Theoretical Study of Affecting Parameters on Drying Process of Organic Material

دراسة نظرية للعوامل المؤثرة على عملية تجفيف المادة العضوية

M. G. Wassel, M. G. Mousa, A. Fouda and M. Gh. Jehad*

*Faculty of Engineering, Mansoura University, Mansoura, Egypt.

Abstract

Drying is considered one of the most complex processes encountered in engineering, the drying of porous material has a vital role in many applications and industrial fields. Drying is process accompanied with a simultaneous heat and moisture transport within material and from its surface to the surroundings caused by a number of mechanisms. The moisture can be either transported to the surface of the material and then evaporated, or evaporated internally at a liquid vapor interface and then transported as vapor to the surface. The transfer of heat depends on the air temperature, relative humidity, air flow rate, exposed area of material and pressure. The physical nature of the material, including temperature, pore structure, and moisture content, governs the rate of moisture transfer. A numerical model is developed for simulating a convective drying process. The model incorporates mass and heat transfer relationships within the porous material, as well as the heat and mass transfer at the air–solid interface of the material and drying medium. A computer program in FORTRAN is developed to solve the two-dimensional coupled heat and mass transfer equations inside a porous material during the drying process. The model initially validated by comparing the numerical results with published results. This validated numerical model is used to investigate the effect of external conditions of the drying medium and internal conditions of the porous material. The numerical results of drying curves, heat and mass transfer coefficients in terms of Nusselt and Sherwood numbers are presented. In addition, the numerical predictions for average moisture content are in good and acceptable agreement with experiments.

الملخص :

تم في هذا البحث دراسة العوامل المؤثرة على عملية التجفيف للمواد العضوية . وقد استخدمت المواد العضوية الموجودة في الطبيعة واخذ منها على سبيل المثال في هذا البحث العنب ، حيث أجريت عملية التجفيف بإمرار هواء على العينة الموجودة في مسلك هواء وتم فرض إن ظروف الهواء ثابتة وحلت المعادلات الحاكمة للحركة وانتقال الحرارة والكتلة حيث حولت تلك المعادلات إلى الصيغة اللابعدية ابتداءً من ثم حولت إلى الصورة اللابعدية باستخدام تقنية الفروق المحددة وتم الحل باستخدام طريقة جاووس سيدل. أجريت مقارنة لنتائج النموذج المستخدم مع عدد من الدراسات النظرية والعملية السابقة ووجد توافق إلى حد ما .

Accepted September 29, 2013

1. Introduction

Drying of materials is one of the oldest and most common unit operations that found its applications in different fields; such as chemical, agricultural, polymer, ceramics, food drying, wood drying, coated laminates, granulated synthetic materials and pharmaceutical industry. The operating conditions and desired quality of the product are the main determinants of the industrial drying process. In addition, utilization of high amount of energy in drying industry makes drying one of the most energy intensive operations in industrial applications. The study of the drying behavior of different materials has recently been a subject of interest for various investigators on both theoretical and application grounds.

Hernandez *et al.* (2000) developed an analytical solution of mass transfer equation with concentration-dependent shrinkage and constant water diffusivity of food drying process, the study involved an experimental one dimensional unsteady mango and cassava slices drying with different thicknesses and different drying air temperatures and velocities. Dincer and sahin (2004) presented a new analytical model for prediction the drying times during drying of multidimensional irregular shapes of moist objects. Irregular shapes were approximated as cylinders and ellipsoids. The geometric shape factor considered based on the reference of drying time for infinite slab geometry. The method represented a one-dimensional Fickian equation in the dimensionless form for the moisture transfer of organic materials without considering the coupling effects. Also the drying times of irregular organic material product were proposed by Akpinar *et al.* (2003) were used an experimental drying data for drying process of different shapes determined through the model and comparison the drying times between the mathematical model and the experimental drying data. The theoretical calculations illustrated that the accuracy close to 10% from the experimental data.

Pel *et al.* (2002) and Babalis and Belessiotis (2004) considered Fickian second law of the unsteady state diffusion neglecting the effect of total pressure gradients and temperature to describe the moisture content transport during the drying process of organic material products that occurred during the falling drying rate period, where the effective diffusivity coefficient determined experimentally by correlation and fitting the experimental data based on Arrhenius-type equation.

