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Thin-Layer Drying Kinetics of Pseudapocryptes Elongatus Fish in a Convective Dryer

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ABSTRACT

The present work determines the thin-layer drying kinetics of Pseudapocryptes Elongatus fish in a convective dryer. The experiments were conducted in the range of 0.5–1.5 m s^{-1} air velocity, 50–70^{o}C drying temperature, fish size with 45 fish/kg, and 140 ± 5 mm fish length. The drying process reduces the moisture content of fish from 3.237 to 0.11 (d.b). Results indicated that the best model describing the drying behaviour of Pseudapocryptes Elongatus fish was the Two-term model with the correlation coefficient $R^2 > 0.99976$. The E_a and the D_{eff} of fish were 42–46.16 kJ mol^{-1} and $1.621 \times 10^{-10} - 5.618 \times 10^{-10}$ m^2 s^{-1}, respectively. The present work is helpful in designing and operating the drying process of Pseudapocryptes Elongatus fish in the convective dryer.

1. Introduction

Drying is an important stage in harvesting agricultural and aquatic because it extends the shelf life and preserves the product's quality. Open sun drying (OSD) and convective drying are two traditional methods widely used in actual. The OSD has the advantages of investment costs, but the disadvantages of OSD exposure are the long drying time, weather dependence, and dirt pollution. To overcome some disadvantages of OSD, solar dryers using the air collector have been considered in many studies [1,2]. The results show that solar dryers improve efficiency, product quality and reduce drying time. Drying in a convective dryer has the advantages of fast drying, reduced dust pollution, and a well-controlled drying mode, but the main disadvantage is the high operating cost. However, the convective dryer has a simple structure and operation, so it is still widely used in drying agricultural and aquatic products [3,4].

Drying kinetics is one of the important research directions in drying technology. Drying kinetics provides data describing the macroscopic and microscopic mechanisms of mass transfer in drying. The drying kinetics data are significant in the design, operation, and optimization drying mode. In recent decades, a study on the thin-layer drying (TLD) kinetics in the convective dryer of various

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agricultural and aquatic products has been carried out. For the agricultural products group: cassava chips [5], banana [6], potato [7], burdock root [8], *Etc*. For the aquatic products group: shrimp [9], silverside fish [10], Atlantic salmon fillets fish [11], silver carp fillets fish [12], freshwater fish [13], and sardine muscles fish [14]. The above studies show that the TLD kinetics of many materials have been considered in a convective dryer.

The Pseudapocryptes Elongatus fish is a fish that belongs to the Oxudercidae family. Fish has high nutritional content and economic value. It is widely distributed in many countries in Asia. The Pseudapocryptes Elongatus fish is one of the specialty fish of Southwestern Vietnam. The fish has been intensively farmed and exploited, bringing many economic benefits to Vietnam's Mekong Delta. Drying of the Pseudapocryptes Elongatus fish is significant in preserving and exporting the finished fish. Drying in a convective dryer is one of the primary methods used to dry finished Pseudapocryptes Elongatus fish in Vietnam. However, to the best author's knowledge, no studies have determined the TLD model of Pseudapocryptes Elongatus in a convective dryer and the characteristic parameters of the drying process, including effective moisture diffusivity coefficient and the activation energy. Thus, to address this research gap, a convective dryer model was developed, and experiments TLD were conducted for Pseudapocryptes Elongatus fish. Research results provide new data on the TLD kinetics of Pseudapocryptes Elongatus fish in a convective dryer, which is unavailable in the previous technical literature. The present work is useful for designing and operating the drying process of Pseudapocryptes Elongatus fish in a convective dryer.

2. Materials and Methods

2.1 Materials

The Pseudapocryptes Elongatus fish is bought from the supermarket, washed with brine to remove slime, rinsed with fresh water, and drained. Fish samples of 45 fish/kg and 140 ± 5 mm fish length were selected. The initial moisture content of the fish was 3.237 (d.b), which was determined by drying in the Oven at 105^{o}C for 24 hours [8,15]. The fish has a cylindrical body but gets smaller towards the tail. Thus, the fish can be considered a cylindrical shape. The five fish was measured in size, then 3D modelling on Autodesk Inventor. The average radius of the fish was r = 5.6978mm, which was determined based on the volume and length of the fish.

2.2 The Experimental Facility

The convective dryer model in this study shows in Figure 1. It is tailor-made with one mesh drying tray. Detailed specifications are as follows: the 320 x 320 x 600 mm drying chamber dimension; the 8 kW resistor (2 kW/pcs); the axial blower with 980 m^3/h volume flow and 80W power. The resistor power and blower speed were regulated by the rheostats. The device measures the drying temperature with an accuracy of 1% and a resolution of 0.1°C. An electronic balance is arranged below the dryer to measure the weight of the material with an accuracy of 0.01g. Air velocity is measured by Testo 410-2 with an accuracy of 2% and a resolution of 0.1 m s^{-1}. The electronic calliper measures fish size with an accuracy of 0.03 mm and a resolution of 0.01 mm. Each sample weighs about 400 ± 10 g. The experiments were repeated twice, the calculated value was average, and the time to check the sample was 15 minutes. The test ended when the final moisture content was around 0.11 d.b (10%, w.b), the lowest moisture content for dried fish in actual production [3]. The drying modes were conducted with 0.5–1.5 m s^{-1} air velocity and 50–70^{o}C drying temperature.

