Drying Strategy of Shrimp using Hot Air Convection and Hybrid Infrared Radiation/Hot Air Convection

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ABSTRACT

The main objective of the research was to study the effect of drying temperatures using infrared irradiation and electric heating convection on dehydration and was to investigate the effect of drying conditions on the quality of the shrimp. Two sizes of fresh shrimp (100 shrimp/kg and 200 shrimp/kg) with initial moisture content of 270 - 350 % dry-basis were dried under various conditions while the final moisture content of dried shrimp was in ranges between 20 and 25 % dry-basis. Hot air flow rates of 1.0 - 1.2 m/s, drying temperatures of 40 - 90 °C and infrared intensities of 1,785.7 - 3,571.4 W/m^2 were used in these experiments. The experimental results showed that the rate of moisture content transfer of both sizes of shrimps decreased exponentially with drying time while increasing drying temperature significantly affected to the drying kinetics and quality of the shrimps. Effective diffusion coefficients of both shrimps were determined by a diffusion model forming a finite cylindrical shape was in order of 10^{-7} m^2/s and this effective diffusion coefficient value was relatively dependent on the drying temperature compared to the initial moisture content. The quality analysis of dried shrimp using an infrared source and electric heating source found that the redness value (Hunter *a-value*) of dried samples using hybrid infrared radiation and electric heating had a higher colour uniformity than other drying methods. Additionally, shrinkage and rehydration properties were insignificantly different for all drying strategies ($p < 0.05$) and drying using infrared radiation had higher drying rates compared to electric heat convection, corresponding to relatively low drying times.

Keywords: Diffusion coefficients, infrared radiation, quality of shrimp, thin-layer drying

INTRODUCTION

Dried shrimp is one of the most important fishery products in Thailand. Its price depends on shrimp qualities such as colour, size, dryness and taste. Commonly, shrimp drying is mostly composed of boiling shrimp with salt water and then it is traditionally dried in the sun for 3 - 5 days [1]. Although natural sun drying represents a low cost processing technique, it has limitations such as the control of the drying process and parameters, weather uncertainties, large drying area, insect infestation, mixing with dust and other foreign materials [1]. The effect of salt concentration and boiling time on the quality of dried shrimp has been reported [2]. To reduce degradation and enhance the quality of the dried shrimp, research [3-6] has focused on the development of various alternative drying techniques to dry shrimp such as superheated steam drying [4,5], spouted-bed drying [3], heat pump drying [5] and solar drying [7]. Electromagnetic waves, namely microwave and infrared (IR) irradiation have also been used. Microwave and infrared radiation enhance conventional drying and are much more rapid than conventional methods [8-14]. This is because microwave and infrared waves yield unique characteristics and improved quality compared to conventionally dried products [4,15,16].

Infrared heating offers many advantages over conventional hot air drying. When infrared is used to heat or to dry fruits, the radiation impinges on the exposed fruit surfaces and penetrates to create internal heating with molecular vibration of the material, and the energy of radiation is converted into heat [10,11,13]. The depth of penetration depends on the composition and structure of the fruit and also on the wavelength of infrared radiation. Infrared and microwave, which are electromagnetic waves, can penetrate into the interior of the food, where they are converted into thermal energy, providing a rapid heating mechanism [11,13]. However, the effect of infrared radiation and hot air drying on the physical properties of the food and parameters related to moisture transfer have rarely been reported, especially the diffusion mechanism. Recently, far-infrared radiation (FIR) has been tested as a possible means for the above purpose [15,17,18]. During drying with an infrared heat source, the energy in the form of electromagnetic waves is absorbed directly by the product without loss to the environment leading to considerable energy savings [14,16-18]. However, there is only limited research on seafood drying using an infrared heat source or combined infrared and other heat sources in Thailand, especially the effect of infrared radiation on the quality of samples.

Thus the aims of this work are to investigate the quality of dried shrimp due to drying using an infrared heat source and/or hot air drying using parameters such as the Hunter *L-a-b value*, percentage of shrinkage, percentage of rehydration and effective diffusion coefficient. An equilibrium moisture content and thin-layer drying equation for determining thin-layer drying kinetics are also discussed.

MATERIALS AND METHODS

Materials

Two different sizes (100 shrimp/kg and 200 shrimp/kg) of fresh *Penaeus* spp. shrimps were provided by Songkhla central market. To deactivate and disinfect the shrimp of micro-organisms, raw samples were washed and boiled using salt water with concentration of 3 % (weight per volume) for 3 min [18]. The initial moisture content of the sample was between 270 and 350 % dry-basis and after drying the desired final moisture content was about 20 - 25 % dry-basis [2,3,5,15].

Methods

A tray drying system with a hybrid heat source was designed and constructed as shown in **Figure 1**. Solar energy, electric heating and infrared radiation energy were the heat sources for drying seafood raw materials in this work. In this experiment, the 3 stainless steel trays of boiled shrimps (1.0 kg) were dried using 2 drying strategies illustrated in **Figure 2**. Two drying strategies were carried out by using 1-stage drying with electric heating (hot air) and two-stage drying with combined electric heating and infrared heating. More details are given in the drying procedure.

The drying room has volume of $60 \times 80 \times 158.5$ cm^3. The drying room was made of stainless steel and the wall inside the drying room was insulated by a microfiber sheet 5 cm thick. The electric heater was made from a fin electric heating rod $1{,}000 \times 10$ W and an infrared rod of 500×3 W was used for these experiments while solar heating was provided by a solar collector. The dimensions of the solar collector were $32.5 \times 133 \times 240$ cm^3 and the top of the collector was covered by 0.5 cm thick Perspex glass. The solar collector was placed at 14 degree from horizontal for taking direct solar radiation. A forward-blade blower driven by a 1 HP AC motor was used for hot air convection. Hot air after drying was released to the surroundings using an air outlet pipe but could be feed back into the drying room using a recycle pipe.

The drying temperature, inlet and outlet temperature and shrimp temperature in each tray were measured using a K-type thermocouple connected to a data logger (Supcon) with an accuracy of $\pm$ 0.5 °C while the surrounding temperature (wet-bulb and dry-bulb) was also continuously recorded. Inlet air flow at the entrance tube was measured by a hot wire anemometer (Digicon model DA-45) with an accuracy of $\pm$ 0.01 m/s. Moisture loss was recorded hourly during the drying time. The weighing of shrimp was done on an electronic balance with an accuracy of $\pm$ 0.1 g. Drying was continued until the sample reached the desired final moisture level.