Baronas and Ivanauskas (2004) studied the measure of reliability of one and two dimensional diffusion models during moisture movement in solid organic material, wood, during coating or rewetting. The summary of their study was in two dimensional model had guarantees perceptibly better prediction of drying process than the corresponding one dimensional model if the width to thickness ratio of the material was rather small (less than 10), also the concluded that the drying conditions as well as the thickness of the organic material have a notable effect on the error of applying the one dimensional model on the two dimensional problems.

Luikov (1975), one of the first researchers that studied the interrelation between heat and mass transfer in capillary-porous bodies, who developed a unique approach to describe porous material drying process based on the phenomenological theory of irreversible thermodynamics principles. In Luikov's theory, the moisture flux consists of three components, as he assumed, due to temperature gradient, moisture gradient and pressure gradient. With constant pressure assumption, the Luikov equations were reduced to a coupled heat and moisture transfer equations during drying. Luikov's model has a wide acceptable and uses to simulate the organic porous material drying although there are many heat and mass transfer models based on different mechanisms.

Dantas *et al.* (2003) solved the inverse problem parameter estimation involved heat and mass transfer in capillary porous media, wood and ceramics, that described by the dimensionless linear Luikov's equations. The equations were one dimensional moist porous sheet with using transient temperature and moisture content measurement. Kulasiri and Woodhead (2005), solved analytically one dimensional Luikov's equations of heat and mass transfer in drying process of organic porous material, wood, they shown the significant effect of temperature gradients on the moisture profile within the material at large thickness. The moisture diffusivity in organic materials during drying was studied by Chen (2007), with describing some controversial aspects, such as Luikov's theory, of the concept depended on the effective Fickian liquid moisture diffusivity, the researcher concluded the need for microstructural characterization of the moist organic materials whose parameters can be used to interpret the (vapor) diffusivity variability as well as to improve the fundamental understanding of the transport phenomena beyond the effective liquid diffusion model.

Aversa *et al.* (2007), presented a theoretical model described the transport phenomena involved in food drying, this study aimed to determine the influence of some of the important variables especially velocity, humidity and temperature of drying air on the performance of drying process of organic materials.

Curcio (2010) presented a theoretical model describing the transport phenomena involved in food drying. A fundamental multiphase approach was utilized to account for the simultaneous presence of both liquid water and vapor within the cylindrical organic material, potato, sample undergoing drying.

Barati and Esfahani (2011) presented analytical modeling of coupled heat and mass transfer during convective drying process, the studied model was described the temperature and moisture evolutions of organic material, mango slab. The mathematical model describing the transport phenomena involved in mango drying under the convective boundary conditions at the surface. The one dimensional governing equation was the non-steady mass transfer equation for moisture diffusion within the organic material, and the lumped capacity method was employed to describe the heat transfer.

Whitaker (1985), proposed a theoretical foundations of heat, mass and momentum transport in granular porous media, wet sand, the researcher used the mechanistic model that based on volume-averaging transport equations. Initially, he stated with conservation equation for mass, momentum and energy for each gas and liquid phases in microscopic level within the granular porous media, also the study applied the volume averaging theory for the different phases in the dried material.

Masmoudi and Prat (1991), presented a numerical method to predict the heat and mass transfer between an unsaturated porous medium and an external air flow. Various numerical simulations were carried out to study the behavior of heat and mass convective transfer coefficients at the interface during drying process, that simulations showed that leading edge effects gave rise to a space non-uniformity of the variables at the interface surface, where the interfacial transfer coefficients differed from the standard values of flat plate with uniform temperature and concentration at the surface.

Zhang *et al.* (1999) studied the heat and mass transfer during constant rate and falling rate periods in convective drying of porous material numerically. The results of a two-zone model made up of wet zone and the dry zone compared with a three-zone model results computed by Przesmycki and Strumillo (1985). In two-zone model, air and vapor in pores were regarded as a mixture phase based on Whitaker continuum averaging method and irreversible thermodynamics theory, heat and mass transfer during porous media convection drying was described in the combined model. So, the researchers introduced the concept of iterative correction for the moving boundary problem in numerical simulations of drying processes. Mhimid *et al.* (2000), proposed a numerical solution of heat and mass transfer equations of grain drying in a vertical cylindrical bed. The numerical model used the volume averaging Whitaker theory with two temperature equilibrium models. The study expressed the relationship between the local temperature equilibrium model. Lee *et al.* (2002), studied a transient two-dimensional mathematical model to simulate the through-air drying process for tufted textile materials. Where, the heat and mass transfer in a cylindrical porous medium and air flowing around the material were analyzed. The governing equations of the conservations of mass and energy were written for the drying agent.