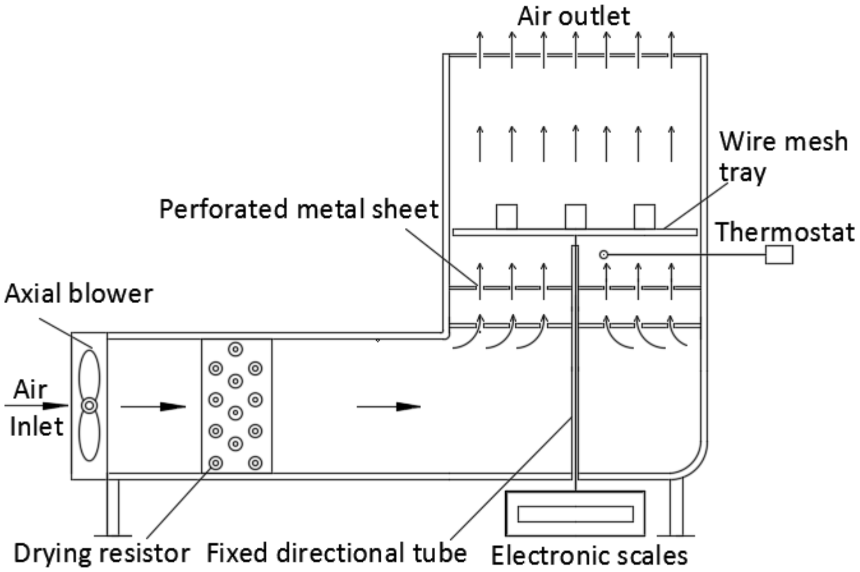


Fig. 1. The convective dryer models

2.3 Analytical Methods

According to the American National Standards Institute and the American Society of Association Executives (ANSI/ASAE 2014), a thin layer is a material layer wholly exposed to air during drying. Then it can be considered that temperature distribution in the material is uniform. Thus, lumped parameter models are suitable for the TLD [2,4]. In the study of drying kinetics, TLD models are useful in explaining the moisture reduction mechanism of materials. There are three types of TLD models: theoretical, semi-theoretical, and empirical. The theoretical model takes into account the internal resistance mechanisms of material. The results of this model have low accuracy due to many assumptions. Meanwhile, the semi-theoretical and empirical models suggest that the primary determinant of moisture transfer is the external drying conditions. Semi-theoretical models are obtained from solutions of Fick's second law or a simplified form according to Newton's law of cooling. Empirical models show a direct relationship between moisture content and drying time, which does not follow the theoretical foundations of drying. Both models make good predictions about material drying behaviour because they are based on experimental data with fewer assumptions. The main assumptions applied to the study on TLD include the following: the uniform thickness of the grain layer; should not be more than three layers; the drying mode is maintained stable (air temperature and relative humidity) [2]. However, the thin layer thickness can be increased when increasing air velocity, and then the heat and mass transfer process is in equilibrium with the thermodynamic state of the air [16].

This study developed a convective dryer model, and the drying modes were set to determine the TLD model of Pseudapocryptes Elongatus fish. Based on experimental data, the twelve TLD models were used to choose the best model describing the drying behaviour of Pseudapocryptes Elongatus fish. The models are selected because of their popularity; details are shown in Table 1 [4,17,18].

In the mathematical models in Table 1: DM is the dimensionless moisture content of the fish; t is the drying time; a, b, and n are the model constant; s, s_1, and s_2 are drying constants.

Table 1
The models used for predicting the drying behaviour of Pseudapocryptes Elongatus fish

No.	Name Model	Model
1	Newton	$DM = \exp(-s.t)$
2	Henderson and Pabis	$DM = a.\exp(-s.t)$
3	Page	$DM=\exp(-s.t^n)$
4	Logarithmic	$DM = a.\exp(-s.t)+b$
5	Demir *et al.,*	$DM = a.\exp(-s.t)^n+b$
6	Two-term	$DM = a.\exp(-s_1.t)+b.\exp(-s_2.t)$
7	Two-term exponential	$DM = a.\exp(-s.t)+(1-a).\exp(-a.s.t)$
8	Diffusion approach	$DM = a.\exp(-s.t)+(1-a).\exp(-b.s.t)$
9	Midilli-Kucuk	$DM = a.\exp(-s.t^n)+b.t$
10	Modified Midilli-Kucuk	$DM = a.\exp(-s.t^n)+b$
11	Weibull	$DM = a - b.\exp(-s.t^n)$
12	Wang and Singh	$DM = b.t^2+a.t+1$

**s, s_1, s_2 - drying constant (h^{-1})*

The dimensionless moisture content of the fish is calculated by the formula (ignoring equilibrium moisture) [8,9]:

$$DM = \frac{M}{M_o} \tag{1}$$

where M is the moisture content dry basis, M_O is the initial moisture content dry basis.

The values a, b, n, s, s_1, s_2 in the mathematical model (see Table 1) are determined by non-linear regression analysis of experimental data; It was conducted on the Stagraphic software [19]. The root means square error (RMSE), the correlation coefficient (R^2), and the reduced chi-square (C_r^2) are three statistical criteria used to choose the good fit model with the experimental data. The R^2 represents the linear relation between experimental and predicted values. The RMSE and C_r^2 represent deviations between experimental data and predicted values. Thus, the best model has the highest R^2, the smallest C_r^2, and the smallest RMSE. The statistical coefficients are determined as follows [8,20]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(DM_{e,i} - DM_{p,i}\right)^2}{\sum_{i=1}^{n}\left(DM_{e,m} - DM_{e,i}\right)^2} \tag{2}$$

$$C_r^{\,2} = \frac{1}{n-j}\sum_{i=1}^{n}\left(DM_{p,i} - DM_{e,i}\right)^2 \tag{3}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(DM_{p,i} - DM_{e,i}\right)^2} \tag{4}$$

where j, n, $DM_{e,i}$, $DM_{e,m}$, and $DM_{p,e}$, are the number of constants, the number of data points, the experimental value, the experimental mean value, and the predicted value, respectively

The drying rate of fish is determined by the formula [5,21]:

$$DR = \frac{M_i - M_{i+1}}{t_{i+1} - t_i} \tag{5}$$

The effective moisture diffusivity coefficient *(D_{eff})* can be explained using Fick's second law of diffusion, which is determined through drying experimental data [9,22]:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \tag{6}$$

