TRANSACTIONS OF THE CHINESE SOCIETY FOR AGRICULTURAL MACHINERY
Vol. 47, No. 8, 2016

doi:10.6041/j. issn. 1000-1298. 2016. 08. 029

Dynamic Study on Instant Pressure Drop Puffing of Granny Smith Apple Slices Using Superheated Vapor

An Fengping Guo Rui Song Hongbo Huang Qun Teng Hui Li Tao
(*College of Food Science, Fujian Agriculture and Forestry University, Fuzhou* 350002, *China*)

Abstract: Unclear puffing power has always been an important problem for instant pressure drop puffing process using superheated vapor. And the condensation water produced by superheated vapor is absorbed by the food material before puffing, which possibly makes bad effect on puffing ratio. A general mathematical model of puffing power was established. Results indicated that puffing energy was produced by flash evaporation of superheated water from internal material and instant release of superheated vapor. Besides, porosity of sample varied with different sample moisture contents and condensation water generated in thermal transfer process before puffing. Thus, puffing ratio was related to the sample moisture content, porosity and status of superheated vapor. Using Granny Smith apple slice as experimental objects, results suggested that porosity of sample was significantly decreased with the increase of sample moisture content. At temperature of 430 ~ 470 K, pressure of 0.1 ~ 0.5 MPa and apple moisture content of 15% ~ 35%, the established puffing power model could effectively predict and evaluate the relationship between puffing condition and puffing ratio ($R^2 > 0.89$). High vapor pressure had insignificant influence on condensation water, and distinctively elevated the energy of superheated water and superheated vapor, which resulted in the biggest puffing ratio. High temperature of superheated vapor can only strengthen superheated water energy, but significant increase of condensation water mass led to superheated vapor energy reduction, and it had slight effects on puffing energy improvement and puffing effect. Moreover, high moisture content of sample significantly increased superheated water energy, but condensation water reduced superheated vapor energy, which generally showed great effects on improvement of puffing power and puffing ratio. The research results illustrated the power mechanism of instant pressure drop puffing process using superheated vapor, which would be helpful to further study on the control of puffing ratio.

Key words: Granny Smith apple slices; superheated vapor; instant pressure drop; puffing; model

0 Introduction

Superheated steam puffing is a technology that places fruits, vegetables, or other materials that have been dehydrated to a specific moisture content into a high-pressure vessel. The vessel is filled with steam and maintained for a certain time, after which the materials are puffed by instant release of pressure to form a porous structure[1-4]. Compared with conventional puffing, superheated steam has the advantages of energy savings, freedom from pollution, and high nutrient preservation[3-6]. It has a wide range of applications in processing food and vegetable chips and in modification of dehydrated agricultural products. Previous studies focused on the optimization of process parameters such as raw material moisture content, steam temperature, pressure, and residence time. However, the dynamic mechanism that produces puffing is still unclear, resulting in uncertainty about how to control it. In particular, large parameter variations between experimental research and industrial applications are the main reason for difficulties in practical application of this process.

Before puffing, the superheated steam heats the material, and hence the moisture inner material is at high temperature and pressure. At the instant pressure drop, flash evaporation of superheated water takes place[7], often accompanied by instant energy release. ABBASI et al.[8] studied the explosion mechanism of boiling liquid expanding to vapor and indicated that

Received date: 2016-01-20 Revised date: 2016-04-06
Supported by Natural Science Foundation of China (Grant No. 31271913)
Correspondence author: Song Hongbo, Professor. E-mail: sghgbode@163.com. Tel: +86-0591-83789294.

when superheated liquid in a container instantly drops in pressure, rapid expansion of the boiling liquid to vapor led to an explosion. The material moisture content has a strong influence on water flash evaporation[9], which is important in promoting puffing[10]. SUI et al.[11] performed an energy analysis of a multi-stage steam explosion process, dividing it into three stages: pressurizing, pressure-holding, and decompression. The instant release of superheated steam generated enormous energy. The pressure difference in puffing has a significant impact on the volume of material generated[12-14]. At this time, no research into the puffing dynamics of the superheated-steam instant pressure drop has been reported.

This study takes sheet material as research objects, with Granny Smith apples as experimental materials, to study the power mechanism of the instant pressure drop puffing process using superheated steam and to provide a theoretical basis and practical guidance for controlling the puffing ratio using the dynamics of the puffing mechanism.

1 Materials and methods

1.1 Sample preparation

Fresh Granny Smith apples without physical damage from a local supermarket were stored in a cold storage room at (4 ± 1)℃ and 90% ~95% relative humidity. The average moisture content of Granny Smith apples was 86.3% (wet base), and their sugar content was 10.6 ~ 11.8° Brix. The apples were washed, peeled, and cut into slices with specifications of 35 mm × 35 mm × 10 mm and immersed in a 0.02% (mass fraction) sodium sulfite solution for 20 min, after which the surface liquid was drained off[15]. The color-protected Granny Smith apple slices were put in the oven at (70 ± 1)℃ to dehydrate to a certain moisture content, then immediately trimmed into 20 mm × 20 mm × 5 mm slices. The slices were packed in aluminum foil bags and cooled down to room temperature (20℃) over 2 h[16].

1.2 Sample heating and puffing

Fifteen dewatered Granny Smith apple slices were placed into the puffing chamber, and a TT - K - 30 - SLE - 1000 thermocouple was inserted into the middle of a Granny Smith apple slice. When the puffing chamber was closed, the vacuum pump was turned on until the puffing chamber was evacuated to 100 Pa. Superheated steam at a certain temperature and pressure was piped into the puffing chamber; after heating for a certain period of time, the relief valve was immediately opened to puff the sample. The central temperature of the sample was displayed by a digital thermometer; pressure was detected by a pressure sensor[17].

1.3 Instruments and equipment

DHG - 9003A hot air oven, Jing Hong Experimental Equipment Co., Shanghai; DZF6050 vacuum oven, Jing Hong Experimental Equipment Co., Shanghai; BSA124S analytical balance, Beijing Sartorius Instrument Systems, Inc.; VP - 100 superheated steam extruder, self-made.

1.4 Indicators and measurements

1.4.1 Moisture content

Sample moisture content was determined by thevacuum oven method. The samples were dried to constant weight in a vacuum oven at 70℃, 133 Pa. Moisture content was calculated from the difference in weight before and after vacuum drying and expressed as a mass percentage of the dried sample[18].

1.4.2 Puffing ratio

Puffing ratio is the relative change in sample volume, specifically the ratio of the sample apparent volume after and before puffing. The apparent volume of the sample was determined by the liquid displacement method[19-20].

1.4.3 Mass of condensation water

The masses of the 15 samples were determined by an analytical balance, after which the samples were heated in the puffing chamber until their core temperature reached superheated steam temperature; then they were taken for weighing. The difference between the mass before and after sample heating was the mass of condensation water.

1.4.4 Water mass of flash evaporation

Fifteen samples dehydrated to a specific moisture content were heated in the puffing chamber until their core temperature reached superheated-steam temperature and pressure; then they were taken out and weighed on an analytical balance to obtain the material mass before puffing. Fifteen dehydrated samples with the same moisture content were heated in the puffing chamber until their core temperature reached superheated-steam temperature and were puffed; then they were taken out and weighed to obtain the material mass after puffing. The mass of flash evaporation water was the mass difference before and after puffing.

1.4.5 Pore volume

Pore volume is the difference between the apparent volume and the solid volume of a sample. The apparent volume was measured by the liquid displacement method; the solid volume was determined by the gas conversion method[21].

1.5 Data processing

DPS 7.5 was used to analyze the significance of between-group differences in condensation water mass and puffing ratio. The degree of congruence between predicted and measured values was represented by the coefficient of determination R^2, which was obtained using Microsoft Excel 2003.