Lewis and Malan (2005), developed numerical modeling to solve the coupled heat and mass transfer processes in drying non-hygroscopic and hygroscopic capillary particulate materials. The solved governing equations were based on a balance mathematical and mechanistic approach. Younsi *et al.* (2007) studied numerically the heat and mass transfer during the high temperature heat treatment of wood, the heat and mass transfer occurred between the solid and the drying medium, and the moisture evaporation took place within the solid due to the capillary action and diffusion.

Thibeault *et al.* (2010), developed a new approach able to simulate three dimensional heat and moisture transfer coupled with the mechanical behavior of wood drying process. The mechanical model toke into account the hydrous, thermal, mechano-sorptive and elastic deformations as well as the changes of wood properties, caused by porosity and permeability.

The basic idea of discrete models depended on disassembling the dried organic material into discrete nodes or elements and constructs a model that simulates heat and mass transfer in drying process at every discrete element in the model. In these models, the moist organic material was represented by one, two and three dimensional governing equations; these equations represent mass, momentum and energy conservation during the drying process.

Wu *et al.* (2004), established a three dimensional theoretical model describing the coupled heat and mass transfer inside a single rice kernel during drying process. The moisture contents at some selected nodes and moisture content gradients inside the rice kernel were predicted under three different drying conditions. Karim and Hawlader (2005), developed a mathematical model for food products drying under a considerable shrinkage. The model, which included the influence of both material and equipment, was capable of predicting dynamic behavior of the dryer. They solved simultaneously the heat and mass equations using a numerical technique. The material model was capable of predicting the instantaneous temperature and moisture distribution inside the organic material. On the other hand, the equipment model described the transfer process in the tunnel dryer and predicted the instantaneous temperature and humidity ratio of air at any location of the tunnel. A tunnel type fruits dryer was used to conduct experiments, where the prediction of average moisture content and material temperature compared favorably with the experimental results. The model was capable of predicting the dynamic behavior of fruits drying undergoing shrinkage.

Kaya *et al.* (2006), performed a two dimensional analysis of heat and mass transfer during drying of rectangular moist object using an implicit finite difference method with applying the convective boundary conditions at all moist object surfaces. The variable convective heat and mass transfer coefficients were considered during the drying process. The modeling was divided to external flow of the drying fluid and the modeling of the object. Firstly, the partial differential equations governing the force convection motion of a drying fluid in two dimensional geometry formulas were the mass, momentum and energy conservation equations with assuming constant fluid properties were solved using the FLUENT CFD package based on the finite volume method. The results obtained from their study were compared with the experimental data taken from Velic *et al.* (2004), who investigated airflow velocity influence on the kinetics of convection drying of organic material apple, the comparison illustrated a good agreement.

Mohan and Talukdar (2010), analyzed numerically the drying behavior of a moist object subjected to convective drying by solving heat and moisture transfer equations. A three dimensional numerical model was developed for the prediction of transient temperature and moisture distribution in a rectangular shaped moist object during the convective drying process. The governing partial differential equations for the forced convection motion of drying fluid in a three dimensional geometry were the mass, momentum and energy conservation equations, also a mathematical model was developed to analyze heat and mass transfer through diffusion inside the object being dried with assuming constant material properties and neglected all of shrinkage, heat generation and radiation effects. The results illustrated a comparison between the numerical model and experimental data of Simal *et al.* (1998) and Sarsavadia *et al.* (1999) that dealt with organic materials drying, a good agreement was obtained.

Villa-Corrales *et al.* (2010), developed a theoretical-physical two dimensional model to study the heat and moisture transfer inside a rectangular, organic material, mango slices during drying process. The proposed model was based on Fourier law and Fick second law to calculate the temperature and moisture fields inside the slice during the drying, with assumptions that convective drying with constant air temperature and constant thermo-physical properties of mango with neglecting the shrinkage, heat generation and radiation effects, they assumed moisture evaporation only for the upper surface with moisture transfer inside the slice only by diffusion. Midilli *et al.* (2002), developed a new empirical model with the addition of an extra term that included the drying time (t) to Henderson and Pabis model. The new model represented the combination of an exponential term and a linear term. They applied this new model to the drying of organic materials; pollen, mushroom and pistachio for different drying methods.

