# Drying characteristics and modeling of tomato thin layer drying in combined infrared-hot air dryer

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**Abstract:** In this study tomato slices were dried with three thicknesses (3, 5 and 7 mm), three temperatures (60 ℃, 70 ℃ and 80 ℃) and air speed of 1.1 m $s^{-1}$ in a combined infrared-hot air dryer. Distance from infrared source was 70 cm, while, input air temperature was 60 ℃. The experiment was conducted as factorial based on a completely randomized design. Results showed that energy consumption reduced along with the increase in temperature and slice thickness. Decrease in the slice thickness from 7 to 3 mm resulted in a significant decrease in drying time. Maximum diffusion coefficient was related to the thickness of 7 mm and the temperature of 80 ℃, while, the minimum value was related to the thickness of 3 mm and the temperature of 60 ℃. Effective diffusion coefficient and activation energy is, respectively, 9-10 $m^2$ $s^{-1}$ to 10-11 $m^2$ $s^{-1}$ and 12.7-110 kJ $mol^{-1}$. Middili's model had the maximum $R^2$ and the minimum RMSE and SSE at different temperatures and speeds, thus, it was considered as the fittest model to predict the moisture.

**Keywords:** drying time of tomato, diffusion coefficient, effective diffusion coefficient, activation energy, tomato thin-layer drying, infrared-hot air dryer

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## 1 Introduction

Tomato is a valuable vegetable, which economically has the second place after potato (Abano et al., 2011). Storage life of fresh tomato is short and mainly it is not suitable for storing. Therefore, tomato drying is a very important processing method to preserve it. Dried tomato is considered as a palatable food item in developed countries. Recently, dried tomato has shifted from food cart to the main section of production in food industry, such as it is used in pizza and various kinds of plant-based food (Demiray and Tulek, 2011; Latapi and Barrett, 2006). Drying is scientifically and economically important in many industries. This process is one of the most important energy-consumer processes in different industries. It is performed to remove product moisture, to prevent biological degradation and to reach the material moisture to equilibrium moisture. Considering the high thermal efficiency, high energy price, environmental problems and maintenance of drying material quality, this process is very important in industrial scale (Mola et al., 2010). New technologies such as drying with convective and radiative heat sources are necessary to increase drying speed and capacity of dryers as well as to reduce wastes (Afzal et al., 1999; Honarvar et al., 2009). Several studies have been conducted on drying of a variety of products including potato and carrot (Umesh Hebbar et al., 2004), on thin layer drying and modeling of drying kinetic of onion (Sharma et al., 2005a, b), garlic (Abdelmotaleb et al., 2009), barley (Afzal et al., 1999) and rice (Bualuang et al., 2009) using a combination of infrared and hot air dryer suggesting a significant decrement in drying time. The aim of this study was to examine the drying kinetic of tomato and to model the process of experimental and regression models at different temperatures and thicknesses. Also, changes in effective moisture diffusion coefficient, the

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factors affecting this coefficient, activation energy and energy consumption were investigated during tomato drying using a combined infrared and hot air dryer.

## 2 Materials and methods

### 2.1 The experimental dryer

A combined infrared-hot air dryer was developed at the experimental scale, in which, temperature of drying case, air input temperature, air speed and the distance from the infrared source were adjustable (Figure 1). Tomato slices were dried under the different combinations of these parameters.

