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Analysing the Effect of Temperature-Dependent Diffusivity in Convective Drying of Food Material

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Abstract:
This study investigates the effect of temperature-dependent diffusivity in convective drying of food material. The governing equations have been decoupled using perturbation method and solved via eigenfunction expansion technique. The influences of the dimensionless parameters on temperature and moisture concentration profile were plotted on graphs. It is noteworthy to mention that the temperature increases with increase in peclet energy number (P_e), moisture concentration rises with increase in peclet mass number (P_{em}). It is also found that temperature and moisture concentration decreases with increase in reference velocity (u).

Keywords: Drying, expansion, food, temperature, diffusivity

Introduction

The process of food drying involves the dehydration of moisture in order to preserve fruits by preventing microbial spoilage. It further reduces transport and packaging cost by reducing weight and volume. Dried food has the advantage that it can be stored at ambient conditions in comparison to other food preservation methods. However, drying is an energy intensive process and accounts for up to 15% of all industrial energy usage and the quality of food may degrade during the drying process (Kumar *et al.*, 2014).

Drying is a process wherein moisture is removed from the food material as a result of concurrent heat and mass transfer (Sontakke and Salve, 2015). Mujumdar (2004) reported that the main reason of food drying is not to only remove moisture content by adequate supply of heat energy but also to produce quality food. To minimize the rate of energy consumption and improve product quality, a physical understanding of the drying process is very much important.

Patel et al. (2013) examined critically a review of the solar dryer and concluded that the use of solar dryer led to considerable reduction in drying time in comparison to that of conventional sun drying, and the product dried using this dryer were of better quality as compare to their conventional sun dried. The efficiency of solar drying system is affected by the properties of drying materials. e.g. moisture content, size, shape, and geometry as well as ambient conditions which includes solar radiation and temperature, relative humidity, velocity and atmospheric pressure of ambient air.

Maisnam *et al.* (2017) worked on recent advances in conventional drying of foods and stated that, the major concern with drying using artificial dryer is that it is energy intensive even though drying time is shorter as compared to the natural method of drying.

There are several fundamental mathematical models that have been developed for food drying. Barati and Esfahani (2011) developed a food drying model wherein they considered the material properties to be constant. However, in reality, during the drying process physical properties such as diffusion coefficients and dimensional changes occur as the extent of drying progresses. Calculation of the effective diffusivity is crucial for drying models because it is the main parameter that controls the process with a higher diffusion coefficient, implying an increased drying rate. The diffusion coefficient changes during drying due to the effects of sample temperature and moisture content (Batista *et al.*, 2007).

In terms of heat and mass transfer, evaporation plays an important role during drying process. During the initial stage of drying, the surface is almost saturated, which induces both higher evaporation and moisture removal rates. Due to this higher evaporation rate, the temperature drops at this stage for a short period of time (Golestani *et al.*, 2013). Komolafe *et al.* (2021) studied the determination of moisture diffusivity and activation energy in the convective drying of fish and used locally fabricated drying system for the experiments. It was concluded that, the highest drying rates were observed during the convective drying process at $90^0 C$ drying temperature.

Several works have been carried out on convective drying of food material, but there are limited studies that have investigated the temperature variation during convection drying process.

In this context, the aim of this article is to investigate the effect of temperature-dependent diffusivity in convective drying of food material using eigenfunction expansion technique to obtain analytical solution.

