Drying Kinetics of House Cricket by Hot Air Drying using Full Air Re-circulation Tunnel under Varying Temperatures and Air Velocities

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Abstract. *House cricket is a kind of insect to be used as an alternative protein source to create a new food in the present because of its high yield protein content therefore there are a lot of cricket farm was established for new economics in Thailand. The cricket was processed into easy food by frying or more technology to be cricket power and pasta. However, cricket must be dried and easy method for small scale is hot air drying by solar or in hot air oven. Therefore, this paper aims to kinetic study of thin layer drying of house cricket by hot air in 60, 70, and 80 ℃ varying with 1.0, 1.5, and 2.0 m/s. Six semi-theoretical model were used to describe the experiment having confirm the best model by statistic values includes R^2, χ^2, and RMSE. The experimental result was shown that the Midilli drying model is the best fit of thin layer drying of cricket for all temperature and air velocity. The effective moisture diffusivity was obtained in ranged between 4.78×10^{-9} and 1.31×10^{-8} m^2/s for all experiment. The activation energy of diffusion of cricket is 30.74 – 41.73 kJ/mol which is in the normal range of food materials. Predicted moisture ratio agreed well with experimental values.*

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1. Introduction

Insects are a class of animals within the arthropod group that have a chitinous exoskeleton, a three-part body (head, thorax, and abdomen), three pairs of jointed legs, compound eyes and two antennae. In fact, the using insects as a food has been a feature of human activity since prehistoric times and insects have formed a major part of the human diet for thousands of years. In tropical countries, insects are often consumed whole depending on the dish, fresh insects can be processed by roasting, frying, or boiling. In many countries of Asian, insect can be found in markets as ready-to-eat snacks or fried with kiffir lime leaves [1].

In term of nutritional value, insects may provide more protein than meat, chicken eggs, and dairy products [2]. They contain a fatty acid profile, monounsaturated and polyunsaturated fatty acids [3]. Moreover, the insect shells are chitin, a great source of insoluble dietary fiber [4]. Moreover crickets (Acheta domesticus) are extremely valuable in terms of nutritional value. They do not contain only significant amounts protein or fat, but also of vitamins and minerals [5]. Edible insects are interesting in source of vitamin B2, B5 and B7 and high contents of minerals, including iron (Fe), zinc (Zn), calcium (Ca), potassium (K), sodium (Na), phosphorus (P), manganese (Mn), magnesium (Mg) and copper (Cu) [6].

The process of insects is including of boiling, baking, roasting and more techniques having significantly affect the nutritional value of edible insects. Actually, the simple technique to dry the cricket conduct by hot air drying because it is familiar, easy, and no need high skill labor to operate. While there are report about herb drying by infrared lamp and hot air recirculation [19], therefore it was found that the simple technique is proper for local economy. Moreover, there are more advance technique to dry another vegetable and herb by microwave having optimized proper power using [20]. Whereas the thin layer drying of cricket under full air re-circulation by hot air tunnel has not been reported yet. Therefore, this paper aim to study the drying kinetics of house cricket by hot air drying using full air re-circulation tunnel under varying temperatures and air velocities.

2. Cricket and Methodology

2.1 Cricket (*Acheta domestica*)

House cricket used in the experiment supplied from local farm at Chumpae, KhonKaen (Siam Tech Farm). In this farm, there are four buildings for raising cricket with size 8×20 sqm. Inside each of building, there are 9 cricket ponds made of concrete block wall and inside contained egg panels for shelter. The recipe food for cricket is made from organics material such as the mulberry leaf. The duration of insect cultivation in each cycle is approximately 40-45 days. The size of cricket is varying from small – big (1-2 cm). The retail price of house cricket is about 100-150 baht/kilogram depend on season.

The cricket was prepared by boiling and dry it before keep in freezer for extending shelf life. The hot air drying of cricket experiment were conducted by varying the air temperature 60, 70, and 80° C and air velocity 1.0, 1.5, and 2.0 m/s. Initial moisture content of cricket was determined in triplicate in heating oven (Binder model FED115) at temperature 103°C, drying to constant weight (AOAC 16-192) and initial average moisture content is 285% dry basis. For each test, 280 grams approximately of cricket was tested in hot air tunnel. The final average moisture content is 6% dry basis.

