Research Article
Mathematical Modeling on Combined Mid-infrared and Hot Air Drying of Beef Meat

Xiao-Lei Xie, Jin-Zhi Wang, Xia Li, Wei Jia and Chun-Hui Zhang
Institute of Agro-products Processing Science and Technology, Chinese Academy of Agricultural
Sciences/Comprehensive Key Laboratory of Agro-products Processing, Ministry of Agriculture,
Beijing, China

Abstract: To investigate the drying models and characteristics of Combined Mid-Infrared and Hot Air (CMIHA) drying BEEF MEAT (BM), a laboratory scale CMIHA dryer was applied to the treatment of BM samples in a temperature range from 40-70°C, with air velocity of 1m/s and mid-infrared of 2.8-3.1 μm. Microsoft visual C sharp (C#) was used to develop a Moisture Prediction System (MPS) to digitize the prediction process. The results indicated that the Modified Henderson and Pabis model could present better predictions for the moisture transfer than others and the MPS could predict the moisture ratio through the whole drying process conveniently. Besides, higher temperature could accelerate effective diffusivities to increase drying rate, thus shorten the drying time. The activation energy of BM dried with CMIHA was 32.83 kJ/mol. All of these could be used in the design and operation of the combination drying beef meat.

Keywords: Beef Meat (BM), combination drying, mid-infrared, modeling, Moisture Prediction System (MPS)

INTRODUCTION

Beef Jerky (BJ) is one of the oldest types of meat products that preserved by drying to reduce water activity (Putranto *et al*., 2011; Xie *et al*., 2013). Its easy preparation, rich nutrient content and long shelf life make it a popular item for sports enthusiasts, travelers and mountaineers (Choi *et al*., 2008). However, drying of BJ is a complicated process involving simultaneous heat and mass transfer (Yilbas *et al*., 2003). Currently, two methods are used in BJ. One is air drying which is a low energy-consumption but time-consuming, so it is not common in industrial production. The other is Hot Air (HA) drying which can save more time compared with air drying but energy-consuming, for its low thermal conductivity and case hardening of material (Afzal *et al*., 1999). Such weak points of drying methods are not benefit to economic increase of enterprises. Therefore, it is necessary to develop innovative techniques to increase drying efficiency of BM.

Due to the better synergistic effect between mid-infrared and hot air, Combined Mid-Infrared and Hot Air (CMIHA) drying has recently attracted much attention as a heat source to augment other drying techniques to enhance the efficiency of the overall process (Hebbar *et al*., 2004; Prakash, 2011). Afzal *et al*. (1999) reported combination drying of barley can save total energy nearly 245% compared with hot air drying at 70°C. Besides, time required for the combination drying was only 52% of hot air drying and 63% of mid-infrared drying (Hebbar *et al*., 2004). Furthermore, several researchers have applied combined infrared and hot air drying successfully to other food products, such as rice kernel (Prakash, 2011), onion slices (Pathare and Sharma, 2006), murta (Luis *et al*., 2013) and so on. As we can see combination drying mode has lots of benefits and most of the studies aimed to vegetables or cereal which is rich in cellulose and starch, or either of them (Prakash, 2011), but lack of information focus on the application of jerky which is rich in protein. Xie *et al*. (2013) reported that CMIHA drying could improve drying efficiency and quality of jerky. However, still detailed information is needed to do further research on drying model of BM.

Mathematical modeling is important to the optimization of operating parameters and performance improvements of the drying systems. Some studies have been carried out on modeling of CMIHA drying. Prakash *et al*. (2011) reported the modeling of a rice kernel during convective and infrared drying, while Luis *et al*. (2013) reported the modeling of combined infrared with convection drying on murta. However, no detailed information published seems to be available about the drying model of CMIHA drying BM.