Model Formulations

Considering the plane geometry of the food product. The Temperature-dependent diffusivity obey an Arrhenius-type relation and thermal conductivity is assumed to be constant. The primary dependent variables are the temperature, $T\,(x,t)$ and moisture concentration $C\,(x,t)$. Under these assumptions, the equations that describe diffusivity in convective drying of food materials are:

Mass transfer equation

$$\frac{\partial C}{\partial t'}+u'\frac{\partial C}{\partial x'}=\frac{\partial}{\partial x'}\left(D_0\frac{T}{T_0}\frac{\partial C}{\partial x'}\right) \tag{1}$$

Heat transfer equation

$$\rho c_p\left(\frac{\partial T}{\partial t'}+u'\frac{\partial T}{\partial x'}\right)=K\frac{\partial^2 T}{\partial x'^2} \tag{2}$$

Satisfying initial and boundary conditions

$$\left.\begin{array}{lll} C(x',0)=C_0, & C(0,t')=C_b, & C(L,t')=C_b \\ T(x',0)=T_{air}, & \mathrm{T}(0,t')=T_0, & \mathrm{T}(L,t')=T_0 \end{array}\right\} \tag{3}$$

where

T is the temperature, C is the moisture concentration, t' is the time, D_o is the diffusion coefficient, u' is a convective flow, x' is the distance, ρ is the density, c_p is the specific heat of the material and K is the thermal conductivity.

Method of Solution

Non-dimensionalisation

Here we make the variables in (1)—(3) dimensionless by introducing dimensionless variables for temperature, moisture concentration, distance in space and time;

$$\left.\theta=\frac{T-T_0}{T_{air}-T_0},\quad \phi=\frac{C-C_b}{C_0-C_b},\quad x=\frac{x'}{L},\quad t=\frac{Ut'}{L},\ u=\frac{u'}{U}\ \right\} \tag{4}$$

where T_0 is the initial temperature, C_0 is the initial moisture concentration, U is the reference velocity, x, t are the dimensionless distance and time.

Using equation (4) on equations (1)—(3) we have;

$$\left.\begin{array}{l} \dfrac{\partial\phi}{\partial t}+u\dfrac{\partial\phi}{\partial x}=\dfrac{1}{\rho_{em}}\dfrac{\partial}{\partial x}\left((1+a\theta)\dfrac{\partial\phi}{\partial x}\right) \\ \phi(x,0)=1,\quad \phi(0,t)=0,\quad \phi(1,t)=0 \end{array}\right\} \tag{5}$$

$$\left.\begin{array}{l} \dfrac{\partial\theta}{\partial t}+u\dfrac{\partial\theta}{\partial x}=\dfrac{1}{\rho_e}\dfrac{\partial^2\theta}{\partial x^2} \\ \theta(x,0)=1,\quad \theta(0,t)=0,\quad \theta(1,t)=0 \end{array}\right\} \tag{6}$$

where

$P_e = \frac{\rho c_p U}{K}$; Peclet energy number, $P_{em} = \frac{LU}{D_o}$; Peclet mass number $a = \left(\frac{T_{air}-T_o}{T_o}\right)\}$

Approximate Analytical Solution

In this section, we let

$$\left.\begin{aligned}\theta(x,t) &= \theta_o(x,t) + a\theta_1(x,t) + \ldots \\ \phi(x,t) &= \phi_o(x,t) + a\phi_1(x,t) + \ldots\end{aligned}\right\} \qquad (7)$$

and processing gives

$$\left.\begin{aligned}&\frac{\partial \phi_0}{\partial t} + u\frac{\partial \phi_0}{\partial x} = \frac{1}{P_{em}}\frac{\partial^2 \phi_0}{\partial x^2} \\ &\phi_0(x,0) = 1,\quad \phi_0(0,t) = 0,\quad \phi_0(1,t) = 0\end{aligned}\right\} \qquad (8)$$

$$\left.\begin{aligned}&\frac{\partial \phi_1}{\partial t} + u\frac{\partial \phi_1}{\partial x} = \frac{1}{P_{em}}\frac{\partial^2 \phi_1}{\partial x^2} + \frac{1}{P_{em}}\theta_o\frac{\partial^2 \phi_o}{\partial x^2} + \frac{1}{P_{em}}\frac{\partial \theta_o}{\partial x}\frac{\partial \phi_o}{\partial x} \\ &\phi_1(x,0) = 0,\quad \phi_1(0,t) = 0,\quad \phi_1(1,t) = 0\end{aligned}\right\} \qquad (9)$$