With the assumption:

i. The moisture diffusivity is constant
ii. Uniform initial moisture distribution inside fish
iii. At steady state conditions, the uniform temperature distribution inside fish and the temperature of fish equals the drying temperature.
iv. Fish without shrinkage during the drying process

The solution of Eq. (6) in the drying rate falling period can be obtained using the developed Crank. For cylindrical shape material [22,23]:

$$DM = \sum_{n=1}^{\infty} \frac{4}{\beta^2} \exp\left(-\beta^2 \frac{D_{eff} t}{r^2} \right) \tag{7}$$

where r (m) is the cylinder radius, and β is the roots of the Bessel function. For long drying times and the *r* is small. Eq. (7) can be rewritten as follows [22,23]:

$$DM = \frac{4}{\beta^2} \exp\left(-\beta^2 \frac{D_{eff} t}{r^2} \right) \tag{8}$$

The simplified form of the Eq. (8) can be rewritten as follows:

$$\ln(DM) = \ln\left(\frac{4}{\beta^2} \right) - \beta^2 \frac{D_{eff} t}{r^2} \tag{9}$$

The slope of Eq. (9) is the basis for determining the effective moisture diffusivity coefficient.

The activation energy is determined by the Arrhenius correlation, which is the energy required to initiate the moisture diffusion during drying [5,24]:

$$D_{eff} = A.\exp\left(-\frac{E_a}{R_g.T_K} \right) \tag{10}$$

where E_a (kJ kmol^{-1}), A (m^2 s^{-1}), R_g (kJ kmol^{-1} K^{-1}), and T_k (K) are activation energy, the pre-exponential factor of the Arrhenius correlation, the gas constant, and the absolute drying temperature, respectively.

The Logarithmic-linear form of Eq. (10) can be rewritten as follows:

$$\ln\left(D_{eff}\right) = -\frac{E_a}{R_g.T_K} + \ln\left(A\right) \tag{11}$$

Eq. (11) is the basis for determining the activation energy.

The uncertainty of the calculated results (U_Y) is determined by Eq. (12), which is performed on EES software [9,25].

$$U_Y = \sqrt{\sum_i^n \left(\frac{\partial Y}{\partial z} U_Z\right)^2} \tag{12}$$

where U_Z is the uncertainty in the measured quantity Z.

3. Results and Discussion

3.1 The Drying Curve and Drying Rate Curve

Figure 2 explains the variation of moisture content with drying time. The shortest drying time at the drying mode with V = 1.5 m s^{-1} and T = 70°C. The longest drying time at the drying mode with V = 0.5 m s^{-1} and T = 50°C. At the mode with T= 70°C, the drying time was reduced on average by 1.48 times and 2.03 times compared with the mode with T = 60°C and T = 50°C. The drying time decreases by 1.25–2.25 hours at higher velocity at the same drying temperature. The fish receives much heat at high-drying temperatures, increasing the moisture diffusion inside the fish. The moisture on the fish's outside is better removed at high-air velocity, creating momentum for moisture diffusion inside the fish. Thus, the high-drying temperature and air velocity make the fish dry faster. The drying temperature is a factor that significantly affects the drying time, consistent with previous studies [8,24]. The highest uncertainty found for moisture content dry basis was 0.101%.

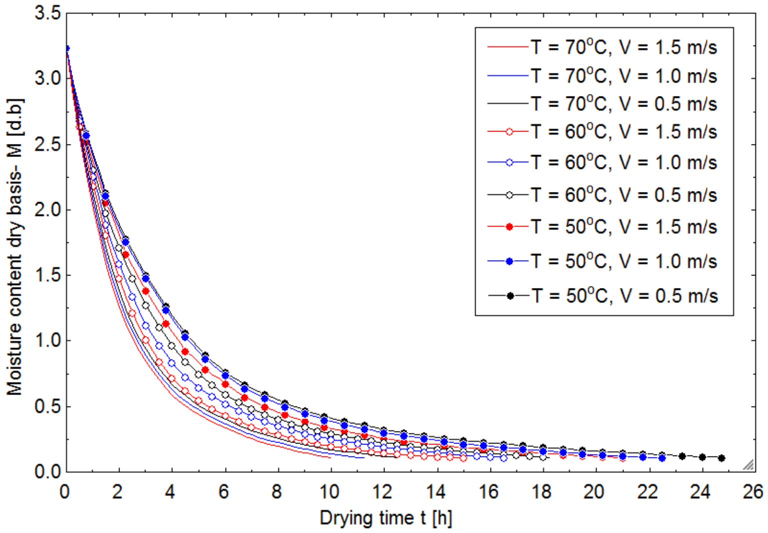


Fig. 2. The drying curve of Pseudapocryptes Elongatus fish

Figure 3 is the data extracted to discuss the influence of air velocity and drying temperature on drying rate. The average drying rate at 70°C and 60°C is about 1.99 and 1.37 times better than that at 50°C (see Figure 3a). The moisture connection is mainly connection-free and connection-osmotic in the first drying period. Thus, air velocity and drying temperature significantly influence the removal of moisture content in this period (Figure 3a, 3b). The effect of drying temperature is insignificant in the period of the low moisture content dry basis (M < 0.32), possibly because the moisture connection is more stable and difficult to separate in this period with connection-adsorption and connection-capillary. The effect of air velocity is insignificant in the period of the low moisture content dry basis (M < 0.5). It is due to the small amount of water separated, with low moisture content at the surface of the fish. Thus, low-air velocity still ensures a pressure gradient between the fish's surface and the air. Thus, this period should reduce the air velocity to reduce energy cost consumption.

