0.204 kg), which has the least impact on the operation time of the previous stage. With the extension of time, the precipitation water in the expansion stage slightly decreases (from 0.1622 kg to 0.156 kg).

It can be seen from Figures 5c, 6c and 7c that, as the pressure in the tank at the high-pressure heating section increases, the moisture content of dried fruit will be maintained at about 19.7%, which is caused by the increase in total precipitation water during expansion. The moisture content of dried fruit at high-pressure heating increases with the pressure in the tank, so the moisture content after expansion will be maintained at about 19.7%; however, with the extension of the operation time of the high-pressure heating section, the dry moisture content of the expanded fruit decreased from 20.18% to 19.26% and the water content of the dried fruit during the expansion stage decreased with the extension of time. However, the moisture content of the dried fruit before expansion decreased with the extension of the operation time, so the moisture content after expansion will slightly decrease. The most influential factor is the temperature in the high-pressure heating section. As a result of expansion, the moisture content of the dried fruit decreases from 21.36% to 17.85%, as, with the increase in temperature in the high-pressure heating section, the precipitation water in the expansion stage increases and the moisture content of the dried fruit decreases before expansion. Therefore, the moisture content of the dried fruit decreases after expansion.

5. Conclusions

In this paper, the theory of heat and mass transfer and the related laws of thermodynamics were used to establish the theoretical model of the two stages of heating at high-pressure and expansion puffing during a low-temperature and high-pressure process. The laws of mass conservation and energy conservation were used to couple the heat and mass transfer process and analyze the influencing factors. The effects of process operation temperature, pressure and time on the drying performance of dried fruits were studied. The following conclusions were obtained:

1. Increasing the temperature in the tank can develop the heat transfer performance and water evaporation rate of dried fruit and reduce the water content of dried fruit; however, the heat transfer performance of the heat source decreases and the heating time of the heat source increases.
2. The pressure change in the tank has little effect on the mass transfer performance. When the pressure is reduced, the drying performance of dried fruit will be slightly increased. When the pressure decreases by 0.04 MPa, the water content of dried fruit decreases by only 0.06%.
3. The moisture content of dried fruit decreases by 0.475% when the operation time is prolonged for 1 min.
4. The precipitation water in expansion mainly comes from the instant expansion stage; the increase in temperature in the tank during the heating and pressurization stage has the greatest impact on the moisture content of the expanded dried fruit, followed by the operation time. The change in pressure in the tank has little impact on the moisture content of the expanded dried fruit.

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Nomenclature

Symbol Table

Symbol	Significance	Company	Symbol	Significance	Company
	Subscript		h''	Saturated steam enthalpy	kJ/kg
0	Before heating and pressurization		k	Heat transfer coefficient of expansion tank jacket	W/(m^2·K)
1	After heating and pressurization/before instant expansion		l	Characteristic length	m
2	After instant expansion/before evacuation expansion		m	Mass	kg
3	After evacuation and expansion		M_w	Mass flux density	kg/(m^2·s)
a	Air in tank		p	Pressure	MPa
aw	Air moisture in tank		Q	Heat transfer efficiency	W
f	Dried fruit		r	Latent heat of steam condensation	kJ/kg
fd	Lower surface of dried fruit		t	Temperature	°C
fu	Upper surface of dried fruit		T	System temperature	K
fw	Dried fruit moisture		U	System thermodynamic energy	kJ
g	Dried fruit solid		τ	Time	s
h	Heat source		λ	Thermal conductivity	W/(m·K)
i	Expansion tank and jacket		δ	Thickness	m
j	Expansion tank jacket		ρ	Density	kg/m^3
ι	Condensate		η	Dynamic viscosity	Pa·s
w	Water content		ν	Kinematic viscosity of air	m^2/s
	Text symbols		Nu_m	Nusselt number	
ω	Moisture content	%	Pr	Prandtl number	
Δx	Mass transfer distance	m	Gr	Grashof number	
A	Heat transfer area	m^2			
c_p	Specific heat capacity	J/(kg·K)			
c	concentration	mol/m^3			
d	Jacket diameter	m			
D	Mass diffusion concentration	m^2/s			
h	Convective heat transfer coefficient	W/(m^2·K)			
h'	Saturated water enthalpy	kJ/kg			

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