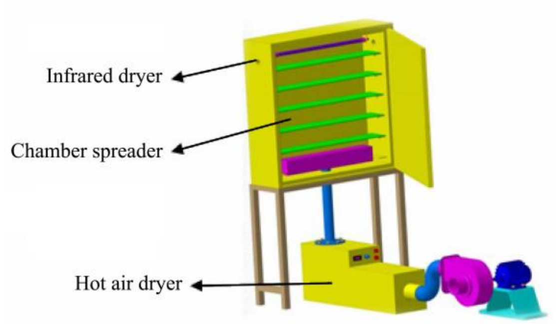


Figure 1 Schematic view of a combination infrared with hot air dryer

### 2.2 Tomato slices' drying

To investigate the kinetic of tomato slices' drying, three temperatures (60℃, 70℃ and 80℃), three slices' thicknesses (3, 5 and 7 mm), an air speed of 1.1 m $s^{-1}$, input air temperature of 60℃ and a 70 cm distance from the infrared source were used. In each experiment, curve of moisture content against drying time was drawn and effective diffusion coefficient and activation energy were calculated from the curve slope. Finally, to obtain a suitable model to predict the drying kinetic, different models were fitted on the curves.

### 2.3 Sample preparation and analyses

Tomatoes were purchased from a local store and were kept in refrigerator at 4℃ in order to reduce rate of physical and chemical changes (Abano et al., 2011). Before drying, tomatoes were placed in lab environment to reach environment temperature (25±1 ℃). Then, they were washed and sliced into three thicknesses of 3, 5 and 7 mm. The dryer was set up 30 min before experiment initiation to reach the steady conditions. Drying temperature was adjusted and 60±2 g of the product was placed on an aluminum mesh as a 10 cm ×10 cm fine layer. Reduction in the product moisture was measured by weighing samples in certain intervals using a digital scale with the accuracy of 0.01 g (Kern, EMB School balance, German) till reaching equilibrium moisture. The initial moisture content of the product (95.6% based on wet) was measured by placing them in an oven at 105℃ over 24 h, using Equation (2) A vane anemometer (Lutron, Taiwan, AM-4206) was used to measure the air speed.

### 2.4 Moisture content

Moisture content refers to the weight of product water content divided by weight of wet matter or dry matter which are respectively called moisture based on wet and moisture based on dry, which are calculated using Equations (1) and (2).

$$M_d = \frac{W_w - W_d}{W_d} \tag{1}$$

$$M_w = \frac{W_w - W_d}{W_w} \tag{2}$$

where, $M_d$ was tomato slices' moisture based on dry, kg water/kg dry matter; $M_w$ was tomato slices' moisture based on wet, kg water/kg wet matter; $W_w$ was sample weight, kg, during drying; $W_d$ was dried sample weight, kg (Abdelmotaleb et al., 2009, Ibrahim et al., 2011).

### 2.5 Calculation of moisture ratio

Moisture ratio was calculated using Equation (3) during the experiment.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{3}$$

where, $M_0$: initial moisture content of the tomato slices, kg water/kg dry matter; $M_e$: equilibrium moisture, kg water/kg dry matter; $M_t$: moisture content at each time, kg water/kg dry matter. Since $M_e$ is usually less than $M_t$, error derived from ignoring $M_e$ is very trivial and consequently we can convert the equation to a simpler form (Taheri-Garavand et al., 2011).

### 2.6 Calculation of effective diffusion coefficient

Fick's law was used to calculate effective diffusion coefficient (Doymaz, 2004).

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial x^2} \tag{4}$$

Moisture diffusion coefficient for agricultural products thin layer drying can be calculated using the equation presented by Crank (1975) or the following assumptions

(Crank, 1975):

1- Moisture is first dispersed inside the sample mass uniformly.
2- Sample surface moisture content is rapidly equilibrated with the ambient condition.
3- Surface resistance against mass transfer is negligibly different from the internal resistance.
4- Mass transfer occurs only via diffusion.
5- Diffusion coefficient is constant and its reduction is negligible (Sharma et al., 2005b; Valeh ghoozhdi, 2009).