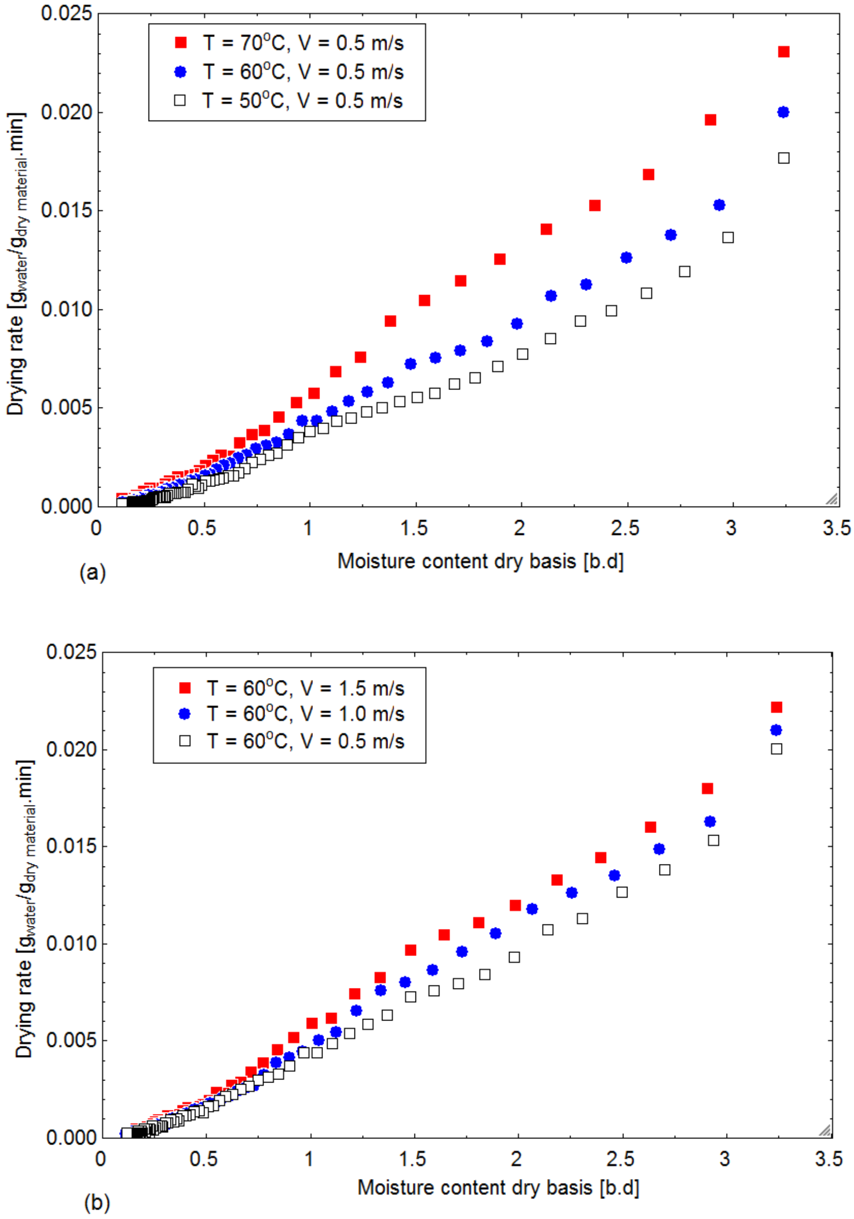


Fig. 3. The drying rate curve of Pseudapocryptes Elongatus fish (a) Modes with T = 50–70°C, V = 0.5 m/s (b) Modes with T = 60°C, V = 0.5–1.5 m/s

3.2 Thin-Layer Drying Model

Table 2 shows the coefficients in the mathematical models and statistical coefficients. The Two-term model best predicts the drying behaviour of Pseudapocryptes Elongatus fish due to having the highest R^2, the smallest C_r^2, and the smallest RMSE in the drying cases.

Table 2
The mathematical models predict the drying behaviour of Pseudapocryptes Elongatus fish

T(°C)	V (m s^{-1})	Model	Regression parameters	R^2	RMSE	C_r^2 x 10^4
70	1.5	1	s = 0.434469	0.990617	0.024256	6.03069
		2	a = 0.956839, s = 0.414223	0.992642	0.021753	4.97481
		3	s = 0.49903, n = 0.866128	0.997804	0.011883	1.48441
		4	a = 0.947123, s = 0.48869, b = 0.0425892	0.998975	0.008226	0.73014
		5	a = 0.94713, s = 0.233297, n = 2.09483, b = 0.0425979	0.998975	0.008337	0.77014
		6	**a = 0.292065, s_1 = 0.207869, b = 0.713196, s_2 = 0.635587**	**0.999851**	**0.003182**	**0.11220**
		7	a = 0.359981, s = 0.887797	0.998924	0.008317	0.72727
		8	a = 0.271169, s = 0.200369, b = 3.08403	0.999832	0.003332	0.11975
		9	a = 1.0114, s = 0.503514, n = 0.908724, b = 0.00277276	0.999222	0.007263	0.58452
		10	a = 0.976288, s = 0.515947, n = 0.931649, b = 0.0323731	0.999415	0.006298	0.43950
		11	a = 0.0321845, b = -0.976782, s = 0.516363, n = 0.930569	0.999415	0.006297	0.43938
		12	b = 0.0196878, a = -0.280496	0.901601	0.079550	66.52681
	1.0	1	s = 0.411298	0.989172	0.025583	6.69009
		2	a = 0.953633, s = 0.390586	0.991415	0.023036	5.54785
		3	s = 0.48038, n = 0.857518	0.997255	0.013026	1.77390
		4	a = 0.94612, s = 0.46379, b = 0.0428283	0.998915	0.008285	0.73427
		5	a = 0.946133, s = 0.227394, n = 2.03975, b = 0.04284	0.998915	0.008383	0.76965
		6	**a = 0.253364, s_1 = 0.177403, b = 0.75167, s_2 = 0.58798**	**0.999845**	**0.003164**	**0.10966**
		7	a = 0.354538, s = 0.854525	0.998368	0.010043	1.05455
		8	a = 0.236933, s = 0.171145, b = 3.3556	0.999829	0.003293	0.11598
		9	a = 1.01233, s = 0.482474, n = 0.905167, b = 0.00266953	0.999134	0.007488	0.61406
		10	a = 0.975172, s = 0.493648, n = 0.931258, b = 0.0338046	0.999374	0.006366	0.44391
		11	a = 0.0335859, b = -0.975819, s = 0.494262, n= 0.929827	0.999374	0.006365	0.44371
		12	b = 0.0162306, a = -0.25614	0.880823	0.085831	77.01749
	0.5	1	s = 0.388434	0.987058	0.027476	7.70016
		2	a = 0.950495, s = 0.367406	0.989547	0.024944	6.47579
		3	s = 0.462435, n = 0.84749	0.996305	0.014831	2.28938
		4	a = 0.944691, s = 0.441963, b = 0.0448222	0.998888	0.008221	0.71800
		5	a = 0.944701, s = 0.221365, n = 1.99665, b = 0.0448295	0.998888	0.008308	0.74888
		6	**a = 0.21096, s_1 = 0.143766, b = 0.794214, s_2 = 0.541443**	**0.999808**	**0.003448**	**0.12904**
		7	a = 0.349077, s = 0.820244	0.997371	0.012509	1.62883
		8	a = 0.198642, s = 0.138661, b = 3.82749	0.999791	0.003566	0.13511