Corresponding Author: Chun-Hui Zhang, Institute of Agro-products Processing Science and Technology, Chinese Academy of Agricultural Sciences/Comprehensive Key Laboratory of Agro-products Processing, Ministry of Agriculture, No. 2 Yuan Ming Yuan West Road, Haidian District, Beijing 100193, China, Tel.: (+86) 10 62815950; Fax: (+86) 10 62815950
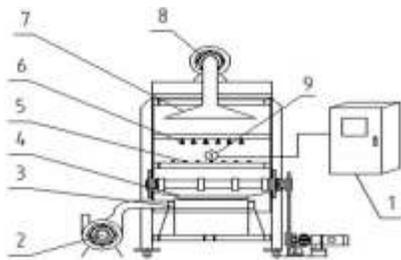
Fig. 1: Experimental setup of combined mid-infrared and hot air dryer; 1: Temperature control panel; 2: Exhauster blower; 3: Exhauster pipe; 4: Exhauster scoop; 5: Material tray; 6: Infrared generator; 7: Air scoop; 8: Blower; 9: Temperature sensor

Furthermore, the application of programming software, such as Visual Basic (VB) or visual C sharp (C#) for developing a Moisture Prediction System (MPS) that can predict the moisture content fast and conveniently, is still in a blank.

Therefore, in this study, attention is focused on the investigation of the drying models and characteristics of BM in a CMIHA dryer and then to develop a MPS. All of this could be used in the design and operation of the combination drying BM.

MATERIALS AND METHODS

Materials: Fresh beef were obtained from local market and kept in refrigerator at -26°C, which would be thawing at 4°C until the internal temperature achieved to 0°C. Prior to dehydration, samples were washed to remove the dirt and cut into slices of 2×2×6 cm, which were the pretreatments of traditional technology of Chinese beef jerky. Samples were then immediately weighted and placed into the dryer. The initial moisture content of the slices was ranged from 76.0±1.0% (wet basis, wb), which was determined in an air-circulated

oven at 105°C until weight was constant (Gunhan *et al.*, 2005; Wang *et al.*, 2007).

Combined Mid-Infrared and Hot Air (CMIHA) dryer: The experimental setup used for CMIHA drying of the samples was shown in Fig. 1. The dryer was in a laboratory scale with a material dish (40×35 cm), which could be regulated to any desired drying temperature between 20 and 300°C with high accuracy. Since infrared energy was converted into heat only when the material absorbed the radiation, it was essential to select a heat source emitting radiation range in which the material to be processed had maximum absorption (Hebbar *et al.*, 2004). So, the range of 2.8-3.1 μm was selected based on the infrared spectra of beef (Fig. 2) that measured by attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) (Tensor27, BRUKER spectral instruments company, Germany). A quartz infrared generator surrounded with a gold-plated reflective film was used for heating, which could offer nearly 80% of efficiency in converting electrical energy to infrared energy (Ginzburg, 1969). The rated power of the dryer was 0.875 kW (infrared generator 0.675 kW and blower 0.2 kW).

Experimental procedure: Drying experiments were performed at 40, 50, 60 and 70°C in the CMIHA dryer. The thickness of the sample was about 20 mm with load of 23±0.02 g, the air velocity was 1.0 m/s, the drying distances was 8 cm and the radiation intensity was 0.48 W/cm^2. Samples were taken out of the drying chamber at 10 min interval, weighted separately and placed back into the chamber. The drying procedure was continued till the moisture content of the samples was reduced to 50% (wet basis, wb). Each run in the experiment was done in triplicate.
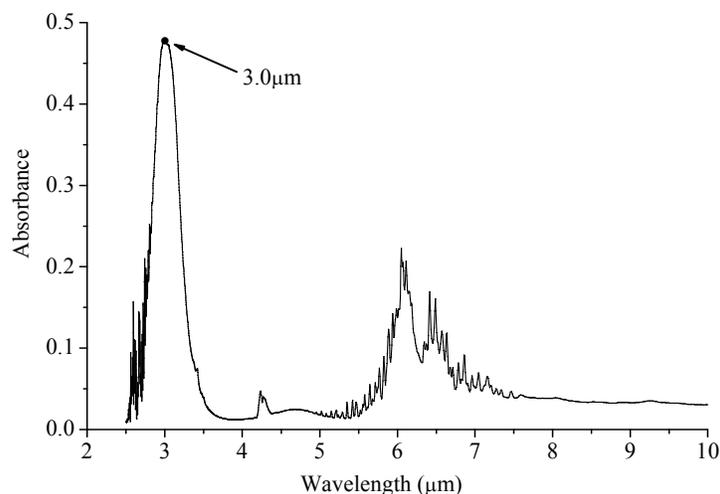
Fig. 2: Infrared spectra of beef

