Experimental Research on the Drying Process of Pear and Mango Slices in Hot Air and Super Heated Steam Agents

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Abstract

Drying is an area that consumes a lot of energy and degrades the nutritional components of dried products if the right drying mode is not chosen. The drying process in different drying agent environments is being studied to find the right drying mode to increase product quality, reduce drying time, and reduce energy consumption. In this study, the drying processes of common agricultural products, namely pear slice and mango slice are conducted in a lab-scale dryer using hot air and superheated steam. Experimental calculation models are established, and product quality will be studied in several aspects including color change and shrinkage to comprehensively evaluate the applicability and suitable drying conditions for pears. The empirical models are built based on the Newton model which give the good agreement results in compared with the experimental model. For both fruit kinds, color of products obtained from superheated steam drying is darker than that from hot air-drying exception of at 110 °C, while the porosity of dried product in superheated steam is higher than dried product in hot air. The research results are the basis for expanding the application ability of modulated gas and superheated steam for post-harvest processing technology.

Keywords: Superheated steam drying, pear, shrinkage, experimental model, color.

1. Introduction

Post-harvest processing has been greatly improved because of the development of technology [1]. Drying methods can be divided into two main forms, which are hot drying and cold drying. Hot drying is a method that uses heated drying agents to heat the materials up, resulting in transferring heat and moisture. The cold drying method has many advantages when producing products that retain the taste and color of the product, but in general, it is costly in terms of investment and operating costs. In addition, the drying time is also very long and when applied on a large scale, it is even more difficult [2]. It is important to develop a drying technique which enhances the evaporation, but the quality of the product must be retained. Modified air and superheated steam replacing hot air are potential methods in this case. Modified air includes chemically inert gases such as CO_2, N_2, Ar, etc., or a mixture of air and volatile gas which removes completely or partially O_2 from the drying agent, has been applied as modified air drying (MAD). MAD can be used to replace O_2 to reduce browning, increase product quality, and shorten the drying period [3]. Superheated steam drying (SSD) is also an advanced drying technique in which gas agent is replaced by superheated steam. Superheated steam is steam at temperatures above saturation temperature at a specific vapor pressure. Superheated steam has been applied to drying agricultural products [4-5]. When saturated steam is heated up to superheated steam and then passed through the drying material, the superheated steam will absorb moisture from the drying material and transfer heat to it until the object reaches an equilibrium state [6]. The use of SSD has been known for decades [7-8]. However, in recent years, along with energy-saving movements in the world, research on the application of superheated steam to agricultural product drying processes is becoming extremely necessary.

The main objective of this study is to evaluate the applicability of superheated steam drying for pear and mango slices by comparisons between dried processes in hot air and superheated steam. The dynamics of the drying process are surveyed and comments are drawn, in addition to the quality of the product is also analyzed. The experimental results are then used as data to establish experimental models of the drying process. Thereby, the effectiveness of the application of superheated steam to dry pear slices can be evaluated.

2. Experiment Methodology and Data Evaluation

2.1. Experiment Description

The diagram of the experimental system is shown in Fig. 1 and Fig. 2. Agricultural products were dried in a drying chamber (4). The water pump (1) supplies water from the tank to the steam

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generator (2). Here, the water is heated and reaches a boiling point and produces saturated vapor. Saturated steam is led to an electric heater (3) to heat and adjust the desired temperature to a superheat steam state. The superheated steam is blown into the drying chamber (4). The steam is then sucked out by the exhaust fan (6).

During the drying process, the sample is placed on a mesh rack, allowing the drying agent to circulate through with a low-pressure drop, this holder rests on an electronic scale (RAD WAG PS750, Radom, Poland) with an error of 0.1 mg (5) that monitors the volume change of the sample continuously. For air, the evaporator (2) is replaced by the gas tank.