Bimbenet *et al.* (1985), produced an experimental study to determine the drying kinetics of several biological products had been measured in warm air of various characteristics, the obtained curves were drying rate versus product water content, as well as the evolution of the product temperature, showed no constant drying rate period in most cases studied. Dutta *et al.* (1988), proposed an experimental and theoretical study to explain the drying behavior of spherical maize, rice and corn grains. The experimental results of grain drying correlated with the theoretical results. They established a correlation to describe the diffusivity of the grain with moisture content and temperature.

Babalis and Belessiotis (2004) investigated the influence of the drying air conditions on the drying constants and moisture diffusivity during organic materials drying. The drying of figs occurred predominately in the falling rate period for the entire range of air velocity and temperature values investigated. Doymaz (2004), studied experimentally the effects of air temperature, airflow rate and sample thickness on drying kinetics of organic material, carrot cubes. The study evaluated the convective air drying characteristics in cabinet dryer.

Chemkhi *et al.* (2005), developed an experimental modeling to study the drying process of biological products with high moisture contents. Ademiluyi *et al.* (2008), investigated the drying process of three different popcorns varieties under different drying temperatures and air velocities in falling rate period, the verified experimental data were fitted in different empirical correlation models. Giner (2009), investigated the influence of internal and external resistances to mass transfer on the constant drying rate period in high-moisture foods, fruit pectic gels. The researcher observed that the average moisture content of the product began drying by decreasing linearly with time. Mihoubi *et al.* (2009), proposed experimental and theoretical study dealt with modeling of convective drying of carrot slices with infrared heat source.

Mota *et al.* (2010), investigated the drying of organic material, onion, in terms of drying kinetics, which was evaluated at three different air drying temperatures. The experimental data was fitted to different empirical kinetic models; Lewis and modified Page models, and this kinetic study was then complemented with the modeling of Fick's diffusion equation, for estimation of the diffusion coefficients.

Seiiedlou *et al.* (2010), developed an experimental work to study the drying behavior of the organic material, apple slices, in a thin layer hot air dryer at three different air velocities and temperatures.

Motevali *et al.* (2011), developed an experimental comparison of energy consumption for drying of mushroom slices using six various drying methods including hot air, microwave, vacuum, infrared, microwave-vacuum and hot air-infrared. Their results of data analysis showed that the lowest and highest energy consumption levels in drying mushroom slices were associated with microwave and vacuum dryers, respectively.

Singh and Pandey (2012), investigated the effects of drying conditions on the drying behavior of organic material, sweet potato, in a cabinet dryer. The convective air dryer was carried out under five different air temperatures, five different air velocities and three different sweet potato cubes thickness.

Liu *et al.* (2012), investigated the effects of shrinkage, porosity and density of bio-porous material during convective drying.

2. Mathematical model

The drying medium, air, flows over wet flat plate inside rectangular duct of height H_C and length L_C with initial velocity (u_{in}), temperature (T_{in}) and concentration (C_{in}) as shown in figure (1). The flow over flat plate is assumed two dimensional and unsteady. The flow describing equations are continuity, momentum, energy and mass equations in Cartesian coordinates (x, y).

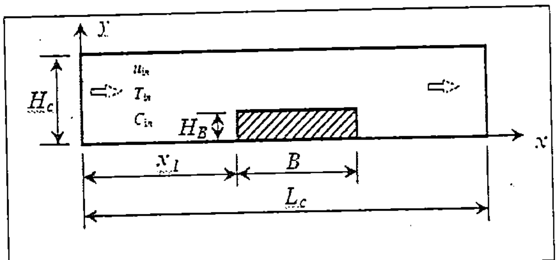

Figure (1) Schematic Diagram of Mathematical Model.

