DEVELOPMENT OF DRYING KINETICS OF BITTER GOURD SLICES (*Momordica charantia L.*) IN A COMBINED HEAT PUMP-HOT WATER SOLAR SYSTEM

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ABSTRACT

In this study, the drying of sliced bitter gourd (*Momordica charantia L.)* at low temperature in a heat pump system combined with solar hot water was studied. Due to the role of heat pump and hot water from solar energy, the drying process can be operated at low temperature, high drying speed while still maintaining the quality of dried products such as vitamins, proteins, and colors. Experiments with pre-drying time using solar hot water system (for 1, 2 and 3 hours) and then continuing drying with heat pump system with different thicknesses of sliced bitter gourd slices (2mm, 4mm and 6mm) at the same temperature was conducted to find effective operating conditions. The kinetic model for drying sliced bitter gourd in a heat pump combined with solar hot water was then proposed to optimize the drying process.

Keywords: *Combined; heat pump; hot water solar; drying.*

TÓM TẮT

Nghiên cứu này thực hiện việc sấy mướp đắng thái lát ở nhiệt độ thấp bằng hệ thống sấy bơm nhiệt kết hợp hệ thống nước nóng năng lượng mặt trời. Các thực nghiệm sấy được thực hiện ở nhiều điều kiện khác nhau về thời gian sấy bằng nước nóng năng lượng mặt trời và chiều dày lắt mướp đắng khác nhau để tìm ra chế độ sấy phù hợp. Đồng thời nghiên cứu cũng đưa ra mô hình động học quá trình sấy mướp đắng thái lát bằng hệ thống sấy bơm nhiệt kết hợp hệ thống nước nóng năng lượng mặt trời nhằm ứng dụng trong việc tối ưu quá trình sấy.

Từ khóa: *Kết hợp; bơm nhiệt; nước nóng năng lượng mặt trời; sấy.*

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NOMENCLATURE

M_0: Initial moisture content (-)
M_t: Moisture content at time t (-)
M_e: Equilibrium moisture content (-)
a, b, c, n: Empirical constants (-)
k : Model parameter (h^{-1} or h^{-n})
t: Drying time (h)

1. INTRODUCTION

The bitter gourd *(Momordica charantia L.)* is one of the important members of the Cucurbitaceae family. It is a well-known tropical vegetable grown across the world for both culinary and medicinal purposes due to its health-related benefits [1, 2]. Bitter gourd is recognized for its nutritional and therapeutic properties and is a nutrient- and antioxidant-rich vegetable regarding polysaccharides, protein, vitamins, β-carotene and minerals [3, 4]. The bioactive components of bitter gourd, comprising polysaccharides, saponins, triterpenoids, alkaloids, and flavonoids, are valuable for their diverse pharmacological functions, such as antimicrobial, antioxidant, antidiabetic, neuroprotective, and immune enhancing effects [1]. Bitter gourd is used to treat high blood pressure, diabetes, cancer, malaria and other gastrointestinal problems [9]. Moreover, bitter gourd is easily cultivable that this plant is farmed quite widely in many countries including Vietnam for the purpose of nutritive and medicinal applications.

In order to utilize precious components from the plants, processing and preservation methods should be carried out. One of the common preservation techniques applied to plants leaves and fruits is drying and/or dehydration. In general, drying can cause some negative effects such as loss of nutrients and vitamins. However, under suitable technology and effective operating conditions, preservation by drying can improve the shelf life of the vegetable and medicinal plants without a change in nutritional value [5]. In this study, bitter gourd slices were treated for preservation and further processing by drying method using a combined heat pump - hot water solar system. Various drying regimes at low temperature were conducted for the development of the drying kinetics.