$$MR = \frac{M}{M_0} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-\frac{(2n-1)^2\pi^2 D_{eff} t}{4L^2}\right) \quad (5)$$

where, $D_{eff}$ was moisture effective diffusion coefficient, m$^2$/s; $L$ was half of the product thickness, m; and $n$ was number of drying terms. For long time, just initial part of the equation is used. So that (Taheri-Garavand et al., 2011):

$$MR = \frac{M}{M_0} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (6)$$

Finally, diffusion coefficient is calculated using the Ln(MR) curve slope against time in Excel software according to the following Equation (7) (Doymaz, 2004):

$$D_{eff} = \frac{-Slope 4L^2}{\pi^2} \quad (7)$$

### 2.7 Calculation of activation energy

Activation energy ($E_a$) refers to action needed to isolate one mole of moisture from a certain amount of a material. The effect of hot air on effective diffusion coefficient ($D_{eff}$) is obtained from Arhenius equation (Strumillo and Cudra, 1999).

$$D_{eff} = D_0 \exp\left[-\frac{E_a}{R(T+273.15)}\right] \quad (8)$$

where, $E_a$ is activation energy, kJ mol$^{-1}$; $R$ is the gases constant coefficient, 8.3143 kJ mol$^{-1}$K$^{-1}$; $T$ is temperature, K; and $D_0$ is reference diffusion coefficient, m$^2$ s$^{-1}$.

To calculate the activation energy ($E_a$) from Arhenius equation, the graph of $Ln(D_{eff})$ is plotted against 1/($T$+273.15) and the line slope is used to calculate the activation energy (Kargar Nemati, 2010).

$$Ln(D_{eff}) = Ln(D_0) - \frac{E_a}{R}\frac{1}{(T+273.15)} \quad (9)$$

### 2.8 Modeling for prediction of drying kinetic

Five models were used to predict the drying kinetic (Table 1).

**Table 1 The used models in tomato drying trial**

| Model name | Equation models | Reference |
|---|---|---|
| Midilli | $MR = a\exp(-kt^n) + bt$ | Motevalli et al., 2010 |
| Logarithmic | $MR = a\exp(-kt) + c$ | Minaee et al., 2010 |
| Handerson and Pabis | $MR = a\exp(-kt)$ | Abbasi et al., 2010 |
| Binominal | $MR = a\exp(-k_0 t) + b\exp(-k_1 t)$ | Laohavanich and Wongpichet, 2008 |
| Lewis | $MR = \exp(-kt)$ | Nuthong et al., 2011 |

Note: $t$: time, min; $a$, $b$, $c$, $n$: coefficients, dimensionless; $k$: constant drying ratio coefficient, l/min.

The models' fitting on the drying data was performed using MATLAB software and correlation coefficient ($R^2$), sum of squared error (SSE) and root mean squared error (RMSE) were compared to find the most suitable model to estimate the moisture ratio. These variables could be calculated using the following equations:

$$SSE = \frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pred,i})^2 \quad (10)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pred,i})^2} \quad (11)$$

where, $MR_{exp,i}$ is the ith experiment moisture ratio; $MR_{pred,i}$ is the $i$th of moisture ratio predicted by model, and $N$ is number of observations.

Finally, the most suitable model is someone with the maximum $R^2$ and minimum SSE and RMSE (Motevalli et al., 2010).

### 2.9 Calculation of energy consumption

Energy consumption during the drying process was obtained from total required energy for air warming and energy for net infrared (Abdelmotaleb et al., 2009). Dryer consumed power was calculated from the time of being turned on using following equation:

$$Power = I \times V \times PF \quad (12)$$

where, $Power$ is consumed power, W; $V$ is voltage, V; $I$ is amperage, A; and $PF$ is power coefficient, dimensionless.

Power coefficient of the constructed dryer was measured to be 1 using power analyzer (DW-6090, Lutron, Taiwan).