Table 1: Mathematical models given by various authors for the drying curves

Name	Model equation	References
Lewis	MR = exp(-kt)	O'Callaghan *et al.* (1971)
Page	MR = exp(-kt^n)	Zhang and Litchfield (1991)
Yagcioglu *et al*	MR = aexp(-kt)+c	Chandra and Singh (1995)
Henderson and Pabis	MR = aexp(-kt)	Chhinnan (1984)
Midilli and Kucuk	MR = aexp(-kt^n)+bt	Midilli *et al.* (2002)
Wang and Singh	MR = 1+at+bt^2	Wang and Singh (1978)
Two-term	MR = aexp(-kt)+bexp(-k$_1$t)	Rahman *et al.* (1997)
Modified Henderson and Pabis	MR = aexp(-kt)+bexp(-gt)+cexp(-ht)	Karathanos (1999)

Modeling of the Beef Meat (BM) drying curves: For investigation of drying characteristics of BM, it was important to model the drying behavior effectively. In this study, the drying data of BM obtained at different drying temperature (40, 50, 60 and 70°C) were processed to find the most convenient drying model among eight different moisture ratio equations given in Table 1. In these models, MR represents moisture ratio, namely, MR = M_t/M_0 instead of the $(M_t-M_e)/(M_0-M_e)$ because the values of M_e were relatively smaller than M_t or M_0 (Yaldiz *et al.*, 2001; Togrul and Pehlivan, 2002; Shi *et al.*, 2008). Where M_t is the moisture content of samples at each moment, M_e is the equilibrium moisture content and M_0 is the initial moisture content.

Correlation coefficients and error analyses: The correlation coefficient (R) was one of the primary criteria for testing the linear relation between measured and estimated values. Besides, the Residual Sum of Squares (*RSS*) and reduced chi-square (χ^2) were used to determine suitability of the fit. These parameters were defined as follows:

$$R^2 = \frac{\sum_{i=1}^N \left(M_{Ri} - M_{Rpre,i}\right)*\left(M_{Ri} - M_{Re\,xp,i}\right)}{\sqrt{\left[\sum_{i=1}^N \left(M_{Ri} - M_{Rpre,i}\right)^2\right]*\left[\sum_{i=1}^N \left(M_{Ri} - M_{Re\,xp,i}\right)^2\right]}} \quad (1)$$

$$RSS = \sum_{i=1}^N \left(M_{Rpre,i} - M_{Rexp,i}\right)^2 \quad (2)$$

$$\chi^2 = \frac{\sum_{i=1}^N \left(M_{Re\,xp,i} - M_{Rpre,i}\right)^2}{N - N_e} \quad (3)$$

where,
R^2 = The coefficient of determination
$MR_{exp,I}$ = Stands For the experimental moisture ratio found in any measurement
$MR_{pre,i}$ = The predicted moisture ratio for this measurement
N = The total number of observations
N_e = The number of constants

The ideal value of R^2 is 'one' and the lower are the values of the RSS and χ^2 the better is the goodness of fit (Gunhan *et al.*, 2005).

Developing of Moisture Prediction System (MPS): To predict the moisture ratio of BM during CMIHA drying conveniently, it was important to digitize the drying behavior effectively. The Microsoft visual C sharp (C#) was applied to program the drying models that used to predict the moisture content to digitize the prediction process.