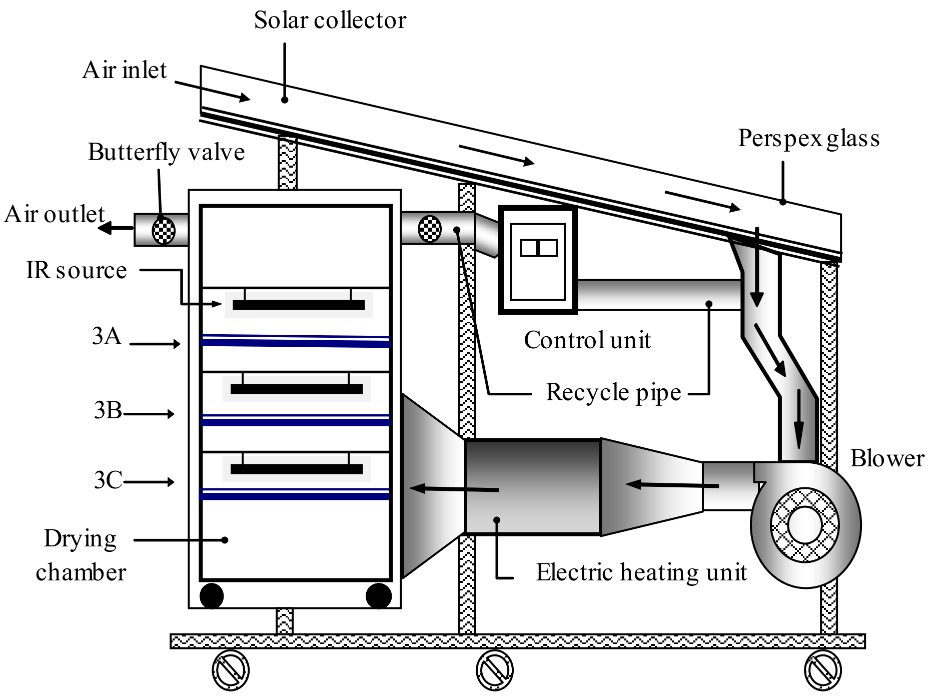


Figure 1 Hybrid heat sources tray dryer for shrimp (3A-3C are drying trays for samples).

Equilibrium moisture content (EMC)

The 5 saturated salt solutions for achieving an equilibrium moisture content stage used in this experiments were KNO_3, NaCl, $Mg(NO_3)_2$•$6H_2O$, $MgCl_2$•$6H_2O$ and LiCl. These salt solutions provided relative humidity values of 10 to 90 % [18-23] and then they were put into airtight vials. The vials was placed in an incubator at temperatures of 30, 50 and 65 °C to obtain dry matter weight. The moisture content was determined using the Association of Official Analytical Chemists (AOAC) method [24] such that the sample weight remained unchanged after 2 consecutive weighings (± 0.05 g). This phenomenon implies that the sample is in an equilibrial state with the salt solution and the surrounding air. The sample weight was taken by means of triplication. Then, the isotherm models for predicting EMC were chosen to fit the experimental data, surrounding temperature (T) and relative humidity (RH) using models proposed by Chung and Pfost [19], modified Chung and Pfost [18], Henderson [20], modified Henderson [21], Halsey [23] and Oswin [2]. All of calculated EMC equations and their coefficients were determined and are shown in **Table 1**.

Table 1 Arbitrary constants for EMC equations for large shrimps.

Model	A	B	C	R^2	RMSE
Modified Chung & Pfost [18]					
$M_{eq} = -\frac{1}{C}\left[\frac{\ln(RH)}{-A/(T+B)}\right]$	188.97	45.26	7.6	0.83	0.61
Modified Henderson [21]					
$M_{eq} = \left[\frac{\ln(1-RH)}{-A/(T+B)}\right]^{1/C}$	0.06	22.86	0.9	0.88	0.54
Halsey [23]					
$M_{eq} = \left[\frac{\ln(RH)}{-A/RT}\right]^{\frac{1}{B}}$	28.26	−1.026	-	0.92	0.14
Oswin [2]					
$M_{eq} = A\left(\frac{RH}{1-RH}\right)^{B}$	$A = 1.444\times10^{-5}\,T^{2} - 1.483\times10^{-3}\,T + 0.1023$	$B = -9.109\times10^{-4}\,T^{2} + 7.019\times10^{-2}T + 0.2999$		0.92	0.18

Note: A, B are arbitrary constants.
M_{eq} is equilibrium moisture content in decimal dry-basis.
R is the universal gas constant (8.314 kJ/kmol-K).
RH is the relative humidity, decimal.
T is the surrounding temperature, K.
RMSE is the root mean square error which was defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Data_{predicted,\,i} - Data_{experiment,\,i})^2}{N}}$$

Table 2 Arbitrary constants for EMC equations for small shrimp.

Model	A	B	R^2	RMSE
Chung & Pfost [19] $\ln RH = \frac{-A}{RT}\exp(-BM_{eq})$	5549.210	9.079	0.88	0.03
Henderson [20] $1\text{-}RH = \exp(-ATM_{eq}^{B})$	0.019	1.000	0.89	0.02
Halsey [23] $M_{eq} = \left[\frac{\ln(RH)}{-A/RT}\right]^{\frac{1}{B}}$	167.888	−1.024	0.88	0.02
Oswin [2] $M_{eq} = A\left(\frac{RH}{1-RH}\right)^{B}$	0.103	0.645	0.92	0.02

Note: A, B are arbitrary constants.
M_{eq} is equilibrium moisture content in decimal dry-basis.
R is the universal gas constant (8.314 kJ/kmol-K).
RH is the relative humidity, decimal.
T is the surrounding temperature, K.
RMSE is the root mean square error which was defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Data_{predicted,\ i} - Data_{experiment,\ i})^2}{N}}$$

Theoretical procedure

There are 3 methods to predict drying kinetics of grain kernels, fruits, cereal grains and herbal samples and used for plotting drying curves [11,20-23]. Theoretical, semi-theoretical and empirical methods are used in drying models. The drying constant is defined as the thin-film equation [Eq. (1)]. The Eq. (1) is used for calculation of the drying constant (k) in several agricultural products, dried in the falling drying rate period. According to this equation, the drying follows first-order reaction kinetics:

$$\frac{dM}{dt} = -k\left(M - M_{eq}\right) \tag{1}$$

where M is the moisture content at any time (t), decimal dry-basis.
M_{eq} is the moisture content at equilibrium, decimal dry-basis.
t is the drying time, minutes or seconds.
k is the drying constant.