## 3 Results and discussion

### 3.1 Kinetic of moisture drop in the dryer

Figure 2 shows the curves of moisture drop kinetics based on the moisture ratio at different temperatures and thicknesses for tomato slices. The tomato slice initial moisture was high at the beginning of the drying process and therefore the rate of moisture loss is high. However, with time progression, rate of moisture gradually reduced. At the late drying stages, the product surface shrinkage formed a resistance against water transfer to the product surface, which in turn, caused a reduction in drying and rate of moisture loss (Minaee et al., 2010; Abbasi et al., 2010). Similar results were reported in other studies (Demiray and Tulek, 2011; Laohavanich and Wongpichet, 2008; Doymaz, 2004; Nuthong et al., 2011).

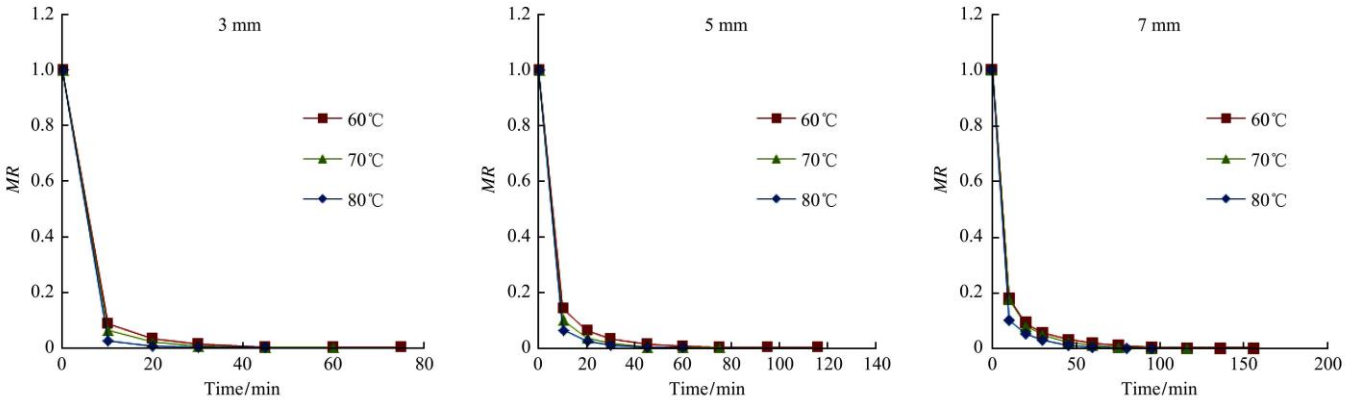

Figure 2 Effect of dryer temperature on tomato slices moisture ratio in the combined dryer at different thicknesses

Table 2 shows the time needed for tomato slices drying till equilibrium moisture and the dryer's electrical energy consumption at different temperatures and thicknesses. The energy consumption increased along with increase in temperature and thickness.

**Table 2 Drying time and energy consumption of the dryer for tomato slices at the different temperatures and thicknesses**

| Thickness, mm | Temperature, ℃ | Drying time, min | Electrical energy, w·h |
|---|---|---|---|
| 3 | 60 | 75 | 1150.05 |
| | 70 | 60 | 1312.781 |
| | 80 | 45 | 1709.813 |
| 5 | 60 | 116 | 1506.45 |
| | 70 | 75 | 1648.68 |
| | 80 | 60 | 1717.76 |
| 7 | 60 | 156 | 1739.678 |
| | 70 | 116 | 1203.063 |
| | 80 | 95 | 2403.135 |

### 3.2 Results of analyses of variance

Table 3 shows the analysis of variance for the effect of temperature and thickness on tomato slice drying time. The results showed that the effect of temperature and thickness on tomato slice drying time was significant at $P$=0.01. Duncan's test showed that there were significant differences among the different temperature and thickness levels (Tables 4, 5). Drying time significantly decreased along with the decrease in the thickness from 7 to 3 mm (Table 4). The thicknesses 3 to 7 mm needed the minimum and maximum drying time, respectively. Drying time at the temperature of 80 ℃ was significantly shorter than the other temperatures and the maximum drying time was related to the temperature of 60 ℃ (Table 5).