2. MATERIAL AND METHODS

2.1. Material

Bitter gourds, 150.5 ± 10.44mm long and 40.87 ± 7.5mm in diameter, ripe in color and softness, were kindly harvested from a private garden in Dong Cao commune, Thach That district, Hanoi city. In order to prevent the bitter gourds from being damaged, they were stored in separate boxes and transported to the laboratories of Hanoi Industrial University. During the trials, harvested bitter gourds were rinsed with tap water and dried with towels, then sliced into 2, 4, and 6mm thicknesses. After the slicing process, the slices that could not achieve a uniform ring form were separated for further processing. All sliced bitter gourds were weighed and placed on drying trays. The initial and final moisture contents of materials were determined by the standard methods.

2.2. Drying equipment

The heat pump drying system combined with the solar hot water system used in this study was designed and manufactured at Hanoi University of Industry. This system includes a heat pump system, a heat exchanger using solar hot water, a centrifugal blower and a thermostat installed in the drying chamber. The ingredients to be dried are stacked on the drying tray so that the bitter gourds slices on the tray can absorb energy evenly. The operation of the heat pump and solar hot water heat exchanger is controlled through a HMI and PLC control system. The system's principle diagram is depicted in Fig. 1. The temperature of the drying air can be adjusted in the range of 25 - 60^{o}C.

2.3. Drying experiments

Prior to the conduction of drying experiments, initial and final moisture contents of the raw materials were determined as mentioned above. The moisture content of bitter gourds slices before drying was 77.5% (wet basis) and that of the finished product was 10% (wet basis). Nine experiments at three different drying time with hot water solar (1h, 2h and 3h) with different thickness (2, 4, and 6mm) at 50^{o}C. The sample weight of raw materials was kept constant at 1000g for each run. Before drying, the chamber was heated up to the desired temperature and the materials were distributed uniformly on dryer tray. During the drying time, moisture loss was recorded and the process was continued until the moisture content of the dried materials reached about 10%. The design of experiments is given in Table 1 for the study of bitter gourds slices on a heat pump - hot water solar drying system.