2.2 Air Circulation Tunnel

Full air return of tunnel is used to conduct the kinetic experiments. The tunnel is made of galvanized steel sheet forming as a square duct with 40 cm x 40 cm of cross section embedded the axial blower having flow rate adjustable by manual dimmer whereas hot wire anemometer (Testo 435) is used to measure the air velocity inside the tunnel. 6,000 watts of fin heater were installed in front of testing chamber having adjust air temperature by PID controller. The re-circulation tunnel is shown in Fig 1.

Fig. 1 The re-circulation tunnel for drying experiment

2.3 Mathematical Modelling

The moisture content of cricket obtained from experiment in the range of drying temperatures of 60, 70, and 80°C under air velocity 1.0, 1.5, and 2.0 m/s were converted to the dimensionless of moisture ratio:

$$\mathrm{MR} = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

The moisture equilibrium was determined from the experiment by recording weight of cricket hourly until weight is steady. Experimental results of moisture ratio varying drying time were fitted to the semi-theoretical models in Table 1 which is widely used in the kinetics of the drying process [9,11-17]. Non-linear regression techniques were used to obtain the constants in each model.

Model No.	Model	Analytical expression
1	Lewis	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^y)$
3	Henderson and Pabis	$MR = a\exp(-kt)$
4	Wang and Singh	$MR = 1 + at + bt^2$
5	Logarithmic	$MR = a\exp(-kt) + c$
6	Midilli	$MR = a\exp(-kt^n) + bt$

Table 1 Semi-theoretical models for thin layer drying considered in the study

The coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE) were calculated to evaluate the fitting of each model to experimental data. The higher values of the coefficient of determination (R^2) and the lower values of the reduced chi-square (χ^2), and RMSE were chosen for goodness of fit, according to the criterion followed by Midilli and Kucuk [7], Akpinar et al. [8], and more author [11-17]. These parameters can be calculated as

$$R^2 = \left\{ \frac{N(\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{exp,i}} \times \mathrm{MR}_{\mathrm{pre,i}}) - (\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{exp,i}})(\sum_{i=1}^{N}MR_{\mathrm{pre,i}})}{\sqrt{[N\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{exp},i}^2 - (\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{exp,i}})^2][N\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{pre},i}^2 - (\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{pre,i}})^2]}} \right\}^2 \quad (2)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp},i} - \mathrm{MR}_{\mathrm{pre},i})^2}{N - p} \quad (3)$$

$$\mathrm{RMSE} = \left[\frac{1}{N} \sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i})^2 \right]^{1/2} \quad (4)$$

where $\mathrm{MR}_{\mathrm{exp},i}$ and $\mathrm{MR}_{\mathrm{pre},i}$ is the experiment and predicted moisture ratio respectively, while N is the number of data point and p is the number of constants in the regression model.

2.4 Determination of Effective Moisture Diffusivity

The effective moisture diffusivity is an important transportation property in materials and described the drying characteristics of food. Fick's second diffusion law can be used to estimate the effective moisture diffusivity of the house cricket. The solution of Fick's second diffusion law for spherical geometry is defined by following equation [10]: (1)

$$\mathrm{MR} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \pi^2 D_{eff}\, t}{R^2} \right) \quad (6)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), t is drying time (s), R is the radius of the samples (m), n is a positive integer. For long drying period, the equation (6) can be simplified to only the first term of the series. The natural logarithmic form is

$$\ln \mathrm{MR} = \ln \frac{6}{\pi^2} - \frac{\pi^2 D_{eff}\, t}{R^2} \quad (7)$$

From equation (7), effective moisture ratio can be calculated by plotting $\ln \mathrm{MR}$ varying with drying time (t), the experimental data gives a straight line with slope expressed as

$$\mathrm{Slope} = \frac{\pi^2 D_{eff}}{R^2} \quad (8)$$

2.5 Determination of Activation Energy

The effective moisture diffusivity is related with temperature by the Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T + 273.15)} \right) \quad (9)$$

where D_0 is pre-exponential factor of Arrhenius equation in m^2/s, E_a is the activation energy in kJ/mol, R is the universal gas constant in kJ/mol·K, T is the drying air temperature in °C.