(a) Empirical modeling for drying kinetics

Average moisture content ratio for thin-layer drying is given by the following expression:

$$MR = \frac{\left(M - M_{eq}\right)}{\left(M_i - M_{eq}\right)} \tag{2}$$

where MR is the moisture ratio, dimensionless.
M_i is the initial moisture content, decimal dry-basis.

The solution of this first order differential equation, using appropriate initial and equilibrium conditions, is the following:

$$MR = \frac{\left(M - M_{eq}\right)}{\left(M_i - M_{eq}\right)} = C\exp(-kt) \tag{3}$$

where C is an arbitrary constant.

Eq. (3) is applied for porous hygroscopic materials which are dried in the falling rate period. It is assumed that the layer of the drying material is quite thin, so that the conditions of the drying air (temperature and humidity) are kept constant throughout the material. However, in order to determine the moisture content as function of the drying time, various empirical equations of a similar type were presented by several investigators [6,7,11,20,23]. The empirical model of Page's equation [6] has often been applied to fit drying data of porous hygroscopic materials, dried in the falling drying rate period as follows:

$$MR = exp(-kt^n) \tag{4}$$

where k, n are arbitrary constants.
t is the drying time.

The simulated thin-layer drying equation is normally suitable to explain experimental data but it is not widely used for other drying conditions. Therefore, for predictions in a wide range of drying conditions, the drying equation simulated by semi-theoretical methods is used and described in the next sub-section.

(b) Semi-theoretical modeling and effective diffusion coefficient

The diffusion coefficient (D) is normally used to predict the flow of moisture transfer of material during dehydration and drying. In the falling rate period of drying, moisture is transferred by molecular diffusion [27]. In this research, an important assumption to solve the moisture transport is that water moves out in the directions of the vertical axis and that the shrimp is an isotropic solid and has the form of a spherical and finite cylinder. The partial differential equation of moisture diffusion for a single shrimp can be solved and the solution of this diffusion equation for different geometries has been formulated by Crank [27] as follows:

$$\frac{\partial M}{\partial t} = D\nabla^2 M \tag{5}$$

where D is the effective diffusion coefficient, m^2/h.
t is the drying time, h.

Applying analytical methods with initial and boundary conditions, then the following solution of moisture ratio can be derived by the following equations:
For a spherical shape [27],

$$MR = \frac{6}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(n)^2}\exp\left[\frac{(n)^2\pi^2 Dt}{r_0^2}\right] \tag{6}$$

For a finite cylinder shape [27],

$$\overline{MR} = \left(\frac{8}{\pi^2}\right)\sum_{m=1}^{\infty}\frac{4}{\lambda_m^2}\exp\left(\frac{\lambda_m^2 Dt}{r_o^2}\right)\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{\pi^2(2n+1)^2 Dt}{4\ell}\right) \tag{7}$$

where λ_m is the root of the Bessel function of the n^{th} kind of zero order.
r_o is the initial radius of the cylinder, m.
ℓ is the half length of the cylinder, m.

An effective diffusion coefficient (D) is namely described by the Arrhenius type equation as follows [21,27]:

$$D = D'\exp\left(\frac{-E_a}{RT_{abs}}\right) \tag{8}$$

where D' is the Arrhenius factor of the heterogeneous solid, m^2/h.
E_a is the activation energy, kJ/mol-K.
R is the universal gas constant, 8.314 kJ/mol-K.
T_{abs} is absolute temperature, K.

D' which is the Arrhenius factor, depends on the drying air temperature [27]. Some previous researchers also reported that the Arrhenius factor (D') in the form of the second order polynomial in relation to the moisture content of paddy kernel. The D' and E_a values are determined by the non-linear regression analysis from the experimental data. The acceptability of the models has been determined by the coefficient of determination, which should be close to one.

Drying procedure

The boiled shrimp with initial moisture contents of 270 - 350 % dry-basis was thin-layer dried by hot air temperatures of 40 - 90 °C at inlet air flow rate of 1.0 ± 0.2 m/s. The inlet drying air temperature was controlled by a proportional-integral-derivative (PID) controller with an accuracy of ± 1 °C. During the drying period, the sample was weighed continuously using an electric balance (A&D model GF3000) with an accuracy of ± 0.1 g. A flow chart of the drying strategy and quality analysis of the shrimp is shown in **Figure 2**.