2 Establishment of puffing power general model

Materials formed a porous structure after dehydration. When the sample was placed in a puffing chamber and subjected to vacuum, the air was drawn from the sample. During the process of sample heating by superheated steam, a small amount of condensation water was produced and absorbed by the material, occupying a small amount of pore space, and other pores were filled with superheated steam. When the pressure relief valve was instantly opened, part of the superheated water inside the sample was immediately vaporized, and the superheated steam inside the pores was released instantaneously, puffing up the sample. Therefore, the total energy of material puffing includes the work of flash evaporation of superheated water and the work of instant release of superheated steam.

2.1 Puffing work

The moisture inside the material before puffing included the water initially contained and the condensation water generated during superheated steam heating, so that the water mass in the material before puffing is:

$$m_l = m\omega + M \tag{1}$$

where m_l is the water mass of 1 kg sample before puffing, kg; m is the sample mass before puffing, fixed at 1 kg; ω is the moisture content of the sample before puffing, %; M is the mass of condensation water generated by heating 1 kg sample before puffing, kg.

In the puffing process, the pressure inside the material is instantly reduced to 1 atm, and part of the superheated water inside the material undergoes flash evaporation, releasing energy. The work of superheated water can be expressed as[22]:

$$W_l = [h_1 - h_2 - (s_1 - s_2)T_2]m_1 \tag{2}$$

where W_l is the work of superheated water in puffing 1 kg material, J; h_1 is the enthalpy of water at pressure condition before puffing, J/kg; h_2 is the enthalpy of water at pressure condition after puffing, J/kg; s_1 is the entropy of water at pressure condition before puffing, J/(kg·K); s_2 is the entropy of water at pressure condition after puffing, J/(kg·K); T_2 is the boiling point of water at pressure condition after puffing, K; m_1 is the mass water flash-evaporated by puffing 1 kg material, kg.

According to previous tests, only a little water in the material underwent flash evaporation. The flash rate λ indicates how much water is evaporated:

$$\lambda = \frac{m_1}{m_l} \tag{3}$$

The work formula for flash evaporation of superheated water can be obtained by combining Eqs. (1) ~ (3):

$$W_l = [h_1 - h_2 - (s_1 - s_2)T_2](m\omega + M)\lambda \tag{4}$$

There was an enthalpy difference in water before and after puffing, which provided energy for flash evaporation of superheated water. According to the energy conservation law[23]:

$$h_1 - h_2 = \lambda r \tag{5}$$

where r is the latent heat of vaporization of water at pressure condition after puffing, J/kg.

A simplified formula for the work done by superheated water can be obtained by combining Eqs. (4) and (5):

$$W_l = [h_1 - h_2 - (s_1 - s_2)T_2](m\omega + M)\frac{h_1 - h_2}{r} \tag{6}$$

Puffing was accomplished instantly, and because the process is extremely short, the work done by instant release of superheated steam inside the material can be considered as the work of an ideal gas adiabatic process[24], namely,

$$W_g = \frac{p_1 V_g}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right] \tag{7}$$

where W_g is the work done by superheated steam in puffing 1 kg sample, J; p_1 is the absolute pressure inside the sample before puffing, MPa; V_g is the overheated water volume inside 1 kg of sample before puffing, m^3; p_2 is the absolute pressure inside the sample after puffing, MPa; k is the adiabatic index of superheated steam.

Because the sample pores were filled with condensation water and superheated steam before puffing, it follows that:

$$V_h = M\rho_l^{-1} + V_g \tag{8}$$

where V_h is the pore volume of 1 kg sample before puffing, m^3, ρ_l is the density of saturated water, kg/m^3.

The expression for the work done by superheated steam in puffing can be obtained by combining Eqs. (7) and (8):

$$W_g = \frac{p_1 (V_h - M\rho_l^{-1})}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right] \tag{9}$$

The total energy to puff 1 kg material is the sum of the work of superheated water and superheated steam inside the material:

$$W = W_l + W_g = [h_1 - h_2 - (s_1 - s_2) T_2](m\omega + M) \cdot \frac{h_1 - h_2}{r} + \frac{p_1 (V_h - M\rho_l^{-1})}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right] \tag{10}$$

where W is the work required to puff 1 kg sample, J.

2.2 Model of puffing ratio

According to previous tests, for sheet material, the thickness increased greatly after puffing, where as the length and width changed very little. This was because the length and width of the sample were much larger than the thickness; puffing resistance in the length and width directions was much higher than puffing resistance in the thickness direction, so that deformation was mainly in the thickness direction.

Pre-dehydrated sheet materials can be viewed as composed of numerous planes. By expressing the infinitesimal of thickness as dy and the infinitesimal of work as dW_s, the expression for the infinitesimal of work can be written as[25]:

$$dW_s = \frac{p_1 + p_2}{2} a^2 dy \tag{11}$$

where a is the length of one side of the sample before puffing, m.

The expression for the work needed to puff sheet material under different internal and external pressures can be obtained by integrating Eq. (11):

$$W_s = 2\int_{\delta}^{\delta'} \frac{p_1 + p_2}{2} a^2 dy \tag{12}$$

where δ is the thickness of the sample before puffing, m; δ' is the thickness of the puffed sample, m.

Eq. (12) can be simplified to:

$$W_s = a^2 (\delta' - \delta)(p_1 + p_2) \tag{13}$$

The puffing ratio expression is then:

$$S = \frac{V}{V_0} = \frac{2\delta' a^2}{2\delta a^2} = \frac{\delta'}{\delta} \tag{14}$$

where S is the puffing ratio; V is the apparent volume of the puffed sample, m^3; V_0 is the apparent volume of the sample before puffing, m^3.

Combining Eqs. (13) and (14) yields:

$$S = 1 + \frac{W_s}{\delta a^2 (p_1 + p_2)} \tag{15}$$

Given 1 kg pre-dehydrated material containing N samples, the total energy to puff 1 kg material can be expressed as:

$$W = W_l + W_g = N W_s \tag{16}$$

Combining Eqs. (15) and (16), the puffing ratio expression for the sample becomes:

$$S = 1 + \frac{W_l + W_g}{N\delta a^2 (p_1 + p_2)} \tag{17}$$

3 Results and analysis

This study took Granny Smith apple slices as the test material, using a general mathematical model of puffing power to determine the influence of superheated steam temperature, pressure, and sample moisture content on puffing power and puffing ratio.

Because of variations in the moisture content of pre-dehydrated Granny Smith apple slices, the number of samples N in 1 kg material varies (Tab. 1).

Tab. 1 Single weight and number of samples for 1 kg pre-dehydrated sample with different moisture contents

ω/%	m/kg	N
15	8.741×10^{-4}	1144
20	9.359×10^{-4}	1069
25	1.022×10^{-3}	979
30	1.116×10^{-3}	896
35	1.192×10^{-3}	839

From Tab. 1, the single-sample weight increased at higher moisture content, whereas the number of samples N in 1 kg material decreased. This was the case because under the same sample volume, a rise in moisture content led to greater weight, and therefore the number of samples in 1 kg material became less.

The pore volume of Granny Smith apple slices measured at different moisture contents is shown in Tab. 2; the greater the sample moisture content, the smaller is the pore volume.

Tab. 2 Pore volume of pre-dehydrated material with different moisture contents

ω/%	V_h/m^3
15	8.470×10^{-4}
20	6.712×10^{-4}
25	5.072×10^{-4}
30	3.793×10^{-4}
35	2.423×10^{-4}

3.1 Effect of superheated steam temperature on the work of puffing and the puffing ratio

Samples with 25% moisture content were puffed at a pressure of 0.3 MPa with superheated steam temperatures of 430 K, 440 K, 450 K, 460 K, and 470 K. The condensation water mass M generated by heating pre-dehydrated samples with superheated steam was determined. Referring to the enthalpy and entropy of saturated water under different superheated steam pressures (Spirax Sarco Engineering Co., Ltd.), the work of superheated water W_l, work of superheated steam W_g, and total work of puffing under different temperature conditions was calculated by Eqs. (7) ~ (10). Then the puffing ratio could be calculated by substituting W_g and W_l into Eq. (17). Related calculations and measured values are shown in Tab. 3.