$$\left.\begin{aligned}&\frac{\partial \theta_0}{\partial t} + u\frac{\partial \theta_0}{\partial x} = \frac{1}{P_e}\frac{\partial^2 \theta_0}{\partial x^2} \\ &\theta_0(x,0) = 1,\quad \theta_0(0,t) = 0,\quad \theta_0(1,t) = 0\end{aligned}\right\} \qquad (10)$$

$$\left.\begin{aligned}&\frac{\partial \theta_1}{\partial t} + u\frac{\partial \theta_1}{\partial x} = \frac{1}{P_e}\frac{\partial^2 \theta_1}{\partial x^2} \\ &\theta_1(x,0) = 0,\quad \theta_1(0,t) = 0,\quad \theta_1(1,t) = 0\end{aligned}\right\} \qquad (11)$$

Next, transforming (8)—(11) using

$$\left.\begin{aligned}\phi_o(x,t) &= e^{(\alpha t+\beta x)}u_o(x,t) \\ \theta_o(x,t) &= e^{(\alpha_1 t+\beta_1 x)}v_o(x,t) \\ \phi_1(x,t) &= e^{(\alpha t+\beta x)}u_1(x,t) \\ \theta_1(x,t) &= e^{(\alpha_1 t+\beta_1 x)}v_1(x,t)\end{aligned}\right\} \qquad (12)$$

and obtain;

$$\left.\begin{aligned}&\frac{\partial u_o}{\partial t} = \frac{1}{P_{em}}\frac{\partial^2 u_o}{\partial x^2} \\ &u_o(x,0) = e^{-\beta x},\quad u_o(0,t) = 0,\quad u_o(1,t) = 0\end{aligned}\right\} \qquad (13)$$

where $\alpha = -\frac{1}{4}P_{em}u^2$, $\beta = \frac{1}{2}P_{em}u$

$$\left.\begin{aligned} &\frac{\partial v_o}{\partial t}=\frac{1}{P_e}\frac{\partial^2 v_o}{\partial x^2} \\ &v_o(x,0)=e^{-\beta_1 x},\ v_o(0,t)=0,\ v_o(1,t)=0 \end{aligned}\right\} \tag{14}$$

$$\alpha_1=-\frac{1}{4}P_e u^2, \quad \beta_1=\frac{1}{2}P_e u$$

$$\left.\begin{aligned} &\frac{\partial u_1}{\partial t}=\frac{1}{P_{em}}\frac{\partial^2 u_1}{\partial x^2}+\frac{1}{P_{em}}\left(\begin{aligned}&\left(\beta^2+\beta\beta_1\right)u_o v_o+\left(\left(2\beta+\beta_1\right)v_o\frac{\partial u_o}{\partial x}\right)+v_o\frac{\partial^2 u_o}{\partial x^2}\\ &+\beta u_o\frac{\partial v_o}{\partial x}+\frac{\partial u_o}{\partial x}\frac{\partial v_o}{\partial x}\end{aligned}\right)e^{\alpha_1 t+\beta_1 x} \\ &u_1(x,0)=0, \quad u_1(0,t)=0, \quad u_1(1,t)=0 \end{aligned}\right\} \tag{15}$$

$$\left.\begin{aligned} &\frac{\partial v_1}{\partial t}=\frac{1}{P_e}\frac{\partial^2 v_1}{\partial x^2} \\ &v_1(x,0)=0,\ v_1(0,t)=0,\ v_1(1,t)=0 \end{aligned}\right\} \tag{16}$$

