Influence of air flow velocity and temperature on drying parameters: An experimental analysis with drying correlations

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Abstract. Experiments were conducted to analyse the effect of air flow velocity and air drying temperature on convective drying of moist object. The air drying temperatures are selected from 40 to 70°C and it is analysed with the range of air flow velocities from 2 to 6 m/s. Fresh potato is selected for sample moist object. Drying curve is drawn and drying correlations are presented for various air drying temperatures and velocities. Diffusion coefficient, density and shrinkage of the object are calculated from observed experimental measurements and these parameters are analysed with the impact of air flow velocities and temperatures.

Keywords: convective drying, diffusion coefficient, drying curve, drying stages, shrinkage, uncertainty and repeatability test, drying correlations.

1. Introduction
It is essential to remove moisture content by mechanical drying methods to prevent spoilage effects in moist objects. There are varieties of drying operations found in literatures. They are convective or direct drying, indirect or contact drying, dielectric drying, freeze drying, natural air drying etc. Convective drying is one of the most widely used methods for restricting fermentation in food stuffs, preventing breakage in ceramic products, clay products, wood etc. For food materials the thermal conductivity is too low, the heat transfer rate within the product is also low, thus drying rate reduces. Similarly, the other factors like initial moisture content, air velocity, drying air temperature, air humidity and shrinkage of object are involved in the drying mechanisms of any moist object. So, it is important to analyze these drying parameters experimentally which are related to convective drying. A well-designed and well-controlled experimental facility is necessary to carry out such an analysis.

A large fraction of the experimental works focused on the measurement of the rate of moisture transfer and thereby finding the properties like moisture diffusivity [1-3], surface transfer coefficient [4,5], shrinkage [6,7] etc. Effect of air velocity [3,7,8] and temperature [3,7] was also discussed in literatures. An experimental attempt was made to evaluate the convective heat transfer coefficient during drying of various crops and to investigate the influences of drying air velocity and temperature on the convective heat transfer coefficient [4,5]. The effect of shrinkage during convective drying was analyzed by Simal et al. [6]. A good agreement was noticed by them with their experimental results.
with the numerical results with shrinkage. Velic et al. [8] investigated experimentally the convective drying of apple in laboratory conditions and investigated the influence of airflow velocities on drying kinetics and heat transfer coefficient. Oztop and Akpinar [9] analyzed about moisture transfer in potato and apple by both experimentally and numerically.

There are few numerical works [10, 11] found on drying of potato. Lot of experimental works [2-5, 8, 9] on drying of food products therefore, experimental correlations were also available in convective drying, but the air flow velocity and temperature dependent drying correlations were not found in the literatures. Effect of air velocity and temperature are not analysed in drying problems. Therefore, the main objectives of this work are, (i) estimating the drying parameters from observed experimental parameters and analyze the effect of air flow velocity and temperature on the estimated parameters, (ii) constructing the drying correlations of average diffusion coefficient, average density, shrinkage and volume of water.

2. Experimental setup and procedure

The experiments are conducted by a wind tunnel type convective dryer. The experimental setup is achieved to conduct the experiments to a maximum velocity of 8 m/s and maximum temperature of 70°C in the test section. The detailed experimental setup and procedures were explained in the previous work [12]. For finding the initial moisture content, a thermostatically controlled hot air oven is used. A rectangular shaped moist object (4 cm x 2 cm x 2 cm) is covered with an aluminum paper and is kept in a hot air oven to 24 hours (YSI – 431, IS – 3119) where the temperature is maintained at 105°C. It is noted that 83% of initial moisture (Initial moisture content = \( \frac{m_{\text{initial}} - m_{\text{final}}}{m_{\text{final}}} \times 100\% \)) in terms of mass is existing in the moist object. The uncertainty and repeatability tests were done for confirming the experimental results.

3. Results and discussion

The initial mass of moist potato (\( m_{\text{wet}} \)) and final mass of the dry potato (\( m_{\text{dry}} \)) are measured with the weighing balance. The moisture content in dry basis is calculated from the expression,

\[
M = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{dry}}} \tag{1}
\]

The initial moisture content is found to be \( M_0 = 4.8862 \) kg/kg of dry basis (db). In a similar way using Eq. (1), the transient moisture content of the moist object is calculated at different times.