Tab. 3 Relationships of superheated vapor temperatures, condensed water quantity and puffing power (p_1 = 0.3 MPa, ω = 25%)

T/K	M/kg	W_l/J	W_g/J	W/J	S_p	S_m
430	0.0956 ± 0.0016^{E}	138.8	91.6	230.4	1.588	1.568 ± 0.016^{c}
440	0.1019 ± 0.0019^{D}	141.3	90.1	231.4	1.591	1.581 ± 0.012^{bc}
450	0.1082 ± 0.0015^{C}	143.8	88.7	232.5	1.594	1.593 ± 0.008^{ab}
460	0.1144 ± 0.0012^{B}	146.3	87.2	233.5	1.597	1.594 ± 0.007^{ab}
470	0.1205 ± 0.0008^{A}	148.8	85.8	234.6	1.599	1.598 ± 0.010^{a}

Note: T is the temperature of superheated steam; different superscript capital letters in the same list indicate significant differences at the 99% confidence level, different superscript lowercase letters in the same list indicate significant differences at the 95% confidence level, as also in the following tables. The coefficient of determination R^2 between the measured value S_m and the predicted value S_p of the puffing ratio was 0.898 1.

As shown in Tab. 3, the coefficient of determination R^2 was greater than 0.89, indicating that the predicted values were highly consistent with the measured values. As the superheated steam temperature T rose from 430 K to 470 K, the puffing ratio S_m increased from 1.568 to 1.598. Although the variation in the condensation water mass M generated at different temperatures by superheated steam was highly significant, the variation in puffing ratio was not significant. As shown by Eq. (17), the puffing ratio varies in proportion to the work both of superheated water and of superheated steam. At a constant material moisture content and a constant superheated steam pressure, the higher the temperature of superheated steam, the greater will be the work performed by superheated water, W_l (Tab. 3). This relation exists because the higher the temperature of hot water, the greater is its internal energy, and the greater is its capacity for instant flash evaporation of water in puffing. However, at higher superheated steam temperature, the amount of work performed by superheated steam inside the material, W_g, decreased to some extent rather than increased. Because the condensation water mass M generated by the higher-temperature superheated steam became greater, the condensed water was absorbed by the material, decreasing the pore volume inside the material and the amount of superheated steam that could be accommodated. The work performed by superheated water occupied a dominant position, and hence the puffing ratio generally increased with superheated steam temperature.

3.2 Effect of superheated steam pressure on work and puffing ratio

Samples with 25% moisture content were puffed at a heating temperature of 450 K and superheated steam pressures of 0.1 MPa, 0.2 MPa, 0.3 MPa, 0.4 MPa, and 0.5 MPa. The condensation water mass was determined, and the work of puffing under different superheated steam pressure conditions was calculated by Eqs. (7) ~ (10). Then predicted puffing ratio could be calculated by substituting W_g and W_l into Eq. (17). The corresponding theoretical and measured values are shown in Tab. 4.

Tab. 4 Relationships of superheated vapor pressures, condensed water quantity and puffing power (T = 450 K, ω = 25%)

p_1/MPa	M/kg	W_l/J	W_g/J	W/J	S_p	S_m
0.1	0.105 8 ± 0.001 5[d]	0	0	0	1.000	1.001 ± 0.106[e]
0.2	0.107 2 ± 0.000 9[c]	39.2	32.8	72.0	1.245	1.169 ± 0.062[d]
0.3	0.108 2 ± 0.000 8[bc]	143.8	88.7	232.5	1.594	1.440 ± 0.130[c]
0.4	0.109 1 ± 0.000 7[ab]	311.2	144.1	455.3	1.931	1.755 ± 0.192[b]
0.5	0.109 9 ± 0.000 7[a]	517.2	203.5	720.7	2.227	2.195 ± 0.240[a]

Note: The coefficient of determination R^2 between the measured value S_m and the predicted value S_p of the puffing ratio was 0.943 8.

Tab. 4 shows predicted values that are highly consistent with measured values. As the superheated steam pressure p_1 was increased from 0.1 MPa to 0.5 MPa and the puffing ratio S_m increased from 1.001 to 2.195, the impact of superheated steam pressure on puffing ratio became significant. In the low-pressure range (0.1 ~ 0.2 MPa) of superheated steam, the effect of increasing pressure on the condensation water mass M became significant. Further pressure increases did not significantly affect the condensation water mass. As superheated steam pressure increased, both the work of superheated water W_l and the work of superheated steam W_g inside the sample increased, so that the puffing power W was significantly increased. On the other hand, when the superheated steam pressure was constant, the work performed by superheated water was much greater than that performed by superheated steam, indicating that the work of superheated water was dominant in puffing.

3.3 Influence of moisture content on work and puffing ratio

The samples were puffed at a heating temperature of 450 K and a superheated steam pressure of 0.3 MPa. The sample moisture contents were 15%, 20%, 25%, 30%, and 35%. The problem was to determine the condensation water mass M during heating, to calculate the work of puffing and the predicted puffing ratio, and finally measured puffing ratio. The results are shown in Tab. 5.

Tab. 5 Relationships of condensed water quantity produced with different sample moisture contents and puffing power (T = 450 K, p_1 = 0.3 MPa)

ω/%	M/kg	W_l/J	W_g/J	W/J	S_p	S_m
15	0.083 8 ± 0.001 8[E]	93.9	170.4	264.3	1.577	1.461 ± 0.059[d]
20	0.096 2 ± 0.001 0[D]	118.9	128.1	247.0	1.578	1.549 ± 0.042[c]
25	0.108 2 ± 0.001 2[C]	143.8	88.7	232.5	1.594	1.588 ± 0.033[bc]
30	0.119 6 ± 0.000 8[B]	168.5	57.4	225.9	1.630	1.608 ± 0.013[ab]
35	0.132 0 ± 0.000 4[A]	193.5	23.9	217.4	1.648	1.646 ± 0.008[a]

Note: The coefficient of determination R^2 between the measured values S_m and the predicted values S_p of the puffing ratio was 0.924 6.

Tab. 5 shows that the determination coefficient between measured and predicted values of the relationship between puffing ratio and moisture content was 0.924 6. When the sample moisture content ω was 15%, the puffing ratio S_m was 1.461; when the sample moisture content ω was 35%, the puffing ratio S_m increased to 1.646. For moisture contents of 15% and 20%, the impact of moisture on puffing ratio was significant, but the impact of further moisture increases on puffing ratio was not significant. As the moisture content of the sample to be puffed increased, the pore volume V_h was significantly reduced (Tab. 2), and the condensation water mass was significantly increased. The increase in sample moisture content significantly increased the condensation water mass M (Tab. 5), so that the superheated steam capacity of the sample was reduced, and the work done by superheated steam W_g was also significantly decreased. Although the work done by superheated water increased at higher sample moisture content, but the work of puffing W decreased.

On the other hand, as the sample moisture content increased, the number of samples N in 1 kg pre-dehydrated material decreased (Tab. 1), and therefore the puffing ratio, which depended on the work of puffing, also increased.

Our earlier studies on the technology for puffing fruits and vegetables by superheated steam[4-5] showed that after the puffing ratio was increased to a certain point, it would gradually decline because condensation water generated during thermal transfer between the steam and the device was absorbed by the material. To address this problem, this study improved the experimental setup by adding a water guide apparatus to avoid the adverse effects of absorption of condensation water by the material[5].

4 Conclusions

(1) The energy to puff sheet materials came mainly from the work of flash evaporation of superheated water and instant release of superheated steam inside the material. Establishment of a general mathematical model of the relationship between puffing ratio and puffing power when puffing sheet material indicated that the puffing ratio was related to material moisture content, porosity, pressure difference before and after puffing, and the thermal properties of water.