		9	a = 1.01319, s = 0.461229, n = 0.904341, b = 0.00274295	0.998979	0.007959	0.68743
		10	a = 0.971553, s = 0.471456, n = 0.935711, b = 0.0373442	0.999300	0.006589	0.47111
		11	a = 0.0370925, b = -0.972417, s = 0.472366, n = 0.93376	0.999301	0.006587	0.47076
		12	b = 0.0135795, a = -0.235161	0.860427	0.091146	86.46738
60	1.5	1	s = 0.361535	0.986371	0.027427	7.64752
		2	a = 0.951612, s = 0.342348	0.988584	0.025313	6.62466
		3	s = 0.435163, n = 0.846678	0.995080	0.016617	2.85483
		4	a = 0.948569, s = 0.409343, b = 0.0421711	0.999135	0.007029	0.51964
		5	a = 0.948578, s = 0.213436, n = 1.91796, b = 0.0421763	0.999135	0.007091	0.53804
		6	**a = 0.137848, s_1 = 0.0962478, b = 0.865229, s_2 = 0.467082**	**0.999760**	**0.003735**	**0.14928**
		7	a = 0.361875, s = 0.732082	0.996130	0.014738	2.24564
		8	a = 0.132372, s = 0.0932155, b = 4.961	0.999754	0.003781	0.15040
		9	a = 1.01142, s = 0.426267, n = 0.915306, b = 0.00248673	0.998966	0.007751	0.64297
		10	a = 0.967843, s = 0.432411, n = 0.953012, b = 0.0378711	0.999365	0.006075	0.39495
		11	a = 0.037613, b= -0.968947, s = 0.4337, n = 0.950429	0.999366	0.006071	0.39441
		12	b = 0.0100531, a = -0.204291	0.817472	0.101216	105.9187
	1.0	1	s = 0.320562	0.982283	0.030832	9.64991
		2	a = 0.937759, s = 0.298404	0.986057	0.027561	7.82972
		3	s = 0.406118, n = 0.822543	0.995174	0.016215	2.71002
		4	a = 0.936141, s = 0.366109, b = 0.0469344	0.998690	0.008515	0.75898
		5	a = 0.936157, s = 0.201977, n = 1.81276, b = 0.046943	0.998690	0.008582	0.78327
		6	**a = 0.193291, s_1 = 0.104496, b = 0.808002, s_2 = 0.447316**	**0.999859**	**0.002802**	**0.08352**
		7	a = 0.331444, s = 0.716084	0.995433	0.015773	2.56452
		8	a = 0.191154, s = 0.103754, b = 4.29317	0.999858	0.002827	0.08365
		9	a = 1.01457, s = 0.398681, n = 0.885869, b = 0.00226463	0.998890	0.007900	0.66365
		10	a = 0.969401, s = 0.404081, n = 0.922508, b = 0.0393282	0.999302	0.006265	0.41743
		11	a = 0.0389777, b = -0.97077, s = 0.405543, n = 0.919583	0.999303	0.006260	0.41678
		12	b = 0.00819485, a = -0.183799	0.812316	0.101118	105.3951
	0.5	1	s = 0.286093	0.982769	0.030208	9.25045
		2	a = 0.93095, s = 0.264253	0.987503	0.025904	6.89651
		3	s = 0.371261, n = 0.820701	0.996275	0.014143	2.05595
		4	a = 0.928943, s = 0.322177, b = 0.045635	0.999129	0.006885	0.49404
		5	a = 0.928953, s = 0.189207, n = 1.70286, b = 0.0456406	0.999129	0.006934	0.50826
		6	**a = 0.171275, s_1 = 0.086856, b = 0.818815, s_2 = 0.382297**	**0.999930**	**0.001961**	**0.04066**
		7	a = 0.321416, s = 0.662912	0.996017	0.014624	2.19800
		8	a = 0.193567, s = 0.0945092, b = 4.20246	0.999870	0.002664	0.07396
		9	a = 1.00775, s = 0.357382, n = 0.8867, b = 0.00197477	0.999511	0.005198	0.28567
		10	a = 0.964947, s = 0.361459, n = 0.918591, b = 0.0374978	0.999754	0.003684	0.14350