The non-dimensional moisture content (\( \Phi \)) is calculated as,

\[
\Phi = \frac{M - M_{\text{eq}}}{M_0 - M_{\text{eq}}} \tag{2}
\]

Where, \( M_0 \) is the initial moisture content and \( M_{\text{eq}} \) is the equilibrium moisture content of the object.

The effect of logarithmic non dimensional moisture content with drying time for different temperatures and at air flow velocity of 6 m/s is shown in Fig. 1 (a). It is observed that most of the drying curves have two well defined falling rate periods. Initially the drying takes place by following an average diffusion coefficient and after a particular drying period the product experiences different average diffusion coefficient because of its temperature and moisture dependence. Therefore, the total drying curve is looking like two different straight lines. At a particular temperature (60°C) the natural logarithm of non-dimensional moisture content is decreased with increasing air flow velocity (Fig. 1b). The rate of convection increases, thus moisture diffusion rate increases while the air flow velocity increases. Air velocity 4 and 6 m/s are giving more drying rate compare to 2 m/s.

The drying rate is estimated by moisture content of the object divided by drying time. From the Fig. 2(a) it is observed that there are three drying stages. The first one is called initial drying rate period and in this period the sensible heat is transferred to the product and moisture within the object. The
rate of evaporation increases dramatically during this period with mostly free moisture being removed. There are two falling rate period (2nd and 3rd stage) observed from the drying rate curve as already explained in Fig. 1. At a particular temperature the drying rate is very fast during the first falling rate period because of the large difference in the moisture content of the potato and dry air. In 2nd falling rate period, the drying rate gradually reduces compared to previous stage. Because in this period, the interior moisture needs to migrate towards the surface of the product and consequently, it delays the drying rate. The drying rate is noticed to be 5.6, 7.6, 8.2 and 9.2 kg/hr.kg of db to reach non dimensional moisture content of 0.8 for different drying air temperatures at 40, 50, 60 and 70°C respectively. So, the drying rate of the moist object increases with increase in the drying temperature (Fig. 2a).

Figure 1. Variation of natural logarithmic of non dimensional moisture content with drying time for different temperatures at 6 m/s (a) and for different velocities at 60°C (b)

Figure 2. Variation of drying rate with non-dimensional moisture content at (a) different temperatures at 6 m/s (b) different velocities at 60°C

The influence of air flow velocity on drying rate at 60°C is shown by Fig. 2(b). It can be seen from the figure that higher air flow velocity (4 and 6 m/s) did not make much difference in drying rate. As the airflow velocity is increased, the object surface transfer coefficient is also increased almost proportionally, resulting an increase in moisture transfer. So, it is seen that the drying rate of the moist object increases with increase in the drying temperature (Fig. 2a) and as well as air flow velocity (Fig. 2b) at a particular moisture content.

A one dimensional analytical solution of moisture transfer is given by Rossello et al. [1], from that expression the diffusion coefficient of current experimental data is calculated as,

\[ \ln(\Phi) = \frac{3\pi^2(D_{eff}/4)}{(L/2)^2} t \]  

(3)

Where, \( \Phi \) is non-dimensional moisture content, \( D_{eff} \) is effective diffusion coefficient in m²/s, \( L \) is length of the object in m and \( t \) is time in s.
Figure 3(a) gives the variation of experimental effective diffusion coefficients at various drying air temperatures and for velocity of 6 m/s. It is noticed that if the moisture content is higher, the diffusion coefficient is also higher and at the final stage of drying when the moisture content is lower (non-dimensional moisture content from 0.3 to 0), the diffusion coefficient is seen to be almost constant.

Figure 3(b) gives the variation of experimental effective diffusion coefficient at various air flow velocities and at air drying temperature of 60°C. At particular moisture content the diffusion coefficient is higher for larger air flow velocity. An increase in air flow velocity increases the heat and mass transfer coefficients and hence the surface temperature of the object increases, so the diffusion coefficient also increases. Diffusion coefficient does not change much when the air flow velocity increases from 4 to 6 m/s compared to its increase when the air flow velocity increases from 2 to 4 m/s irrespective of the all temperature considered. This can be correlated to the minimum increase of drying rate observed when the air flow velocity increases from 4 to 6 m/s previously discussed with Figs. 1(b) and 2(b).