To solve these governing equations, one has to know the pressure field which is difficult to obtain. To avoid solving the pressure field directly, one employ the widely used vorticity-stream function method. The dimensionless stream function (ψ) and vorticity (ω) are defined as follows:

$$u=\frac{\partial \psi}{\partial y} \quad \& \quad v=-\frac{\partial \psi}{\partial x} \qquad (1)$$

$$\omega=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y} \qquad (2)$$

Where u and v are velocity component in x-direction and y-direction respectively. Substituting in governing equations with the corresponding expressions of velocity components, one can eliminate the pressure from both momentum equations. Then the following transport governing equations for ψ and ω are obtained:

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}=-\omega \quad (3)$$

$$\frac{\partial\omega}{\partial t}+u\frac{\partial\omega}{\partial x}+v\frac{\partial\omega}{\partial y}=\nu\left(\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}\right) \quad (4)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (5)$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right) \quad (6)$$

Where ν, α and D are kinematics viscosity, thermal diffusivity and diffusion coefficient of the flow respectively. A wet porous material consists of a matrix and void spaces, which are fully saturated with moisture content, the void space either interconnected or disconnected and moisture content either free or trapped within the solid matrix. The volume averaging technique [20] is used to describe the various transport equations at the macroscopic level. The macroscopic coefficients in the governing equations will be material properties as well as the physical properties of the moisture content. Several assumptions are made regards the material and thermodynamic conditions of different phases within the moist material [45]. Therefore, the system of the coupled heat and mass transfer during drying process of porous materials without pressure gradients governed by the following moisture and energy equations:

$$\frac{\partial w}{\partial t}=D_m\nabla^2 w+D_m\delta\nabla^2 T \quad (7)$$

$$\frac{\partial T}{\partial t}=\frac{\varepsilon h_{fg}D_m}{c_p}\nabla^2 w+\left(\frac{k_{eff}}{\rho_s c_p}+\frac{\varepsilon\delta h_{fg}D_m}{c_p}\right)\nabla^2 T \quad (8)$$

Where w, D_m and δ are moisture content, total isothermal moisture diffusivity and thermal gradient coefficient respectively. Also, ε, h_{fg}, c_p, k_{eff} and ρ_s are the phase conversion factor, the latent heat due to evaporation, the equivalent specific heat capacity of the organic material, the effective thermal conductivity of the wet organic porous material and the dry organic material density respectively. To put the governing equations of the drying medium and porous medium in dimensionless form, one introduces the following dimensionless independent and dependent variables as;

$$X=\frac{x}{H_B},\quad H=\frac{H_c}{H_B},\quad L=\frac{L_c}{H_B},\quad X_L=\frac{x_l}{H_B},\quad X_B=\frac{B+x_l}{H_B},$$

$$Y=\frac{y}{H_B},\quad U=\frac{u}{u_{in}},\quad V=\frac{v}{u_{in}},\quad \tau=\frac{t u_{in}}{H_B},$$

$$\Psi=\frac{\psi}{u_{in}H_B},\quad \Omega=\frac{\omega H_B}{u_{in}},\quad \theta=\frac{T-T_{in}}{T_o-T_{in}} \text{ and}$$

$$C^*=\frac{C-C_o}{C_{in}-C_o},\quad W=\frac{w-w_e}{w_o-w_e}$$

Substituting the dimensionless variables into equations (3-6), the dimensionless form of governing equation of the drying medium are obtained.

$$\frac{\partial^2\Psi}{\partial X^2}+\frac{\partial^2\Psi}{\partial Y^2}=-\Omega \quad (9)$$

$$\frac{\partial\Omega}{\partial\tau}+U\frac{\partial\Omega}{\partial X}+V\frac{\partial\Omega}{\partial Y}=\frac{1}{Re_B}\left(\frac{\partial^2\Omega}{\partial X^2}+\frac{\partial^2\Omega}{\partial Y^2}\right) \quad (10)$$

$$\frac{\partial\theta}{\partial\tau}+U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial Y}=\frac{1}{Pr\,Re_B}\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right) \quad (11)$$

$$\frac{\partial C^*}{\partial\tau}+U\frac{\partial C^*}{\partial X}+V\frac{\partial C^*}{\partial Y}=\frac{1}{Sc\,Re_B}\left(\frac{\partial^2 C^*}{\partial X^2}+\frac{\partial^2 C^*}{\partial Y^2}\right) \quad (12)$$

The dimensionless Prandtl number (Pr), Reynolds number (Re) and Schmidt number (Sc) are defined according to the following relations:

$$Pr=\frac{\upsilon}{\alpha},\quad Re_B=\frac{u_{in}H_B}{\upsilon} \text{ and } Sc=\frac{\upsilon}{D} \quad (13)$$

Substituting the dimensionless variables into equations (7 and 8), the dimensionless form of governing equation within the organic material are obtained.

