Experimental study on drying kinetics of anchovy using centrifugal fluidized bed technique

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Abstract: The present study investigated the drying kinetics of anchovy experimentally using centrifugal fluidized bed technique. The main purpose was to experimentally investigate the effect of the inlet air temperature on the drying kinetics of anchovy in a centrifugal fluidized bed dryer, to fit the experimental data to the widely used mathematical models of drying. Further, the effective moisture diffusivity and activation energy in anchovy drying were investigated in the current work. The drying experiment was conducted at drying air temperatures ranging over 70-120°C. The air velocity and rotating speed of the air-distributor were fixed at 1.5 m/s and 150 r/min, respectively. Pressure drop across bed was approximately 390 Pa, while the layer height was fixed at approximately 2 cm. The anchovies were dried starting from 412% db down to 16% db; drying time ranged from 64 min to 172 min. It was found that the drying temperature was a significant factor in decreasing the moisture content, moisture diffusivity and drying time. The moisture diffusivity and activation energy were investigated at 0.11×10^{-9}–0.25×10^{-9} m^2/s and 20.32 kJ/mol, respectively. When compared to existing models, the Midilli model proved to be in good agreement with change in moisture ratio.

Keywords: centrifugal fluidized bed, drying kinetics, anchovy, moisture diffusivity, activation energy

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1 Introduction

Anchovies were found in scattered areas throughout the world's oceans. They range from 2-4 cm (0.79-1.58 inch) in adult length, and their body shapes are variable, with more slender fish. Smaller anchovies are usually served as a snack and are mainly composed of calcium. Cooling is a widely used and important preservation technique to maintain quality and prevent spoilage, and the simplest method of cooling fish is icing[1,2]. Drying of fish is important, because it preserves fish by inactivating enzymes and removing the moisture necessary for bacterial and mould growth[3,4]. Dried fish is one of the most important exported marine products in many countries. The drying is chosen instead of cooling because of products must be processed snack foods.

Fluidized bed dryers have been used successfully for the drying of wet products for many years. Improvements of fluidization quality to fluidize particles have been classified in four types: (i) mechanically assisted fluidization, (ii) vibrated fluidized bed, (iii) agitated fluidized bed and (iv) centrifugal or rotating fluidized bed[5]. In the centrifugal fluidized bed technique, the centrifugal force which is generated by chamber rotation balances the drag force caused by the radial gas. The advantages over the traditional fluidized bed have been summarized as needing very small space[6], preventing growth of large bubbles[7], having higher efficiency in heat and mass transfer[8] and having a wide

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variety of process operations[5]. The techniques have been used successfully in industries, i.e. granulator[9], fluid catalytic[10], and drying of biopolymer or poly-hydroxybutyrate[11], coating of sustained-release microparticles[12], drying of thermally-weak organic powder[13] and drying of chilies[14]. Drying is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously. Mathematical models of the drying processes were used for designing new or improving existing drying systems, or even for the control of the drying process.

Drying using the centrifugal fluidized bed technique was found in only a few studies in the published literature. They are mostly for spherical grains. On the other hand, the literature on fish drying and mathematical models is scanty. The main purpose of this study was to investigate experimentally the effect of the inlet air temperature on the drying kinetics of anchovy in a centrifugal fluidized bed dryer, to fit the experimental data to the widely used mathematical models of drying. Further, the effective moisture diffusivity and the activation energy in anchovy drying were investigated in the current work.

2 Materials and methods

2.1 Materials

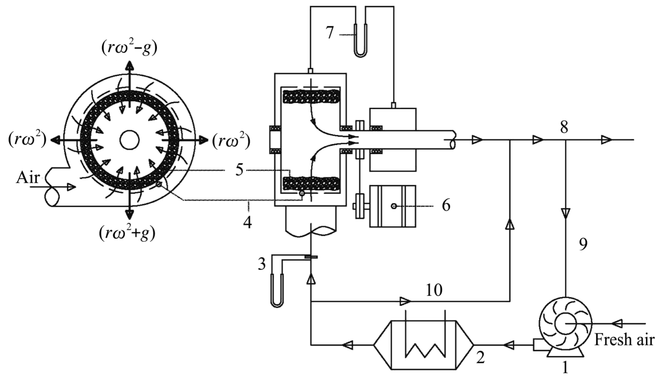
Fresh anchovy was purchased from a fishing market in Thailand, and fishes of 4-6 cm in length and 4-8 mm in diameter were selected for drying. The anchovy were maintained in ice from capture until arriving in the laboratory. Fishes were cleaned with water and the head separated from the body. Surface water was removed by blotting with absorbent paper in order to preserve the original quality. The drying kinetics of the anchovy bodies was investigated. The average initial moisture contents of meat and meat products were determined based on the AOAC No. 950.46B[15] method, this study determined at the Central Laboratory (Thailand) Co., Ltd., Chachoengsao branch, Thailand, under standard of ISO/IEC 17025 i.e. the sample was dried in an oven, the average data were calculated by Equation (1):