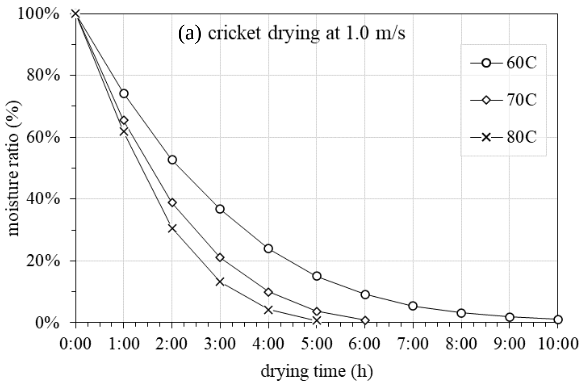
Taking natural logarithms, Eq. (9) can be linearized as

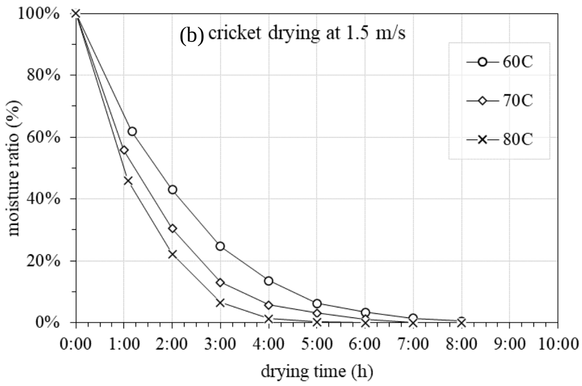
$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R(T + 273.15)} \quad (10)$$

3. Results and Discussion

3.1 Experimental Drying Curves

The variation of moisture ratio with drying time at air velocity 1.0, 1.5, and 2.0 m/s are shown in Fig 2. The cricket moisture ratio decreases with increasing drying time following an exponential decay. The drying time in every experiment from start to equilibrium tend to decrease as the air velocity tend to increase air velocity was effect to the drying time





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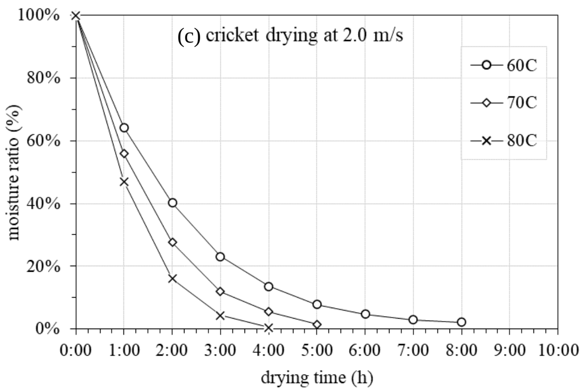
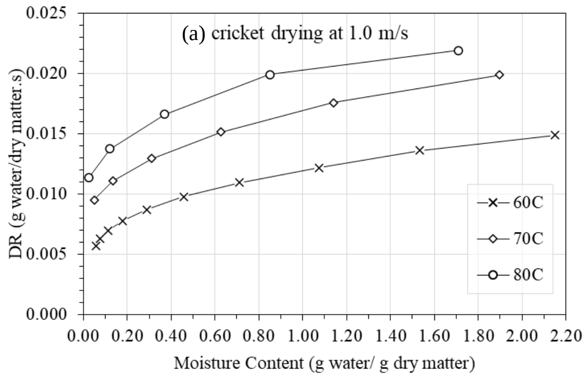


(c)

Fig. 2 Drying curves of cricket at different temperature and varying air velocity at 1.0, 1.5, and 2.0 m/s as (a), (b), and (c)

Data from Fig. 3, it was show that the moisture content and drying rate decrease continuously with drying time and was no constant drying rate period while the falling rate period occurred in whole of drying process. Therefore, diffusion is dominant mechanism governing moisture movement in crickets.



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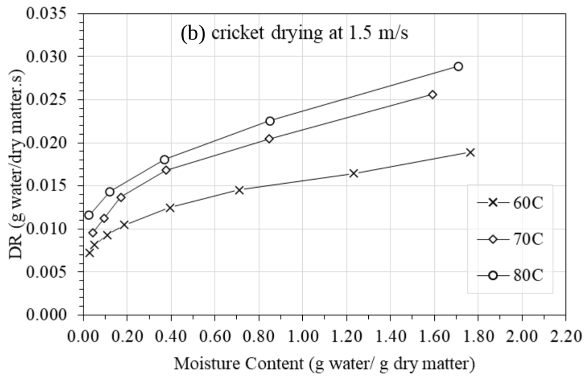