Many of the literatures [8,9] predicted drying curves for food materials assuming a constant diffusion coefficient. The current experimental investigation shows that the diffusion coefficient is actually a function of temperature of drying air and hence, it is a function of temperature as well as moisture content of drying object. So, it is found that any mathematical model (with or without shrinkage) that assumes diffusivity to be independent of temperature and moisture content will be insufficient to deliver accurate prediction especially in convective drying applications. A curve fitting tool DATAFIT 9 is used for finding a correlation from the experimental data. The experimental average diffusion coefficient data at different velocity and temperature conditions are regressed by 2nd order polynomial equation which is given as,

$$D_{av} = -1.126E-9 + 1.575E-9 v - 6.495E-12 T + 6.093E-12 vT - 1.804E-10v^2 + 3.246E-13T^2 \quad (R^2 = 0.983) \quad (4)$$

Where, $v$ is air velocity in m/s and $T$ is drying temperature in °C.

The maximum density is observed almost at the end of the drying process which is decreased with increasing air flow velocity and temperature (Table 1). The maximum value of density varies from 1240 to 1340 kg/m$^3$ for different temperatures (40 - 70 °C) and at velocity of 2 m/s and it is almost the same for other cases of velocities. The variation of maximum density with temperature for all the velocities considered in this work is less than 100 kg/m$^3$. On the other hand, at a specific temperature, the maximum density is varied by a very small amount (20 - 40 kg/m$^3$) for different velocity conditions.

Table 1. Experimental maximum density variation with different air temperature and velocity conditions.

| Drying air temperatures, °C | Maximum density of the object, kg/m$^3$ |
|---------------------------|-----------------------------------------|
| Air velocity =2 m/s       | Air velocity =4 m/s                     | Air velocity =6 m/s |
|                           |                                         |                   |

4
Based on the experimental data, the average density of the object is regressed by a regression analysis and it is given by,

$$\rho_{av} = 1270 - 2.97v - 1.18T \quad (R^2 = 0.96) \quad (5)$$

where, $\rho$ is density in $\text{kg/m}^3$, $v$ is air velocity in m/s and $T$ is air temperature in °C. $R^2$ is a coefficient of determination which shows how much near the experimental values and curve fitted for the solution.

Shrinkage being an important phenomena in a drying process, it has been discussed in the next paragraphs. Shrinkage during drying may be related to the density through a mass balance as follows [13]

$$\frac{V}{V_0} = \frac{\rho(1+M)}{\rho(1+M_0)} \quad (6)$$

where, $V_0$, $\rho_0$ and $M_0$ are initial volume, density and moisture content of the moist object respectively.

Volume of water in the moist object at moisture content $M$ is defined as,

$$V_w = \frac{V_0 \rho M}{\rho_0 (1+M)} \quad (7)$$

Figure 4 shows the volume shrinkage with respect to non-dimensional moisture content at different temperatures for velocity at 6 m/s (Fig. 4a) and at different air velocities for temperature of 60 °C (Fig. 4b). The volume shrinkage ($V/V_0$) of a moist object during drying decreases almost linearly with decrease in moisture content. The volume shrinkage does not show much variation with air temperature and air velocity conditions. The similar results are obtained for all remaining velocity and temperature conditions (not shown here). It is observed that the volume loss (volume loss = $\frac{V_{\text{initial}} - V_{\text{final}}}{V_{\text{initial}}} \times 100\%$) experienced by the sample is from 74.13 to 84.67% for temperatures range of 40 to 70°C and velocity conditions from 2 to 6 m/s (Table 2).