Using eigenfunction expansion method by Myint-U and Debnath, (1987) as follows

$$\left.\begin{aligned} &\frac{\partial u}{\partial t}=k\frac{\partial^2 u}{\partial x^2}+\alpha u+F(x,t) \\ &u(x,0)=f(x), \quad u(0,t)=0, \quad u(L,t)=0 \end{aligned}\right\}, \tag{17}$$

we assume

$$u(x,t)=\sum_{n=1}^{\infty}u_n(t)\sin\frac{n\pi}{L}x. \tag{18}$$

Where,

$$u_n(t)=\int_0^t e^{\left(\alpha-k\left(\frac{n\pi}{L}\right)^2\right)(t-\tau)}F_n(\tau)\,d\tau+b_n e^{\left(\alpha-k\left(\frac{n\pi}{L}\right)^2\right)t}, \tag{19}$$

where

$$\left(\begin{array}{l}
D_1=\dfrac{1}{P_{em}},K_1=\dfrac{1}{P_e},\ A=\dfrac{2}{n\pi}\left(1-(-1)^n e^{-\beta}\right),\ \ A_1=\left(1+\dfrac{\beta^2}{(n\pi)^2}\right), \\
A_2=\dfrac{A}{A_1},c=D_1(n\pi)^2,\ \ A_3=\dfrac{\dfrac{2}{n\pi}\left(1-(-1)^n e^{-\beta_1}\right)}{\left(1+\dfrac{\beta_1^{\,2}}{(n\pi)^2}\right)},\ c_1=K_1(n\pi)^2, \\
A_4=A_2A_3,\ \ A_5=\left(\left(\beta^2+\beta\beta_1\right)-(n\pi)^2\right),\ A_6=((2\beta+\beta_1)n\pi+\beta n\pi) \\
A_7=\dfrac{1}{\left(9(n\pi)^2+10(n\pi\beta_1)^2+\beta_1^{\,4}\right)}\left(\begin{array}{l} 3e^{\beta_1}(n\pi)^3(-1)^{3n}+3e^{\beta_1}n\pi\beta_1^{\,2}(-1)^{3n} \\ -9e^{\beta_1}(n\pi)^3(-1)^n-3e^{\beta_1}n\pi\beta_1^{\,2}(-1)^n \end{array}\right), \\
A_8=\dfrac{1}{\left(9(n\pi)^2+10(n\pi\beta_1)^2+\beta_1^{\,4}\right)}\left(\begin{array}{l} e^{\beta_1}(n\pi)^2\beta_1(-1)^{3n}+e^{\beta_1}\beta_1^{\,3}(-1)^{3n}- \\ 3e^{\beta_1}(n\pi)^2\beta_1(-1)^n-e^{\beta_1}\beta_1^{\,3}(-1)^n+ \\ 2(n\pi)^2\beta_1 \end{array}\right), \\
A_9=\dfrac{1}{\left(9(n\pi)^2+10(n\pi\beta_1)^2+\beta_1^{\,4}\right)}\left(\begin{array}{l} 3e^{\beta_1}(n\pi)^3\beta_1(-1)^{3n}+3e^{\beta_1}n\pi\beta_1^{\,2}(-1)^{3n} \\ -2e^{\beta_1}(n\pi)\beta_1^{\,2}(-1)^n-3(n\pi)^3-n\pi\beta_1^{\,2} \end{array}\right), \\
A_{10}=\left(A_5A_7+A_6A_8-A_9\right),\ \ c_2=\left(c+c_1-\alpha_1\right),\ \ A_{11}=\left(c-c_2\right)
\end{array}\right)$$

The computation were done using computer symbolic algebraic package MAPLE 17 to generate the graphs.

Results and Discussion

The system of partial differential equations describing diffusivity in convective drying of food material are solved analytically. The numerical values of temperature (θ) and moisture concentration (ϕ) are computed for different parameters such as: Peclet energy number, Peclet mass number and reference velocity and depicted graphically with their respective discussions.