Calculation of diffusion coefficient: The effective moisture diffusivity of BM was calculated using the equation of Shi *et al.* (2008) with modifications, assuming the shape of beef jerky as square and that moisture migration was due to diffusion with a constant temperature and diffusion coefficient (El-Beltagy *et al.*, 2007). The equation is given as:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^\infty \frac{1}{\pi^2} \exp\left(\frac{-n^2\pi^3 D_e t}{l^2}\right) \quad (4)$$

where,
D_e (m^2/s) = Moisture diffusivity
l (m) = The thickness of BM
t (s) = Drying time
MR = The moisture ratio which was simplified to $MR = M_t/M_0$ (Togrul and Pehlivan, 2002)
M_t = The moisture content of the product at each moment
M_0 = The initial moisture content of the sample

For a long duration, the effective moisture diffusivity D_e can be determined from the Eq. (5):

$$D_e = \frac{-0.032 \ln MR - 0.016}{(t/l^2)} \quad (5)$$

The average effective moisture diffusivity $D_{e,avg}$ is determined from all effective positive D_e as in Eq. (6) (Singh and Gupta, 2007):

$$D_{e,avg} = \frac{\sum_1^{n_1} D_e}{n_1} \quad (6)$$

Calculation of activation energy: Activation energy was calculated by the Arrhenius relation (Shi *et al.*, 2008; Singh and Gupta, 2007), which can be determined from Eq. (7):

$$\ln(D_{e,avg}) = -\frac{1}{R(T+273)}E_a + \ln(D_0) \qquad (7)$$

where,

R	= Gas constant with a constant value of 8.314×10^{-3} kJ/mol/K
T (°C)	= Dry temperature
E_a (kJ/mol)	= Activation energy
D_0	= Effective moisture diffusivity at temperature 273K.

And $-E_a/R$ was obtained as the slope of the straight line of $\ln(D_{e,avg})$ vs.$1/(T+273)$.

RESULTS AND DISCUSSION

Analysis of drying characteristics of Beef Meat (BM): The moisture ratios versus drying time for BM at the selected temperatures were shown in Fig. 3. To reach the 50% wb for the samples, drying time were 440, 300, 220 and 140 min at 40, 50, 60, 70°C, respectively. Obviously, within a certain temperature range (40-70°C), increasing drying temperature

speeded up the drying process, thus shorten the drying time. This result was similar to the report of Pekke *et al.* (2013). In each equal increased temperature interval of 10°C from 40 to 70°C, the drying time decreased by 31.82, 26.67 and 36.36%, respectively correspondingly which means the drying time did not present equal decrease with the temperature increasing at equal interval. Also the increased temperature interval of 10°C from 60-70°C had the greatest effect on the decrease of drying time, suggested by 36.36%. Thus, with a view of optimization of drying efficiency, the heating temperature zone between 60 and 70°C was the best option for drying BM.

As can be seen from Fig. 4, the drying process took place in a falling rate period except a very short accelerating period at the beginning. The water loss rate of BM was faster at the beginning than that in the end. This result was in agreement with previous results on infrared and hot air drying of blueberries (Shi *et al.*, 2008). However, in our study, differences among other temperatures (40, 50 and 60°C), the water loss rate of BM at 70°C had one rising rate period, which occurred at 20 min and then dropped at 40 min. This might be
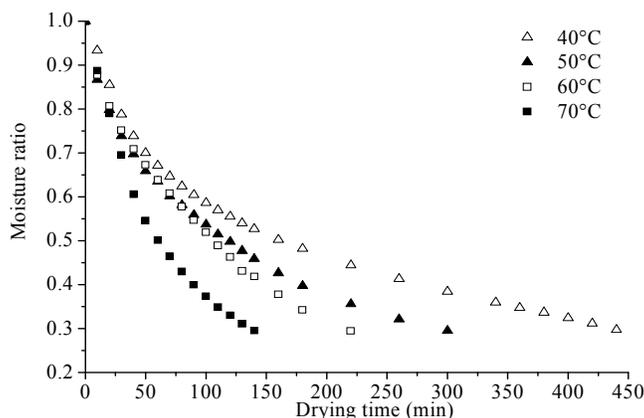
Fig. 3: Drying curves of beef meat at different temperatures
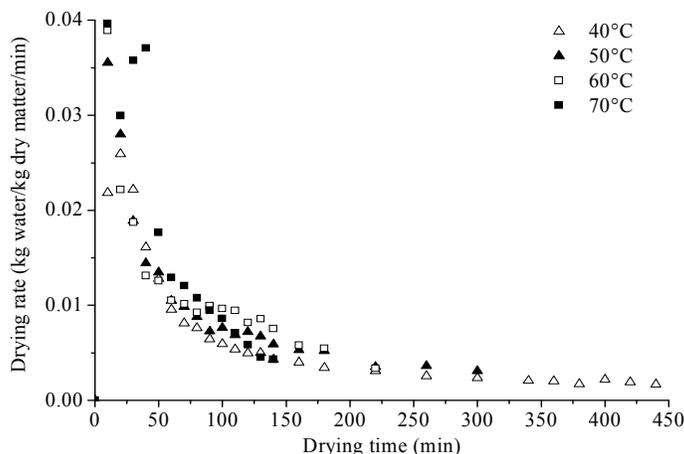
Fig. 4: Drying rate verse drying time of beef meat at different temperatures