$$M_{in}=\left(\frac{m_w-m_d}{m_d}\right)100\% \tag{1}$$

where, m_w is wet weight; m_d is dry weight; M_{in} is moisture content on dry basis (db), which is found to be around 412% db for the anchovy in this study.

2.2 Experimental apparatus

An experimental apparatus was constructed using the centrifugal fluidized bed technique as shown in Figure 1. The thin layer of anchovy at the wall of the air-distributor will be called the "bed" while a "fluidized bed" means the mixture of anchovy and air which behaves as a fluid. The sample of anchovy was introduced inside an air-distributor and was forced to the wall by centrifugal force due to the rotation of the air-distributor, while the air flow which was radially inward through the air-distributor caused forces which were balanced, i.e. drag force, buoyancy force and centrifugal force[12,16].



1. Ring blower 2. Electric heater 3. U-tube manometer and orifice plate for measuring the air velocity 4. Air-distributor 5. Bed of anchovy 6. Driver motor of air-distributor 7. U-tube manometer for measuring the bed pressure drop 8. Exhaust duct 9. Recycling duct 10. Bypass duct.

Figure 1 Schematic representation of the centrifugal fluidized bed dryer

The air-distributor always rotates in the clockwise direction with 40 cm diameter and 10 cm width and is rotated around a horizontal axis, while the rotating speed can be adjusted by a frequency inverter and measured by a Tachometer Digital Meter with an accuracy of ±1%. The ratio of centrifugal force against gravity force will be called "G" and can be calculated as Equation (2):

$$G=\frac{r_b\omega^2}{g} \tag{2}$$

where, m is mass of solid; r_b is average radius of bed; ω is angular velocity (ω=2πn) n is frequency of revolution (speed of motor). The G can be adjusted by varying the speed of the motor based on drying conditions. The air-distributor was made of stainless metal mesh with diameter of 3.17 mm, 40% open area and was driven by a

3 kW electrical motor. The drying air was blown by a 5 kW ring blower which had its rotating speed adjusted by a frequency inverter. The air flow rate and pressure drop through the bed were measured by an orifice and U-shaped manometer with an accuracy of ±2%. Drying air was heated by a 10 kW electrical heater and adjusted by PID control with an accuracy of ±1°C. The temperatures were monitored using an indicator with an accuracy of ±1°C and Type-K thermocouples.

2.3 Experimental procedure

The experimental apparatus was operated with an operation time of 30 min for stabilizing the drying conditions. An electrical heater was started for heating to the drying air temperatures of 70°C to 120°C with 10°C increments. Then, a 1000 g sample (estimated to have a 2 cm bed layer height) was filled into the air-distributor drying chamber. The rotating speed of the air-distributor was fixed at $G = 5$ (motor speed of 150 r/min) and then the blower supplied air to the air-distributor at 1.5 m/s based on the superficial air velocity for minimum fluidization. Some samples were removed at each nominated interval in the drying process; a sample of anchovy was collected for gauging the moisture content. Anchovies were dried from initial moisture content of 412% db down to moisture of 16% db, which is the safe storage level.

