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HEAT AND MASS TRANSFER IN INFRARED ASSISTED HEAT PUMP DRYING OF PURPLE YAM

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ABSTRACT

This study focused on an engineering problem of heat and mass transfer in infrared (IR) assisted heat pump (HP) drying of purple yam including both a drying experiment and theory of heat and mass transfer mathematical equations. The experimental drying of yam by the IR assisted HP drying method was performed to evaluate the effect of IR power on drying rate and heating rate. The input drying parameters included the drying air temperature of 50°C, drying air velocity of 2.5 $m \cdot s^{-1}$ and IR power of 0, 300 and 350 W, in which, at the IR power of 0 W, the HP-only drying mode was performed. The experimental drying results showed that the IR assisted HP drying method could improve the drying rate and heating rate as compared to HP-only drying. At the IR power of 350 W, the drying time was the shortest (150 minutes), followed by the IR power of 300 W (210 minutes) and HP-only drying (300 minutes). The IR assisted HP drying obtained the high heating rate as the time required for the drying material to reach the drying temperature was about 35 and 25 minutes corresponding to the IR power of 300 and 350 W. While in HP-only drying, it took about 270 minutes for the drying material's temperature to reach nearly the drying air temperature value. Besides, the comparison between the predicted data by numerically solving the heat and mass transfer equations and experimental drying data was also conducted. The analysis results indicated that the predicted data could be used to predict the experimental data accurately. The theoretical results of heat and mass transfer in the IR assisted HP drying process as well as experimental drying results would be the basis for improving the IR assisted HP drying equipment to achieve the drying efficiency including the drying rate, quality of dried products, and energy consumption.

Introduction

Yam has been statistically classified into over 600 species in the world. Yams are grown in many tropical countries such as Burkina Faso, Ghana, Togo, Nigeria, and Vietnam. Some types of yams as purple yam, yellow yam and water yam were used commonly for food purposes (Olatoye and Arueya, 2019). Yams contain many nutrients such as carbohydrates, proteins, minerals, starch, lipids, and vitamin C, that are very good for human health (Kartik et al., 2023; Kai-Nong et al., 2019). However, yams as well as other agricultural products, have a high moisture content of about 50-80 (%, w.b). The high moisture content in material will stimulate bacterial activities, and biochemical reactions (Kaveh et al., 2019). So, high moisture could make yam spoilt during a long-term storage (Linlin et al., 2019). Drying has been used as an effective preservation method for agricultural products (Abbaspour et al., 2019; Srikanth et al., 2019). The drying process was a complex thermal exchange process, in which the heat and mass transfer process occurred simultaneously (Siyabonga et al., 2022). The drying method and input drying parameters have a great influence on not only the structure, color, surface appearance of dried products but also the drying rate and energy consumption (Priyanka et al., 2022; Bei et al., 2020; Milivoj et al., 2021; Chojnacka et al., 2021; Abhishek et al., 2020; Abhishek et al., 2019; Osman and Fatma, 2019; Waheed and Komolafe, 2019; Villalobos et al., 2019; Kadriye et al., 2019).

The drying process commonly includes three major heat transfer methods such as conduction, convection, and radiation (Liu et al., 2019). There have been some common drying technologies applied for drying agricultural products including sun drying, hot air convective drying, heat pump drying, vacuum drying, microwave drying, radio frequency drying, infrared drying and hybrid drying (Fakhreddin, 2021; Omari et al., 2019; Abbaspour et al., 2019). Sun drying is a low-cost method of drying materials in large quantities. However, this method does not guarantee food hygiene and safety and it depends on the weather condition. Vacuum drying is an effective drying method for some precious materials such as medicinal herbs, and the dried products can retain a high sensory and nutritional quality. However, vacuum drying has some disadvantages such as a high cost of the drying equipment, long drying time, and the strict equipment operating techniques required. Hot air convective drying with some advantages as a high drying rate, easy operation and low operating cost has been widely used for drying agricultural products (Omari et al., 2019). But the high drying air temperature could reasonably affect the quality of dried products. In heat pump drying, the drying air with low humidity and low temperature could support the moisture diffusion process and improve the drying rate (Fakhreddin, 2021). Drying techniques using infrared radiation have several advantages such as a higher heating rate, shorter drying time and higher drying product quality (Salam et al., 2019). In which, IR heating mechanism is the effect of the electromagnetic radiation on drying material, that causes the internal heating generation within material and increases the heating rate (Fasina et al., 2001; Dan et al., 2021). Hybrid drying using IR combining with other drying methods as hot air convective drying and heat pump drying can obtain an effective drying process, in which, the drying rate becomes higher due to the IR heating mechanism, and the dried products obtained a better quality (Onwude et al., 2019; Qu et al., 2019; Wu et al., 2019; Zi et al., 2020).