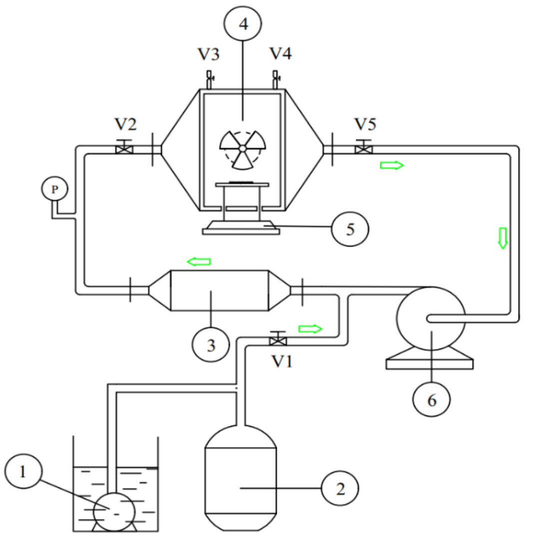


Fig. 1. System diagram (1): water pump; (2): steam generator; (3): heater; (4): drying chamber; (5): balance; (6): exhaust fan

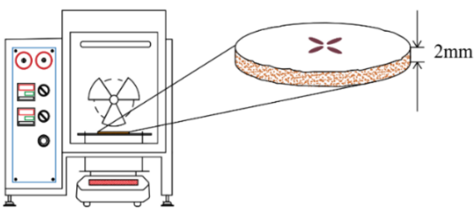


Fig. 2. Built drying chamber

The experiment procedure is conducted by the following steps.

- Fresh pears and mangos were purchased from Winmart, Hanoi. The bright yellow pears and soft, ripe avocados were chosen. After that, they were cleaned and cut to slices with thickness of 2 mm.
- Superheated steam or gas is heated to the setting temperature. One pear slice is put on the tray. The drying process is started when the temperature difference is less than 0.5 °C.
- The scale is turned on to record the mass of the drying sample every 5 minutes. The experiment ends when the mass change ceases.

Each experiment is repeated at least 3 times to eliminate random errors in measurements. In addition, the initial humidity of the samples is determined using a GMP500 standard drying chamber (GMP500, ThermoPlus Air Inc, New York, NY, USA). The new sample is dried at 70 °C for 4 hours and the remaining sample volume is evaluated. The initial moisture content is about 87.78%.

Experiments were conducted for air with the condition: t_g equal 50 - 130 ºC, v_g equal 3 - 6 m/s, for superheated steam at t_g equal 110 ºC - 130 ºC, v_g equal 3 - 6 m/s. All experiments were at atmospheric pressure.

2.2. Data Analyzing

From the mass reduction of the sample, the dimensionless moisture content *MR* [9] can be calculated as follows:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

where: M_o, M_t and M_e are mass of the sample at the initial time, at the time of τ, and equilibrium respectively.

In terms of the product's color, the difference between the color of the fresh sample and the dried sample is determined by the WR-100QC digital colorimeter. The measured points are 4 symmetrical areas including 2 areas on the line parallel to the gas direction and 2 areas on the line perpendicular to the gas direction. Colors are analyzed according to the LAB color system. This color system is characterized by coordinates CIE *L*(brightness)* *a*(green)* *b*(red). Total difference of dried sample and fresh sample [2] is determined by :

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2} \quad (2)$$

where: *L, a, b* are obtained from the dried sample and L_0, a_0, b_0 are measured from fresh samples.

Besides the color analysis, shrinkage is also an important aspect to evaluate product quality. The deformation after drying process is analyzed by comparisons of surface area before and after drying. The percentage of shrinkage is calculated by:

$$\Delta SH = \frac{S_1 - S_2}{S_1} \times 100\% \quad (3)$$

where: S_1 and S_2 are the initial surface and final surface area of product. It is assumed that the pear sample surface is circle while the mango surface is semi-circle. The diameters parallel and perpendicular to airflow directions are measured. The average diameter followed by area surface is calculated from diameter values of final product and initial sample.