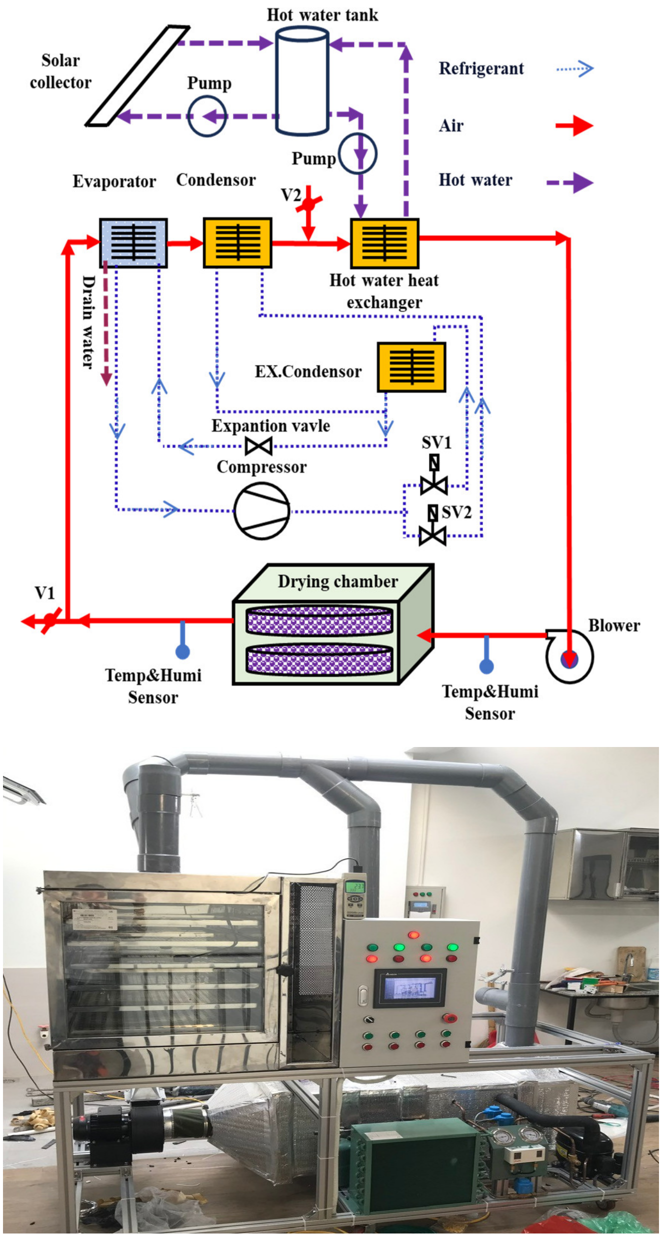


Fig. 1. Schematic diagram of the combined heat pump - hot water solar dryer used in this study

Table 1. Design of experiments for the drying characteristics of bitter gourds slices

Experiments	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9
Thickness (mm)	6	4	2	6	4	2	6	4	2
Pre-drying time with hot water solar system (h)		1			2			3	
Drying temperature (°C)					50				

2.4. Kinetic development

In order to study the kinetics of drying process, establishment of drying curves is required as the first step. This drying characteristic was created from experimental data through the calculation of the moisture ratio - a dimensionless variable describing the moisture loss with respect to drying time. The moisture ratio is usually determined by Equation (1) as follows:

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

In most studies, authors often use the simplified moisture ratio expressing by Equation (2) since the value of equilibrium moisture content is small compared to that of other variables.

$$MR = \frac{M_t}{M_o} \quad (2)$$

Table 2. Mathematical models used to describe the drying kinetics

Model designation	Model equation	Number of model parameters
Newton	MR = exp(-kt)	1
Page	MR = exp(-kt^n)	2
Page modified	MR = exp(-(kt)^n)	2
Wang and Singh	MR = 1 + at + bt^2	2
Logarithmic	MR = aexp(-kt) + c	3
Two-term exponential	MR = aexp(-kt) + (1 - a)exp(-kat)	3
Midilli	MR = aexp(-kt^n) + bt	4

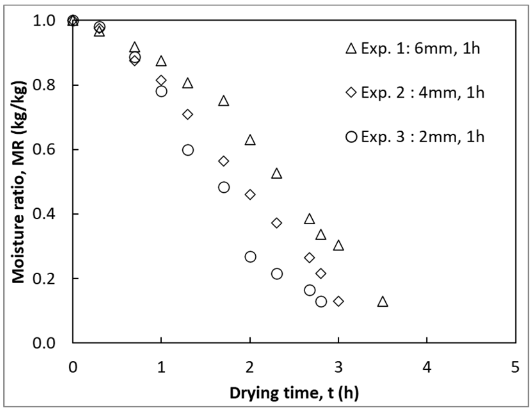
Kinetics parameters of air drying process are often estimated based on a mathematical model. Many empirical models were reported in the literature [6, 7] and some popular ones that can be applicable to the drying of fruits and vegetables were given in Table 2.

It was suggested that the Page model was widely applicable in the drying of thin layer; therefore, this model was selected for the kinetics development in this study. The kinetics parameters were determined by nonlinear regression method in which the goodness of fit between numerical results and experimental data was evaluated based on the coefficient of determination (R^2), root mean squared error (RMSE), and chi-square (χ^2) analyses. The higher value of R^2 and the lower values of χ^2 and RMSE are, the better-predicted parameters are. Detailed calculations of these statistical parameters (R^2, χ^2, and RMSE) can be found elsewhere [8].