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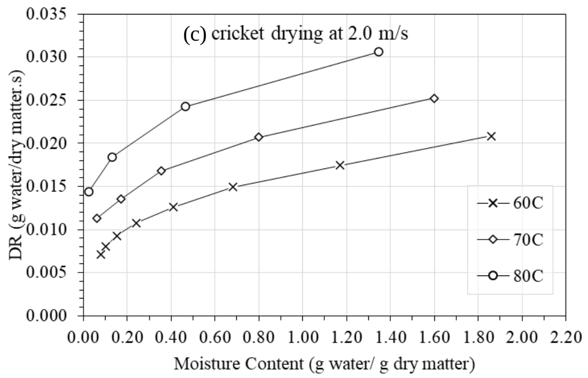


(c)

Fig. 3 Drying rate as a function of moisture content at different temperature and varying air velocity at 1.0, 1.5, and 2.0 m/s as (a), (b), and (c)

3.2 Modeling of Drying Curves

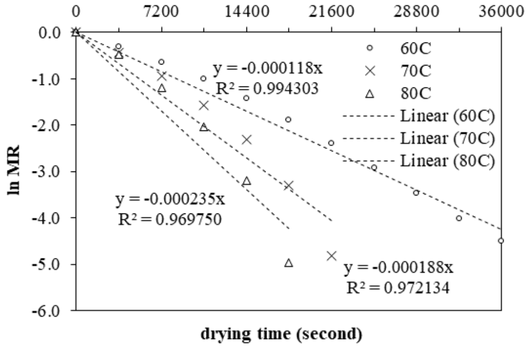
The average moisture ratio of house cricket at various drying air temperature at 60, 70, 80°C were fitted in six semi-theoretical models and the statistical values were summarized in Table 2. The best model describing the thin layer drying characteristic of house cricket was Midilli's model (model no. 6) for all air velocity experiment corresponds to the experiment data and describes the best drying behavior with values of R^2 more than 0.998 for all drying temperature and air velocity. Values of χ^2 and RMSE are very low.