(2) Using Granny Smith apple slices as experimental objects, the relationship between puffing work and puffing ratio was investigated. At temperatures of 430 ~ 470 K, pressures of 0.1 ~ 0.5 MPa, and material moisture contents of 15% ~ 35%, the established general dynamic puffing model for sheet materials could effectively predict and evaluate the relationship between puffing conditions and the puffing ratio.

(3) The condensation water during heating by superheated steam had a significant impact on puffing power and puffing ratio. Increased superheated steam pressure had little effect on condensation water mass, but the amounts of work performed by both superheated water and superheated steam were increased, significantly enhancing puffing capacity. Increasing superheated steam temperature not only increased the work done by superheated water, but also significantly increased the amount of condensation water and decreased the work done by superheated steam, meaning that the increased puffing effect was counteracted. The increase in material moisture content was good for increasing the work done by superheated water, but significantly increasing the amount of condensation water decreased the work done by superheated steam. Overall, the effect was an obvious increase in puffing ratio.

References

[1] KAREL H, MILAN H, JIŘINA P, et al. Optimization of puffing naked barley [J]. Journal of Food Engineering, 2007, 80(4): 1016-1022.

[2] JOSE M A, PETER J L, GUSTAVO V B C. Food materials science: principles and practice [M]. New York: Springer-Verlag, 2007: 284-285.

[3] SACA S A, LOZANO J E. Explosion puffing of bananas [J]. International Journal of Food Science and Technology, 1992, 27(4): 419-426.

[4] SONG H B, AN F P. Optimization of super heated stream puffing drying technology for carrot [J]. Transactions of the Chinese Society for Agricultural Machinery, 2010, 41(2): 127-131. (in Chinese)

[5] SONG H B, MA S X, LAI C R, et al. Instant pressure drop evaluation during saturated steam puffing of carrots [J]. International Journal of Agricultural Science and Technology, 2015, 3(2): 46-57.

[6] KOZEMPEL M F, SULLIVAN J C, CRAIG J C Jr, et al. Explosion puffing of fruit and vegetables [J]. Journal of Food Science, 1989, 54(3): 772-773.

[7] MUTAIR S, IKEGAMI Y. On the evaporation of superheated water drops formed by flashing of liquid jets [J]. International Journal of Thermal Sciences, 2012, 57: 37-44.

[8] ABBASI T, ABBASI S A. The boiling liquid expanding vapour explosion (BLEVE): mechanism, consequence assessment, management [J]. Journal of Hazardous Materials, 2007, 141(3): 489-519.

[9] AVIRA P, TOMAS P E, BALLESTEROS M, et al. Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis: a review [J]. Bioresource Technology, 2010, 101(13): 4851-4861.

[10] LIU C H, ZHENG X Z. Comparison of puffing characteristics for blackcurrant slice obtained by microwave and microwave-vacuum method [J]. Transactions of the Chinese Society for Agricultural Machinery, 2011, 42(Supp.): 194-198. (in Chinese)

[11] SUI W J, CHEN H Z. Multi-stage energy analysis of steam explosion process [J]. Chemical Engineering Science, 2014, 116(6): 254-262.

[12] MIR S A, BOSSO S J D, SHAH M A, et al. Effect of puffing on physical and antioxidant properties of brown rice[J]. Food Chemistry, 2016, 191(15): 139 – 146.

[13] RESSING H, RESSING M, Durance T. Modeling the mechanisms of dough puffing during vacuum microwave drying using the finite element method[J]. Journal of Food Engineering, 2007, 82(4): 498 – 508.

[14] ZHENG X Z, LIU C H, SHI J, et al. Analysis of volume expansion and dehydration rate of berry slab under microwave-vacuum puffing conditions[J]. LWT—Food Science and Technology, 2013, 52(1): 39 – 48.

[15] CHENG L L, HE X Y, GUO F F, et al. Effects of colour protection treatment and puffing drying process on the quality of apple slices[J]. Food & Machinery, 2011, 27(1): 127 – 129. (in Chinese)

[16] HUANG L L, ZHANG M, WANG L P, et al. Influence of combination drying methods on composition, texture, aroma and microstructure of apple slices[J]. LWT—Food Science and Technology, 2012, 47(1): 183 – 188.

[17] AN F P, QIU D Z, SONG H B, et al. Effects of instant pressure drop puffing with super-heated vapor on the physical properties of granny smith apple chips[J]. Journal of Food Process Engineering, 2015, 38(2): 174 – 182.

[18] ACEVEDO N C, BRIONES V, BUERA P, et al. Microstructure affects the rate of chemical, physical and color changes during storage of dried apple discs[J]. Journal of Food Engineering, 2008, 85(2): 222 – 231.

[19] KROKIDA M K, MAROULIS Z B. Effect of microwave drying on some quality properties of dehydrated products[J]. Drying Technology, 1999, 17(3): 449 – 466.

[20] YAN Z, SOUSA-GALLAGHER M J, OLIVEIRA F A R. Shrinkage and porosity of banana, pineapple and mango slices during air-drying[J]. Journal of Food Engineering, 2008, 84(3): 430 – 440.

[21] MAYOR L, MOREIRA R, SERENO A M. Shrinkage, density, porosity and shape changes during dehydration of pumpkin (*Cucurbita pepo* L.) fruits[J]. Journal of Food Engineering, 2011, 103(1): 29 – 37.

[22] WANG Q H, DAI G, WANG D F. The analysis of the superheated liquid explosive energy and overpressure[J]. Transactions of the Chemical Machinery, 2011, 38(3): 301 – 304. (in Chinese)

[23] HU L Y, ZHANG L. Flash evaporation of condensation water and flash evaporating condensation water[J]. Energy Conservation, 2006, 25(1): 58 – 60. (in Chinese)

[24] YU Y B. Discussion and correction on the model of boiling liquid expanding vapor explosion[J]. Hunan Security and Disaster Prevention, 2011(3): 46 – 47. (in Chinese)

[25] HU C W. Application of micro-element method[J]. Journal of Yangtze University: Natural Science Edition, 2008, 5(3): 142 – 143. (in Chinese)

doi:10.6041/j.issn.1000-1298.2016.08.029

青苹果片过热蒸汽瞬时压降膨化动力研究

安凤平　郭　瑞　宋洪波　黄　群　滕　慧　李　涛
(福建农林大学食品科学学院, 福州 350002)

摘要: 针对过热蒸汽瞬时压降膨化动力不明晰、膨化程度调控困难的问题,建立了片状物料膨化动力通用数学模型,表明膨化的能量源自于物料内部过热液体闪急蒸发做功和过热蒸汽瞬时释放做功2部分。由于不同含水率的待膨化样品孔隙率不同,而且膨化前过蒸汽加热过程中热交换所产生的冷凝水质量也不同,从而膨化前样品的孔隙率产生了不同的变化。因此,膨化度与物料的含水率、孔隙度有关,也与过热蒸汽的状态有关。以青苹果片为试验材料,结果表明待膨化样品的孔隙率随着含水率的增大而明显减小。采用温度和压力分别为430~470 K和0.1~0.5 MPa、过热蒸汽膨化含水率为15%~35%的青苹果片,运用建立的膨化动力模型可有效地预测和评价膨化条件与膨化度的关系($R^2>0.89$)。增大蒸汽压力,对冷凝水的影响不大,可增大过热液体和过热蒸汽做功,对提升膨化动力和膨化效果最明显;升高过热蒸汽温度仅能提高过热液体做功,但显著增大的冷凝水量使得过热蒸汽做功减小,对提高膨化动力及膨化效果不明显;增加物料的含水率明显地增大过热液体做功,但是由于冷凝水量明显增加而降低了过热蒸汽做功,总体上表现为较大程度增大了膨化动力和膨化度。

关键词: 青苹果片; 过热蒸汽; 瞬时压降; 膨化; 模型
中图分类号: TS255.36　　**文献标识码**: A　　**文章编号**: 1000-1298(2016)08-0227-06

Dynamic Study on Instant Pressure Drop Puffing of Granny Smith Apple Slices Using Superheated Vapor