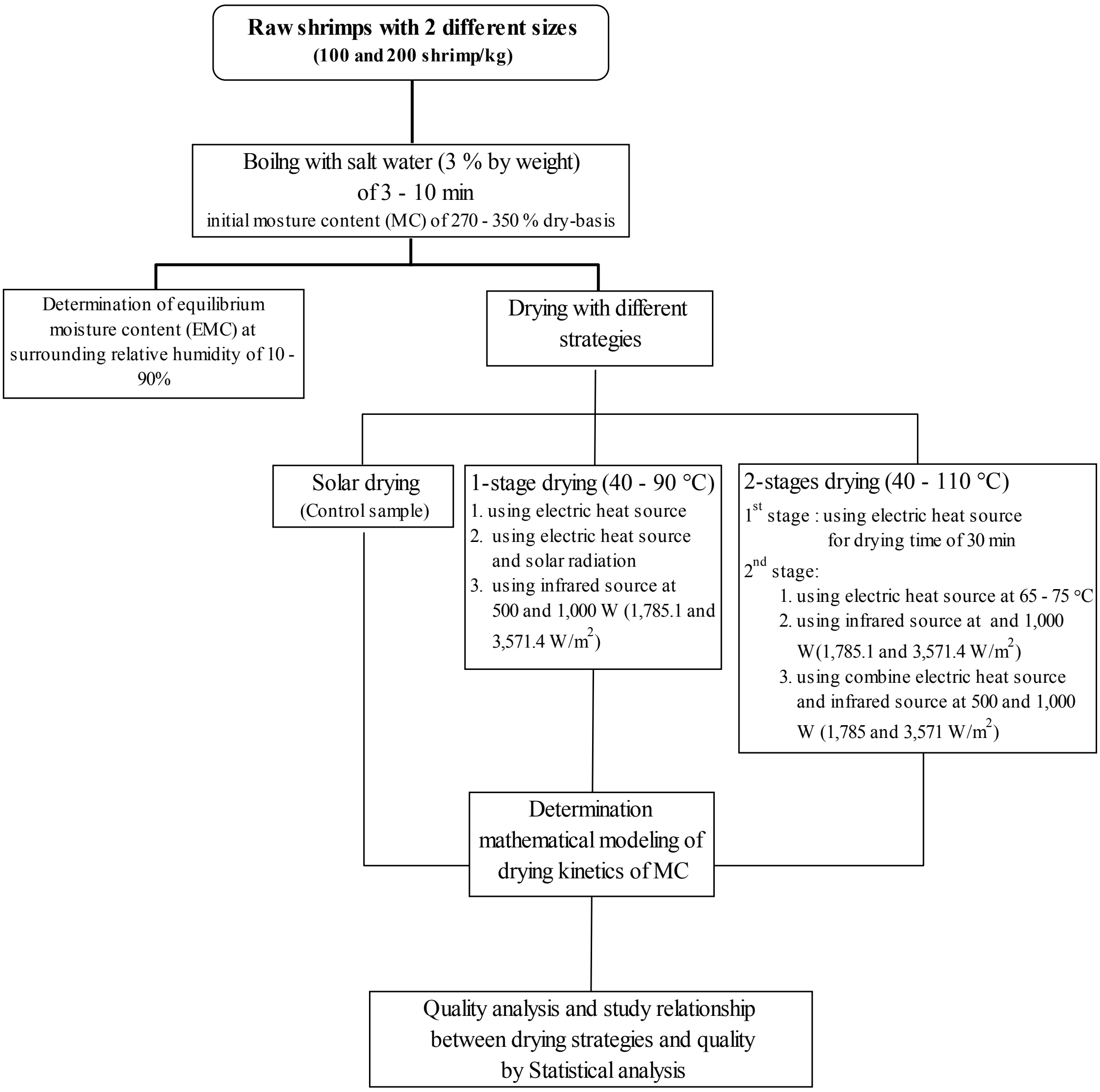


Figure 2 Flowchart of shrimp drying and quality analysis.

The drying experiments were run by using 2 drying strategies. One-stage drying strategy with drying temperatures of 40 - 90 °C was divided into 3 drying conditions as shown in **Figure 2**. Two-stage drying strategy was also divided into 3 drying conditions as illustrated in **Figure 2**. After drying with an electric heater for 30 min, the shrimp were further dried until the final moisture content reached 20 - 25 % dry-basis [3,5]. Both drying strategies used air recirculation of 67 % [28] and velocity of hot air was fixed at 1.0 ± 0.2 m/s [8,17,18,21]. The control shrimp sample was dried in the sun because it is the same method as traditional drying in Thailand.

Quality analysis

(a) Measurement of colour

The colour value of samples was measured in Hunter *a-value* by using a Juki colour meter (JP7100p). Colour values of dried shrimps were measured in three positions: P1 (the head), P2 (middle part) to P3 (the tail) as illustrated in **Figure 3**. In addition, positive Hunter *L-a-b* values indicate brightness, redness and yellowness whilst negative Hunter *L-a-b* values indicate darkness, greenness and blueness, respectively [11]. Additionally, the total colour difference (ΔE) was determined as described in Eq. (9) [3,5,25].

$$\Delta E = \left[(L_0 - L_f)^2 + (a_0 - a_f)^2 + (b_0 - b_f)^2\right]^{1/2} \tag{9}$$

where L_0, L_f are the initial and final brightness value of sample, respectively.
a_0, a_f are the initial and final redness value of sample, respectively.
b_0, b_f are the initial and final yellowness value of sample, respectively.

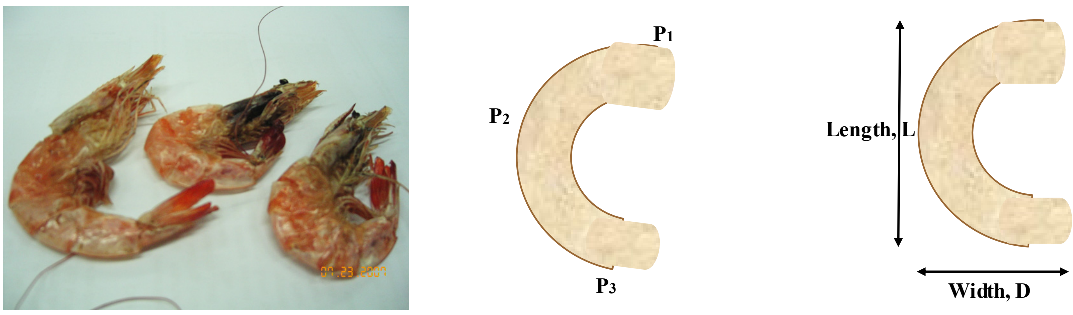


Figure 3 Measuring positions of color values of shrimp.

The percentage of shrinkage of samples was determined by an average of that measured with vernier calipers with an accuracy of ± 0.05 mm and the experiments were replicated 3 times and the percentage of shrinkage was defined as follows:

$$shrinkage\left(\%\right) = \frac{\left(D_{initial} - D_{final}\right)}{D_{initial}} \times 100 \qquad (10)$$

where $D_{initial}$, D_{final} are the geometric mean diameters of the shrimp at the beginning and at the end of the drying experiment, respectively.

(b) Measurement of rehydration

Each dried shrimp sample was weighed and then soaked in hot water at 100 °C for 10 min. After soaking, the samples were weighed. The experimental data was confirmed by duplication. Percentage of rehydration was calculated according to the equation below [3,5]:

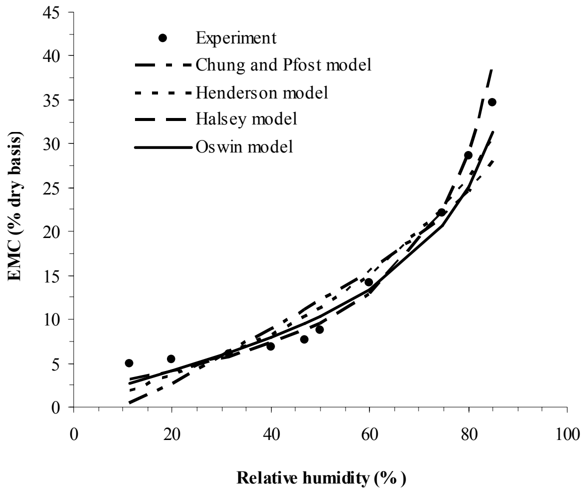
$$rehydration\left(\%\right) = \left(\frac{X_{initial} - X_{final}}{X_{initial}}\right) \times 100 \qquad (11)$$

where $X_{initial}$ is the geometric average diameter of shrimp before soaking.
X_{final} is the geometric average diameter of shrimp after soaking.