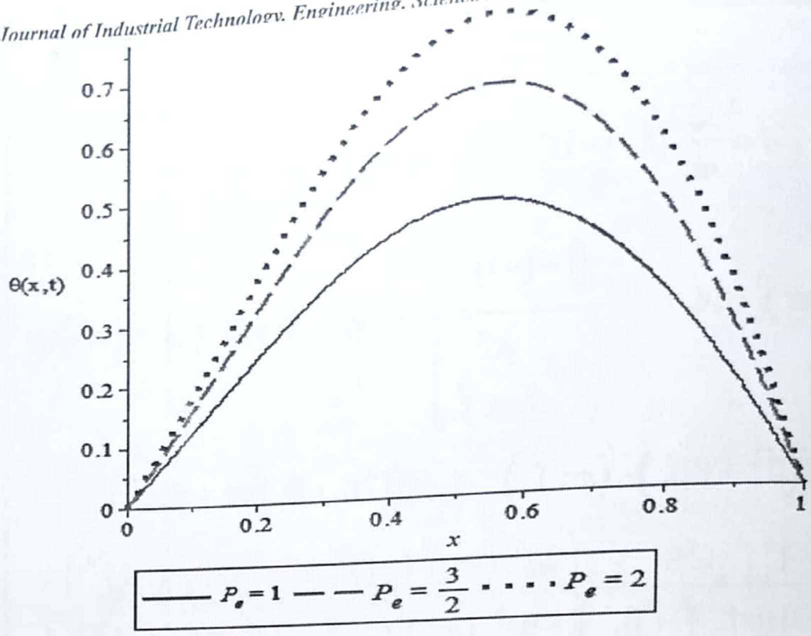


Figure 1: Graph of temperature $\theta(x,t)$ against x at various values of P_e when $a=0.01,\ \ u=1,\ P_{em}=1$

Figure 1 depicts the graph of temperature $\theta(x,t)$ against distance for different values of Peclet energy number (P_e). It is observed that, the temperature increase and later decrease along the distance and the maximum temperature increases as Peclet energy number increases.

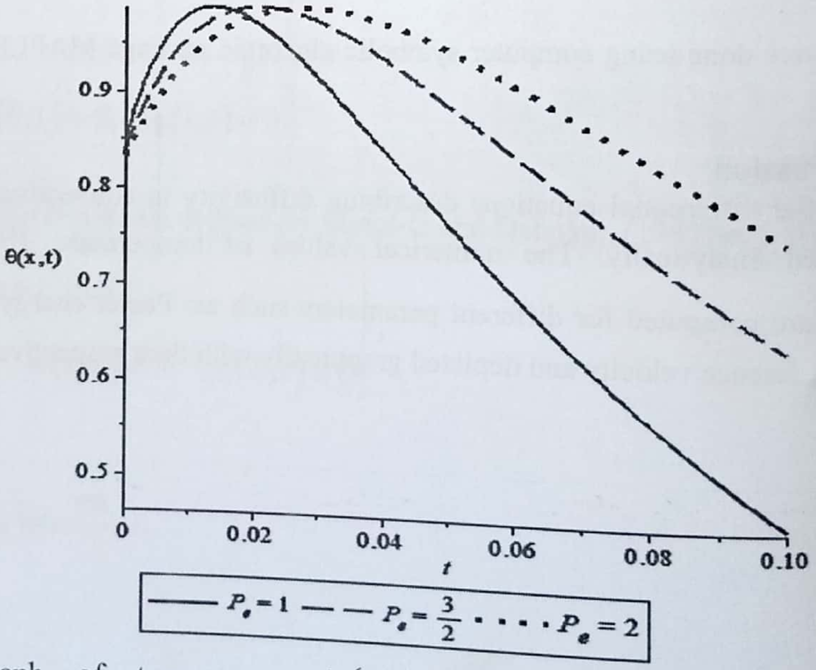


Figure 2: Graph of temperature $\theta(x,t)$ time t at various values of P_e when $a=0.01,\ \ u=1,\ P_{em}=1$

