3-D HEAT AND MASS TRANSFER AND MANIPULATION USING MICROWAVES

Saber M. Ali

21 BLDG 1560 , Road 625, Manama Town 306
STATE OF BAHRAIN

Abstract

Investigation is made for three-dimensional heat and mass transfer using microwave power and hot air. Analytical and numerical approach of the microwave drying process is presented. The nonlinear system is solved numerically by finite difference techniques. Simulation is performed for a material of isothermal moisture contents and mass transfer analogue of temperature. The work is done for frequency of operation equals to 2.45 GHz.

Key Words: Heat and mass transfer, Hybrid microwave drying, modeling, Non-linear system, Energy balance, Power absorption.

I. INTRODUCTION

In the last few decades, microwave energy has been applied in a wide domain of the industrial field. One of the important applications is the microwave drying of wood, ceramics, textile, alimentation products etc.

The aim of this paper is to present three-dimensional study of the drying process using microwave energy. Drying out may be considered as a series of moisture fluxes that give rise to material accumulation or depletion. The underlying drying phenomena makes interference of two physical mechanisms: Firstly; migration of the humidity from the pores to the surface of the processed porous material in two phases:

(a) Liquid phase, by capillarity.
(b) Vapor phase, under the influence of vapor pressure gradient.

Consequently mass transfer occurs. Secondly humidity transfer occurs conjointly with the gradient of both humidity and temperature.

The removal of moisture from a body may result in physical and chemical or biological changes in the material. These changes are mostly undesirable from the viewpoint of the end use of the material. In order to avoid these undesirable side effects, the design and efficient operation of microwave drying require an energy balance and control. The processing of the numerical technique is arranged in such a way that the mathematical model within the program, prevents the un-preferable changes (Limit the temperature rise).

The microwave power required for drying is related to the moisture content of the material. The profile of the power is determined by repartition of the water content in the porous medium and its evolution with time. The waves then dissipate their energy, preferentially, in the zones of higher humidity and so they have the tendency to behave as a factor of auto-regulation of the humidity distribution. The energy required for evaporation is higher than that required for

 ISSN 1516-7399

migration. Use of microwave power increases the migration rate while hot air helps the evaporation of the surface humidity. Both microwave energy and hot air are used to form hybrid drying.

Change of mass, m, and temperature, T, as a function of the material thickness, d, during hybrid drying is shown in Fig.1. The non-linear system consists of the equation of mass transfer, the equation of heat, and the equation of absorbed microwave power.

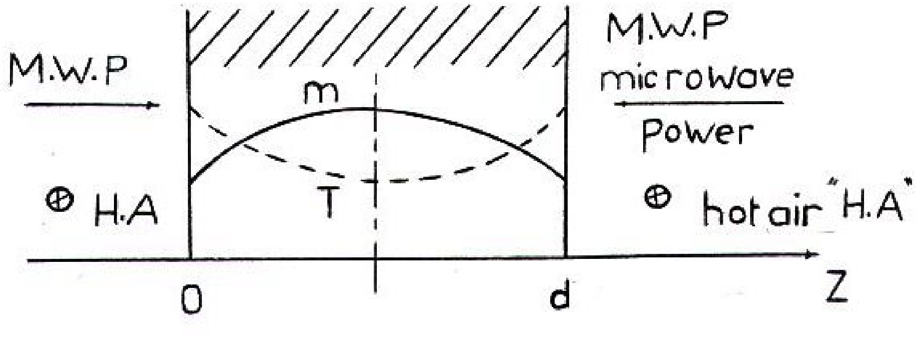

Fig. 1 General profiles for the change of humidity m and temperature T as a function of the material thickness d, for hybrid drying.

II. MATHEMATICAL FORMULATION

(a) The Governing Equation

The heat and mass transfer equations, which describe the drying process, can be respectively expressed by the following equations [1-2]:

$$dT/dt = (1/\rho_0 c') [(d/du)A_q \, dT/du] + (e'L/c')dm/dt + P_{m.W} \quad (1)$$

$$dm/dt = d/du \{a_m[dm/du + \eta \, dT/du]\} \quad (2)$$

where A_q is the coefficient of thermal conductivity in the coordinate directions (x , y , and z) and it is measured as a nonlinear function of humidity [2], L is the latent heat of evaporation of free water , e' is the coefficient of phase change , c' is the specific heat of the processed material and ρ_0 is its bulk density , a_m is the mass diffusion coefficient (in x, y and z directions), $m = M/M_0$, M and M_0 are respectively masses of humidity and dried body, η is the coefficient of thermo migration (in x, y and z directions). For the underlying case η and a_m are the same in all the coordinate directions. T is the absolute temperature, t is the time and $P_{m.W}$ is the microwave power. Equation (1) represents conservation of energy for the system, d/du is the derivative with respect to coordinate system (x , y and Z) of the processed material..

(b) The Solution Technique and Finite Difference Formulation:

Using Crank-Nicholson finite difference relation [3], for coordinate system (x , y and Z), in equations (1) and (2) , and after some mathematical arrangements the results can be written in the following form :

 ISSN 1516-7399

$$\left| A \right\| \begin{matrix} m \\ T \end{matrix} \left|^{n+1} = \right| B \left\| \begin{matrix} m \\ T \end{matrix} \right|^{n} \tag{3}$$

where n+1 and n denote new and old iterated values, [A] and [B] are the coefficient matrices.