![Figure 4](image-url)

**Figure 4.** Variation of shrinkage ($V/V_0$) with non-dimensional moisture content of the object at (a) different temperatures and at 6 m/s and (b) different air velocities at 60°C

**Table 2.** % volume loss of the object with different air temperatures and velocities

| Drying air temperatures, °C | Air velocity =2 m/s | Air velocity =4 m/s | Air velocity =6 m/s |
|-----------------------------|---------------------|---------------------|---------------------|
| 40                          | 74.13               | 81.25               | 81.54               |
| 50                          | 80.62               | 82.27               | 82.69               |
| 60                          | 81.25               | 83.40               | 84.38               |
| 70                          | 81.56               | 83.85               | 84.67               |

The experimental data of shrinkage are regressed by a non linear regression analysis and is given by,
\[ \frac{V}{V_0} = a\Phi + b \quad (R^2 = 0.987) \quad (8) \]

Where, \( a = 0.812 \), \( b = 0.234 \) and \( \Phi \) is non-dimensional moisture content. In food products, the drying time is defined as the time required to condition the moist object at a moisture content of almost 15% of its initial moisture content [14]. The influence of drying time to reach 15% moisture content of its initial value with different air temperatures from 40 to 70°C at different air flow inlet velocities are shown in Fig. 5(a). At particular air temperature with the increase of the air flow velocity, the time required to achieve certain moisture content is decreased. This is because, the drying rate of a material depends on how quickly the moisture can be evaporated into the surrounding air followed by the diffusion of vapour from the inner region. The average percentage difference of drying time between 2 and 4 m/s is found to be 36.5% and the same is noticed only 6.7% between 4 and 6 m/s, which is approximately 6 times lower than the case between 2 and 4 m/s. Hence, it can be concluded that the higher air flow velocities (above 6 m/s) are not desirable for increasing the drying rate and it is enough to choose an optimized air flow velocity in between 2 to 6 m/s for convective drying applications. Figure 5(b) shows the variation of drying time with air velocity to a moisture content of 5%, 10% and 15% of its initial moisture content value at 60°C. It is observed that for an air velocity of 2, 4 and 6 m/s, the drying time is respectively 960 min (16 hr), 672 min (11.21 hr) and 585 min (9.75 hr) to reach an moisture content of 5% to its initial moisture content value. It can be seen that the increasing the air velocity by three times, drying time (time to reach 5% of its initial moisture content) can be saved approximately by 39% at 60°C.

**Conclusion**

The following are the major conclusion drawn from this work: The sample object loses its mass, moisture content and volume of water during the continuous drying process. Drying rate increases with increasing air temperature and air flow velocities. However, the drying rate is not much affected by higher airflow velocities like 4 and 6 m/s because of almost constant diffusion coefficient, observed for these higher air flow velocities. The diffusion coefficient is higher at higher moisture content level and it reduces and remains almost constant at lower moisture content level. Experimental results proved that the diffusion coefficient is a function of temperature and moisture content of the moist product. Volume shrinkage is reduced linearly with decrease in moisture content. The sample loses volume from 74.13 to 84.67% for different air drying temperatures of 40 to 70 °C and different air flow velocities 2 to 6 m/s. The drying time is saved by approximately 45% at 4 m/s and 46.5% at 6 m/s while increasing drying temperature from 40 to 70 °C. The correlations were proposed for average density, shrinkage and average diffusion coefficient of object at different drying air temperatures and different air flow velocities. It is concluded that the optimum drying rate is achieved at 6 m/s. hence, it is proved that no need to do experiment with higher air flow velocities beyond 6 m/s in drying of food materials.
Nomenclature

| a,b | Constants | V | Volume [cm$^3$] |
|-----|-----------|---|----------------|
| B   | Breadth of the moist object [cm] | Greek Symbols |
| C   | Width of the moist object [cm] | Φ | Non dimensional moisture content |
| D   | Diffusion coefficient [m$^2$/s] | ρ | Density of object [kg/m$^3$] |
| db  | dry basis |
| L   | Length of the moist object [cm] | a | air |
| m   | Mass of the object [g] | av | average |
| M   | Moisture content [kg/kg of db] | eff | effective |
| R$^2$ | Coefficient of determination | eq | equilibrium |
| t   | Time [s] | s | solid or dry matter |
| T   | Temperature [°C] | w | water |
| v   | velocity [m/s] | 0 | initial condition |

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