Model	Temp	Model constants	R^2	Chi^2	RMSE
		for air velocity 1.0 m/s			
1	60°C	k=0.353914	0.9968	0.00070	0.02514
	70°C	k=0.507244	0.9942	0.00131	0.03350
	80°C	k=0.603659	0.9911	0.00204	0.04119
2	60°C	k=0.283042, y=1.178872	0.9997	0.00004	0.00620
	70°C	k=0.408298, y=1.245088	0.9994	0.00010	0.00923
	80°C	k=0.474867, y=1.337078	0.9998	0.00004	0.00585
3	60°C	a=1.029284, k=0.363345	0.9959	0.00058	0.02296
	70°C	a=1.025281, k=0.518394	0.9931	0.00118	0.03186
	80°C	a=1.026244, k=0.616743	0.9899	0.00188	0.03960
4	60°C	a=-0.246520, b=0.015197	0.9942	0.00082	0.02733
	70°C	a=-0.363775, b=0.033551	0.9984	0.00024	0.01444
	80°C	a=-0.432407, b=0.047144	0.9991	0.00014	0.01098
5	60°C	a=1.066894, k=0.316940, c=-0.052239	0.9984	0.00018	0.01278
	70°C	a=1.111016, k=0.410670, c=-0.102161	0.9987	0.00018	0.01226
	80°C	a=1.130817, k=0.474340, c=-0.119363	0.9968	0.00048	0.01997
6	60°C	a=0.997580, k=0.284963, n=1.156194, b=-0.001141	0.9998	0.00002	0.00466
	70°C	a=0.999404, k=0.411533, n=1.175311, b=-0.004948	0.9999	0.00001	0.00301
	80°C	a=0.999925, k=0.475289, n=1.290847, b=-0.003415	1.0000	0.00000	0.00161
		for air velocity 1.5 m/s			
1	60°C	k=0.476055	0.9990	0.00018	0.01268
	70°C	k=0.625310	0.9980	0.00038	0.01808
	80°C	k=0.799257	0.9979	0.00044	0.01917
2	60°C	k=0.431863, y=1.097900	0.9999	0.00002	0.00405
	70°C	k=0.568628, y=1.132610	0.9994	0.00008	0.00846
	80°C	k=0.752202, y=1.112962	0.9984	0.00026	0.01470
3	60°C	a=1.008426, k=0.479630	0.9989	0.00016	0.01198
	70°C	a=1.010273, k=0.630768	0.9978	0.00036	0.01761
	80°C	a=1.005044, k=0.802428	0.9978	0.00044	0.01906
4	60°C	a=-0.319315, b=0.025134	0.9883	0.00225	0.04442
	70°C	a=-0.422373, b=0.044113	0.9900	0.00163	0.03737
	80°C	a=-0.475484, b=0.053156	0.9791	0.00444	0.06083
5	60°C	a=1.038879, k=0.429112, c=-0.040610	0.9991	0.00011	0.01000
	70°C	a=1.036190, k=0.579064, c=-0.03172	0.9988	0.00016	0.01187
	80°C	a=1.025983, k=0.746777, c=-0.024881	0.9989	0.00017	0.01199
6	60°C	a=0.996149, k=0.436286, n=1.038602, b=-0.003475	0.9993	0.00009	0.00864
	70°C	a=0.999028, k=0.568433, n=1.120074, b=-0.000826	0.9994	0.00008	0.00826
	80°C	a=0.999073, k=0.751652, n=1.071311, b=-0.002480	0.9988	0.00019	0.01243
		for air velocity 2.0 m/s			
1	60°C	k=0.476387	0.9990	0.00016	0.01196
	70°C	k=0.649054	0.9974	0.00057	0.02182
	80°C	k=0.854860	0.9954	0.00110	0.02962
2	60°C	k=0.438512, y=1.086081	0.9998	0.00002	0.00404
	70°C	k=0.577306, y=1.176663	0.9999	0.00002	0.00388
	80°C	k=0.752422, y=1.297389	1.0000	0.00001	0.00276
3	60°C	a=1.011147, k=0.481216	0.9989	0.00014	0.01125
	70°C	a=1.012857, k=0.656090	0.9971	0.00054	0.02112
	80°C	a=1.011249, k=0.862105	0.9951	0.00106	0.02917
4	60°C	a=-0.322736, b=0.025901	0.9864	0.00202	0.04233
	70°C	a=-0.460196, b=0.053659	0.9954	0.00075	0.02499
	80°C	a=-0.589194, b=0.086148	0.9969	0.00057	0.02133
5	60°C	a=1.066894, k=0.316940, c=-0.052239	0.9992	0.00009	0.00907
	70°C	a=1.111016, k=0.410670, c=-0.102161	0.9991	0.00014	0.01063
	80°C	a=1.130817, k=0.474340, c=-0.119363	0.9982	0.00031	0.01580
6	60°C	a=0.999142, k=0.435928, n=1.101088, b=0.000704	0.9999	0.00001	0.00353
	70°C	a=0.999891, k=0.577333, n=1.152915, b=-0.001712	0.9999	0.00001	0.00285
	80°C	a=1.000007, k=0.750498, n=1.269995, b=-0.001881	1.0000	0.00000	0.00020

Table 2 Model constants and statistic values of each mathematical models at air velocity 1.0, 1.5, and 2.0 m/s

3.3 Determination of Moisture Diffusivity and Activation Energy

The moisture diffusivity for each drying temperature was determined by plotting experimental data in terms of $\ln \mathrm{MR}$ versus drying time as shown in Fig 4.



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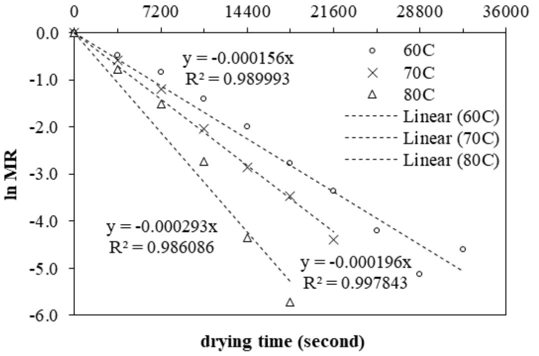

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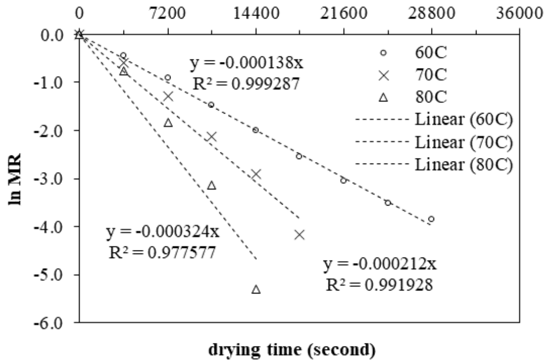