2.4 Drying kinetics

Products usually dry solely during the falling-rate period, namely the drying rate decreases continuously during the course of drying. Prediction of the drying rate of a biological product is more complicated with only semi-theoretical and empirical relationships having been proved useful to the dryer designers[18]. Fick's second law of diffusion for cylindrical materials has been published as Equation (3)[19,20]:

$$MR = \sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp\left(-\frac{\lambda_n^2 D_{eff} t}{r^2}\right) \tag{3}$$

where, λ_n is the roots of the Bessel function of zero order; D_{eff} is effective moisture diffusivity; t is drying time; r is radius of product, and MR is dimensionless moisture ratio which can be expressed as Equation (4)[20].

$$MR = \frac{M - M_{eq}}{M_{in} - M_{eq}} \tag{4}$$

Since the values of M_{eq} are relatively small compared with M_{in} and M the moisture ratio can be simplified as Equation (5)[21, 22]:

$$MR = \frac{M}{M_{in}} \tag{5}$$

For investigating the effective moisture diffusivity (D_{eff}), an Equation (3) is written in a logarithmic form as Equation (6):

$$\ln(MR) = \ln\left(\frac{4}{\lambda_n^2}\right) - \left(\frac{\lambda_n^2 D_{eff}}{r^2}\right)t \tag{6}$$

The effective moisture diffusivity (D_{eff}) increases with the increase in drying temperature[20,23,24]. The temperatures effects are modeled using the well-known Arrhenius type relationship as Equation (7):

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \tag{7}$$

where, D_o is pre-exponent; E_a is activation energy for moisture diffusion; R is ideal gas constant and T is absolute temperature. By taking the natural logarithm of both sides of Equation (7), the above exponential form of Arrhenius can be transfigured into a linear Logarithmic form as Equation (8):

$$\ln(D_{eff}) = \ln(D_o) - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right) \tag{8}$$

The activation energy (E_a) and the constant D_o were determined by plotting $\ln(D_{eff})$ versus $(1/T)$. Thin layer models at Table 1 were used for modeling the anchovy drying. The best model for describing the drying characteristics of anchovy was chosen as the one based on the lowest reduced values of Chi-square (χ^2), root mean square error ($RSME$) and highest coefficient of determination (R^2). They are used to compare the counts of categorical responses between the experimental moisture ratios ($MR_{\exp,i}$) and the predicted moisture ratios ($MR_{pre,i}$). The regression analysis was performed by using the SPSS computer program. The statistical parameters such as the χ^2 and $RSME$ were calculated by using Equation (9) and (10)[21,24]:

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pre,i})^2}{N - p} \tag{9}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_{pre,i} - MR_{\exp,i})^2\right]^{1/2} \tag{10}$$

where, N is the number of observations and p is the number of constants. Analysis of variance was carried out to find the effects of the drying air temperature.

Table 1 Thin-layer models fitted for modeling

No	Model	Equation
1	Newton or Lawis[25]	$MR=\exp(-kt)$
2	Page[26]	$MR=\exp(-kt^n)$
3	Henderson and Pabis[27]	$MR=a\exp(-kt)$
4	Logarithmic[28]	$MR=a\exp(-kt)+b$
5	Two term[29]	$MR=a\exp(-kt)+b\exp(-gt)$
6	Midilli[30]	$MR=a\exp(-kt^n)+bt$
7	Verma[31]	$MR=a\exp(-kt)+(1-a)\exp(-gt)$
8	Wang and Singh[32]	$MR=1+at+bt^2$

Note: MR is moisture ratio, a, b, g, k and n are model constants and t is the drying time in minutes.

3 Results and discussion

3.1 Fluidization

The fluidization behavior was studied in order to determine the drying conditions. Figure 2 shows the relation of pressure drop to gas velocity under the rotating speed of air-distributor in G values from 2.5 to 7.5 (range 130-170 r/min). The pressure drop linearly increases with an increase in gas velocity, and the pressure drop slightly increases at higher values of G. Firstly, pressure drop shows a rise with air velocity, and followed by a constant value regardless of an increase in gas velocity. Due to the large radial acceleration, the pressure drop increases with an increase in centrifugal acceleration. While it rotates under high revolution speed, the body of air-distributor is rather vibrated that is disadvantage of this technique.