An Fengping　Guo Rui　Song Hongbo　Huang Qun　Teng Hui　Li Tao
(*College of Food Science*, *Fujian Agriculture and Forestry University*, *Fuzhou* 350002, *China*)

Abstract: Unclear puffing power has always been an important problem for instant pressure drop puffing process using superheated vapor. And the condensation water produced by superheated vapor is absorbed by the food material before puffing, which possibly makes bad effect on puffing ratio. A general mathematical model of puffing power was established. Results indicated that puffing energy was produced by flash evaporation of superheated water from internal material and instant release of superheated vapor. Besides, porosity of sample varied with different sample moisture contents and condensation water generated in thermal transfer process before puffing. Thus, puffing ratio was related to the sample moisture content, porosity and status of superheated vapor. Using Granny Smith green apple slice as experimental objects, results suggested that porosity of sample was significantly decreased with the increase of sample moisture content. At temperature of 430~470 K, pressure of 0.1~0.5 MPa and apple moisture content of 15%~35%, the established puffing power model could effectively predict and evaluate the relationship between puffing condition and puffing ratio ($R^2>0.89$). High vapor pressure had insignificant influence on condensation water, and distinctively elevated the energy of superheated water and superheated vapor, which resulted in the biggest puffing ratio. High temperature of superheated vapor can only strengthen superheated water energy, but significant increase of condensation water mass led to superheated vapor

收稿日期: 2016-01-20　修回日期: 2016-04-06
基金项目: 国家自然科学基金项目(31271913)
作者简介: 安凤平(1965—),女,副教授,主要从事食品科学与工程研究,E-mail: pingfengan@163.com
通信作者: 宋洪波(1966—),男,教授,主要从事食品科学与工程研究,E-mail: sghgbode@163.com

energy reduction, and it had slight effects on puffing energy improvement and puffing effect. Moreover, high moisture content of sample significantly increased superheated water energy, but condensation water reduced superheated vapor energy, which generally showed great effects on improvement of puffing power and puffing ratio. The research results illustrated the power mechanism of instant pressure drop puffing process using superheated vapor, which would be helpful to further study on the control of puffing ratio.

Key words: Granny Smith apple slices; superheated vapor; instant pressure drop; puffing; model

引言

过热蒸汽膨化是将预脱水至一定含水率的果蔬等物料置于高压容器中，通入蒸汽并保持一定时间，瞬时释放压力使物料膨化，形成具有蜂窝状组织结构[1-4]。与传统膨化技术相比，蒸汽膨化具有节能、无污染、营养保存率高等优点[3-6]，在果蔬脆片、脱水农产品加工过程中的组织修饰等方面具有广泛的应用前景。以往的研究集中于原料含水率、蒸汽温度、压力和滞留时间等工艺参数优化，然而产生膨化的动力机制尚不清楚，使得调控膨化程度的方向具有不确定性，特别是由试验研究到产业化应用过程中的参数变化较大，是造成实际应用困难的主要原因。

膨化前过热蒸汽对物料加热，物料内水分处于高温高压状态，当瞬间泄压时，过热态水分发生闪急蒸发[7]。过热液体闪蒸往往伴随着能量的瞬间释放，ABBASI 等[8]研究沸腾液体膨胀蒸汽爆炸的机制，表明容器内过热液体瞬间降压时，沸腾液体迅速膨胀为蒸汽而产生爆炸。物料内含水率对水分闪蒸有很大影响[9]，而水分快速蒸发是促进膨化的重要因素[10]。SUI 等[11]研究了多级蒸汽爆炸过程的能量分析，过程分为增压、保压和减压 3 个阶段，过热蒸汽迅速释放产生巨大能量；膨化压力差对物料体积变化影响很大[12-14]。目前关于过热蒸汽瞬时压降的膨化动力研究尚未见报道。

本文以片状物料为研究对象，以青苹果为试验材料，研究过热蒸汽瞬时压降膨化动力产生的机理，为运用膨化动力原理调控膨化程度提供理论依据和实践指导。

1 材料与方法

1.1 样品准备

新鲜、无机械损伤的青苹果，购于当地超市，贮藏于(4 ± 1)℃、相对湿度为 90% ~ 95% 的冷库中备用。青苹果平均湿基含水率为 86.3%，糖度为 10.6 ~ 11.8°Brix。经清洗、去皮，切成规格 35 mm × 35 mm × 10 mm 的薄片，浸泡于质量分数为 0.02% 的亚硫酸钠溶液中 20 min，沥去表面液体[15]。将护色的青苹果片放在干燥箱中以(70 ± 1)℃ 脱水至一定含水率，立即修整为 20 mm × 20 mm × 5 mm 薄片，包装于铝箔袋中于室温(20 ℃)冷却 2 h[16]。

1.2 样品的加热及膨化

将 15 个预脱水青苹果片放入膨化机的膨化室内，将 TT - K - 30 - SLE - 1000 型热电偶插入一个青苹果片的中部。关闭膨化室，开启真空泵对膨化室抽真空至 100 Pa 后关闭真空泵。再向膨化室中通入一定温度和压力的过热蒸汽，加热一定时间后立即打开卸压阀，完成对样品的膨化。在过热蒸汽加热过程中样品的中心温度由数字温度表显示，压力由压力检测仪传感器显示[17]。

1.3 仪器与设备

DHG - 9003A 型热风干燥箱，上海精宏试验设备有限公司；DZF6050 型真空干燥箱，上海精宏试验设备有限公司；BSA124S 型分析天平，北京赛多利斯仪器系统有限公司；VP - 100 型过热蒸汽膨化机，自制。

1.4 指标及测定方法

1.4.1 含水率

采用真空干燥法测定样品的含水率。将样品置于真空干燥箱中以 70℃、133 Pa 干燥至质量恒定。干燥前后样品质量的差值与干燥前样品质量的百分比即为含水率[18]。

1.4.2 膨化度

膨化度表示样品体积的相对变化，即膨化后样品的表观体积与膨化前样品表观体积的比值。样品表观体积的测定采用液体置换法[19-20]。

1.4.3 冷凝水质量

用分析天平称量 15 个样品的质量，再将样品置于膨化室内加热，使其中心温度达到过热蒸汽温度后取出并称量。加热后样品的质量与加热前样品质量的差值即为冷凝水质量。

1.4.4 闪急蒸发水分质量

将预脱水至一定含水率的 15 个样品置于膨化室内加热使其中心温度达到过热蒸汽温度及压力后，取出并用分析天平称量后得到膨化前物料的质

量。将相同含水率的 15 个样品置于膨化室内加热，使其中心温度达到过热蒸汽温度时进行膨化，取出膨化的样品并称量，得到膨化后物料的质量。膨化前后质量差即为闪急蒸发水分质量。

1.4.5　孔体积

孔体积用样品的表观体积与固体体积的差值表示。表观体积测定采用液体置换法，固体体积的测定采用气体转换法[21]。

1.5　数据处理

采用 DPS 7.5 软件分析过热蒸汽加热物料过程中冷凝水质量以及膨化度测试结果组间差异的显著性。预测值与实测值的符合程度用决定系数 R^2 表示，由 Microsoft Excel 2003 软件求得。

2　膨化动力通用模型的建立

物料经预脱水后，形成多孔结构。当样品放入膨化室内并抽真空后，样品内的空气被抽出。在过热蒸汽加热样品过程中，少量冷凝水产生并被物料吸收，占据少量的孔隙空间；其他孔隙则充满着过热蒸汽。当瞬间打开卸压阀时，样品内部的部分过热水分立即气化、孔隙中过热蒸汽瞬时释放，导致样品膨化。因此，物料膨化的总能量包括过热水分闪急蒸发做功和过热蒸汽瞬时释放做功 2 部分。