**Table 3 Analyses of variance for the effect of temperature and thickness on drying time**

| Source | df | Mean-square | F |
|---|---|---|---|
| Treatment | 10 | $3197.53333^{**}$ | 94.51 |
| Thickness | 2 | $10946.33333^{**}$ | 54.323 |
| Temperature | 2 | $4432.33333^{**}$ | 131.00 |
| Thickness*Temperature | 4 | $291.33333^{ns}$ | 8.61 |
| Error | 16 | 33.83333 | |

Note: ** Significant at $P$=0.01; ns = not significant.

**Table 4 Comparison of the drying time at different thicknesses (Duncan's test, *P*=0.01)**

| Product thickness, mm | Average of drying time, min |
|---|---|
| 7 | 122.333a |
| 5 | 79.000b |
| 3 | 53.333c |

Note: Different letters (a, b, c) indicate significant differences at the level of one percent.

**Table 5 Comparison of the drying time at different temperatures (Duncan's test, *P*=0.01)**

| Dryer temperature, ℃ | Average of drying time, min |
|---|---|
| 60 | 107.667a |
| 70 | 83.667b |
| 80 | 63.333c |

### 3.3 Diffusion coefficient and activation energy

The effective diffusion coefficients for different treatments were obtained by plotting $Ln(MR)$ graph against time and fitting the regression line, using Equation (7) (Figures 3, 4, 5). The results are presented in Table 6.

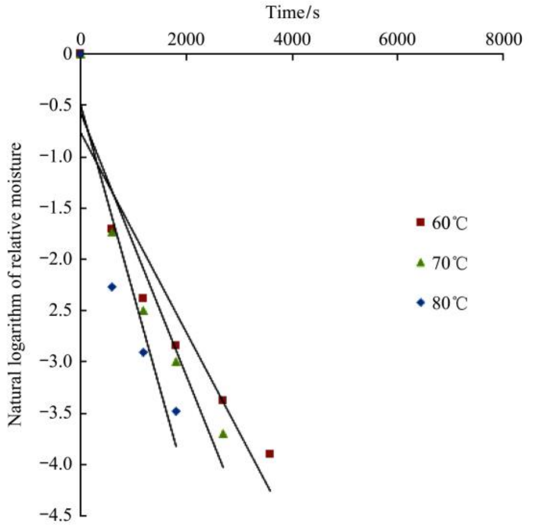


Figure 3 Natural logarithm of moisture ratio against time at the thickness of 7 mm

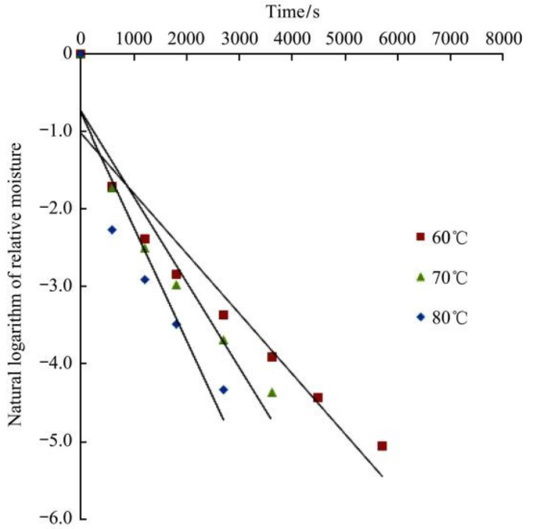


Figure 4 Natural logarithm of moisture ratio against time at the thickness of 5 mm