Table 2: Statistical results obtained from different drying models for the temperature T = 40, 50, 60, 70°C

No.	T (°C)	Constants						R^2	χ^2	RSS
1	40	k = 0.0035						0.8188	6.9×10^{-3}	1.2×10^{-1}
	50	k = 0.0055						0.8997	4.9×10^{-3}	5.0×10^{-2}
	60	k = 0.0066						0.9565	1.6×10^{-3}	2.6×10^{-2}
	70	k = 0.0105						0.9762	1.1×10^{-3}	1.5×10^{-2}
2	40	n = 0.5797	k = 0.0349					0.9967	1.3×10^{-4}	2.2×10^{-3}
	50	n = 0.6388	k = 0.0331					0.9995	2.4×10^{-5}	2.2×10^{-4}
	60	n = 0.7504	k = 0.0212					0.9983	6.3×10^{-5}	9.5×10^{-4}
	70	n = 0.8155	k = 0.0233					0.9941	2.8×10^{-4}	3.4×10^{-3}
3	40	a = -0.0040	b = 5.886×10^{-6}					0.9074	3.5×10^{-3}	6.0×10^{-2}
	50	a = -0.0057	b = 1.003×10^{-5}					0.9249	3.7×10^{-3}	3.3×10^{-2}
	60	a = -0.0067	b = 2.014×10^{-5}					0.9634	1.4×10^{-3}	2.1×10^{-2}
	70	a = -0.0110	b = 5.043×10^{-5}					0.9938	2.9×10^{-4}	3.6×10^{-3}
4	40	a = 0.8516	k = 0.0027					0.9229	2.9×10^{-3}	5.0×10^{-2}
	50	a = 0.8921	k = 0.0045					0.9486	2.5×10^{-3}	2.3×10^{-2}
	60	a = 0.9268	k = 0.0058					0.9836	6.2×10^{-4}	9.3×10^{-3}
	70	a = 0.9595	k = 0.0098					0.9809	9.1×10^{-4}	1.1×10^{-2}
5	40	a = 0.6428	c = 0.3136	k = 0.0080				0.9855	0.5×10^{-4}	8.8×10^{-3}
	50	a = 0.6891	c = 0.2691	k = 0.0100				0.9829	8.4×10^{-4}	6.6×10^{-3}
	60	a = 0.7550	c = 0.2004	k = 0.0090				0.9915	3.2×10^{-4}	4.5×10^{-3}
	70	a = 0.7690	c = 0.2375	k = 0.0176				0.9989	5.0×10^{-5}	5.5×10^{-4}
6	40	a = 1.0058	b = 0.0001	n = 0.6330	k = 0.0290			0.9973	1.0×10^{-4}	1.6×10^{-3}
	50	a = 1.0006	b = -0.0002	n = 0.5928	k = 0.0387			0.9998	1.1×10^{-5}	7.4×10^{-5}
	60	a = 0.9988	b = -0.0004	n = 0.6677	k = 0.0270			0.9993	2.6×10^{-5}	3.4×10^{-4}
	70	a = 1.0037	b = 0.0012	n = 0.9919	k = 0.0145			0.9986	6.6×10^{-5}	6.6×10^{-4}
7	40	a = -0.0694	b = 0.9211	k = 0.0027	k_1 = 0.0027			0.9126	3.3×10^{-3}	5.0×10^{-2}
	50	a = 0.7556	b = 0.2437	k = 0.0034	k_1 = 0.0468			0.9998	8.6×10^{-6}	6.1×10^{-5}
	60	a = -0.1627	b = 1.0896	k = 0.0058	k_1 = 0.0058			0.9811	7.2×10^{-4}	9.3×10^{-3}
	70	a = 0.7543	b = 0.2524	k = 0.0179	k_1 = 0.0003			0.9988	5.5×10^{-5}	5.5×10^{-4}
*8	40	a = -2.8203	b = 0.6695	c = 3.1519	k = 0.0235	g = 0.0018	h = 0.0235	0.9998	8.1×10^{-6}	1.1×10^{-4}
	50	a = 0.1405	b = 0.7234	c = 0.1361	k = 0.0724	g = 0.0032	h = 0.0223	0.9999	1.7×10^{-6}	8.3×10^{-6}
	60	a = 1.0211	b = -0.1543	c = 0.1328	k = 0.0051	g = 0.0051	h = 0.0879	0.9995	1.8×10^{-5}	2.0×10^{-4}
	70	a = 0.6441	b = -3.0114	c = 3.3659	k = 0.0056	g = 0.0585	h = 0.0540	0.9995	2.3×10^{-5}	1.8×10^{-5}