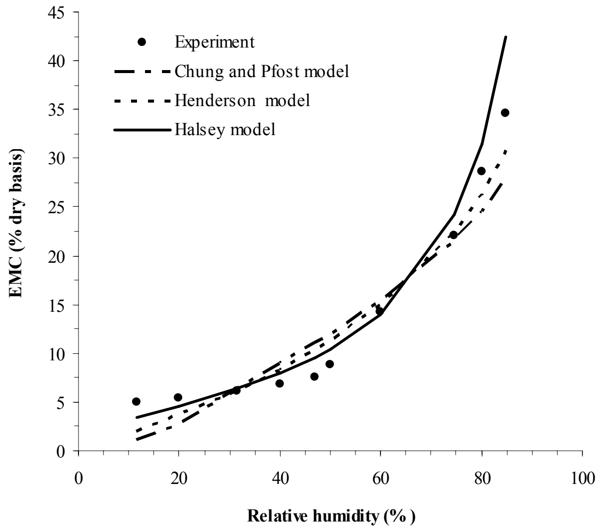
RESULTS AND DISCUSSION

Equilibrium moisture content (EMC)

Table 1 illustrates the relationship between the EMC equations of large size shrimp and RH at temperature of 40 - 70 °C, respectively. **Figure 4** shows predicted and experimental EMC data of shrimp at various temperatures. From **Figure 4**, the experimental results showed that EMC exponentially increased with increasing of RH. This corresponds to the results of previous researchers [2,6,10,11,20,22,23]. The predicted data of Oswin and Halsey's equation for small and large size shrimp was the best fitting model for all drying experiments, respectively. (R^2 are 0.92 and 0.92, respectively while RMSE is 0.02 and 0.14, respectively).



(a) Small size shrimp



(b) Large size shrimp

Figure 4 Experimental and predicted data of EMC of shrimp with surrounding RH ranges between 10 and 90 %.

Determination of drying equation and effective diffusion coefficient

The drying curves of small and large sizes of shrimps dried using inlet drying air temperatures between 40 - 70 °C at an inlet air flow rate of 1.0 ± 0.2 m/s were shown in **Figure 5**. The experimental results were used to formulate the thin-layer drying equation by curve fitting. The drying kinetics of small and large shrimps had significant relation to the inlet drying air temperature. In addition, the drying at high temperature resulted in increased moisture removal rate compared to that of low temperatures.

Figure 5 shows the comparison of moisture content between experimental and predicted values of small size shrimp at various inlet drying air temperatures. The results also showed that the proposed Page model [Eq. (4)] could predict the moisture content in good agreement with the experimental results.

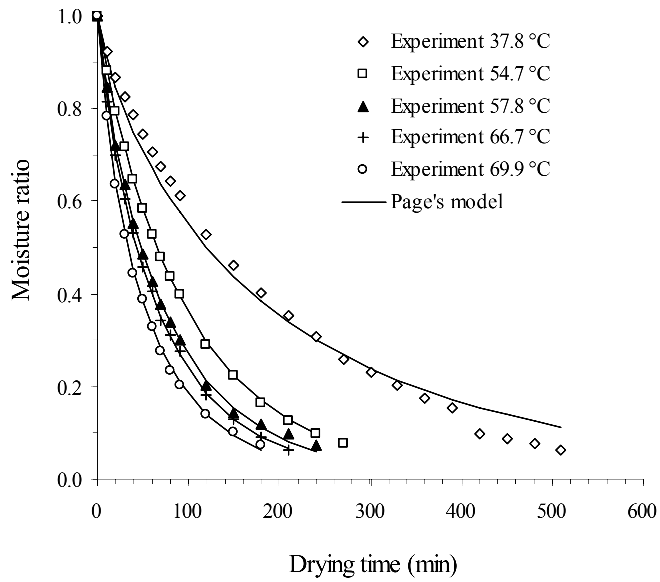


Figure 5 Moisture ratio of predicted and experimental data of small size shrimp under the condition of 1-stage drying using hot air convection with temperatures of 37.8 - 69.9 °C and average hot air flow rate of 1.1 m/s (recycled air of 66.7 %).

From the simulated drying equation, the arbitrary constants *k* and *n* for small-size and large-size of shrimp in Page's model was determined and the results showed that the arbitrary constants depended on the drying temperature as shown in the following equations:

For small size shrimp

$$k = (T^{0.178}) - 2.757 \quad n = 232.63T^{-1} \quad R^2 = 0.96 \tag{12}$$

For large size shrimp

$$k = (T^{0.199}) - 3.115 \quad n = 217.98T^{-1} \quad R^2 = 0.96 \tag{13}$$

where *T* is the drying temperature, K.

For evaluation of the effective diffusion coefficient of shrimp, the experimental results were determined using non-linear regression analysis and the arbitrary constants from the diffusion equation in a sphere and finite cylinder are shown in **Table 3(a)** and **3(b)**. The diffusion coefficient value of both size shrimps showed that the effective diffusion coefficient value increases with increasing drying temperature. The effective diffusion coefficient value when using hybrid heat sources was slightly higher than 1 stage drying with 1 heat source. This is because infrared waves can penetrate into the interior of the food, where it is converted into thermal energy, providing a rapid heating mechanism [8]. From **Table 3(a)** and **3(b)**, it is clear that a diffusion model using a finite cylinder is more suitable than that obtained using a sphere. The effective diffusion coefficient was in the range of 1.0×10^{-7} to 1.8×10^{-7} m^2/s at inlet drying temperatures of 40 - 70 °C, corresponding to previous reports [3,4,12]. At high drying temperatures, the diffusion coefficient (D) was higher than that at low drying temperatures. **Figure 6** shows the calculated data for diffusion modelling in the form of a finite cylinder compared to the experimental data, which is a good fit.

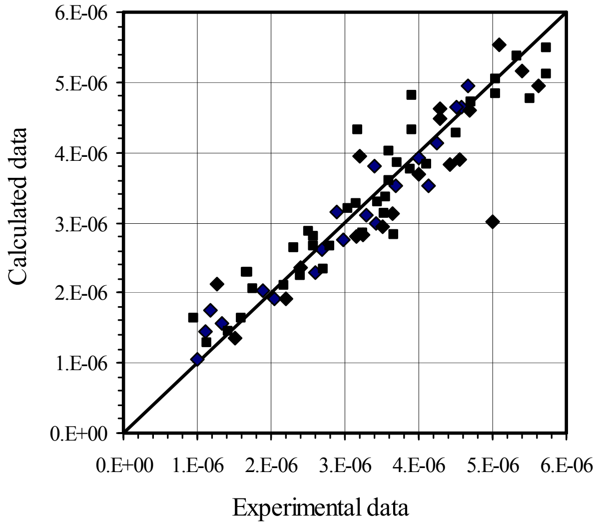


Figure 6 Relationship between calculated data and experimental data of effective moisture diffusion coefficients at various drying temperatures, 40 - 70 °C.