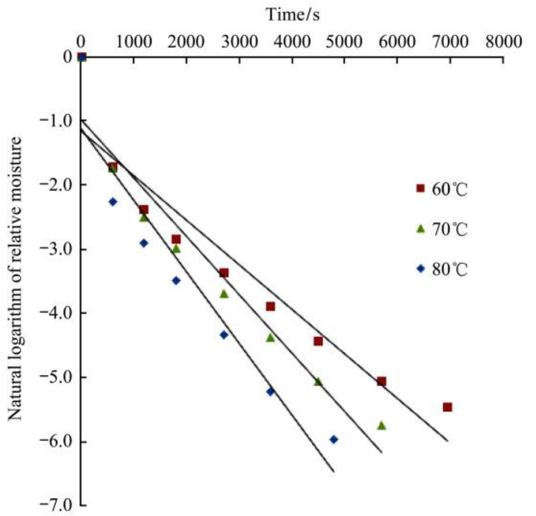


Figure 5 Natural logarithm of moisture ratio against time at the thickness of 3 mm

**Table 6 Effective diffusion coefficient of tomato slices under different experimental conditions**

| Thickness, mm | Temperature, ℃ | $D_{eff}$, $\times 10^{-9}$ $m^2$ $s^{-1}$ | $R^2$ |
|---|---|---|---|
| 3 | 60 | 1.459 | 0.9101 |
| | 70 | 1.914 | 0.9116 |
| | 80 | 3.009 | 0.9096 |
| 5 | 60 | 2.533 | 0.9111 |
| | 70 | 4.052 | 0.9308 |
| | 80 | 5.066 | 0.9197 |
| 7 | 60 | 3.475 | 0.9092 |
| | 70 | 4.448 | 0.9352 |
| | 80 | 5.461 | 0.9111 |

The effective diffusion coefficient increased along with the temperature increment (Table 6) and with reduced in the slice thickness, due to rapid hardening of the tomato at lower thicknesses reducing the effective diffusion coefficient (Aghamasihi et al., 2010). The maximum diffusion coefficient was related to the thickness of 7 mm at 80 ℃, whereas, the minimum value was related to the thickness of 3 mm at 60 ℃. Effective diffusion coefficient and activation energy is, respectively, 9-10 $m^2$ $s^{-1}$ to 10-11 $m^2$ $s^{-1}$ and 12.7-110 kJ $mol^{-1}$, which the values obtained in the present study were within these ranges (Madamba et al., 1996). This is due to the dependency of effective diffusion coefficient to temperature and product type and composition. When product is dried at high temperatures, increase in thermal energy leads to increase in water molecules activity, thus moisture diffusion coefficient increases (Rizvi 1986; Kargar nemati, 2010). Activation energy is obtained by plotting $Ln(D_{eff})$ against the reversed absolute temperature and calculation of the line slope. Using Arhenius Equation (8) and plotting $Ln(D_{eff})$ against $1/T$, the experimental activation energy was calculated (Figure 6). The activation energy and $D_0$ at all tested thicknesses is presented in Table 7. The activation energy under different experimental condition was 22.12-35.31 kJ $mol^{-1}$, which is within the range of activation energy for most products (12.7-110 kJ $mol^{-1}$) (Troncoso and Pedreschi, 2007; Kargar nemati, 2010).

**Table 7 Values of activation energy and Arhenius equation coefficients under the experimental conditions**

| Thickness, mm | Activation energy, kJ $mol^{-1}$ | $D_0$ | $R^2$ |
|---|---|---|---|
| 3 | 22.12435 | 1.03E$^{-5}$ | 0.9977 |
| 5 | 29.56565 | 1.11E$^{-4}$ | 0.9826 |
| 7 | 35.31083 | 4.85E$^{-4}$ | 0.9748 |