2.1　膨化做功

膨化前物料内部水分包括物料本身含有的水分和过热蒸汽加热过程中产生的冷凝水 2 部分，所以膨化前物料中水分质量为

$$m_l = m\omega + M \tag{1}$$

式中　m_l——膨化前 1 kg 样品中水的质量，kg

m——待膨化样品的质量，取 1 kg

ω——待膨化样品的含水率，%

M——加热 1 kg 待膨化样品产生的冷凝水质量，kg

膨化时，物料内压力瞬间降为 1 个标准大气压，其内部的部分过热水分将闪急蒸发，释放能量。过热水分做功的表达式为[22]

$$W_l = [h_1 - h_2 - (s_1 - s_2)T_2]m_1 \tag{2}$$

式中　W_l——膨化 1 kg 样品时过热水分所做的功，J

h_1——膨化前压力条件下水的焓值，J/kg

h_2——膨化后压力条件下水的焓值，J/kg

s_1——膨化前压力条件下水的熵值，J/(kg·K)

s_2——膨化后压力条件下水的熵值，J/(kg·K)

T_2——膨化后压力条件下水的沸点，K

m_1——膨化 1 kg 样品闪急蒸发水分质量，kg

根据预试验，物料中的水分只有少部分发生了闪急蒸发。因此，采用闪蒸率 λ 表示蒸发水分多少的公式

$$\lambda = \frac{m_1}{m_l} \tag{3}$$

联立式(1)~(3)，得到过热水分闪急蒸发做功计算式

$$W_l = [h_1 - h_2 - (s_1 - s_2)T_2](m\omega + M)\lambda \tag{4}$$

膨化前后水分存在焓差，为过热水分闪急蒸发提供能量。根据能量守恒定律得[23]

$$h_1 - h_2 = \lambda r \tag{5}$$

式中　r——膨化后压力条件下水的汽化潜热，J/kg

联立式(4)、(5)，得到过热水分做功简化式

$$W_l = [h_1 - h_2 - (s_1 - s_2)T_2](m\omega + M)\frac{h_1 - h_2}{r} \tag{6}$$

膨化是在瞬间完成的，由于膨化过程极短，因此物料内部过热蒸汽瞬时释放做功可视为理想气体绝热过程做功[24]，即

$$W_g = \frac{p_1 V_g}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right] \tag{7}$$

式中　W_g——膨化 1 kg 样品过热蒸汽所做的功，J

p_1——膨化前样品内的绝对压力，MPa

V_g——1 kg 待膨化样品内过热水分的体积，m^3

p_2——膨化后样品内的绝对压力，MPa

k——过热蒸汽的绝热指数

膨化前样品的孔隙中充满着冷凝水和过热蒸汽，则

$$V_h = M\rho_l^{-1} + V_g \tag{8}$$

式中　V_h——1 kg 待膨化样品的孔体积，m^3

ρ_l——饱和水的密度，kg/m^3

联立式(7)、(8)，得膨化过程中过热蒸汽做功的表达式

$$W_g = \frac{p_1(V_h - M\rho_l^{-1})}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right] \tag{9}$$

膨化 1 kg 物料的总能量为物料内部的过热水分与过热蒸汽做功之和，即

$$W = W_l + W_g = [h_1 - h_2 - (s_1 - s_2)T_2](m\omega + M)\cdot \frac{h_1 - h_2}{r} + \frac{p_1(V_h - M\rho_l^{-1})}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right] \tag{10}$$

式中　W——膨化 1 kg 样品所做的功，J

2.2　膨化度模型

由预试验已知，对于片状物料而言，膨化使得厚度增加较大，而膨化前后样品长度和宽度的变化很小。这是因为样品的长度和宽度远大于厚度，在长度和宽度方向的膨化阻力远大于厚度方向的阻力，

因此变形主要沿厚度方向进行。

预脱水片状物料可以看成是由无数个平面组成。设厚度上的微元为 $\mathrm{d}y$，做功微元为 $\mathrm{d}W_s$，则做功微元表达式为[25]

$$\mathrm{d}W_s=\frac{p_1+p_2}{2}a^2\mathrm{d}y \tag{11}$$

式中 a——待膨化样品的边长，m

对式(11)积分得片状物料在内外压力差作用下膨化做功量表达式

$$W_s=2\int_{\delta}^{\delta'}\frac{p_1+p_2}{2}a^2\mathrm{d}y \tag{12}$$

式中 δ——待膨化样品的厚度，m

δ'——膨化样品的厚度，m

化简式(12)得

$$W_s=a^2(\delta'-\delta)(p_1+p_2) \tag{13}$$

膨化度表达式为

$$S=\frac{V}{V_0}=\frac{2\delta'a^2}{2\delta a^2}=\frac{\delta'}{\delta} \tag{14}$$

式中 S——膨化度

V——膨化样品的表观体积，m^3

V_0——待膨化样品表观体积，m^3

联立式(13)、(14)得

$$S=1+\frac{W_s}{\delta a^2(p_1+p_2)} \tag{15}$$

设1 kg预脱水物料中含有 N 个样品，膨化1 kg物料的总能量可表示为

$$W=W_l+W_g=NW_s \tag{16}$$

联立式(15)、(16)，则样品膨化度表达式为

$$S=1+\frac{W_l+W_g}{N\delta a^2(p_1+p_2)} \tag{17}$$

3 结果与分析

以青苹果片为试验材料，采用膨化动力通用模型研究过热蒸汽温度、压力以及样品含水率对膨化做功以及膨化度等的影响。

预脱水青苹果片含水率不同，则1 kg物料中的样品个数 N 也不同，见表1。

表1 不同含水率的单个样品质量 m 和1 kg物料中的样品个数 N

Tab.1 Single weight and number for 1 kg of pre-dehydrated sample with different moisture contents

ω/%	m/kg	N
15	8.741×10^{-4}	1 144
20	9.359×10^{-4}	1 069
25	1.022×10^{-3}	979
30	1.116×10^{-3}	896
35	1.192×10^{-3}	839

由表1可知，单个样品质量随其含水率的增大而增大，而1 kg物料中样品个数 N 随着含水率的增大而减小。这是因为样品体积相同时，含水率越大，其质量也越大，1 kg物料中的样品数量则越少。

测定不同含水率的青苹果片孔体积如表2所示，样品含水率越大，孔体积越小。

表2 不同含水率预脱水样品的孔体积

Tab.2 Pore volume of pre-dehydrated material with different moisture contents

ω/%	V_h/m^3
15	8.470×10^{-4}
20	6.712×10^{-4}
25	5.072×10^{-4}
30	3.793×10^{-4}
35	2.423×10^{-4}

3.1 过热蒸汽温度对做功和膨化度的影响

以压力为0.3 MPa，温度分别为430、440、450、460、470 K的过热蒸汽膨化含水率为25%的样品。测定预脱水样品经过热蒸汽加热产生的冷凝水质量 M；查阅不同过热蒸汽压力下饱和水的焓值和熵值(斯派莎克工程有限公司提供)，则由式(7)~(10)计算可得不同过热蒸汽温度条件下过热水分做功 W_l、过热蒸汽做功 W_g 以及过热膨汽做功之和 W；再将 W_l 和 W_g 代入式(17)中，计算可得膨化度。相关的计算值和实测值如表3所示。

表3 过热蒸汽温度与冷凝水质量及膨化的关系(p_1=0.3 MPa，ω=25%)

Tab.3 Relationships of superheated vapor temperatures, condensed water quantity and puffing power

T/K	M/kg	W_l/J	W_g/J	W/J	S_p	S_m
430	0.0956 ± 0.0016^{E}	138.8	91.6	230.4	1.588	1.568 ± 0.016^{c}
440	0.1019 ± 0.0019^{D}	141.3	90.1	231.4	1.591	1.581 ± 0.012^{bc}
450	0.1082 ± 0.0015^{C}	143.8	88.7	232.5	1.594	1.593 ± 0.008^{ab}
460	0.1144 ± 0.0012^{B}	146.3	87.2	233.5	1.597	1.594 ± 0.007^{ab}
470	0.1205 ± 0.0008^{A}	148.8	85.8	234.6	1.599	1.598 ± 0.010^{a}