3. Results

3.1. Effect of Drying Conditions on the Evaporation

Changes in moisture rate over time at different temperatures and gas velocity are shown in Fig. 3 to Fig. 10. For all cases, the drying time is about 28 to 221 minutes. On one hand, at all gas velocities, evaporation is faster at higher temperatures, but this effect is significant only at low velocities. The drying speed is greatly influenced by the drying agent temperature for the airdrying agent environment, while for the superheated steam environment, the most obvious difference is in the modes with high drying agent speed. On the other hand, at the same temperature, drying is faster at higher gas velocity. At high temperatures, the effect of velocity on drying time is negligible. The results are consistent with the theory of evaporation. For high temperatures, the large temperature difference between the sample and the drying agent results in a large heat flow, at which point the temperature will control the heat transfer and the change in the volume of water in the sample. In case of large inlet drying agent velocity, it will lead to a high heat transfer coefficient and the velocity will govern the evaporation. At the same gas velocity and gas temperature, the use of superheated steam enhances the rate of evaporation of moisture in the drying material, drying time in the SSD is shorter than that in hot air drying (HAD).

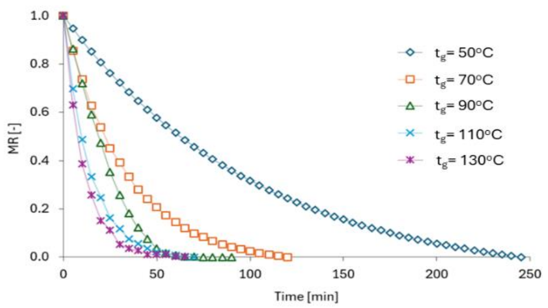


Fig. 3. Evaporation of pear slice at a gas velocity v_g of 3 m/s (HAD)

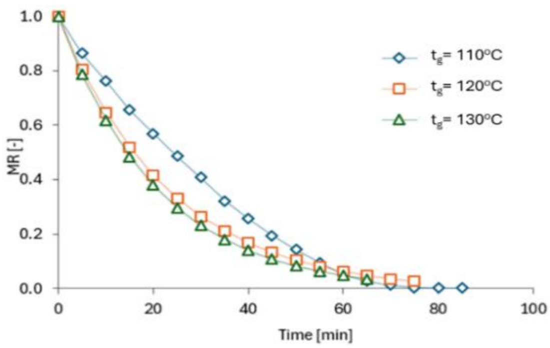


Fig. 4. Evaporation of pear slice at a gas velocity v_g of 3 m/s (SSD)

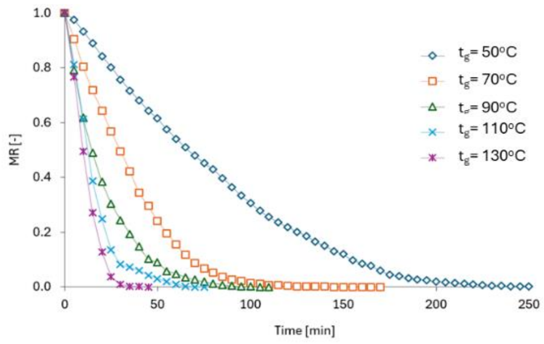


Fig. 5. Evaporation of pear slice at a gas velocity v_g of 6 m/s (HAD)

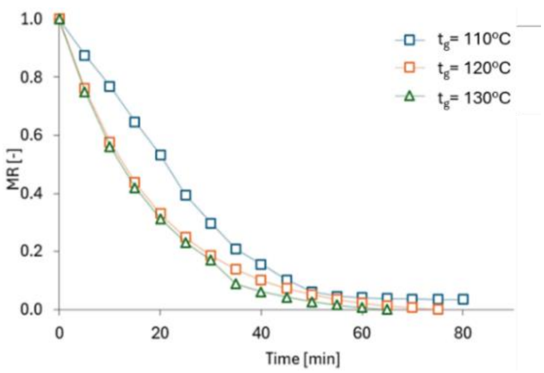


Fig. 6. Evaporation of pear slice at a gas velocity v_g of 6 m/s (SSD)