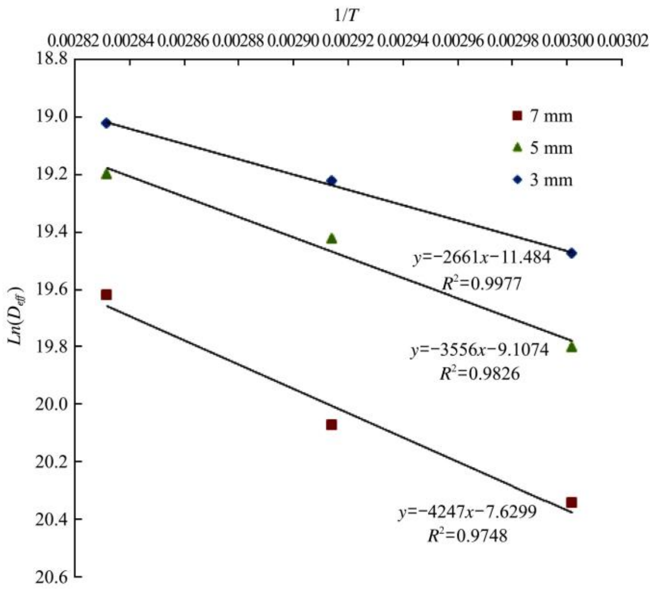


Figure 6 Changes in $Ln(D_{eff})$ against $1/T$

### 3.4 Modeling

To investigate the fitted models (Middili, Logarithmic, Handerson and Pabis, Binominal; and Lewis), $R^2$, SSE and RMSE of each model is presented in Table 8. As shown in Table 8, Middili’s model had the maximum $R^2$ and the minimum RMSE and SSE at different temperatures and speeds, thus, it was considered as the fittest model to predict the moisture. Table 9 shows the coefficients of Middili’s model under different experimental conditions.

**Table 8 Comparison of the statistical results of the fitted models**

| Models | Thickness, mm | Temperature, ℃ | SSE | RMSE | $R^2$ |
|---|---|---|---|---|---|
| Handerson and Pabis | 3 | 60 | 8.408E$^{-4}$ | 0.01297 | 0.99897 |
| | | 70 | 4.250E$^{-4}$ | 0.01031 | 0.99947 |
| | | 80 | 4.501E$^{-5}$ | 0.003873 | 0.99994270 |
| | 5 | 60 | 3.160E$^{-3}$ | 0.02125 | 0.996262 |
| | | 70 | 1.117E$^{-3}$ | 0.01495 | 0.998631 |
| | | 80 | 5.769E$^{-4}$ | 0.01201 | 0.9992793 |
| | 7 | 60 | 7.400E$^{-3}$ | 0.02867 | 0.991436 |
| | | 70 | 4.920E$^{-3}$ | 0.02651 | 0.994115 |
| | | 80 | 2.885E$^{-3}$ | 0.02193 | 0.996528 |
| Logarithmic | 3 | 60 | 4.360E$^{-4}$ | 0.01044 | 0.99946 |
| | | 70 | 1.920E$^{-4}$ | 0.008001 | 0.99976 |
| | | 80 | 9.796E$^{-6}$ | 0.002213 | 0.99998752 |
| | 5 | 60 | 1.856E$^{-3}$ | 0.01759 | 0.997804 |
| | | 70 | 5.956E$^{-4}$ | 0.0122 | 0.999270 |
| | | 80 | E2.682$^{-4}$ | 0.009455 | 0.999665 |
| | 7 | 60 | 4.241E$^{-3}$ | 0.02303 | 0.995092 |
| | | 70 | 2.728E$^{-3}$ | 0.02132 | 0.996737 |
| | | 80 | 1.586E$^{-3}$ | 0.01781 | 0.998091 |
| Midilli | 3 | 60 | 3.569E$^{-6}$ | 0.001091 | 0.999995658 |
| | | 70 | 4.358E$^{-6}$ | 0.001476 | 0.99999456 |
| | | 80 | 3.038E$^{-7}$ | 0.0005512 | 0.999996132 |
| | 5 | 60 | 6.198E$^{-6}$ | 0.001113 | 0.999992668 |
| | | 70 | 4.714E$^{-6}$ | 0.001254 | 0.999994227 |
| | | 80 | 6.407E$^{-6}$ | 0.00179 | 0.999991998 |
| | 7 | 60 | 1.206E$^{-5}$ | 0.001312 | 0.999866049 |
| | | 70 | 1.276E$^{-5}$ | 0.001598 | 0.999984733 |
| | | 80 | 2.751E$^{-5}$ | 0.002623 | 0.999966901 |
| Lewis | 3 | 60 | 11.840E$^{-2}$ | 0.0008409 | 0.998976 |
| | | 70 | 4.250E$^{-4}$ | 0.0092192 | 0.99947 |
| | | 80 | 4.501E$^{-5}$ | 0.003354 | 0.994270 |
| | 5 | 60 | 3.161E$^{-3}$ | 0.01988 | 0.996260 |
| | | 70 | 1.117E$^{-3}$ | 0.01356 | 0.998631 |
| | | 80 | 5.770E$^{-4}$ | 0.010742 | 0.99927 |
| | 7 | 60 | 7.410E$^{-3}$ | 0.02722 | 0.991425 |
| | | 70 | 4.926E$^{-3}$ | 0.02481 | 0.9941086 |
| | | 80 | 2.886E$^{-3}$ | 0.020304 | 0.9965 |
| Binominal | 3 | 60 | 8.408E$^{-4}$ | 0.014498 | 0.9989 |
| | | 70 | 6.5716E$^{-6}$ | 0.001813 | 0.999918 |
| | | 80 | 4.539E$^{-5}$ | 0.006737 | 0.99942 |
| | 5 | 60 | 6.796E$^{-5}$ | 0.000368677 | 0.999916 |
| | | 70 | 1.664E$^{-5}$ | 0.002355 | 0.99979 |
| | | 80 | 6.211E$^{-4}$ | 0.01762 | 0.99922 |
| | 7 | 60 | 3.428E$^{-4}$ | 0.0069976 | 0.9996033 |
| | | 70 | 1.915E$^{-4}$ | 0.0061902 | 0.99977 |
| | | 80 | 8.639E$^{-6}$ | 0.00147 | 0.99989 |