注：T 表示过热蒸汽温度；相同列不同的大写字母上标意味着在99%置信水平显著不同，相同列不同的小写字母上标意味着在95%置信水平显著不同，下同。膨化度实测值 S_m 与预测值 S_p 的决定系数 R^2 为0.898 1。

由表 3 可知，决定系数 R^2 达到 0.89 以上，说明预测值与实测值吻合度高。过热蒸汽温度 T 在 430 ~ 470 K 的范围内，膨化度 S_m 由 1.568 增加至 1.598；尽管不同过热蒸汽温度所产生的冷凝水质量 M 的差异高度显著，但膨化度之间的差异不显著。由式(17)可知，膨化度与过热水分做功以及过热蒸汽做功之和成正比。当物料含水率及过热蒸汽压力一定时，过热蒸汽温度越高则过热水分做功 W_l 也越大(表 3)，这是因为过热水分温度越高其内能也越大，膨化瞬间水分闪蒸的能力也越大；过热蒸汽温度越高，物料内部的气体做功 W_g 反而有所减小，是因为较高温度过热蒸汽所产生的冷凝水质量 M 增大，冷凝水被物料吸收使得其内部孔隙减小，可容纳的过热蒸汽量也减少。过热水分做功占居主导的地位，因此总体上表现为膨化度随着过热蒸汽温度的升高有所增大。

3.2　过热蒸汽压力对做功及膨化度的影响

以温度为 450 K、压力分别为 0.1、0.2、0.3、0.4、0.5 MPa 的过热蒸汽加热和膨化含水率为 25% 的样品。测定产生的冷凝水质量 M，由式(7) ~ (10)计算得出不同过热蒸汽压力条件下膨化所做的功；将过热水分做功量 W_l 和过热蒸汽做功量 W_g 等代入式(17)得到膨化度预测值。相应的理论值和实测值如表 4 所示。

表 4　过热蒸汽压力与冷凝水质量及膨化的关系(T = 450 K, ω = 25%)

Tab.4　Relationships of superheated vapor pressures, condensed water quantity and puffing power

p_1/MPa	M/kg	W_l/J	W_g/J	W/J	S_p	S_m
0.1	0.105 8 ± 0.001 5^{d}	0	0	0	1.000	1.001 ± 0.106^{e}
0.2	0.107 2 ± 0.000 9^{c}	39.2	32.8	72.0	1.245	1.169 ± 0.062^{d}
0.3	0.108 2 ± 0.000 8^{bc}	143.8	88.7	232.5	1.594	1.440 ± 0.130^{c}
0.4	0.109 1 ± 0.000 7^{ab}	311.2	144.1	455.3	1.931	1.755 ± 0.192^{b}
0.5	0.109 9 ± 0.000 7^{a}	517.2	203.5	720.7	2.227	2.195 ± 0.240^{a}

注：膨化度实测值 S_m 与预测值 S_p 的决定系数 R^2 为 0.943 8。

由表 4 可知，预测值与实测值高度吻合。过热蒸汽压力 p_1 由 0.1 MPa 增大至 0.5 MPa 时，膨化度 S_m 由 1.001 增大至 2.195，过热蒸汽压力对膨化度的影响达到显著水平。在较低的过热蒸汽压力范围内(0.1 ~ 0.2 MPa)，增大压力对冷凝水质量 M 的影响达到显著水平；进一步增大压力，对冷凝水质量的影响则不显著；随着过热蒸汽压力的增大，样品内部的过热水分做功 W_l 和过热蒸汽做功 W_g 均增大，因此膨化动力 W 增加明显，膨化效果亦明显变化。另一方面，当过热蒸汽压力一定时，过热水分做功较过热蒸汽做功大得多，说明膨化时过热水分做功量占居主导地位。

3.3　含水率对做功及膨化度的影响

以温度为 450 K、压力为 0.3 MPa 的过热蒸汽加热和膨化含水率分别为 15%、20%、25%、30% 和 35% 的样品，测定加热过程中冷凝水质量 M，计算膨化所做的功和膨化度，并测定膨化度，结果如表 5 所示。

表 5　不同含水率样品产生的冷凝水质量及膨化的关系(T = 450 K, p_1 = 0.3 MPa)

Tab.5　Relationships of condensed water quantity produced with different sample moisture contents and puffing power

ω/%	M/kg	W_l/J	W_g/J	W/J	S_p	S_m
15	0.083 8 ± 0.001 8^{E}	93.9	170.4	264.3	1.577	1.461 ± 0.059^{d}
20	0.096 2 ± 0.001 0^{D}	118.9	128.1	247.0	1.578	1.549 ± 0.042^{c}
25	0.108 2 ± 0.001 2^{C}	143.8	88.7	232.5	1.594	1.588 ± 0.033^{bc}
30	0.119 6 ± 0.000 8^{B}	168.5	57.4	225.9	1.630	1.608 ± 0.013^{ab}
35	0.132 0 ± 0.000 4^{A}	193.5	23.9	217.4	1.648	1.646 ± 0.008^{a}

注：膨化度实测值 S_m 与预测值 S_p 的决定系数 R^2 为 0.924 6。

由表 5 可知，含水率与膨化度关系的预测值与实测值之间的相关系数达 0.924 6。样品含水率 ω 为 15% 时，膨化度 S_m 为 1.461，当样品含水率 ω 为 35% 时，膨化度 S_m 达到 1.646；在含水率为 15% ~ 20% 范围内，含水率对膨化度的影响达到显著水平，进一步增大含水率对膨化度的影响不显著。由于待膨化样品含水率的增加，样品孔体积 V_h 显著减小(表 2)，显著增大冷凝水质量；样品含水率的增大显著增加了冷凝水的质量 M(表 5)，使得样品中过热蒸汽容量减小，因此过热蒸汽做功 W_g 也明显减小；尽管过热水分做功随着样品含水率增大而增大，但膨化做功 W 反而有所减小；另一方面，随着样品含水率增大，1 kg 预脱水物料中的样品个数 N 减小(表 1)，因此膨化做功所表现出的膨化度也增大。

此前关于过热蒸汽膨化果蔬工艺的研究表明[4-5]，膨化度增大至一定值后反而逐渐减小，是由于加热过程中蒸汽与设备之间热交换产生的冷凝水被物料吸收导致的。对此，本研究采用了改进的设备，增加了导水装置，避免了物料吸收该部分冷凝水产生的不利影响[5]。

4 结论

（1）过热蒸汽瞬时压降膨化片状物料的能量主要来自于物料内部过热液体闪急蒸发做功和过热蒸汽瞬时释放做功2个部分。建立了片状物膨化过程中膨化动力与膨化度关系的通用数学模型，表明膨化程度与物料含水率、孔隙度以及膨化前后的压力差、水分的热特性有关。

（2）以青苹果片为试验材料，对物料含水率15%～35%、过热蒸汽温度和压力分别为430～470 K和0.1～0.5 MPa条件下膨化做功及膨化度关系进行研究，预测值与实测值吻合度高（$R^2>0.89$），说明所建立的片状物料膨化动力通用模型可较好地预测和评价膨化条件与膨化度的关系。

（3）膨化前过热蒸汽加热过程中产生的冷凝水对膨化动力和膨化效果有重要影响。仅增大过热蒸汽压力，对冷凝水质量变化影响不大，而过热水分及过热蒸汽做功均增大，因此膨化能力最大。升高过热蒸汽温度可以一定程度增大过热水分做功，但明显增大了冷凝水量使得过热蒸汽做功减小，因此增大膨化效果不够明显。增加物料含水率，有利于增大过热水分做功，但冷凝水量的明显增加使过热蒸汽做功减小，总体上表现为较明显地增大膨化度。

参 考 文 献

1 KAREL H，MILAN H，JIŘINA P，et al. Optimization of puffing naked barley[J]. Journal of Food Engineering，2007，80(4)：1016－1022.

2 JOSE M A，PETER J L，GUSTAVO V B C. Food materials science：principles and practice[M]. New York：Springer-Verlag，2007：284－285.