There were some previous studies on the heat and mass transfer in the hybrid drying process using radio frequency, microwave, and IR for food and agricultural products (Salehi and

Kashaninejad, 2019; Fakhreddin, 2020; Edna et al., 2021; Lisen et al., 2023; Nguyen et al., 2022; Le et al., 2022; Le et al., 2023). In the studies, the heat and mass transfer equations were established, in which, the convective heat exchange, the heat conduction, and the heat generated within the material by radio frequency, microwave, and IR power absorption were considered.

There were some previous studies of yam drying to evaluate the efficiency of the drying method and quality of dried products. Ononogbo et al. (2022) carried out the experimental drying of yam by hot air convective drying to evaluate the drying rate at different drying modes. The input drying parameters were temperature in range of 55-75°C, drying air velocity in range of 1.0-2.0 m s^{-1} and the sample slice thickness of 1.0-2.0 mm. The experimental drying results showed that the drying time varied from 195-705 minutes, and the drying rate was higher at a higher drying temperature and higher drying air velocity. Adebimpe et al. (2021) studied the thin layer drying of yam slices by hot air-drying method under two initial conditions as blanch-assisted and un-blanch-assisted. The input drying parameters were the drying air temperature of 50, 60 and 70°C, the drying air velocity of 0.8 $m \cdot s^{-1}$ and yam slice thickness of 0.8 cm. The results showed that under the blanch-assisted condition, the drying rate was significantly higher than under the un-blanch-assisted condition. Chineze et al. (2020) investigated the effect of different drying methods in drying different kinds of yam. The drying methods were used as sun drying, solar drying, and oven drying. The experimental drying results indicated that the drying time of oven drying was the shortest (180-300 minutes), followed by solar drying (390-480 minutes) and sun drying (780-960 minutes). In which, in the oven drying method, the drying time for purple yam was the shortest (180 minutes), followed by yellow yam (240 minutes) and white yam (300 minutes). Nurdi et al. (2021) investigated the effect of different drying methods on the quality of dried yam with the oven drying, blanching oven drying and blanching freeze-drying. In which, the dried yam of the blanching freeze-drying process retained the original color best with the lowest color change index, followed by the blanching oven drying and oven drying.

There were hardly any previous studies on the heat and mass transfer in yam drying process using the IR technique. Besides, most previous studies focused only on the experimental drying of yam to compare and evaluate the effectiveness of different drying methods and drying modes. Thus, the study of heat and mass transfer in the IR assisted HP drying of yam is very necessary and practical to clarify the heat and mass transfer mechanism and effect of IR power in drying process. That would become the foundation of analyzing and improving the drying method effectively. The objective of the study focused on: i) performance of the experimental drying of yam by the IR assisted HP drying method to evaluate the effect of IR power on the drying rate and heating rate; ii) conduction of the statistical comparison between the predicted data and experimental drying data.

Materials and Methods

Material

Yam samples used for the study were fresh purple yams purchased at Thu Duc Agricultural Market, Ho Chi Minh City, Vietnam. After purchasing, purple yams were washed, peeled, and sliced to 2.5 mm thickness, and they were given in Figure 1. Figure 1 showed that the yam samples have bright purple color, succulent surface, and characteristic aroma. The initial moisture content of fresh yam samples was determined by a moisture analyzer (YOKE DSH-50A-1) and got the value of 73.8 ± 0.1 (%, w.b). The weight of yams per drying batch was 2 kg.

Figure 1. Fresh sliced purple yam samples

Experimental Methods

The IR assisted HP dryer used for the drying experiment was given in Figure 2. In which, 1. Compressor; 2. Condenser; 3. Sub-Condenser 4. Evaporator; 5. Controller unit; 6. Thermistors; 7. air pump; 8. Electronic scale; 9. infrared tubes; 10. Drying tray; 11. Yam sample; 12. Drying chamber; 13. Air pipe.