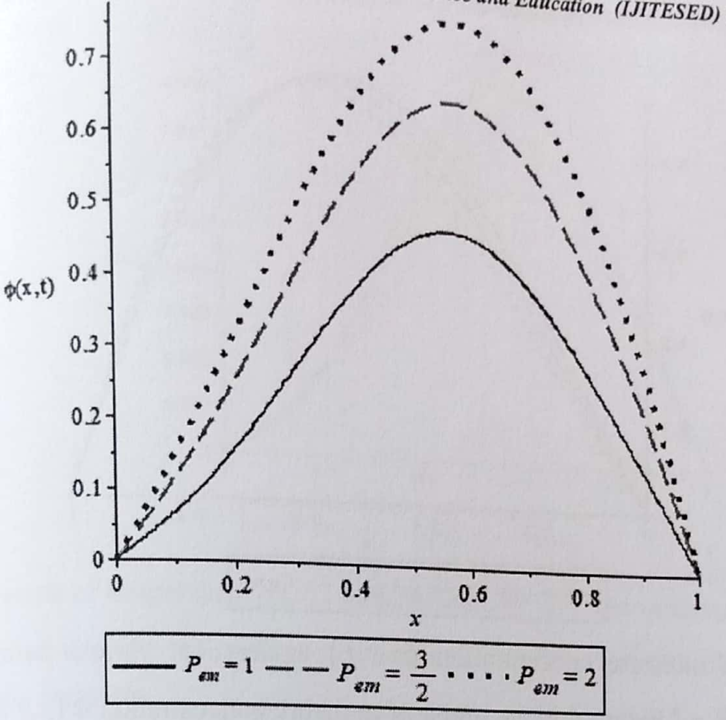
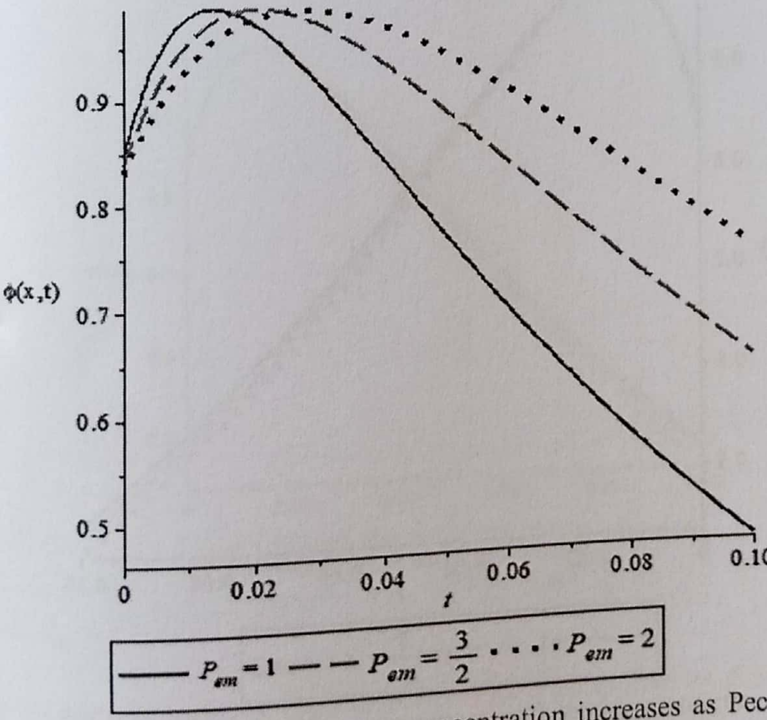


Figure 2 presents the graph of temperature $\theta(x,t)$ against time for different values of Peclet energy number (P_e). It is observed that, the temperature increase and later decrease with time and increases as Peclet energy number increases.Figure 3: Graph t of moisture concentration $\phi(x,t)$ against x at various values of P_{em} when $a = 0.01,\ u = 1,\ P_e = 1$

Figure 3 shows the graph of moisture concentration $\phi(x,t)$against distance for different values of Peclet mass number (P_{em}). It is observed that, the moisture concentration increase and later decrease along the distance and the maximum concentration increases as Peclet mass number increases.