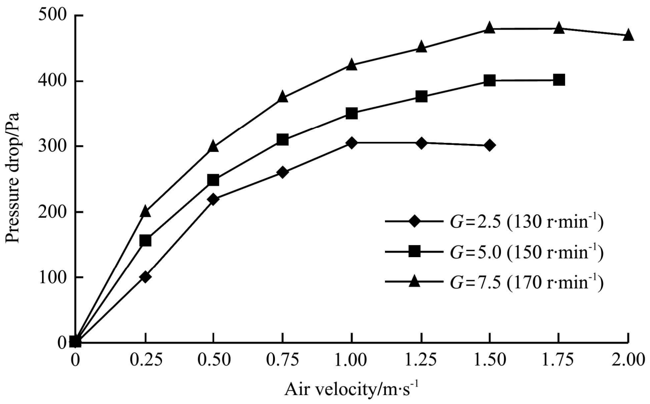


Figure 2 Relation of pressure drop to air velocity

Fluidization behaviors via the air-distributor were investigated and can be seen in Figure 3.

Figure 3a shows an experimental set-up of centrifugal fluidized bed dryer. In Figure 3b, anchovies were put into the air-distributor. In Figure 3c, when the air-distributor is rotated, the centrifugal force acts on the bed, and the bed is forced to the wall of the air-distributor and as a result fluidization does not take place, i.e. due to the drag force acting on the bed being less than the centrifugal force. In Figure 3d, when the radial air velocity (V) increases to 1.3-1.5 m/s, the inner bed at the wall starts to move or fluidize; this is due to the centrifugal force at the inner surface being balanced by the drag force, and the next layer gradually moves until the whole bed is completely fluidized. In Figure 3e, when the air velocity increases over than 1.5 m/s, the fluidization behavior starts to be turbulent.

a. Dryer

b. V = 0 m/s, n = 0 r/min

c. V = 0 m/s, n = 150 r/min

d. V = 1.3-1.5 m/s, n = 150 r/min

e. V > 1.5 m/s, n = 150 r/min

Figure 3 Fluidization behaviors via air-distributor

3.2 Drying kinetics

The rotating speed of the air-distributor was fixed at G=5 (motor speed of 150 r/min) and then the ring blower supplied air to the air-distributor. In the present study, the drying air temperature was set to six levels, namely

70°C, 80°C, 90°C, 100°C, 110°C and 120°C respectively, while the layer height was approximately fixed at 2 cm, and the drying air velocity was fixed at 1.5 m/s for all circumstances. The moisture ratios (*MR*) were calculated by using Equation (8) and plotted versus drying time as Figure 4. The trends of the graph under all conditions were similar to an exponential curve.

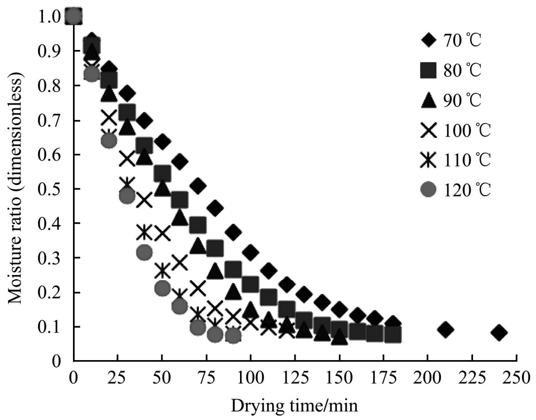


Figure 4 Relation of moisture ratio to drying time

The results can be interpreted as follows, when the air temperature is increased from 70°C to 120°C, the latent heat is intensified while the evaporation from the product is improved. In addition, the high temperatures used for drying can cause both physical and chemical effects on the products[33,34]. The experimental results also illustrated the absence of constant drying period and drying takes place only in the falling rate period. This indicated that diffusion was the most likely physical mechanism governing moisture movement in the anchovies. The equilibrium moisture content of anchovy can be found at infinitely long period of drying time. The effect of drying temperature on moisture migration has been reported for other moisture materials, i.e. Ximeng lignite[34], bananas[35], coarse lignite particles[36], mint plants[37], apple slices[38], chilies[39] and anchovy[40]. The anchovies were dried starting from 412% db down to 16% db drying time requested to dry anchovy based on air temperature of 70°C, 80°C, 90°C, 100°C, 110°C and 120°C were 172 min, 134 min, 112 min, 96 min, 75 min and 64 min, respectively.

3.3 Mathematical model

Numerous models have been proposed to describe the moisture ratio during thin layer drying of biological materials. In the current study, the drying models in Table 1 were selected as representing some of the more commonly adopted. The regression analyses were investigated using the computer program SPSS based on the relation of moisture ratio (*MR*) and drying time ranging over 70°C, 80°C, 90°C, 100°C, 110°C and 120°C. The regression analysis results are shown in Table 2. The highest value of R^2 was obtained with the Midilli model; in addition, χ^2 and *RMSE* are lower than other models.