The IR assisted HP dryer was manufactured based on the working diagram given in Figure 2. The dryer was composed of a heat pump and two infrared tubes installed inside the drying chamber. The heat pump operated with the maximum capacity of 0.75 kW (Nguyen et al., 2022), and the infrared tubes had electromagnetic wavelengths ranging from 0.76-1,000 μm, frequency of 50 Hz and operating capacity of 300 and 350 W (Onwude et al., 2019). The air pump sucked and pushed the drying air to circulate through the heat pump unit concluding a compressor, condenser, expansion valve and evaporator. After circulating through the heat pump, the drying air would achieve the specific temperature, humidity, and velocity, and it continued to enter the drying chamber and combined with infrared energy for the drying process.

The initial moisture content of the yam samples was determined by a moisture analyzer (YOKE DSH-50A-1), the maximum analyzed sample weight: 50 g ± 0.01%, analyzed moisture range: 0-100%.

An electronic scale (OHAUS SPX2202) with a standard measurement value of 2200 ± 0.01 g was used to weigh the yam samples during the drying process. The weighing of yam samples was performed every 15 minutes during the drying process until the yam samples achieved the moisture content of 12 ± 0.1 (%, w.b) and completed in triplicates.

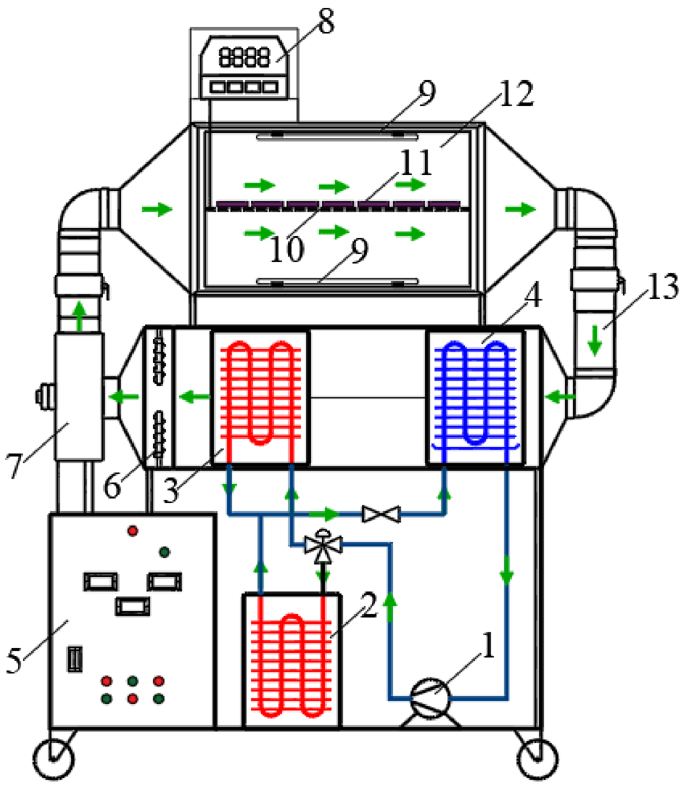

Figure 2. The IR assisted HP dryer model

The temperature of the yam sample was measured by a temperature sensor (TWEJUK00001M0AP7, Sterling Sensors, UK) with measurement ranges of -75°C – 250°C ± 0.01°C. The small head of a sensor was fixed inside the yam sample. The temperature sensor was connected to a computer software via an integrated circuit to record the temperature value of drying material by a computer software every 15 minutes during the drying process.

Method of Comparing Between the Predicted data and Experimental Drying Data

The heat and mass transfer equations in IR assisted HP drying process were used in the study as below (Cui et al., 2023).

The heat transfer equation:

$$\underbrace{\rho C_p \frac{\partial T}{\partial \tau}}_{Q_1} = \underbrace{\lambda \frac{\partial^2 T}{\partial x^2}}_{Q_2} + \underbrace{r\rho \frac{\partial w}{\partial \tau}}_{Q_3} + Q_{IR} \tag{1}$$

In which, Q_1 is internal energy change within the material, and Q_2 is heat transfer by conduction within the material, Q_3 is the heat required for vaporization of moisture within the material, and Q_{IR} is the volume heat generated within the material by infrared heat source.