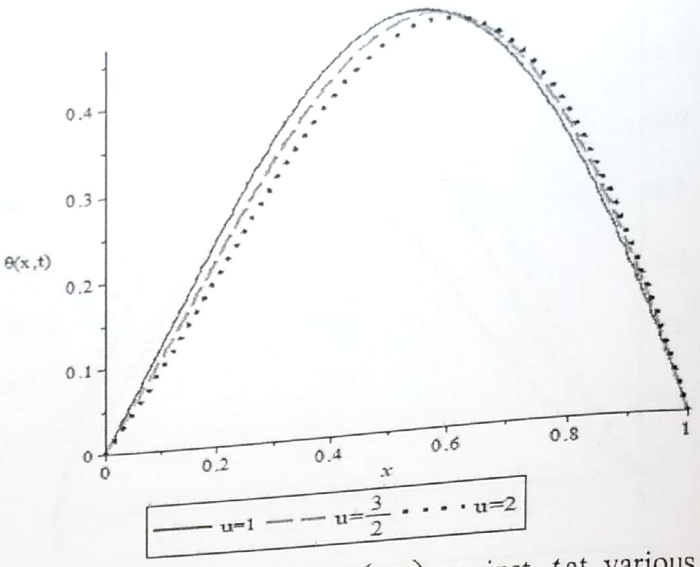
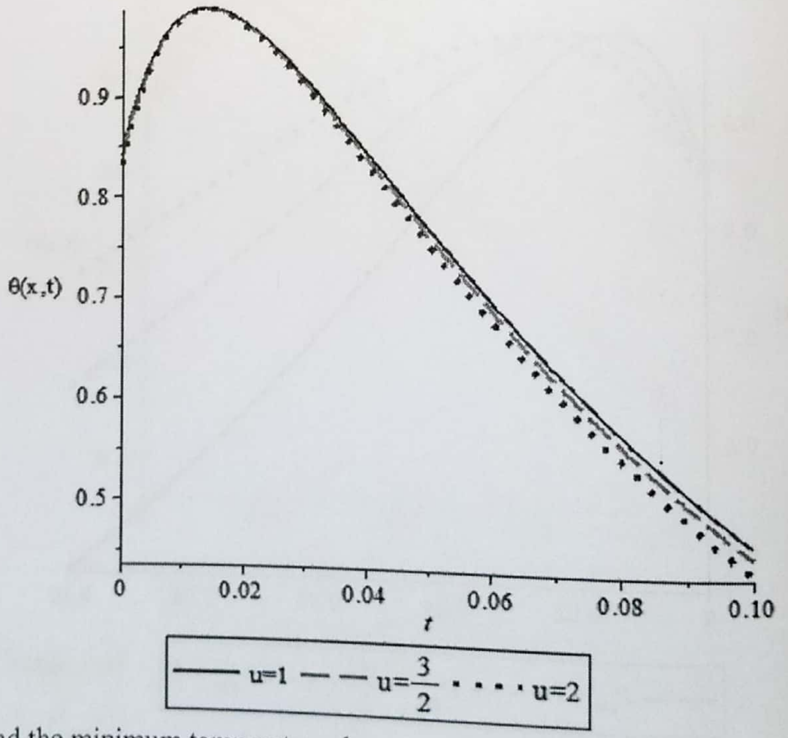


Figure 4: Graph of moisture concentration $\phi(x,t)$ against t at various values of P_{em} when $a=0.01,\ u=1,\ P_e=1$ Figure 4 is the graph of moisture concentration $\phi(x,t)$ against time for different values of Peclet mass number (P_{em}). It is observed that, the moisture concentration increase and later decrease with time and increases as Peclet mass number increases.Figure 5: Graph of temperature $\theta(x,t)$ against x at various values of u when $a=0.01,\ P_e=1, P_{em}=1$

Figure 5 depicts the graph of temperature $\theta(x,t)$ against distance for different values of reference velocity (u). It is observed that, the temperature increase and later decrease along the distance and the minimum temperature decreases as reference velocity increases.