		11	a = 0.0372539, b = -0.965927, s = 0.362471, n = 0.916571	0.999755	0.003681	0.14323
		12	b = 0.00667379, a = 0.165714	0.818558	0.098704	100.1318
50	1.5	1	s = 0.260543	0.980720	0.031300	9.91354
		2	a = 0.923583, s = 0.238414	0.986409	0.026438	7.15791
		3	s = 0.349357, n = 0.810429	0.995883	0.014551	2.16830
		4	a = 0.923279, s = 0.291377, b = 0.0451166	0.999009	0.007182	0.53465
		5	a = 0.923291, s = 0.179936, n = 1.61942, b = 0.0451228	0.999009	0.007226	0.54793
		6	**a = 0.156542, s_1 = 0.0723519, b = 0.827283, s_2 = 0.341794**	**0.999819**	**0.003087**	**0.10000**
		7	a = 0.315071, s = 0.617132	0.994944	0.016124	2.66248
		8	a = 0.188755, s = 0.0827535, b = 4.37991	0.999659	0.004213	0.18398
		9	a = 1.00486, s = 0.330986, n = 0.880363, b = 0.00172821	0.999417	0.005541	0.32224
		10	a = 0.961003, s = 0.332177, n = 0.915428, b = 0.0373553	0.999677	0.004123	0.17837
		11	a = 0.0371653, b = -0.961859, s = 0.333076, n = 0.913658	0.999678	0.004119	0.17807
		12	b = 0.00516377, a = -0.146282	0.789922	0.103939	110.6372
	1.0	1	s = 0.238486	0.979876	0.031926	10.30585
		2	a = 0.919338, s = 0.217072	0.986304	0.026486	7.17265
		3	s = 0.327741, n = 0.805989	0.996375	0.013625	1.89823
		4	a = 0.91937, s = 0.266175, b = 0.045645	0.998650	0.008363	0.72316
		5	a = 0.919384, s = 0.17198, n = 1.54782, b = 0.045653	0.998650	0.00841	0.73988
		6	**a = 0.194883, s_1 = 0.0782684, b = 0.789325, s_2 = 0.327332**	**0.999785**	**0.00336**	**0.11796**
		7	a = 0.303263, s = 0.590761	0.995150	0.015761	2.53985
		8	a = 0.171586, s = 0.0689485, b = 4.74177	0.999531	0.004927	0.25102
		9	a = 1.00803, s = 0.313504, n = 0.866055, b = 0.0014963	0.999348	0.005844	0.35717
		10	a = 0.966166, s = 0.314121, n = 0.898361, b = 0.0356452	0.999599	0.004584	0.21983
		11	a = 0.0354845, b = -0.966909, s = 0.3149, n = 0.896817	0.999599	0.004582	0.21957
		12	b = 0.00444515, a = -0.135476	0.793745	0.102782	108.0160
	0.5	1	s = 0.229883	0.974112	0.035310	12.59384
		2	a = 0.91225, s = 0.20707	0.981533	0.029974	9.167857
		3	s = 0.32873, n = 0.78564	0.994532	0.016311	2.714837
		4	a = 0.915579, s = 0.260671, b = 0.0495398	0.998364	0.008969	0.829258
		5	a = 0.915598, s = 0.170194, n = 1.53174, b = 0.0495482	0.998364	0.009015	0.846627
		6	**a = 0.182121, s_1 = 0.0662631, b = 0.803938, s_2 = 0.319262**	**0.999818**	**0.003009**	**0.094369**
		7	a = 0.300206, s = 0.574155	0.991962	0.019775	3.990296
		8	a = 0.204462, s = 0.0719664, b = 4.64819	0.999702	0.003829	0.15114
		9	a = 1.01253, s = 0.312942, n = 0.853383, b = 0.00156958	0.999013	0.007003	0.510854
		10	a = 0.964205, s = 0.311864, n = 0.893636, b = 0.0402429	0.999439	0.005280	0.290415
		11	a = 0.0401842, b = -0.964942, s = 0.312784, n = 0.892113	0.999439	0.005277	0.29009
		12	b = 0.00378304, a = -0.125383	0.748264	0.110668	124.9745

**Name models: 1-Newton; 2-Henderson and Pabis; 3-Page; 4-Logarithmic; 5-Demir et al.,; 6-Two-term; 7-Two-term exponential; 8-Diffusion approach; 9-Midilli-Kucuk; 10-Modified Midilli-Kucuk; 11-Weibull; 12-Wang and Singh.*

Figure 4 indicates a good agreement between the DM_{pre} and DM_{exp}; the points are distributed around the line between the two graphs axis. All Two-term models have the correlation coefficient $R^2 > 0.99976$, chi-square reduction $C_r^2 < 0.14928 \times 10^{-4}$, and RMSE < 0.003735