Table 2 Results of the fitting statistics

No.	Model	Coefficients and constants	R^2	χ^2	*RMSE*
1	Newton or Lawis[25]	k=0.0003051(T)−0.00961456	0.985	0.02011	0.01958
2	Page[26]	k=0.0001323(T)−0.0060995	0.998	0.00596	0.00283
3	Henderson and Pabis[27]	a=−0.0003471(T)+1.0884325 k=0.0003584(T)−0.0141212	0.989	0.02201	0.01450
4	Logarithmic[28]	a=0.0002862(T)+1.1061210 b=−0.0006151(T)−0.0405836 k=0.0002757(T)−0.0100204	0.993	0.01692	0.00881
5	Two term[29]	a=−0.0226189(T)+3.2008988 b=0.0237906(T)−2.3017960 g=−0.0001984(T)+0.0486377 k=0.0002420(T)+0.0001273	0.994	0.00753	0.00673
6	Midilli[30]	a=0.0003412(T)+0.9570968 b=0.0000086(T)−0.0005942 k=0.0001305(T)−0.0070296 n=0.0029784(T)+1.0550782	0.998	0.00528	0.00149
7	Verma[31]	a=0.0087729(T)−0.5965924 g=0.0003136(T)−0.0080124 k=0.0002567(T)+0.0010113	0.989	0.01175	0.01305
8	Wang and Singh[32]	a=−0.0002573(T)+0.0095912 b=0.0000021(T)−0.0001373	0.998	0.00888	0.00261

The comparison of moisture ratio with the predicted data by the Midilli model[30] is given in Figure 5. The model predictions and the drying data are seen generally to be banded around a straight line, which shows that the assumed model is well suited for describing the drying behavior of anchovy under centrifugal fluidized bed drying.

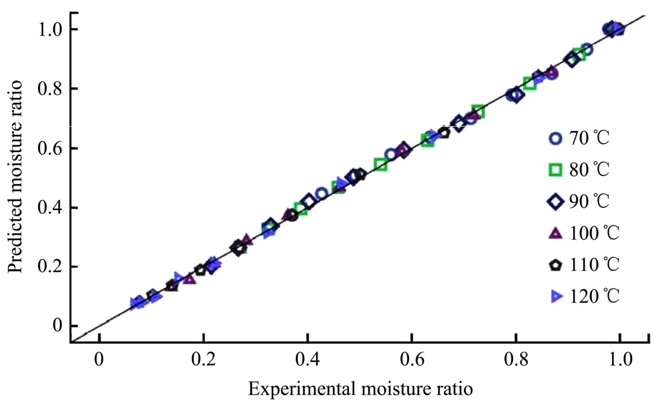


Figure 5 Comparison of moisture ratio between experimental and predicted values by Midilli Model[30]

3.4 Moisture diffusivity

In most studies carried out on drying, moisture diffusivity (D_{eff}) is generally accepted to be the main mechanism during the transport of moisture to the surface to be evaporated[41]. The moisture diffusivity was determined using Equation (6), using slopes derived from the linear regression of lnMR against drying time which can be seen in Figure 6. Moisture diffusivity is used due to the limited information on the mechanism of moisture movement during drying and the complexity of the process. For anchovy, moisture diffusivity ranged from 0.11×10^{-9}-0.25×10^{-9} (m^2/s) while temperature ranged from 70°C to 120°C, as can be seen in Table 3.

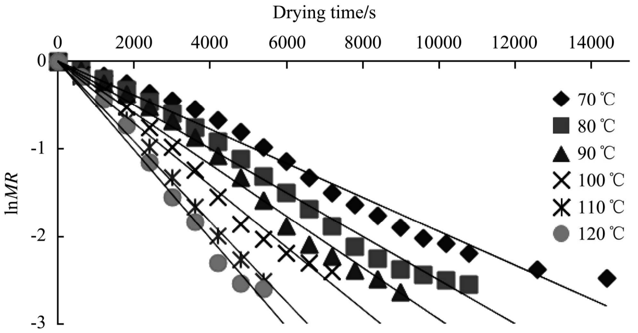


Figure 6 Experimental and predicted logarithmic moisture ratio at different drying times