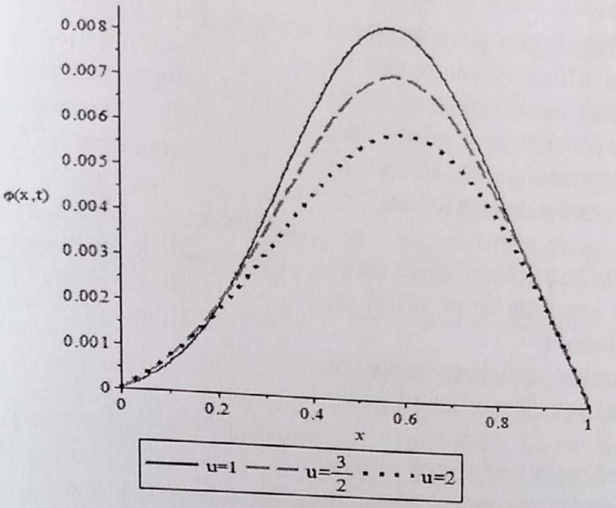
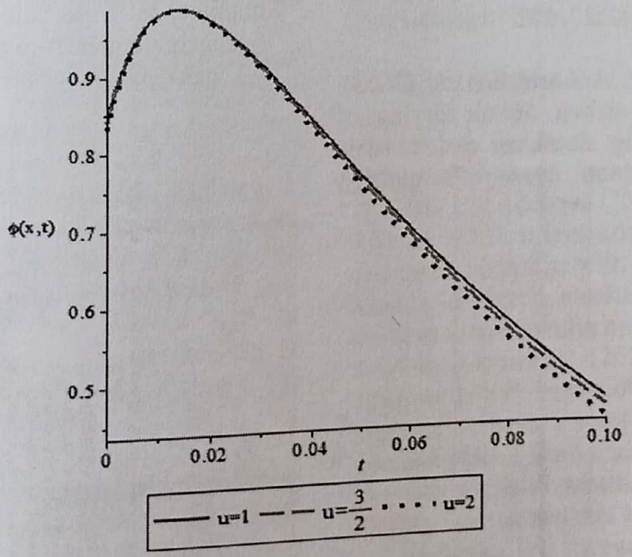


Figure 6 is the graph of temperature $\theta(x,t)$ against time for different values of reference velocity (u). It is observed that, the temperature increase and later decrease with time and decreases as reference velocity increases.

Figure 7: Graph of moisture concentration $\phi(x,t)$ against x at various values of u when $a = 0.01,\ \ P_e = 1,\ P_{em} = 1$

Figure 7 shows the graph of moisture concentration $\phi(x,t)$ against distance for different values of reference velocity (u). It is observed that, the moisture concentration increase and later decrease along the distance and the minimum moisture concentration decreases as reference velocity increases.

Figure 8: Graph t of moisture concentration $\phi(x,t)$ against t at various values of u when



$a = 0.01,\ \ P_e = 1,\ P_{em} = 1$

Figure 8 depicts the graph of moisture concentration $\phi(x,t)$ against time for different values of reference velocity (u). It is observed that, the moisture concentration increase and later decrease with time and decreases as reference velocity increases.

Conclusion

The effect of Peclet energy, Peclet mass numbers and reference velocity on diffusivity in convective drying of food material is considered. The temperature and moisture concentration profiles are obtained and shown through the graphs. In view of the above, the following conclusions are made:

(i) Peclet energy number enhances temperature and has little or no effect on moisture concentration.

(ii) Peclet mass number enhances moisture concentration and has little or no effect on temperature.

(iii) Reference velocity reduces both temperature and moisture concentration

It is evident that an increase in temperature greatly increased the drying rate and accelerate dehydration rate of moisture content in food material. However, peclet mass number has a negligible impact on temperature.

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