3 SACA S A，LOZANO J E. Explosion puffing of bananas[J]. International Journal of Food Science and Technology，1992，27(4)：419－426.

4 宋洪波，安凤平. 胡萝卜过热蒸汽膨化干燥工艺优化[J]. 农业机械学报，2010，41(2)：127－131.
SONG H B，AN F P. Optimization of super heated stream puffing drying technology for carrot[J]. Transactions of the Chinese Society for Agricultural Machinery，2010，41(2)：127－131.(in Chinese)

5 SONG H B，MA S X，LAI C R，et al. Instant pressure drop evaluation during saturated steam puffing of carrots[J]. International Journal of Agricultural Science and Technology，2015，3(2)：46－57.

6 KOZEMPEL M F，SULLIVAN J C，CRAIG J C Jr，et al. Explosion puffing of fruit and vegetables[J]. Journal of Food Science，1989，54(3)：772－773.

7 MUTAIR S，IKEGAMI Y. On the evaporation of superheated water drops formed by flashing of liquid jets[J]. International Journal of Thermal Sciences，2012，57：37－44.

8 ABBASI T，ABBASI S A. The boiling liquid expanding vapour explosion (BLEVE)：mechanism，consequence assessment，management[J]. Journal of Hazardous Materials，2007，141(3)：489－519.

9 AVIRA P，TOMAS P E，BALLESTEROS M，et al. Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis：a review[J]. Bioresource Technology，2010，101(13)：4851－4861.

10 刘成海，郑先哲. 微波与微波真空膨化黑加仑果片膨化特性对比[J]. 农业机械学报，2011，42(增刊)：194－198.
LIU C H，ZHENG X Z. Comparison of puffing characteristics for blackcurrant slice obtained by microwave and microwave-vacuum method[J]. Transactions of the Chinese Society for Agricultural Machinery，2011，42(Supp.)：194－198.(in Chinese)

11 SUI W J，CHEN H Z. Multi-stage energy analysis of steam explosion process[J]. Chemical Engineering Science，2014，116(6)：254－262.

12 MIR S A，BOSSO S J D，SHAH M A，et al. Effect of puffing on physical and antioxidant properties of brown rice[J]. Food Chemistry，2016，191(15)：139－146.

13 RESSING H，RESSING M，Durance T. Modeling the mechanisms of dough puffing during vacuum microwave drying using the finite element method[J]. Journal of Food Engineering，2007，82(4)：498－508.

14 ZHENG X Z，LIU C H，SHI J，et al. Analysis of volume expansion and dehydration rate of berry slab under microwave-vacuum puffing conditions[J]. LWT—Food Science and Technology，2013，52(1)：39－48.

15 程丽丽，何新益，郭飞飞，等. 护色处理和膨化干燥工艺对苹果脆片品质的影响[J]. 食品与机械，2011，27(1)：127－129.
CHENG L L，HE X Y，GUO F F，et al. Effects of colour protection treatment and puffing drying process on the quality of apple slices[J]. Food & Machinery，2011，27(1)：127－129.(in Chinese)

16 HUANG L L，ZHANG M，WANG L P，et al. Influence of combination drying methods on composition，texture，aroma and microstructure of apple slices[J]. LWT—Food Science and Technology，2012，47(1)：183－188.

17 AN F P，QIU D Z，SONG H B，et al. Effects of instant pressure drop puffing with super-heated vapor on the physical properties of granny smith apple chips[J]. Journal of Food Process Engineering，2015，38(2)：174－182.

（下转第324页）

18 YOKOI K. A practical numerical framework for free surface flows based on CLSVOF method, multi-moment methods and density-scaled CSF model: numerical simulations of droplet splashing[J]. Journal of Computational Physics, 2013, 232(1): 252 - 271.

19 GUO Y, WEI L, LIANG G, et al. Simulation of droplet impact on liquid film with CLSVOF[J]. International Communications in Heat and Mass Transfer, 2014, 53: 26 - 33.

20 杨宝海. 喷雾冷却中液滴撞击固体壁面的动态特性及传热特性研究[D]. 重庆:重庆大学, 2013.

21 UBBINK O, ISSA R I. A method for capturing sharp fluid interfaces on arbitrary meshes[J]. Journal of Computational Physics, 1999, 153(1):26 - 50.

22 HSIANG L P, FAEH G M. Drop deformation and breakup due to shock wave and steady disturbances[J]. International Journal of Multiphase Flow, 1995, 21(4): 545 - 560.

23 宋云超. 气液两相流动相界面追踪方法及液滴撞击壁面运动机制的研究[D]. 北京:北京交通大学, 2012.

24 SHINJO J, UMEMURA A. Simulation of liquid jet primary breakup: dynamics of ligament and droplet formation[J]. International Journal of Multiphase Flow, 2010, 36(7): 513 - 532.

(上接第 47 页)

16 陆雄. 单级单吸离心泵后密封环加大量和平衡孔直径最佳值实验研究[J]. 水泵技术,1998(5): 3 - 9.
LU Xiong. The study of single-stage single-suction centrifugal pump based on increasing seal ring and balance hole diameter[J]. Pump Technology, 1998(5):3 - 9. (in Chinese)

17 何玉洁,周广凤, 潘金秋,等. 化多机泵轴向力实验[J]. 排灌机械,2009, 27(2): 108 - 109.
HE Yujie, ZHOU Guangfeng, PAN Jinqiu, et al. Experiment for axial thrust of multi-stage pump for seawater desalination[J]. Drainage and Irrigation Machinery, 2009, 27(2): 108 - 109. (in Chinese)

18 唐炘. 离心泵后盖板上压力分布规律的探索[J]. 水轮泵, 1987(2):30 - 34.
TANG Xin. The exploration of pressure distribution on centrifugal pump rear shroud[J]. Turbine Pump, 1987(2):30 - 34. (in Chinese)

19 刘在伦,董玮,张楠,等. 离心泵平衡腔液体压力的计算与验证[J]. 农业工程学报,2013, 29(20): 54 - 59.
LIU Zailun, DONG Wei, ZHANG Nan, et al. Calculation and validation of fluid pressure of balance cavity in centrifugal pump [J]. Transactions of the CSAE, 2013, 29(20): 54 - 59. (in Chinese)

20 顾永泉. 流体动密封[M]. 北京:石油大学出版社,1990.

(上接第 232 页)

18 ACEVEDO N C, BRIONES V, BUERA P, et al. Microstructure affects the rate of chemical, physical and color changes during storage of dried apple discs[J]. Journal of Food Engineering, 2008, 85(2):222 - 231.

19 KROKIDA M K, MAROULIS Z B. Effect of microwave drying on some quality properties of dehydrated products[J]. Drying Technology, 1999, 17(3):449 - 466.

20 YAN Z, SOUSA-GALLAGHER M J, OLIVEIRA F A R. Shrinkage and porosity of banana, pineapple and mango slices during air-drying[J]. Journal of Food Engineering, 2008, 84(3):430 - 440.

21 MAYOR L, MOREIRA R, SERENO A M. Shrinkage, density, porosity and shape changes during dehydration of pumpkin (*Cucurbita pepo* L.) fruits[J]. Journal of Food Engineering, 2011, 103(1):29 - 37.

22 王庆慧,戴光,王丹枫. 过热液体爆炸能量及超压分析[J]. 化工机械,2011,38(3):301 - 304.
WANG Q H, DAI G, WANG D F. The analysis of the superheated liquid explosive energy and overpressure[J]. Transactions of the Chemical Machinery, 2011, 38(3):301 - 304. (in Chinese)

23 胡连营,张雷. 凝结水闪蒸与闪蒸凝结水[J]. 节能,2006,25(1):58 - 60.

24 余运波. 沸腾液体膨胀蒸汽爆炸模型修正探讨[J]. 湖南安全与防灾,2011(3):46 - 47.

25 胡承望. 微元法的应用研究[J]. 长江大学学报:自然科学版,2008,5(3):142 - 143.