Table 3 Moisture diffusivity and activation energy

Product	Temperature/°C	$D_{eff}\times10^9/m^2\cdot s^{-1}$	E_a/kJ·mol^{-1}
Anchovy (This research)	70-120	0.11-0.25	20.32
Salted fish[42]	40-55	0.25-0.89	14.2-23.9
Parboiled wheat[43]	40-60	0.12-0.28	37.01
Corn[44]	50-70	0.77-9.33	28.36
Carrots[45]	55-75	0.09-0.17	29.56
Apple pomace[46]	75-105	2.02-3.93	24.51

3.5 Activation Energy

The activation energy can be determined by potting (lnD_{eff}) versus ($1/T_{abs}$) that has been shown a linear relationship (Figure 7). Next, an Equation (8) is used for calculating the activation energy which equal 20.32 kJ/mol. The typical values of D_{eff} for food and biological materials were usually found using hot-air tray dryers at temperatures of 40-105°C, while those in the current study were far greater. Due to its effective mixing mechanism, fluidization could expedite heat and mass transfer between air and product, i.e. the more rapidly heat was conveyed to the product, the greater mass transfer rate was achievable; as a result, D_{eff} was enhanced[17].

The encouragement of moisture diffusivity and activation energy on the moisture migration has been reported for other products (Table 3) i.e., swordfish[42], parboiled wheat[43], corn[44], carrots[45] and apple pomace[46].

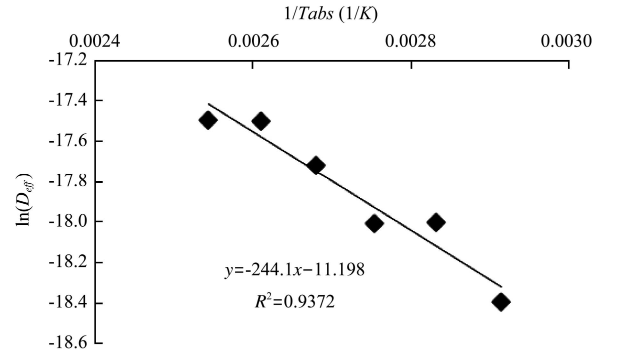


Figure 7 Arrhenius-type relationship between effective moisture diffusivity and reciprocal of absolute temperature

3.6 Drying rate

Drying rate can be defined as the moisture content variation with drying time and calculated by using Equation (11) as follows[21,34]:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{11}$$

where, DR is drying rate; M_t and $M_{t+\Delta t}$ are the moisture content at any interval drying time (Δt). The variations of drying rate with time are given in Figure 8. As results, drying rate decreased during time which there is no constant rate period. The drying process occurred in the falling rate period i.e., the predominant mechanism is the internal mass transfer[22]. The maximum drying rate occurred at 10-40 min of first period drying because of a period of mass transfer at the surface of products. Next period, it is difficult to mass transfer inside products that affect the drying rate decreased significantly[18].

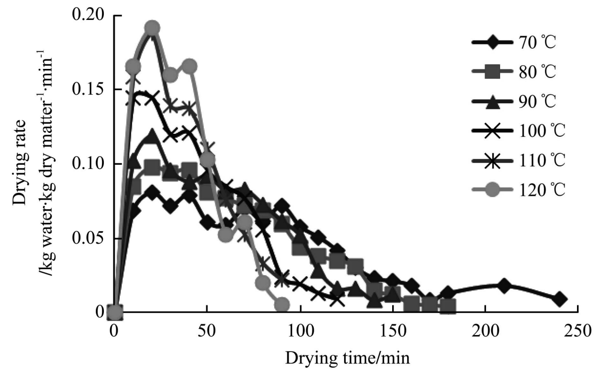


Figure 8 Drying rate period with drying time

3.7 Energy efficiency

Drying air processes are simplified in psychrometric chart at Figure 9a; in addition, the typical drying system is simplified at Figure 9b. They are used to discuss the energy efficiency of anchovy drying. During sensible heating of air at constant humidity ratio, ambient air is heated by a heater (process 1 to 2). Next, the heat required for water evaporation is supplied solely to dryer based on assumed as an adiabatic process (process 2 to 3)[23]. The energy efficiency is defined as the ratio of the latent heat of water evaporation to the sensible heating energy[47]. The experimental data such as dry-bulb and wet-bulb temperatures, humidity ratio, altitude, and absolute pressure are used to get psychrometric values. This study used an application of "HVAC Psychrometrics LT" under the copyright of Carmel Software Corporation. It is derived from Chapter 1 of the American society of heating, refrigerating, and air-conditioning engineering (ASHRAE) 2013 handbook of fundamentals.