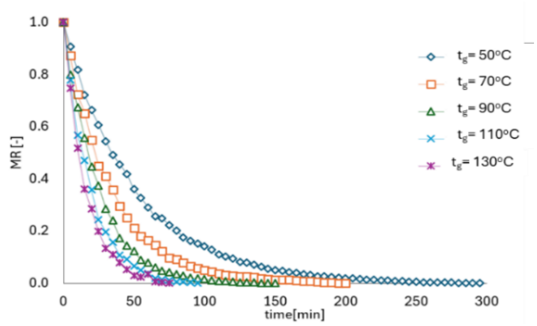


Fig. 7. Evaporation of mango slice at a gas velocity v_g of 3 m/s (HAD)

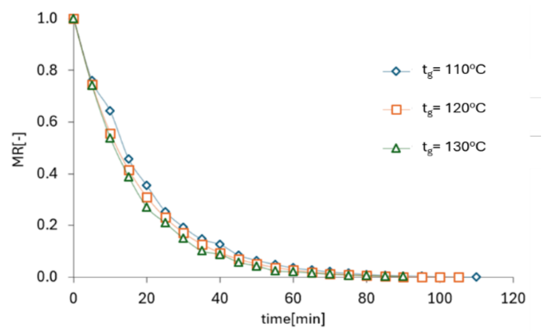


Fig. 8. Evaporation of mango slice at a gas velocity v_g of 3 m/s (SSD)

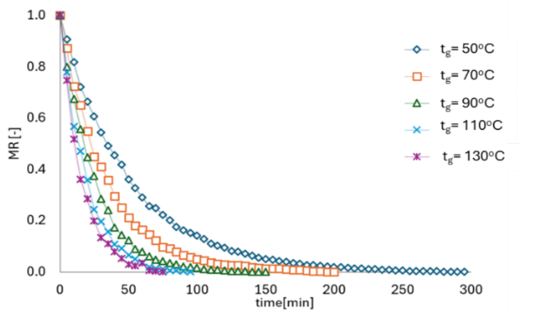


Fig. 9. Evaporation of mango slice at a gas velocity v_g of 6 m/s (HAD)

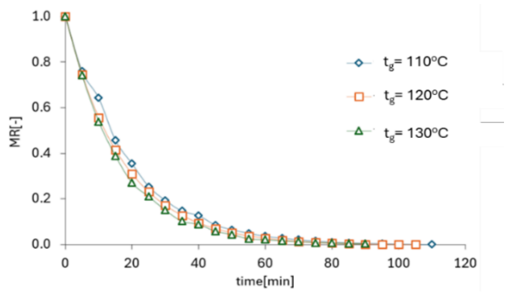


Fig. 10. Evaporation of mango slice at a gas velocity v_g of 6 m/s (SSD)

3.2. Product Color

Table 2 and Table 3 show the pictures of apple slices dried in the hot air and superheated steam corresponding with the color changes in Fig. 11.

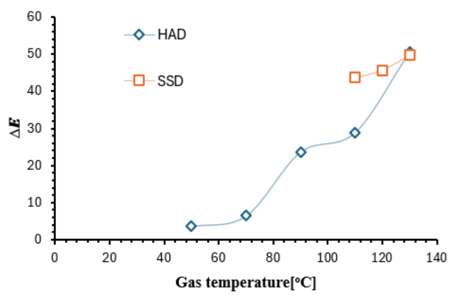


Fig. 11. The effect of temperature and on product color

It is observed that for both HAD and SSD, the color difference increases if the temperature drying rises. However, for HAD, at temperature below 70 °C, the color changes smoothly at different temperatures; dried products brown strongly at temperature higher than 70 °C. At the same drying temperature, products dried in SSD brings slightly worse color than product dried in HAD. In 130 °C, products obtained from both HAD and SSD are burned.