The mass transfer equation:

$$\frac{\partial w}{\partial \tau} = D\frac{\partial^2 w}{\partial x^2} \quad (2)$$

The initial conditions are given as:

At τ = 0:

$$T(x,0) = T_0;\ w(x,0) = w_0 \quad (3)$$

The heat and mass transfer boundary conditions (τ > 0) are given as:

At x = 0:

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0;\ \left.\frac{\partial w}{\partial x}\right|_{x=0} = 0 \quad (4)$$

At x = δ/2:

$$-\lambda\left.\frac{\partial T}{\partial x}\right|_{x\equiv x_s} = \alpha(T_a - T)\Big|_{x\equiv x_s} - r\rho\beta_M(w - w_e)|_{x\equiv x_s} \quad (5)$$

$$-D\left.\frac{\partial w}{\partial x}\right|_{x\equiv x_s} = \beta_M(w - w_e)|_{x\equiv x_s} \quad (6)$$

The heat and mass transfer equations with specific initial conditions and boundary conditions were solved using the finite difference method on Matlab 2022 software (Nguyen et al., 2022). The heat and mass transfer problem were solved based on programming the heat and mass transfer algorithm on Matlab 2022 software.

Thermo-physical properties of yam and the drying conditions used for the numerical solution, simulation and experimental drying process were given in Table 1.

Table 1.
Drying condition and thermo-physical properties of yam

Parameters	Value
The thickness of samples, 2δ (m)	0.0025
λ (W m^{-1} °C^{-1}) (Oke et al., 2009)	$0.164 + 0.001T – 0.000T^2 + 7.676T^3$
ρ (kg m^{-3}) (Oke et al., 2009)	$1100.490 + 4.107T + 0.004T^2 – 0.004T^3$
C_p, (kJ kg^{-1} °C^{-1}) (Oke et al., 2009)	$2750.890 + 2.693T – 2.925T^2 + 0.069T^3$
r (kJ kg^{-1}) (Thuwapanichayanan et al., 2014)	250300 – 2386T
M_e (d.b) (Adesola and Satimehin, 2014)	$\left(-\frac{1}{0.1560}\right) ln\left[-\frac{(T-7.3988)}{190.44} ln(R_H/100)\right]$
w_i (% w.b)	73.8

Parameters	Value
T_i (°C)	27
T_a (°C)	50
R_H (%)	18
α (W m^{-2} °C^{-1}) (Le et al., 2023)	12.323
β_M (m s^{-1}) (Le et al., 2023)	0.012

In which, the correlation between M (d.b) and w (%, w.b) was expressed by the formula below:

$$M = \left(\frac{1}{w} - 1\right)^{-1} \quad (7)$$

The comparing parameters as the Root mean square error (RMSE) and Mean absolute error (MAE) were used for comparing between the predicted data and experimental drying data. The lower value of the comparing parameters would confirm the goodness of fit between the predicted data and experimental drying data. RMSE and MAE were defined as below:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(X_{Exp} - X_{Pre}\right)\right]^{0.5} \quad (8)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\left|X_{Exp}-X_{Pre}\right|}{X_{Pre}}\right) \quad (9)$$

Results and Discussion

The Effect of IR Power on Drying Rate

The moisture content reduction trend of yam samples during IR assisted HP drying process was presented graphically in Figure 3.

As in Figure3, the moisture content reduction trend of yam samples during the IR assisted HP drying process at different drying modes tended to be similar and consistent with the agricultural drying curve theory. In IR-assisted HP drying process, the support of IR heating mechanism improved the drying rate and significantly reduced the drying time as compared to HP-only drying, and the increase in IR power would increase the drying rate. The drying time required for the yam's moisture content to reduce to 12 (%, w.b) was 300, 210 and 150 minutes corresponding to the IR power of 0, 300 and 350 W. At the IR power of 350 W, the drying time could decrease to 28.5% and 50% as compared with the drying time at the IR power of 300 W and 0 kW. This was explained by the IR heating mechanism, in which, the IR electromagnetic radiation impacted the drying material surface, that caused the changes in the electronic, rotational, and vibrational states of atoms and molecules within material (Sakai and Hanzawa, 1994). When the materials absorb the IR radiation energy, the molecules inside the material would vibrate at a high frequency and the friction between molecules resulted in the internal heating within material and the surface temperature increased quickly, which was much faster than that in conduction and convection heat transfer (Fasina et al., 2001; Dan et al., 2021). The result was that the drying rate in the IR-assisted HP drying process was improved.