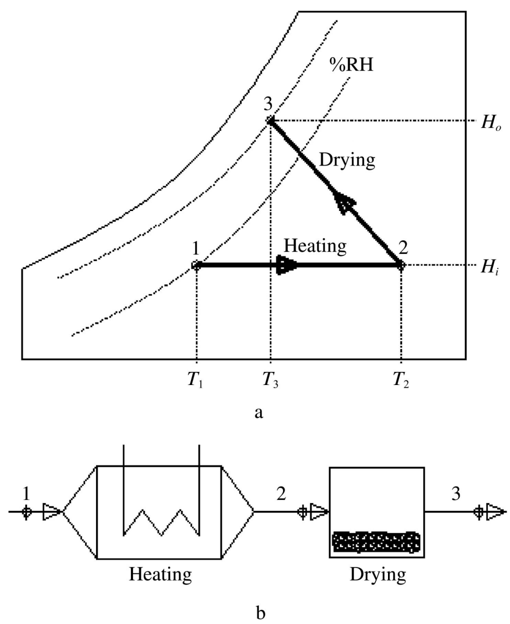


Figure 9 Psychrometric chart for heating and drying processes

The air passed through the heating chamber in processes 1 and 2, the energy for heating air[47], $Q_{heating}$ is given as follows Equation (12):

$$Q_{heating} = \dot{m}_a(h_2 - h_1) \tag{12}$$

where, $\dot{m}_a$ is air flow rate; h_1 and h_2 are enthalpy of air before and after heating, respectively.

The hot air passed through the drying chamber in processes 2 and 3, the drying energy of vaporization has to be calculated at the saturation condition[47], Q_{drying} is given as follows Equation (13):

$$Q_{drying} = \dot{m}_a(H_o - H_i)h_{fg} \tag{13}$$

where, $\dot{m}_a$ is air flow rate; H_i and H_o are humidity ratio before and after drying, respectively; and h_{fg} is latent heat of vaporization of water. Next, the energy efficiency (η) can be calculated by dividing between Equation (13) and (12) as follows Equation (14)[47]:

$$\eta = \frac{(H_o - H_i)h_{fg}}{(h_2 - h_1)} \tag{14}$$

Figure 10 shows the relative between energy and energy efficiency at various drying air temperature. Energy efficiency ranged from 54.48% to 68.62% under the drying air temperature between 70°C to 120°C. It linearly increased with drying air temperatures ranged 70-95°C. The increase of drying air temperatures will promote the latent heat of drying, that affects the increase of energy efficiency. It slightly increased at temperature ranged 95-100°C, followed by a constant value regardless of an increase with drying air temperature and decreased at next period. The energy for heating also increases with all drying air temperature; on the other hand, the energy for water evaporation only increased at temperature ranged 70-100°C, followed by a constant value regardless of increase of drying air temperature that affected the decrease of energy efficiency.