a, b, c, d drying constants, *k, k_1, g, h* drying coefficient (min^{-1}), *n* exponent, *T* temperature, R^2 coefficient of determination, χ^2 reduced chi-square, *RSS* residual sum of squares

the reason why the increased temperature interval of 10°C from 60-70°C had the greatest effect on the decrease of drying time.

Fitting of the drying curves: The moisture content data observed at the drying experiment were fitted to the 8 models listed in Table 1 under drying distance 8 cm and air velocity 1 m/s. The statistical results of the different models are listed in Table 2. The acceptability of the drying models were based on the values that coefficient of determination (R^2) should be close to 1 and Residual Sum of Squares (*RSS*) and reduced chi-square (X^2) which should be very low. Table 2 shows that the most appropriate model in describing CMIHA drying of beef jerky is the Modified Henderson and Pabis model with a minimum R^2 of 0.9995, a maximum *RSS* of 2.0×10^{-4} for T = 60°C and maximum X^2 of 2.3×10^{-5} for T = 70°C. Figure 5 shows the comparison between experimental moisture ratio at different drying temperatures and that predicted by the Modified Henderson and Pabis model. According to Fig. 5, the predicted data generally banded around the straight line, which indicates the excellent suitability of the model proposed in predicting the moisture ratio during CMIHA drying on beef jerky. So, the Modified Henderson and Pabis model was selected as a suitable model to describe the drying process of beef jerky.

In order to explain the effect of drying temperatures on the parameters *a, b, c, k, g* and *h* (Table 1) of Modified Henderson and Pabis model, the regression analysis was used to set up the relations between these parameters and temperatures. Thus, the regression equations of these parameters against drying temperatures *T* (°C) are as follows:

$$MR(a,b,c,d) = a \cdot \exp(-k \cdot t) + b \cdot \exp(-g \cdot t) + c \cdot \exp(-h \cdot t) \qquad (8)$$