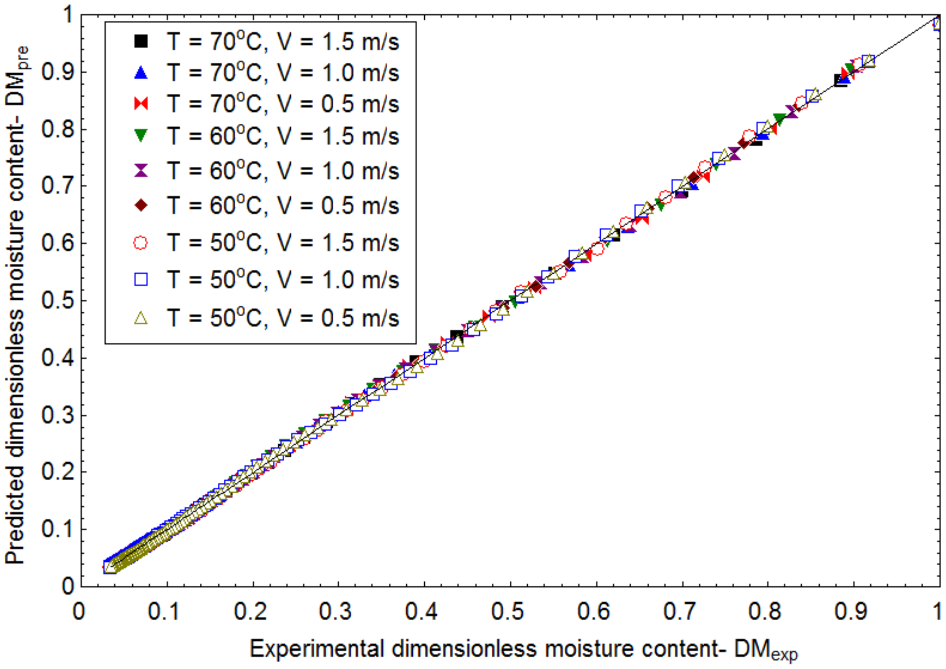


Fig. 4. The correlation between the DM_{pre} and DM_{exp}

3.3 The Effective Moisture Diffusivity Coefficient and Activation Energy

Figure 5 shows the effective moisture diffusivity coefficient of Pseudapocryptes Elongatus fish. This value varies from 1.621×10^{-10} to 5.618×10^{-10} $m^2\ s^{-1}$. The D_{eff} increases with increasing the T and V. Fish receive much thermal energy at high-drying temperatures, increasing water molecules' vibration and the ability to diffuse moisture. Moreover, moisture on the surface of the fish is quickly removed at high air velocity, which contributes to promoting the diffusion of moisture inside the fish. The D_{eff} of Pseudapocryptes Elongatus fish is higher than that of salmon fish fillets [11] and sardine muscles [14] but smaller than that of silverside fish [10]. The D_{eff} of Pseudapocryptes Elongatus fish is similar to silver carp fillets [12]. This difference may be due to different drying conditions, material shapes, and physicochemical properties of the materials.

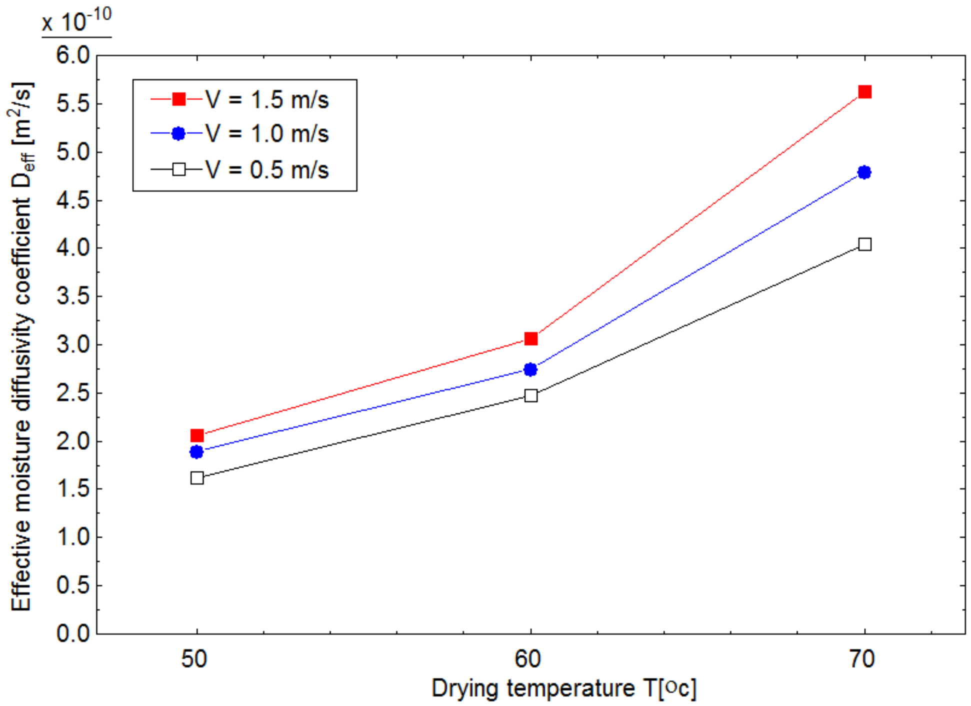
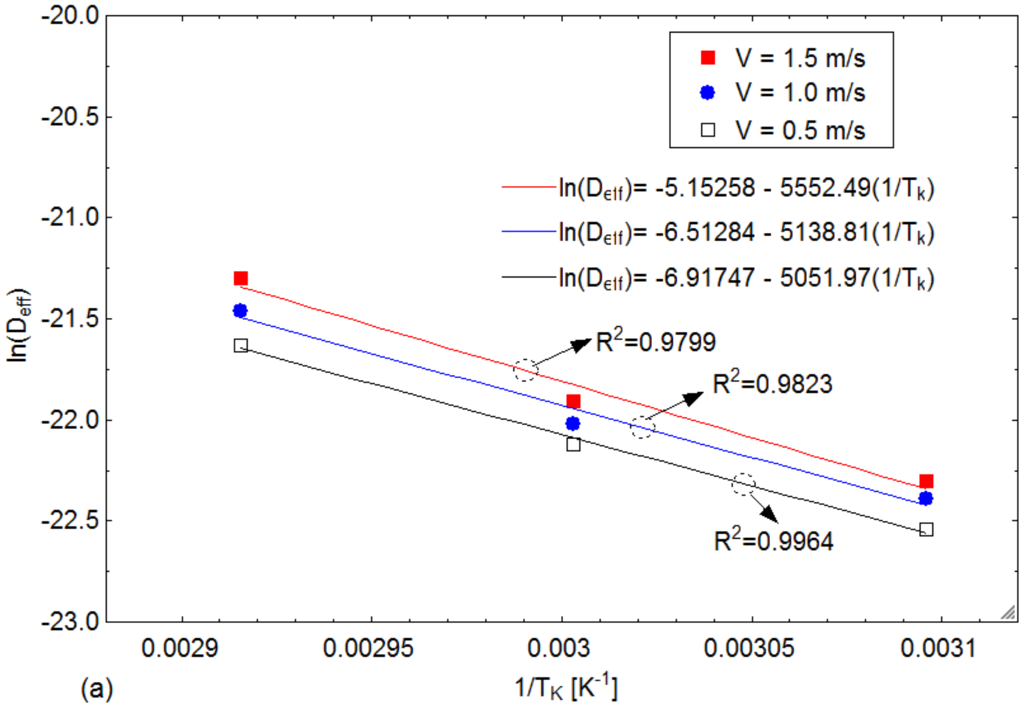