Table 2. Sample image of the pear products in HAD

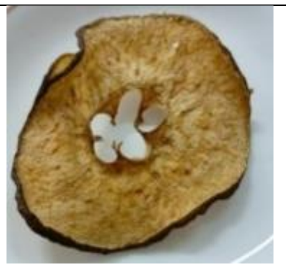
Fresh sample	50 °C
	
70 °C	90 °C
	
110 °C	130 °C
	

Table 3. Sample image of the pear products in SSD

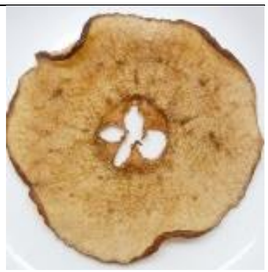
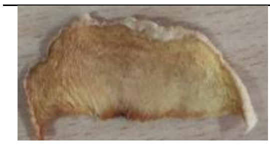
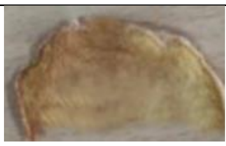
Fresh sample	110 °C
	
120 °C	130 °C
	

Table 4. Sample images of mango products in HAD

Fresh sample	50 °C
	
70 °C	90 °C
	
110 °C	130 °C
	

Like pears, dried mango slices are shown in Table 4, Table 5 and Fig. 12. In HAD, the color difference changes insignificantly at temperatures below 100 °C; however, at temperatures above 100 °C, for both HAD and SSD, color differences change significantly and at 130 °C, products are burned. At temperature lower than 120 °C, color of product in SSD is better than that in HAD.

Table 5. Sample image of mango products in SSD

Fresh sample	110 °C
	
120 °C	130 °C
	

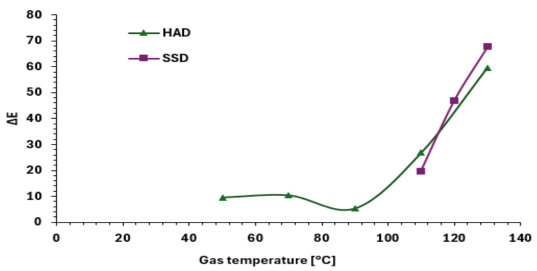


Fig. 12. Color change of dried mango

3.3. Shrinkage

The shrinkage values of pear and mango are shown in Fig. 13 and Fig. 14. Products obtained from SSD at all temperature drying are much lower than those of products from HAD. This proves that dried products in superheated steam have higher porosity than that of products from HAD. At the highest temperature, products from HAD shrink 36.36% while dried sample from SSD shrinks only 24.73%. That can explain that in SSD, the sample dries faster than that in HAD, resulting in the hard layer on the surface of sample dried in SSD is formed earlier and this layer will keep the shape of the sample better sample dried in HAD.

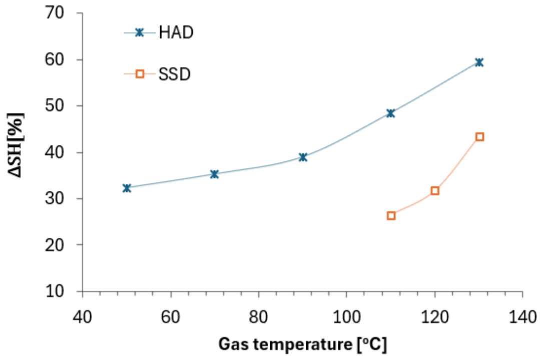


Fig. 13. Shrinkage of dried pear

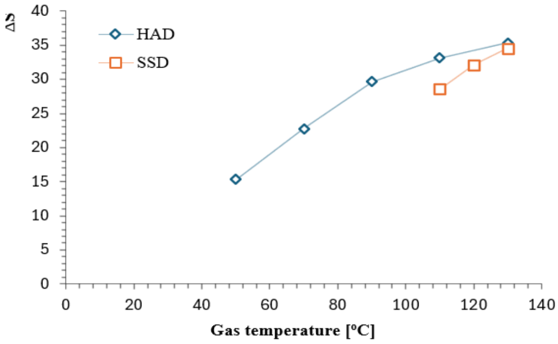


Fig. 14. Shrinkage of dried mango

3.4. Empirical Model

After data analysis and the process of evaluating the dynamics of the drying process, experimental models were built to predict the drying time of sample. Newton's model is applied to describe the drying kinetic as [10]:

$$MR = \exp(-k\tau) \quad (4)$$

where: k is the parameter determined by fitting (4) and experiment data based on least square error R^2. τ (min) is time. Results show that Newton's model is the accurate and simple methods. The obtained parameters k of Newton's model for pear at individual drying conditions are listed in Table 6. From Table 6, k is correlated as functions of gas temperature and velocity. k factors in equations below are functions of two variable which are gas velocity and temperature. Those functions are linear functions with the parameters are determined by the at least square method in Matlab (version 2020). The results for pear slices dried in HAD and SSD are:

$$k = f(t_g, v_g) = -0.03834 + 0.001005 \times t_g - 0.0007474 \times v_g \quad (5)$$

$$k = f(t_g, v_g) = -0.06004 + 0.0007751 \times t_g + 0.003223 \times v_g \quad (6)$$

It is similar for mango slices, the results are shown in Table 7 and the corresponding correlations are expressed by:

$$k = f(t_g, v_g) = -0.0165 + 0.0005 \times t_g - 0.0015 \times v_g \quad (7)$$

$$k = f(t_g, v_g) = -0.0035 + 0.0005 \times t_g + 0.0012 \times v_g \quad (8)$$

To validate the accuracy of the experimental model, change of moisture rate obtained from the model is compared with the experimental data as Fig. 15 to Fig. 18 for SSD and HAD. For all cases, there is good agreement between the experiment and the model. This implies that the built models can be applied for calculation of designing and simulation of the whole dryer.

Table 6. Parameters of the empirical models for pear in two cases: HAD and SSD

t_g (°C)	v_g (°C)	HAD		SSD	
		k	R^2	k	R^2
50	6	0.0125	0.9775	-	-
70	6	0.0259	0.9733	-	-
90	6	0.03862	0.9829	-	-
110	6	0.0735	0.9597	0.04324	0.987
120	6	-	-	0.05364	0.992
130	6	0.08639	0.9748	0.06070	0.996
50	5.5	0.01311	0.9803	-	-
70	5.5	0.02395	0.9795	-	-
90	5.5	0.03859	0.9819	-	-
110	5.5	0.07339	0.9543	0.04298	0.978
120	5.5	-	-	0.05337	0.997
130	5.5	0.07502	0.9506	0.05783	0.996
50	5	0.01621	0.9838	-	-
70	5	0.02569	0.9724	-	-
90	5	0.04494	0.9526	-	-
110	5	0.08008	0.9861	0.03943	0.976
120	5	-	-	0.05035	0.998
130	5	0.1152	0.9673	0.05512	0.994
50	3	0.01309	0.9612	-	-
70	3	0.03241	0.9849	-	-
90	3	0.04457	0.9708	-	-
110	3	0.07033	0.9809	0.03497	0.972
120	3	-	-	0.04457	0.994
130	3	0.08558	0.9741	0.04898	0.995

Table 7. Parameters of the empirical models for pear in two cases: HAD and SSD

t_g (°C)	v_g (°C)	HAD		SSD	
		k	R^2	k	R^2
50	6	0.0201	0.9996	-	-
70	6	0.0302	0.9999	-	-
90	6	0.0414	0.9989	-	-
110	6	0.0538	0.9985	0.0544	0.999
120	6	0.0613	0.993	0.0593	0.999
130	6	0.0649	0.9986	0.0624	0.997
50	5.5	0.0194	0.9996	-	-
70	5.5	0.0297	0.9999	-	-
90	5.5	0.0400	0.9996	-	-
110	5.5	0.0488	0.9975	0.0540	0.978
120	5.5	0.5673	0.9954	0.0573	0.997
130	5.5	0.0604	0.9960	0.0630	0.996
50	5	0.0187	0.9994	-	-
70	5	0.0288	0.9998	-	-
90	5	0.0373	0.9986	-	-
110	5	0.0488	0.9949	0.0527	0.997
120	5	0.5365	0.997	0.0587	0.999
130	5	0.0613	0.9985	0.0629	0.999
50	3	0.0162	0.9971	-	-
70	3	0.0256	0.9998	-	-
90	3	0.0347	0.9917	-	-
110	3	0.0448	0.9978	0.0509	0.997
120	3	0.0579	0.9985	0.0540	0.998
130	3	0.0643	0.9977	0.0603	0.996