where,

$$a = -0.0008\,T^3 + 0.1383\,T^2 - 7.8124\,T + 145.5 \qquad (9)$$

$$b = 0.0003\,T^3 - 0.0414\,T^2 + 2.206\,T - 37.333 \qquad (10)$$

$$c = 0.00004\,T^3 + 0.0095\,T^2 - 1.3811\,T + 40.862 \qquad (11)$$

$$k = 0.00003\,T^3 - 0.0052\,T^2 + 0.2841\,T - 5.0141 \qquad (12)$$

$$g = 0.000009\,T^3 - 0.0013\,T^2 + 0.0628\,T - 1.0188 \qquad (13)$$

$$h = -0.00003\,T^3 + 0.0045\,T^2 - 0.2353\,T + 4.0223 \qquad (14)$$

All correlation coefficients (R^2) of Eq. (10-15) are equal to 1. Thus the moisture ratio of beef jerky at any
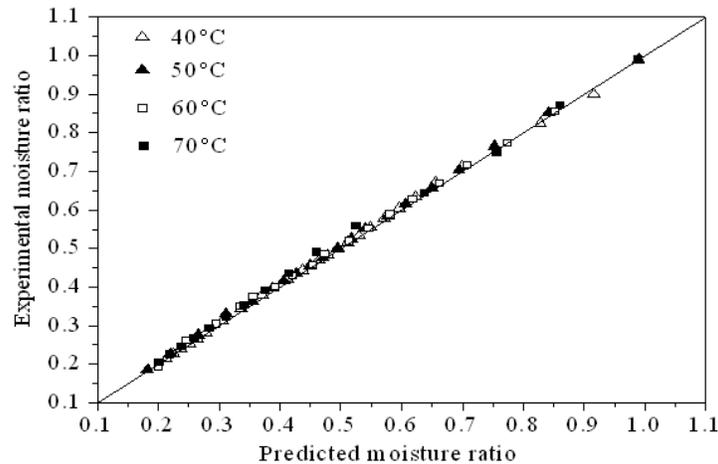
Fig. 5: Experimental and predicted moisture ratio of beef meat at different temperatures. The oblique line meant experimental moisture ratio equaled to predicted moisture ratio
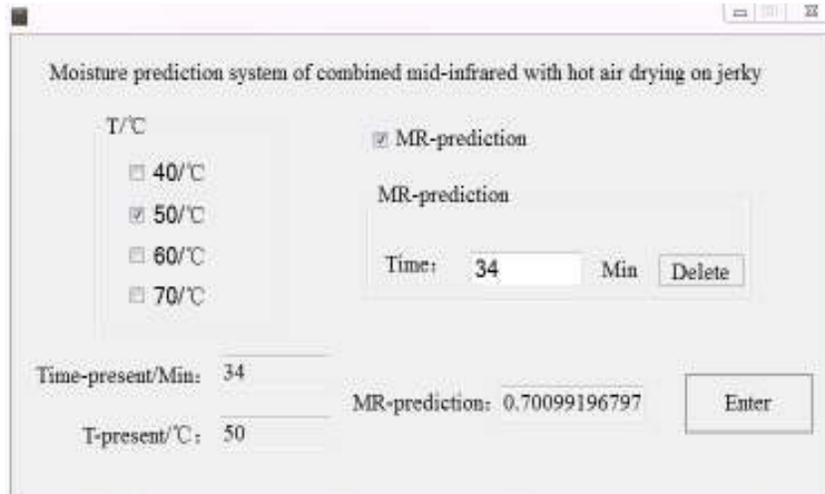
Fig. 6: The control interface of moisture prediction system of combined mid-infrared and hot air drying beef meat at different temperatures

time during CMIHA drying process could be estimated by these expressions.

Development of Moisture Prediction System (MPS): Moisture Prediction System (MPS) was a system that could make the moisture-predicted process become digitized, so as to predict settled moisture ratio through the whole drying process conveniently. This MPS was based on the drying models and developed by Microsoft visual C sharp (C#). The control interface of MPS is shown in Fig. 6, from which we can see, the MPS is very simple and convenient. When choosing the option of MR-prediction, the control interface will run for predicting MR. At the moment, just by selecting temperature and entering the drying time, the corresponding MR value of BM will be shown immediately. Furthermore, the present temperature and time will also be displayed to record the corresponding

parameter. Therefore, with MPS, we could predict the moisture ratio during the whole drying process fast and conveniently.