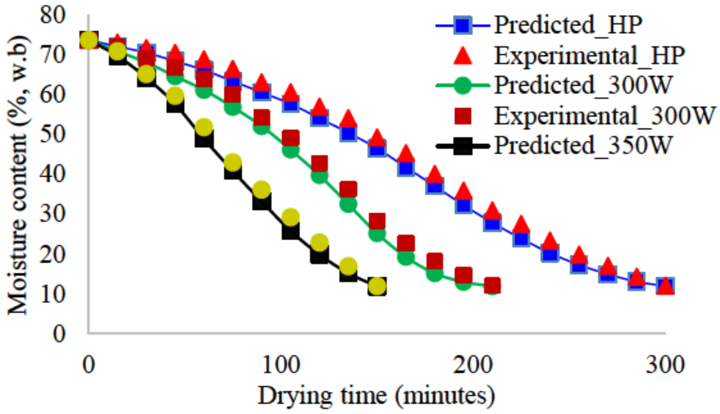

Figure 3. The moisture content reduction of yam samples during IR assisted HP drying process

The Effect of the IR Power on the Temperature of Drying Material

The change of the average temperature of yam samples during the IR assisted HP drying process was shown graphically in Figure 4.

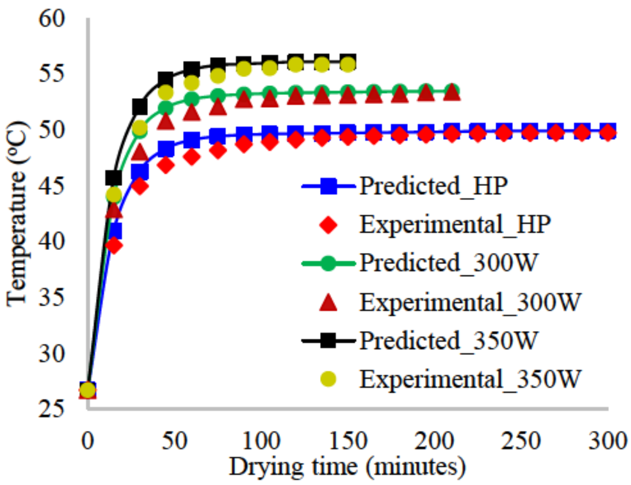

Figure 4. The relationship between the temperature of the drying material versus the drying time

As shown in Figure 4, the change in temperature of yam samples including both predicted data and experimental data during the IR assisted HP drying process at different drying modes had a similar trend. In which, the IR-assisted HP drying process with the IR assistance achieved a higher heating rate than the HP-only drying and the heating rate was proportional to the IR power. This was due to the IR heating mechanism, in which, more IR power absorbed by the material would make the heat generation inside the material by the wet dipole molecules oscillation become faster, and the result was an increase in the heating rate (Fasina et al., 2001; Dan et al., 2021). The heating duration for the temperature of drying material to reach the drying air temperature in about 25 and 35 minutes corresponding to the IR power of 350 and 300 W. While, in HP-only drying, the temperature of drying material reached the nearly drying air temperature value in about 270 minutes. In the IR-assisted HP drying process, after reaching the drying air temperature value, the material's temperature continued to increase beyond the drying air temperature because the IR radiation energy still affected the material continuously. However, the excess temperature was only about 4-6°C. This result agreed with the previous studies of the IR heating mechanism in the IR assisted drying process (Fasina et al., 2001; Dan et al., 2021).

Comparison Between the Predicted Data and Experimental Data

Figure 3 and Figure 4 have given the graph of moisture reduction and temperature change of the yam samples during the IR assisted HP drying process based on the predicted data and experimental data. Figure 3 and Figure 4 confirmed that moisture reduction and temperature change of the yam samples during the drying process based on the predicted data and experimental data had a similar tendency and profile. This indicated the graphical goodness of fit between the predicted data and experimental data.

Besides, a two-sample comparison analyzation by Statgraphics Centurion XVII on a computer was performed to determine the value of P-Ratio, which is a statistical parameter representing the difference between two data in statistically comparing. The value of RMSE and MAE were determined by Eq. (8) and Eq. (9) based on the predicted data and experimental data to validate the accuracy level of the predicted data in predicting the experimental data. The results of comparison parameters were given in Table 2.

The result in Table 2 showed that the P-value was greater than 0.05. This confirmed that there was not a statistically significant difference between the means of the predicted data and experimental data at the 95% confidence level. Besides, RMSE and MAE had a low value. Thus, the analysis results indicated that the predicted data by numerically solving the heat and mass transfer equations could be used to accurately predict the experimental data of the actual IR assisted HP drying process.