Table 3(a) Arrhenius and activation energy constants of diffusion models of small size shrimp drying for initial moisture content of 270 - 350 % dry-basis and inlet drying temperatures of 40 - 90 °C.

Drying conditions	Sphere shape	R^2	Finite cylinder shape	R^2
For 1-stage drying of small shrimp	$D = 0.45424\exp\left(\frac{-33562.07}{RT_{abs}}\right)$	0.947	$D = 0.58521\exp\left(\frac{-33398.6}{RT_{abs}}\right)$	0.943
For 2-stage drying of small shrimp (HA and HA+IR 500 W)	$D = 0.03048\exp\left(\frac{-25156.94}{RT_{abs}}\right)$	0.903	$D = 0.16329\exp\left(\frac{-28796.7}{RT_{abs}}\right)$	0.949
For 2-stage drying of small shrimp (HA and HA+IR 1,000 W)	$D = 0.017025\exp\left(\frac{-23983.13}{RT_{abs}}\right)$	0.979	$D = 0.03993\exp\left(\frac{-25461.8}{RT_{abs}}\right)$	0.978

Table 3(b) Arrhenius and activation energy constants of diffusion models of large size shrimp drying for initial moisture content of 270 - 350 % dry-basis and inlet drying temperatures of 40 - 90 °C.

Drying conditions	Sphere shape	R^2	Finite cylinder shape	R^2
For 1-stage drying of large shrimp	$D = 0.5299794\exp\left(\frac{-33299.42}{RT_{abs}}\right)$	0.749	$D = 0.87297\exp\left(\frac{-33816.7}{RT_{abs}}\right)$	0.737
For 2-stage drying of large shrimp (HA and HA+IR 500 W)	$D = 0.03051\exp\left(\frac{-25150.04}{RT_{abs}}\right)$	0.907	$D = 0.52553\exp\left(\frac{-33205.6}{RT_{abs}}\right)$	0.924
For 2-stage drying of large shrimp (HA and HA+IR 1,000 W)	$D = 0.0008534\exp\left(\frac{-16289.82}{RT_{abs}}\right)$	0.958	$D = 0.00208\exp\left(\frac{-17995.3}{RT_{abs}}\right)$	0.978

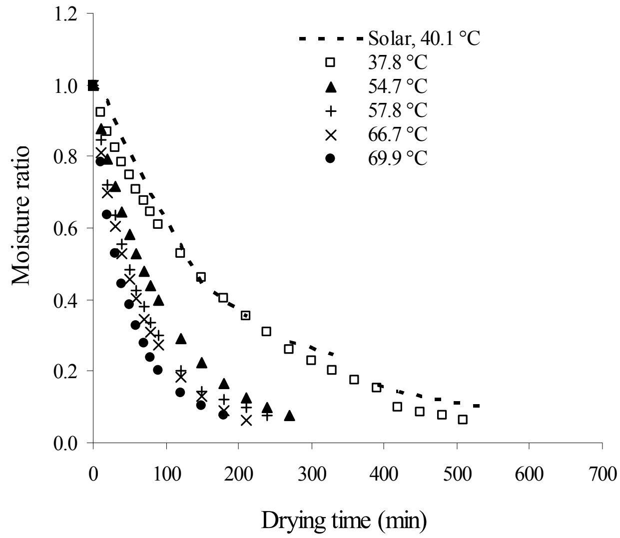


Figure 7 Relationship between moisture ratio and drying time of small size shrimp at various drying temperatures of 37.8 - 69.9 °C and initial moisture content of 270 - 350 % dry-basis.

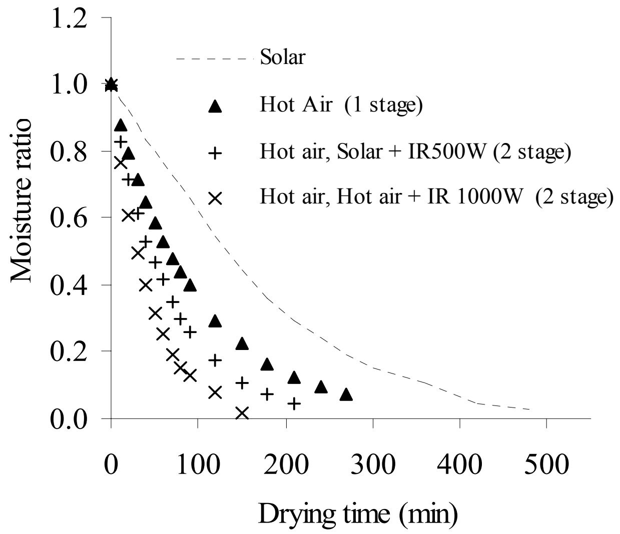


Figure 8 Evolution of moisture transfer of various drying strategies with drying temperatures of 50 - 55 °C, initial moisture contents of 270 - 300 % dry-basis and air flow rate of 1.1 m/s.

To study the effect of infrared intensity of 1,785.7 and 3,571.4 W/m^2 (500 and 1,000 W) on drying kinetics and quality of shrimp, the dried shrimps were comparatively determined with the control dried samples which were dried by solar energy. The experimental results showed that the drying rate of shrimp using high intensity infrared was faster than those of experiments at the same drying temperature.

Consequently, drying with high intensity infrared of 3,571.4 W/m^2 has a relatively high drying rate compared to that of drying with low intensity infrared of 1,785.7 W/m^2.

Quality analysis

(a) Measurement of colour

Figures 9 and **10** show the measured results of color of dried shrimp with 1-stage and 2-stage drying strategies. The experimental results for all drying conditions concluded that in case of drying with 1 stage and 2 stage strategies, higher drying temperatures tended to decrease the total color difference of samples (*ΔE*), dried shrimp with combined infrared heat radiation and hot air convection significantly enhance the redness value (Hunter *a-value*) of the shrimp. However, from **Figures 9** and **10**, the brightness value (Hunter *L-value*) of dried shrimp with 1-stage hot air drying was higher than that found when combined infrared heat radiation and hot air convection were used.