Determination of effective diffusivities and activation energy: The values of effective diffusivity (D_e) at different drying temperatures could be obtained by using Eq. (4) and (5). The average values of effective diffusivities ($D_{e,avg}$) of BM in the drying process at 40-70°C varied in the range of 1.83-5.55 $\times 10^{-10}$ m^2/s (Table 3). As is expected, the values of $D_{e,avg}$ increased with the increase of drying temperature. These results were in agreement with the previous report that the values of D_e lie within the general range of 10^{-11} to 10^{-9} m^2/s for food materials (Shi *et al*., 2008; Madamba *et al*., 1996). In addition, the $D_{e,avg}$ value of 50, 60, 70°C was 1.60, 2.25 and 3.03 times of $D_{e,avg}$ value of 40°C, respectively. This was corresponded

Table 3: Values of average effective diffusivities obtained for beef meat at different temperatures

Temperature(°C)	40	50	60	70
Average effective diffusivity ($\times10^{-10}$ m^2/s)	1.83±0.07	2.92±0.03	4.12±0.01	5.55±0.09
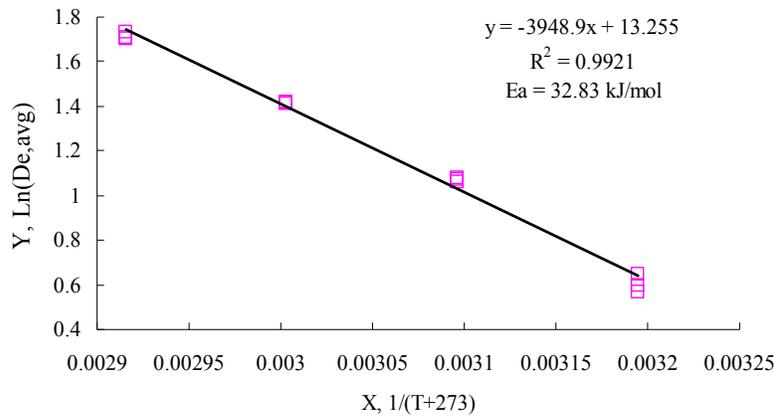
Fig. 7: The Arrhenius-type relationship between average effective diffusivity and drying temperature of beef meat

with conclusions that the rate of diffusion was proportional to the sample temperature and the value of $D_{e,avg}$ increased during the drying process (Wang *et al.*, 2007).

The natural logarithm of $D_{e,avg}$ as a function of the reciprocal of absolute temperature (T+273) was plotted in Fig. 7. The result shows a linear relationship derived from the Arrhenius-type equation with $R^2>0.99$. From the line slope and Eq. (7), the values of activation energy can be determined to be 32.83 kJ/mol for the whole falling rate period (Fig. 7). The value of activation energy indicates that the energy consumption to dry 1mol water for CMIHA drying is 32.83 kJ, which could be a theoretical reference for the application of CMIHA drying on BM.

CONCLUTION

The drying characteristics and kinetics of BM in a CMIHA dryer were studied and the following conclusions were drawn:

- The time consumption of BM dried with CMIHA decreases as the drying temperature increases and the values are ranged from 440 to 140 min among 40 and 70°C. Besides, the water loss rate of BM has a rising period from 20 min to 40 min at 70°C.
- The Modified Henderson and Pabis model fitted the drying experimental data better than the other drying mathematical models and the Moisture Prediction System (MPS) could predict the moisture ratio during the whole drying process conveniently.
- The effective diffusivity of BM dried with CMIHA increases as the drying temperature increases and the values are ranged from 1.83 to 5.55×10^{-10} m^2/s among 40 and 70°C. In addition, the temperature dependence of the average effective diffusivity could be described by Arrhenius-type equation

with $R^2>0.99$ and the activation energy values of 32.83 kJ/mol for the whole falling rate period.

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