$$\frac{\partial W}{\partial Fo}=Lu\,\nabla^2 W+Lu\,Pn\,\nabla^2\theta \quad (14)$$

$$\frac{\partial\theta}{\partial Fo}=\varepsilon\,Lu\,Ko\,\nabla^2 W+(1+\varepsilon\,Lu\,Ko\,Pn)\nabla^2\theta \quad (15)$$

The dimensionless Fourier number (Fo), Luikov number (Lu), Posnov number (Pn)

and Kossovich number (Ko) are defined according to the following relations:

$$Fo = \frac{\alpha_p t}{H_B^2},\ Lu = \frac{D_m}{\alpha_p},$$

$$Pn = \frac{\delta(T_{in} - T_o)}{(w_o - w_e)} \text{ and } Ko = \frac{h_{fg}(w_o - w_e)}{c_p(T_{in} - T_o)} \quad (16)$$

Moreover, the average Nusslet and Sherwood numbers are calculated according to the following relations:

$$\bar{N}u = \bar{h}H_B/k \ \ \& \ \ \bar{S}h = \bar{h}_m H_B/D \quad (17)$$

The foregoing governing equations of the drying medium and the wet organic porous material are subjected to the following initial and boundary conditions:

At inlet, $\tau \geq 0$, for $X = 0$, $0 \leq Y \leq H$:

$$\frac{\partial \Psi}{\partial Y} = 1, \frac{\partial \Psi}{\partial X} = 0, \theta = 1, C^* = 0$$

At exit. $\tau \geq 0$, for $X = L$, $0 \leq Y \leq H$:

$$\frac{\partial \Psi}{\partial X} = 0, \frac{\partial \theta}{\partial X} = 0, \frac{\partial C^*}{\partial X} = 0$$

At the upper wall, $\tau \geq 0$, for $Y = H$, $0 \leq X \leq L$:

$$\frac{\partial \Psi}{\partial X} = 0, \frac{\partial \Psi}{\partial Y} = 0, \frac{\partial \theta}{\partial Y} = 0, \frac{\partial C^*}{\partial Y} = 0$$

At the lower wall without organic material surfaces :

$\tau \geq 0$, for $Y = 0$, $0 \leq X \leq X_L$, $X_B \leq X \leq L$

$$\frac{\partial \Psi}{\partial X} = 0, \frac{\partial \Psi}{\partial Y} = 0, \frac{\partial \theta}{\partial Y} = 0, \frac{\partial C^*}{\partial Y} = 0$$

At organic all surfaces, $\tau = 0$:

$$\theta = 0, C^* = 1$$

At organic left surface, $\tau > 0$ for $X = X_L$, $0 \leq Y \leq 1$:

At organic upper surface, $\tau > 0$ for $Y = 1$, $X_L \leq X \leq X_B$:

At organic right surface, $\tau > 0$ for $X = X_B$, $0 \leq Y \leq 1$:

$$\frac{\partial \Psi}{\partial X} = 0, \frac{\partial \Psi}{\partial Y} = 0, \theta = \theta_s, C^* = C_s^* \quad (18)$$

3.Numerical Solution

The governing partial differential equations describing the drying process of a porous organic material by forced convection by air (9-12, 14 and 15) with the boundary conditions (18), are discretized using finite difference approximation and solved based on proper choice of boundary conditions and algorithms. The unsteady vorticity, energy and concentration equations solved by time marching using FTCS (forward time central space differencing), Possion elliptic equation solved by under relaxation iterative method. The unsteady diffusion equations of heat and moisture transport within the wet organic porous material solved by ADI scheme (alternative direct implicit method) and Crank-Nicolson with TDMA (tri diagonal matrix algorithm). The dimensionless velocity, temperature and concentration at different position along the surface are obtained. Consequently, local, average Nusselt number and Sherwood number are derived with the aid of their definitions. A computer program in FORTRAN is developed to perform the numerical solution.

4.Results and discussion

The mathematical model is used to study the heat and mass transfer associated with drying process of porous materials. The results of the numerical solution is presented and analyzed. The effect of drying conditions of drying medium and various parameters involved with the heat and moisture transport within the porous sample are investigated.

The developed drying model in present work is verified by comparing its results with different numerical, analytical and experimental results available in the literature for some simplified and similar cases. The average surface temperature distribution is predicted and compared with previous studies [20, 25 and 46] as shown in figure (2). The initial drop in temperature is attributed to the evaporative cooling effect caused by phase change so it is an indication of both the rate of evaporation as well as the heat transfer present. After a period of 20–30h the surface evaporation slows down on account of the low moisture content level and the sample temperature rises toward ambient temperature.