Fig. 5. The effective moisture diffusivity coefficient of Pseudapocrypte Elongatus fish

Figure 6 shows the regression lines used to determine the activation energy and the calculation results. The regression lines have a correlation coefficient of $R^2 \geq 0.9799$ (see Figure 6a), which shows good agreement between the line forms and the data. The activation energy increases with increasing air velocity, which is consistent with the conclusion of many previous studies. The activation energy of Pseudapocryptes Elongatus fish was 42–46.16 kJ mol^{-1} (see Figure 6b).



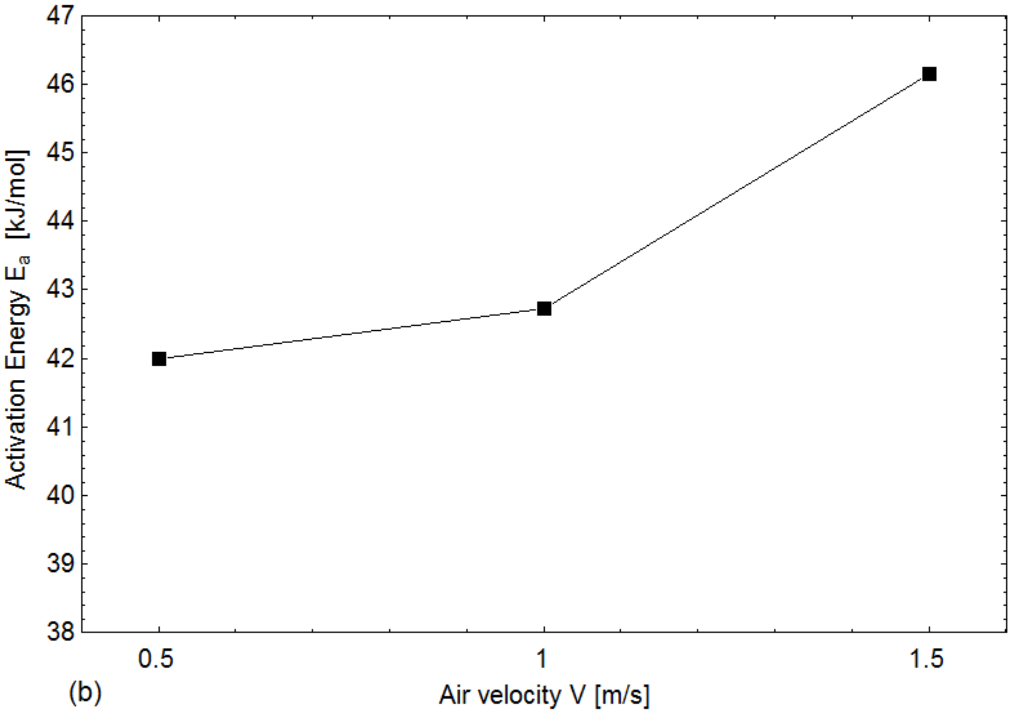


Fig. 6. The Activation Energy of Pseudapocryptes Elongatus fish (a) the regression lines used to determine the activation energy and correlation coefficient (b) Activation Energy value

Table 3 shows the activation energy of several materials (aquatic, agricultural) under different drying conditions. The activation energy of Pseudapocryptes Elongatus fish is higher than that of Salmon fish fillets, Silverside fish, and red chilies and smaller than that of Pumpkin. The activation energy of Pseudapocryptes Elongatus fish is average compared to the general range for some materials (12.7–110 kJ mol^{-1}) [26].

Table 3
The activation energy of Pseudapocryptes Elongatus fish and several materials under different drying conditions

No.	Material	Shape	E_a (kJ mol^{-1})	Drying conditions	Reference
1	Pseudapocryptes Elongatus Fish	cylinder	42-46.16	V = 0.5–1.5 m s^{-1}; T = 50–70°C	**Present work**
2	Silverside Fish	slab	35.65 –37.26	V = 2 m s^{-1}; T = 45–70°C	[10]
3	Salmon Fish Fillets	slab	24.57	V = 2 m s^{-1}; T = 40–60°C	[11]
4	Red chilies	cylinder	37.76	V = 0.4 m s^{-1}; T = 60–65°C	[23]
5	Pumpkin	slab	78.93	V = 1 m s^{-1}; T = 50–60°C	[27]

4. Conclusions

The present work investigates the drying kinetics of Pseudapocryptes Elongatus fish in a convective dryer. Experiments were conducted with 0.5–1.5 m s^{-1} air velocity and 50–70°C drying temperature. Result indicates that the Two-term model is the best model that describes the moisture reduction process of Pseudapocryptes Elongatus fish in a convective dryer with correlation coefficient $R^2 > 0.99976$, chi-square reduction $C_r^2 < 0.141817 \times 10^{-4}$, and RMSE < 0.003735. The effective moisture diffusivity coefficient was $1.621 \times 10^{-10} – 5.618 \times 10^{-10}$ $m^2 s^{-1}$. The activation energy was 42–46.16 kJ mol^{-1}.

The present work is useful for designing and operating the drying process of Pseudapocryptes Elongatus fish in a convective dryer.

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