(c)

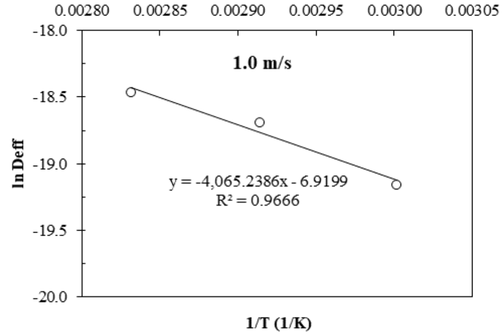
Fig. 4 Plot of ln MR vs. drying time at air velocity 1.0, 1.5, 2.0 m/s as (a), (b), and (c)

The values of the moisture diffusivity were calculated using Eqn. (8) and slope values from Fig 4. The moisture diffusivity values were varied in the range of 4.78×10^{-9} and 1.31×10^{-8} m^2/s as show in Table 3. It was noted that D_{eff} values increased with increasing drying temperature and air velocity. While house cricket was dried in high temperature, heating energy would increase the activity of water molecules inside effecting to higher effective moisture diffusivity.

Temp	Diffusivity at air velocity		
	1.0 m/s	1.5 m/s	2.0 m/s
60C	4.78×10^{-09}	6.32×10^{-09}	5.59×10^{-09}
70C	7.62×10^{-09}	7.94×10^{-09}	8.59×10^{-09}
80C	9.52×10^{-09}	1.19×10^{-08}	1.31×10^{-08}

Table 3 Moisture diffusivity of hot air cricket drying

The activation energy was calculated from the slope of Arrhenius plot between ln D_{eff} and $1/(T+273.15)$ in Fig.5. The final activation energy of all experiment was found in the range of 30.74 – 41.73 kJ/mol. Whereas the value of activation energy stands within the general range of 12.7 to 110 kJ/mol for various food materials.



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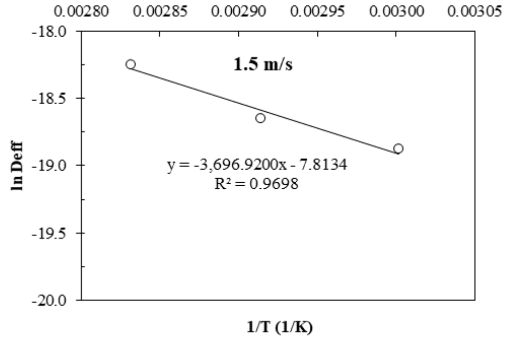

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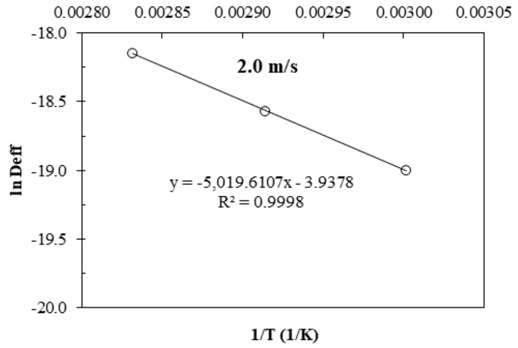

(c)

Fig. 5 Arrhenius-type relationship between the effective moisture diffusivity versus inversely proportional absolute temperature at air velocity 1.0, 1.5, 2.0 m/s as (a), (b), and (c)

4. Conclusions

According to the experiment, the drying kinetics of house cricket in thin-layer dryer was investigated. The approximately initial moisture content about 285% (d.b.) to the equilibrium moisture content in maximum 10, 6, and 5 hours at 60, 70, and 80°C for all experiment. The experiment show that the falling rate period is mainly having the diffusion is dominant mechanism of moisture movement.

Midilli's is the best model describing the thin layer drying characteristic of house cricket with R^2 is over 0.998 and very low χ^2 and RMSE for all experiment.

The moisture diffusivity values were varied in the range of 4.78×10^{-9} and 1.31×10^{-8} m^2/s which is in the normal range of drying of food materials [12-13,16,18]. Finally, by Arrhenius plot, the activation energy for moisture diffusion was found to be 30.74 – 41.73 kJ/mol which is in the normal range of food materials.

By the experiment the drying temperature effect to drying time while the air velocity effect to the drying time but not much because the falling rate was found in the drying rate graph in Fig 3.

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