Table 2.
The analyzing parameters of comparing the predicted data and experimental data

IR power	The moisture content parameter			The temperature parameter		
(W)	P-value	RMSE	MAE	P-value	RMSE	MAE
0	0.719	1.55	7.18%	0.729	0.75	1.19%
300	0.789	1.48	7.27%	0.827	0.75	1.12%
350	0.847	1.36	6.09%	0.842	0.87	1.45%

Conclusion

The experiments of the IR assisted HP drying of purple yam slices were conducted to evaluate the effect of the IR power on the drying rate and heating rate. The results showed that the support of IR could improve the drying rate and heating rate significantly. In the IR assisted HP drying, the drying time reduced by 50% as compared with HP-only drying. The time required for the drying material's temperature to reach the drying air temperature was 25, 35 and 270 minutes corresponding to the IR power of 350, 300 and 0 W. Besides, the statistical parameters of comparison between the predicted data and experimental data confirmed that the predicted data could be used to accurately predict the experimental data. Based on the results of this study, further research in near future will focus on experimental drying and optimizing the yam drying process using the IR assisted HP method. In which, the output parameters would be considered including the drying rate, color change index, protein retention of dried products and energy consumption of drying equipment.

Nomenclature

C_p	specific heat capacity	$kJ \cdot kg^{-1}$ $°C^{-1}$
w	moisture content	% w.b
T	temperature	°C
R_H	drying air humidity	%
M	moisture content	d.b
r	latent heat of vaporization of moisture	$k \cdot kg^{-1}$
Greek letters		
δ	thickness	m
λ	thermal conductivity	$W \cdot m^{-1}$ $°C^{-1}$
ρ	density	$kg \cdot m^{-3}$
α	convective heat transfer coefficient	$W \cdot m^{-2}$ $°C^{-1}$
β_M	convective mass transfer coefficient	$m \cdot s^{-1}$
X_{Exp}	experimental value	
X_{Pre}	predicted value	
Subscripts		
a	drying air	
e	equilibrium	
i	initial	

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WYMIANA CIEPŁA I MASY W SUSZENIU POCHRZYNU SKRZYDLATEGO ZA POMOCĄ POMPY CIEPŁA WSPOMAGANEJ PODCZERWIENIĄ

Streszczenie. Niniejsze opracowanie dotyczy problem wymiany ciepła i masy podczas suszenia pochrzynu skrzydlatego za pomocą pompy ciepła wspomaganej podczerwienią, w tym doświadczenia suszarniczego oraz teorii równań matematycznych wymiany ciepła i masy. Suszenie eksperymentalne pochrzynu za pomocą metody wspomaganej podczerwienią przeprowadzono w celu oceny wpływu mocy podczerwieni na szybkość suszenia i podgrzewania. Wejściowe parametry suszenia to temperatura powietrza suszenia wynosząca 50°C, prędkość temperatury suszenia 2,5 $m \cdot s^{-1}$ oraz moc podczerwieni 0, 300 oraz 350 W, przy których, przy mocy podczerwieni wynoszącej 0W, przeprowadzono wyłącznie suszenie za pomocą pompy ciepła. Wyniki suszenia eksperymentalnego wykazały, że metoda suszenia wspomaganego podczerwienią mogła usprawnić prędkość suszenia i ogrzewania w porównaniu do metody wykorzystującej jedynie pompę ciepła. Przy mocy podczerwieni wynoszącej 350 W, czas suszenia był najkrótszy (150 min.), przy mocy 300 W (210 min.) oraz przy suszeniu pompą ciepła (300 min.). Suszenie wspomagane podczerwienią uzyskało wysokie tempo podgrzewania, ponieważ czas jaki materiał suszony potrzebował do osiągnięcia temperatury suszenia wynosił około 35 i 25 min. odpowiednio przy mocy podczerwieni wynoszącej 300 i 350 W. Podczas gdy, w suszeniu za pomocą pompy ciepła czas ten wynosił około 270 min. do momentu uzyskania przez materiał suszony temperatury suszącego powietrza. Ponadto, dokonano porównania danych przewidywanych przez rozwiązanie równań wymiany ciepła i masy z danymi suszenia eksperymentalnego. Wyniki teoretyczne mogłyby stanowić podstawę ulepszenia sprzętu suszącego wspomaganego podczerwienią w celu uzyskania wydajności suszenia w tym prędkości suszenia, jakości suszonych produktów oraz zużycia energii.

Słowa kluczowe: prędkość suszenia, prędkość podgrzewania, temperatura powietrza suszącego, prędkość suszącego powietrza, moc podczerwieni