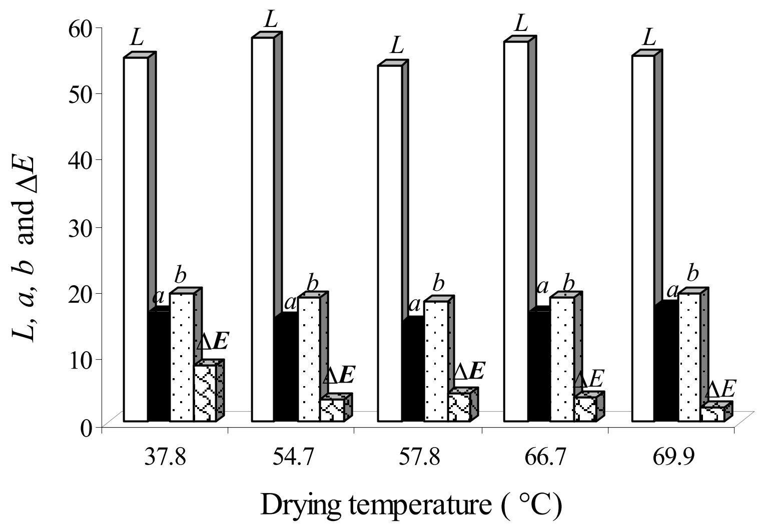


Figure 9 Colour measurements for 1-stage drying of small size shrimp at various drying temperatures (hot air convection).

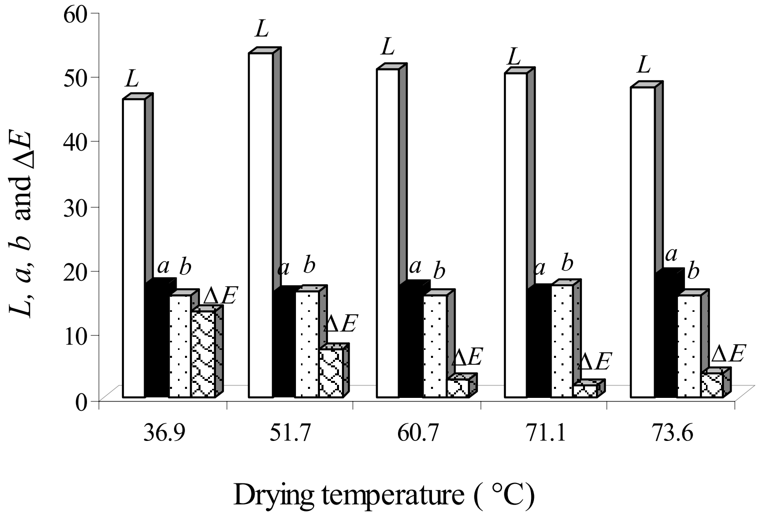


Figure 10 Colour measurements for 2-stage drying of small size shrimp at various drying temperatures (hybrid infrared radiation and hot air convection).

(b) Measurement of shrinkage and dehydration

Table 4 shows the percentage of shrinkage and rehydration of shrimp using the 2 drying methods. The drying temperatures had an insignificant effect to percentage of shrinkage value conversely to percentage of rehydration. The percentage of shrinkage of both sizes of shrimps was between 11.45 and 32.36 %. Percentage of rehydration of shrimps also was between 3.01 and 13.08 %. These results imply that the effect of drying using infrared radiation has no relation to these qualities.

(c) Measurement of texture property

The last column of **Table 4** shows the shear force of shrimps in various drying strategies. The results reveal that the drying temperature does not significantly affect the shear force on the texture of shrimp ($p < 0.05$). However, an increase in the size of the shrimp results in an increase in the shear force.

Table 4 Percentage of shrinkage and rehydration of shrimp.

Drying conditions	Drying temperature (°C)	Shrinkage (%)	Rehydration (%)	Shear force (N)
1. One-stage drying with hot air convection				
Small size shrimp	37.9	22.45 ± 0.07	5.83 ± 0.17	87.51^{a}
	54.7	16.67 ± 0.08	7.50 ± 0.06	93.88^{b}
	57.8	23.61 ± 0.08	10.90 ± 0.08	84.27^{a}
	66.8	24.62 ± 0.07	10.26 ± 0.04	79.56^{ab}
	70.0	24.40 ± 0.09	13.08 ± 0.06	86.62^{ab}
Large size shrimp	36.6	15.74 ± 0.08	3.28 ± 0.05	153.72^{cd}
	54.8	14.47 ± 0.08	5.20 ± 0.02	120.17^{a}
	56.7	16.97 ± 0.08	3.42 ± 0.09	139.89^{cd}
	68.7	17.42 ± 0.08	3.01 ± 0.09	108.69^{ab}
	71.5	16.67 ± 0.06	4.70 ± 0.06	126.06^{bc}
2. Two-stages drying (Combined infrared and hot air)				
Infrared power of	36.9	22.14 ± 0.07	2.59 ± 0.07	84.56^{b}
1,785.7 W/m^2	51.8	16.67 ± 0.08	6.25 ± 0.08	87.31^{b}
(500 W)	60.8	20.80 ± 0.04	4.12 ± 0.07	87.11^{b}
	71.2	32.36 ± 0.10	8.60 ± 0.06	81.52^{a}
	73.7	21.93 ± 0.02	4.85 ± 0.08	80.54^{b}
Infrared power of	39.7	11.45 ± 0.05	3.87 ± 0.07	138.71^{ab}
3,571.4 W/m^2	56.3	15.76 ± 0.07	2.56 ± 0.05	127.33^{a}
(1,000 W)	66.4	20.83 ± 0.07	9.84 ± 0.08	138.71^{ab}
	77.7	18.65 ± 0.07	7.43 ± 0.09	128.71^{a}
	79.5	14.75 ± 0.08	12.24 ± 0.10	137.63^{ab}
Conventional solar drying (Control sample)				
Small size shrimp		22.05 ± 0.09^{cde}	5.93 ± 0.20^{f}	90.70^{b}
Large size shrimp		16.50 ± 0.08^{ab}	3.12 ± 0.09^{b}	155.43^{d}

Note: Different superscripts in the same column mean that the values are significantly different at 95 % confidence level ($p < 0.05$).

(d) Determination of energy consumption

Table 5 shows the specific energy consumption of drying shrimp drying using the 2 strategies. Considering the total specific energy consumption for 1-stage and 2-stage drying and showed that drying using combined infrared radiation and electric heating for both sizes of shrimps at drying temperatures of 36.9 - 79.5 °C were lower than those of 1-stage drying with electric heating. This is because infrared waves can penetrate into the interior of the shrimp, where it is converted to thermal energy, providing a rapid heating mechanism, corresponding with previous work [12,16]. Total specific energy consumption of 2-stage drying of both sizes of shrimp was in range of 32.37 - 63.34 MJ/kg of evaporated water while 1-stage drying consumes 35.68 - 111.00 MJ/kg of evaporated water.