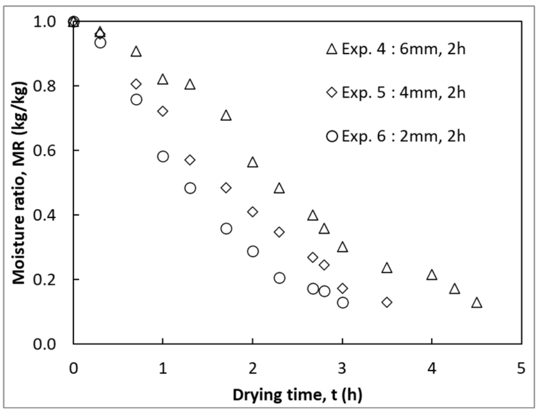
3. RESULTS AND DISCUSSION

3.1. Drying characteristics of bitter gourds on a combine heat pump - hot water solar system

The moisture ratio calculated from nine experimental data for the drying of bitter gourds slices on a heat pump - hot water solar dryer system at different operating conditions was shown in Fig. 2 as a function of drying time. For each run, the temperature in the drying chamber is keeping constant.



a)



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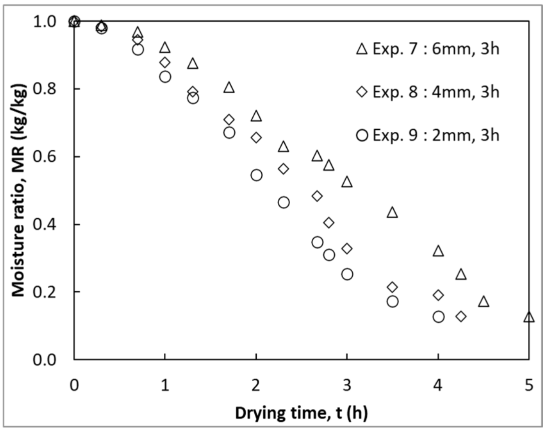

c)

Fig. 2. Drying curves of bitter gourds slices at various operating conditions: (a) 1h with hot water solar, (b) 2h with hot water solar; (c) 3h with hot water solar

It was observed that at a thickness of 2mm, the drying rate of the drying process was the fastest when pre-dried with solar hot water for 1 hour (see Fig. 2(a)). As the thickness increases (4 and 6mm) or the solar hot water pre-drying time becomes longer (2 and 3h), the drying rate tends to decrease. This phenomenon can be explained by the fact that if the material thickness increases, the mass transfer rate of moisture within the material to the surface slows down, causing the overall drying rate to decrease. On the other hand, when pre-drying with solar hot water for a longer time, the air humidity entering the drying chamber is higher than when drying with a heat pump, leading to a decrease in drying rate.

When pre-drying with solar hot water at the same time, the drying rate increases as the thickness of the dried material decreases. This is obviously understandable because the rate of moisture diffusion in the material to the surface is inversely proportional to the thickness of the material. This study shows that the highest drying rate of sliced bitter gourds on the heat pump drying system combined with solar hot water is performed at a pre-drying time of 1 hour and with a bitter gourds slices thickness of 2mm.

3.2. Estimation of kinetics parameters

Data of moisture ratios obtained from experimental measurement as a function of drying time was fitted to Page model for the determination of drying kinetic parameters. As given in Table 1, Page model consists of two empirical constants (k and n). These two parameters were determined by a nonlinear regression method. Values of these constants for nine experimental runs along with statistical evaluation values (R^2, χ^2, and RMSE) are given in Table 3.

The regression results from Table 3 showed that values of R^2 were higher than 0.99 and χ^2 were lower than 1.5E-4. These statistical values indicated that the Page model with the estimated constants agreed well with measured data.

Fig. 3 showed numerical results of the moisture ratio equation developed from the Page model in comparison with experimental data. As expected, the mathematical modeling fitted well with measured data. In overall, the Page model, however, was well represented the drying characteristics of bitter gourds slices on a heat pump - hot water solar assisted system. Therefore, the model is applicable in scale-up design and process control as well.