**Table 9 Coefficients of the fitted Middili's model under different experimental conditions**

| Thickness, mm | Temperature, ℃ | a | b | k | N |
|---|---|---|---|---|---|
| 3 | 60 | 1.003 | 30.047E$^{-6}$ | 0.7732 | 0.4989 |
| | 70 | 1.006 | 5.652E$^{-6}$ | 0.8782 | 0.4913 |
| | 80 | 1.007 | 3.385E$^{-5}$ | 1.162 | 0.4982 |
| 5 | 60 | 0.9971 | 5.648E$^{-7}$ | 0.616 | 0.4985 |
| | 70 | 1.004 | 4.724E$^{-6}$ | 0.6895 | 0.5173 |
| | 80 | 0.9923 | 1.869E$^{-5}$ | 0.97 | 0.4442 |
| 7 | 60 | 0.9969 | 6.299E$^{-7}$ | 0.5911 | 0.4622 |
| | 70 | 0.9959 | 5.811E$^{-6}$ | 0.5405 | 0.5069 |
| | 80 | 0.9927 | 4.608E$^{-5}$ | 0.9158 | 0.3902 |

## 4 Conclusions

In different thicknesses, thin layer drying of tomato at 60 ℃, 70 ℃ and 80 ℃ and at an air velocity of 1.1 m $s^{-1}$ followed falling rate period. Middili's was considered as the fittest model to predict the moisture. The drying time of tomato decreased with the increase of temperature whereas consumed electrical energy increased. The effective diffusion coefficient was 9-10 $m^2$ $s^{-1}$ to 10-11 $m^2$ $s^{-1}$ and increased along with the temperature increment and with reduced in the slice thickness reduced. The activation energy was 22.12-35.31 kJ mol$^{-1}$ under different experimental conditions.

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