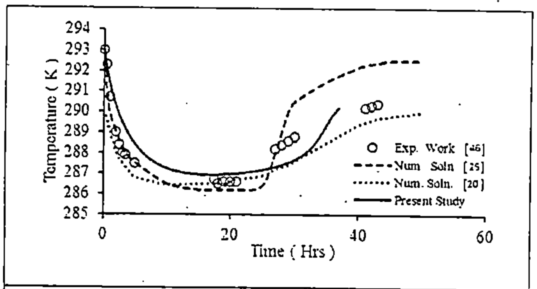

Figure (2) Comparison between predicted average surface temperature of present work and previous studies.

The contours of dimensionless concentration and temperature in the channel around the sample and the moisture content within the sample at Fo = 50 is shown in figure (3). It can be observed that, the drying is accelerated from the left side since the gradients are high at the leading edge.

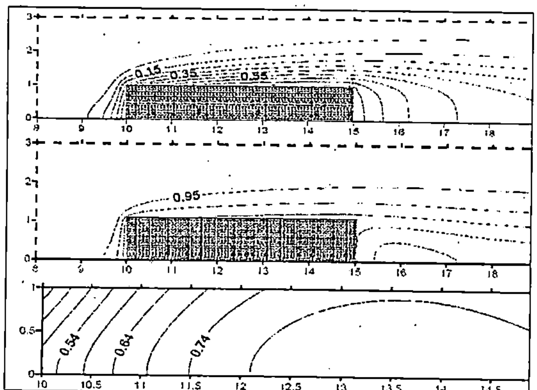

Figure (3) The dimensionless concentration and temperature distributions in channel and moisture content within the sample at Fo=50.

Drying considered as a transient process, the heat and mass transfer coefficients at the air solid interface can be expressed as in terms of Nusselt and Sherwood numbers with Fourier number. The instantaneous local Nusselt (Nu_x) and Sherwood numbers (Sh_x) for different values of Fourier number (Fo) for Re = 200 are shown in figures (4 and 5) respectively. The corners of the porous sample are represented by A, B, C and D. During the initial period of drying, the surface temperature increases to a constant value indicting the wet bulb conditions at the given drying conditions, then the constant drying period starts and the moisture loss continues at constant temperature. It is observed that, the drop of moisture and the rise in temperature at the leading edge (B) is higher than the other regions, indicating higher heat flux and evaporation and consequently local Nusselt and Sherwood numbers. The development of a thin thermal and concentration boundary layers over the top surface is the suggested reason.

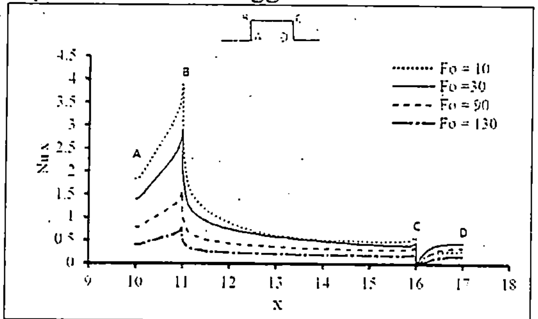

Figure (4) Local Nusselt number around the sample surface for Re = 200.

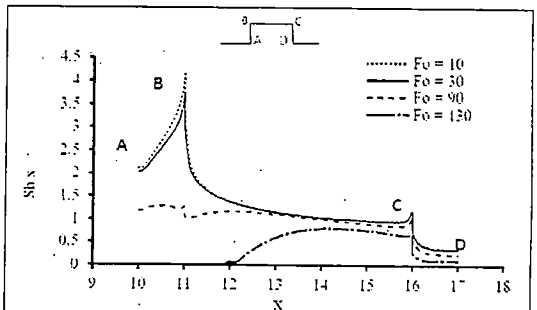

Figure (5) Local Sherwood number around the sample surface for Re = 200.

The average Nusselt and Sherwood numbers versus Fourier number for different values of Reynolds numbers during the drying process are shown in figures (6 and 7) respectively. The initial drying period is observed as an indication of constant drying period during drying process and this period getting shorter as the Reynolds number increases. The average Nusselt