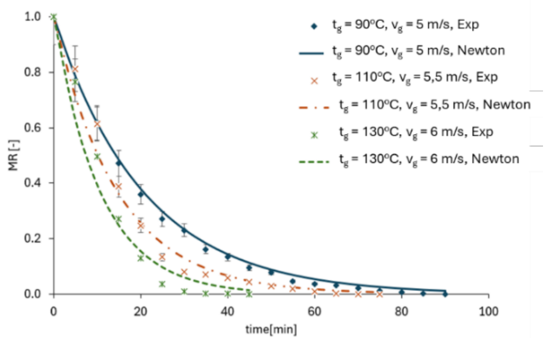


Fig. 15. Comparison of experimental data and simulation of pear in SSD

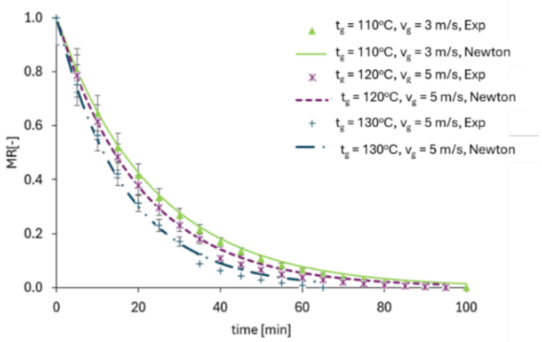


Fig. 16. Comparison of experimental data and simulation of pear in HAD

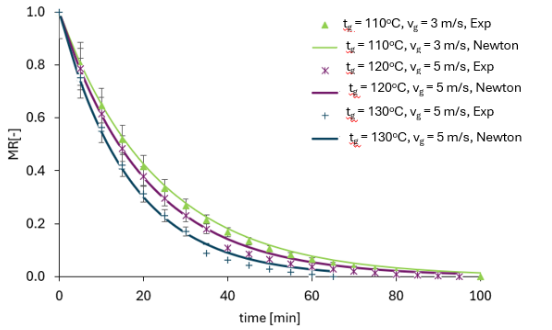


Fig. 17. Comparison of experimental data and simulation of mango in SSD

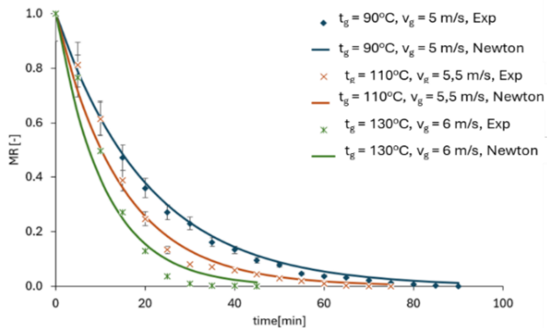


Fig. 18. Comparison of experimental data and simulation of mango in HAD

4. Conclusion

This work presents experiment study on the drying of pear and mango slices in hot air and superheated steam agents. Results show that evaporation speed is faster at higher gas velocity and gas temperature. However, the effects of gas temperature at higher gas velocity are weaker than these effects at lower gas velocity. At the same drying temperature, the drying time of SSD is shorter than in HAD. Besides, the products dried in SSD shrink less than that in HAD. These aspects evident the advantages of SSD in compared with HAD. However, the color of products exposed in SSD is darker than product in HAD. To evaluate the application ability of SSD, the quality should be evaluated in other nutritional aspects which will be the next steps of this work. Besides, the simulation of the whole dryer should be considered to calculate the spatial distributions of gas velocity, temperature, moisture, and effects of those on the evaporation process of the sample to optimize the drying process. In the future work, the different numerical models like the second Fick's law, the average volume technique will be applied to simulate the evaporation process in both micro and macro scale.

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