Table 5 Specific energy consumption of shrimp drying with 1- or 2-stage drying.

Drying conditions	**Drying temperature (^oC)**	**Drying time (min)**	**Initial (Final) moisture content (% d.b.)**	**Specific energy consumption (MJ/kg water evaporated)**
1. One-stage drying using hot air convection				
Small size shrimp	37.9	510	333.1 (21.1)	54.95
	54.7	270	312.3 (23.6)	38.89
	57.8	240	339.0 (25.1)	35.68
	66.8	210	344.5 (21.7)	52.39
	70.0	180	345.2 (25.8)	57.07
Large size shrimp	36.6	540	273.8 (28.7)	95.62
	54.8	450	287.7 (18.7)	111.00
	56.7	210	270.1 (19.6)	70.07
	68.7	270	280.0 (24.0)	89.19
	71.5	120	291.1 (24.6)	46.76
2. Two-stage drying using infrared-hot air drying				
Infrared intensity of 1,785.7 W/m^2 (500 W) Small size shrimp	36.9	420	323.3 (23.7)	45.86
	51.8	210	319.6 (14.5)	36.32
	60.8	270	325.6 (20.1)	41.21
	71.2	150	321.6 (10.0)	38.28
	73.7	90	322.0 (17.4)	32.37
Infrared intensity of 3,571.4 W/m^2 (1,000 W) Large size shrimp	39.7	420	273.1 (24.0)	48.26
	56.3	240	271.1 (22.2)	50.73
	66.4	270	278.6 (21.5)	62.34
	77.7	180	278.8 (39.8)	63.34
	79.5	150	270.9 (26.7)	60.48

CONCLUSIONS

In conclusion, the equilibrium moisture content (EMC) value was dependent on the ambient temperatures and the predicted EMC value from the Oswin and Halsey models were the best fitting to the experiment results of small and large shrimp, respectively. The empirical thin-layer drying equation of shrimp using Page's model was the best fitting to the experimental results. The drying kinetics of shrimps was well explained by a diffusion model while an effective diffusion coefficient can be found using an Arrhenius function of drying air temperature. The value was in the range of 1.056×10^{-7} to 1.7989×10^{-7} m^2/s at inlet drying temperatures of 40 - 70 °C. Considering the properties of dried shrimp after drying, the results showed that an infrared heat source improved the redness value of the shrimps while hot air convection gave a high brightness value compared to all other experiments. However, Hunter *L-a-b* values are significantly affected by drying temperature compared to the initial moisture content of the shrimps. Two-stage drying for small and large size shrimp with infrared radiation of 500 W and a drying temperature of 70 °C was found to be suitable for producing high quality dried shrimp.

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บทคัดย่อ

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แนวทางการอบแห้งกุ้งด้วยลมร้อนแบบการพาความร้อนและระบบผสมผสานระหว่างการแผ่รังสีใต้แดงและการพาความร้อนด้วยลมร้อน

วัตถุประสงค์ของงานวิจัยนี้เพื่อศึกษาปัจจัยของอุณหภูมิอบแห้งที่ใช้เทคนิคการแผ่รังสีใต้แดงและการส่งผ่านความร้อนแบบการพาด้วยขดลวดความร้อนไฟฟ้าที่มีต่อการลดความชื้น และเพื่อศึกษาปัจจัยเงื่อนไขการอบแห้งที่มีต่อคุณภาพของกุ้งแห้ง กุ้งสดที่ใช้ในการทดลองมีสองขนาด (100 ตัวต่อกิโลกรัม และ 200 ตัวต่อกิโลกรัม) และมีความชื้นเริ่มต้นประมาณ 270 - 350 % มาตรฐานแห้ง ทำการอบแห้งภายใต้เงื่อนไขต่าง ๆ โดยใช้อัตราเร็วของลมร้อน 1.0 - 1.2 เมตรต่อวินาที อุณหภูมิอบแห้งอยู่ในช่วง 40 - 90 องศาเซลเซียส และเลือกใช้ความเข้มรังสีใต้แดงในช่วง 1,785 - 3,571.4 วัตต์ต่อตารางเมตร หลังการทดลองกุ้งแห้งมีค่าความชื้นสุดท้ายอยู่ในช่วงร้อยละ 20 ถึง 30 มาตรฐานแห้ง จากผลการทดลองแสดงให้เห็นว่าอัตราการส่งผ่านความชื้นของกุ้งทั้งสองขนาดลดลงกับเวลาอบแห้งเป็นฟังก์ชันเอกซ์โพเนนเชียล และอุณหภูมิอบแห้งมีผลอย่างมีนัยสำคัญทางสถิติต่อจลนศาสตร์ของการอบแห้งและคุณภาพของกุ้ง สำหรับการหาค่าสัมประสิทธิ์การแพร่ของกุ้งทั้งสองขนาดซึ่งหาค่าด้วยแบบจำลองการแพร่โดยเลือกใช้รูปทรงเรขาคณิตแบบกระบอกตัน พบว่า สัมประสิทธิ์การแพร่ที่คำนวณได้มีค่าอยู่ในช่วง 10 - 7 ตารางเมตรต่อวินาที และค่าสัมประสิทธิ์การแพร่ประสิทธิผลสัมพันธ์กับอุณหภูมิอบแห้งมากกว่าค่าความชื้นเริ่มต้นของกุ้งสดก่อนอบแห้ง จากการวิเคราะห์คุณภาพของกุ้งอบแห้งโดยใช้แหล่งกำเนิดรังสีใต้แดงและแหล่งกำเนิดความร้อนขดลวดไฟฟ้า สรุปได้ว่า คุณภาพของกุ้งแห้งที่อบด้วยพลังงานความร้อนร่วมระหว่างรังสีใต้แดงและการให้ความร้อนด้วยขดลวดไฟฟ้า จะให้ความเป็นสีแดง (ค่าของ a ในหน่วย Hunter) ที่สม่ำเสมอกว่าการอบแห้งด้วยเทคนิคอื่นๆ นอกจากนั้น สมบัติของการหดตัวและการคืนตัวของกุ้งแห้งทุกเงื่อนไขที่ใช้อบแห้งไม่มีความแตกต่างที่มีนัยสำคัญ

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