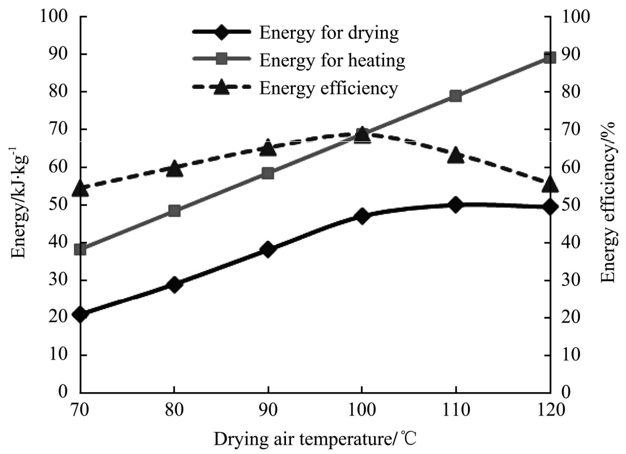


Figure 10 Energy efficiency with different drying air temperature

Comparisons to conventional fluidized bed have shown in Table 4, its space requirement is much smaller because of its small distributor surface area and cylindrical geometry. And it has higher energy efficiency because of the superior mixing between products and hot air. The minimum fluidization air velocity is lower; it leads to the decrease in air bubble formation and the consequent increase in energy efficiency. The higher air velocity could be formed in air bubble that affected poor heat and mass transfer[7] i.e., mass transfer operations are encountered with the transfer of matter from one stream to another especially dehydration in drying processes. The process of moisture transport is explained using mechanisms of moisture diffusion (D_{eff}) which is controlled by drying air temperatures[20].

Table 4 Comparison to conventional fluidized bed

Product	Technique	Conditions	Energy efficiency/%
Anchovy (This research)	Centrifugal fluidized bed	1. Initial and final moisture content 412% db and 16% db 2. Air temperature 70–120°C 3. Minimum fluidization air velocity 1.5 m/s 4. Pressure drop through the bed 390 Pa	54.48-68.62 (56% at 80°C of drying air temperature)
Anchovy[48]	Conventional fluidized bed	1. Initial and final moisture content 65% wb and 10% wb 2. Air temperature 60–80°C 3. Minimum fluidization air velocity 5.5 m/s 4. Pressure drop through the bed 825 Pa	51.8-53.7 (53% at 80°C of drying air temperature)

4 Conclusions

A centrifugal fluidized bed dryer was designed, constructed and operated well under a wide range of drying conditions. Fluidization behavior can occur completely at air velocity of 1.5 m/s under rotating speed of air-distributor of 150 r/min and pressure drop of 390 Pa. The anchovy was dried in a centrifugal fluidized bed dryer at temperatures of 70-120°C with a fixed air velocity and rotating speed of 1.5 m/s and 150 r/min respectively. Moisture ratios were fitted to various drying models; in addition, the effective moisture diffusion and activation energy were investigated. The results showed that the drying kinetics depended on drying temperature. The anchovy were dried starting from 412% db down to 16% db, with drying time required to dry ranging from 64-172 min. The moisture ratio curves provide evidence that internal moisture diffusion predominates in the drying mechanism. The Midilli model can adequately describe the drying kinetics of anchovy. Moisture diffusivity (D_{eff}) range 0.11×10^{-9}-0.25×10^{-9} m^2/s, derived from an Arrhenius type relation, increased substantially with increases in temperature. The activation energy was found to be 20.32 kJ/mol. The energy efficiency was found to 54.48%-68.62% that higher than conventional fluidized bed technique.

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Nomenclature

a, b, c, g, k	Model constant (-)
D_o	Pre-exponent constant (-)
D_{eff}	Moisture diffusivity (m²/s)
DR	Drying rate (kg water / kg dry matter·min)
E_a	Activation energy (kJ/mol)
G	Ratio of centrifugal and gravity force (-)
H	Humidity ratio (kg water /kg dry air)
h_{fg}	Latent heat of vaporization of water (kJ/kg)
h	Enthalpy (kJ/kg)
M_{in}	Moisture content, dry basis (dry basis)
M	Moisture content at any time, (dry basis)
M_{eq}	Equilibrium moisture content (dry basis)
$MR_{\exp,i}$	Experimental moisture ratios (-)
$MR_{pre,i}$	Predictable moisture ratios (-)
MR	Dimensionless moisture ratio (-)
m_w	Wet weight (kg)
m_d	Dry weight (kg)
m	Mass of solid (kg)
$\dot{m}_a$	Mass flow rate of air (kg/s)
n	Frequency of revolution (r/m)
N	Number of observations (-)
p	Number of constants (-)
$Q_{heating}$	Heating energy (kW)
Q_{drying}	Drying energy (kW)
$RSME$	Root mean square error (-)
R^2	Coefficient of determination (-)

r	Radial of product (m)
r_b	Average radius of bed (m)
t	Drying time (min)
T	Temperature (°C)
V	Radial air velocity (m/s)

Greek symbol

λ	The roots of Bessel function of zero order (-)
χ^2	Chi-square value (-)
ω	Angular velocity (rad/s)
η	Energy efficiency (%)

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