Table 3. Predicted constants of Page model and statistical analysis of oleifera leave drying

Experiments	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Exp. 4**	**Exp. 5**	**Exp. 6**	**Exp. 7**	**Exp. 8**	**Exp. 9**
Thickness (mm)	6	4	2	6	4	2	6	4	2
Pre- drying time with hot water solar system (h)	1			2			3		
Drying temperature (°C)	50								
k	0.097	0.204	0.275	0.172	0.345	0.495	0.074	0.118	0.158
n	2.326	1.958	2.027	1.669	1.400	1.327	2.015	1.967	1.915
MSE	0.0007	0.0003	0.0008	0.0007	0.0003	0.0003	0.0005	0.0005	0.0002
RMSE	0.0256	0.0178	0.0276	0.0256	0.0176	0.0181	0.0220	0.0215	0.0131
χ^2	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
R^2	0.9930	0.9966	0.9930	0.9926	0.9960	0.9966	0.9941	0.9947	0.9982

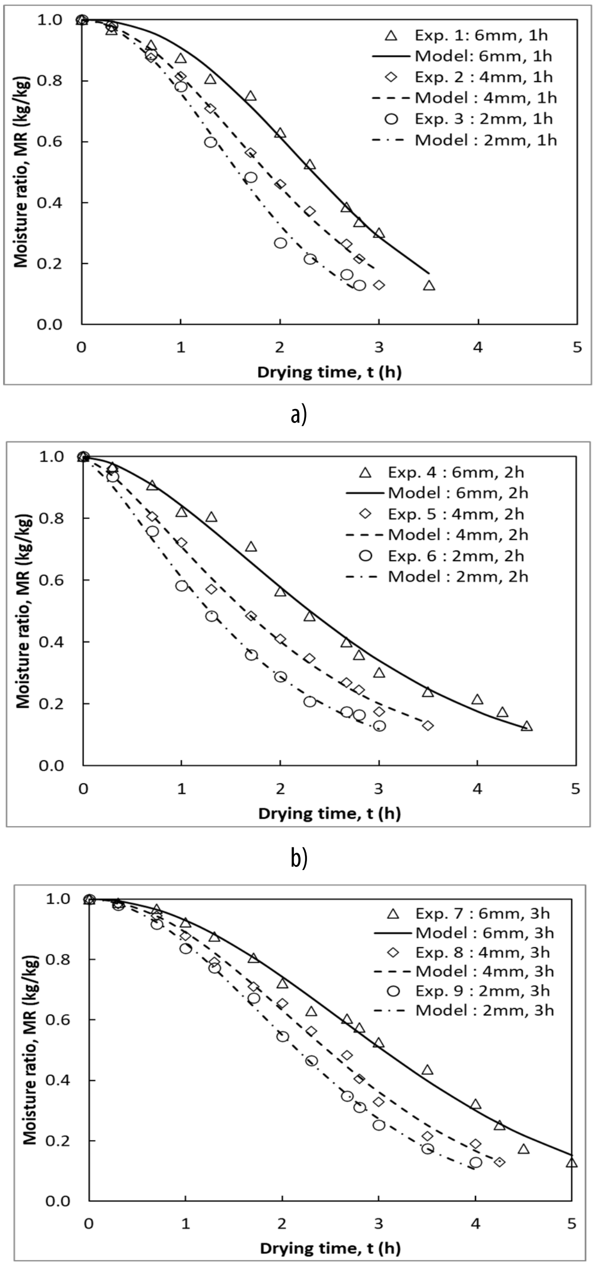

Fig. 3. Kinetic modeling of bitter gourds slices drying on a combined heat pump - hot water solar system in comparison with experimental data: (a) 1h with hot water solar, (b) 2h with hot water solar; (c) 3h with hot water solar

4. CONCLUSIONS

Drying characteristics of bitter gourds slices on a combined heat pump – hot water solar system were studied. Nine different operating conditions were selected for the design of experiments in which thickness varied in the range of 2mm to 6mm, pre-drying with solar hot water with time varied in the range of 1h to 3h and temperature at 50°C. The most efficient operating condition obtained from the experimental data with respect to the thickness were 2mm at 50°C and 1h pre-drying with hot water solar system. Based on measured data, Page model was utilized for the kinetics development. The estimated model constants made the mathematical model agree well with experimental data. Thus, the Page model along with the proposed parameters is applicable for the purpose of process control and scale-up design.

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