Boundary conditions

The total surface boundary conditions [1] must satisfy the following requirements:

1- continuity of the heat flux.

2- the total mass flux that reaches the surface must be equal to the vapor flux.

Fig.2 shows the geometry of processed cub of sand while Fig.3 shows an example of the calculation of one-dimensional (x-direction) points.

As for the material center the difference between the fiction line, surface and interior of the product can be expressed as follows:

$$dT_1^n/dz = (T_2^n – T_0^n) /2\ HZ \tag{4}$$

$$dm_1^n/dz = (m_2^{\,n} – m_0^{\,n}) /2\ HZ \tag{5}$$

where HZ is the step length in z direction, 0 , 1 and 2 respectively denote fiction line , surface and interior of the product (as shown in Fig.3).

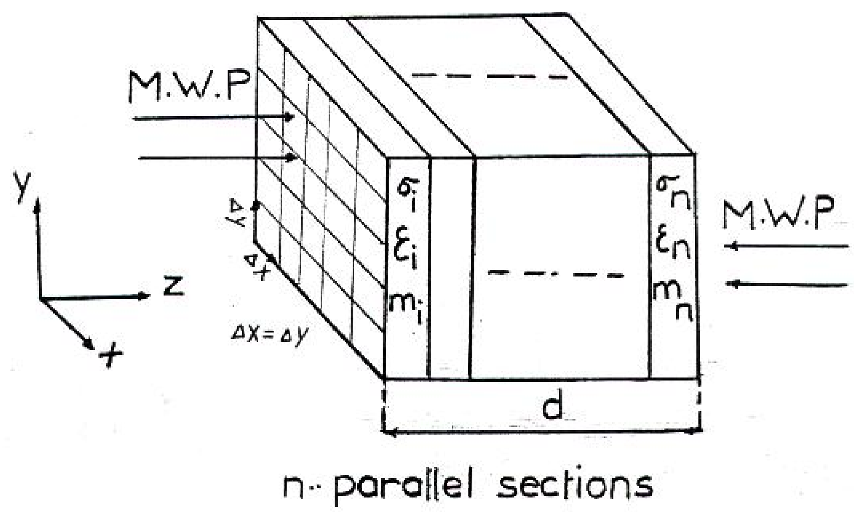

Fig.2 Processed material (cub of sand) divided into n parallel two-dimensional sections, each has specific values of ε , σ, m.

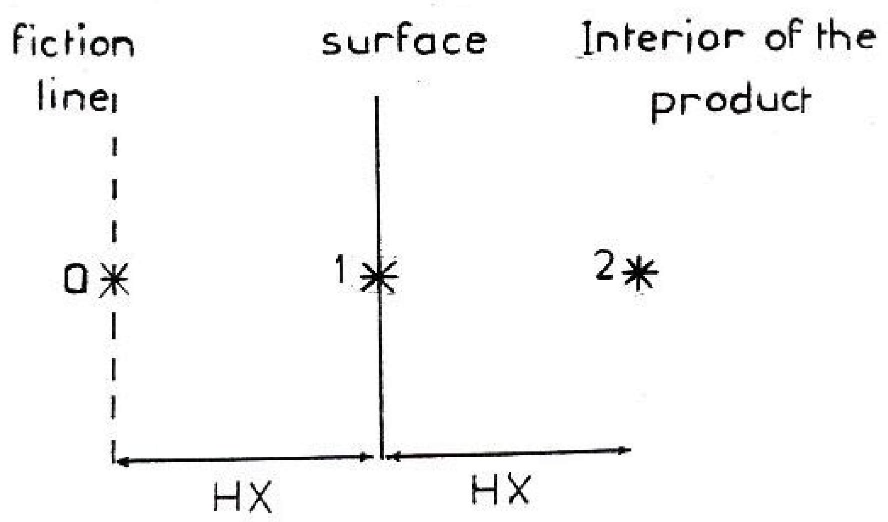

Fig.3 An example of one dimensional (x-direction) central differences between Factious line (point O), surface (point 1), and internal (point 2) of the processed material.

III. DETERMINATION OF DISSIPATED MICROWAVE POWER

The microwave power term, in equation (1) illustrates the power dissipated into the processed material. It is important to precise such term in order to obtain good results. From equations (1) and (2), using boundary, central and initial conditions, the humidity m (x , y)can be determined and hence from the known measured curves between m and the dielectric constant ε , and the loss tang δ , the corresponding values of ε and tang δ can be determined. The length d of the material is divided into n parallel dielectric discs as shown in Fig.2. Each has a number i (i =1, 2 , 3 , ..n), thickness equal to d /n, permitivity ε_i, conductivity σ_i, and constant humidity m_i. Each disc is separated from the others by infinitesimal air cell. Repartition of sources of radiation is done in the two directions of z-axis in such a way that the radiation is symmetric with respect to the middle plane of the material and this means it is a bilateral one [1]. The dimensions of the product inside the applicator and the distribution of the electromagnetic sources maintain constant dissipated power during manipulation. The power dissipated in one dielectric disc is determined as the difference between the incident and reflected ones (Fig.4) and the total bilateral dissipated power per unit surface area can be written [1] as follows :

$$P_t = (1/2)\ ([A_1]^2 - [\ B_1]^2\ )\ \ x\ \ 2 \qquad (6)$$

where A_1 and B_1 are respectively amplitude of the incident and reflected waves at the interface between the air and the dielectric .

 ISSN 1516-7399

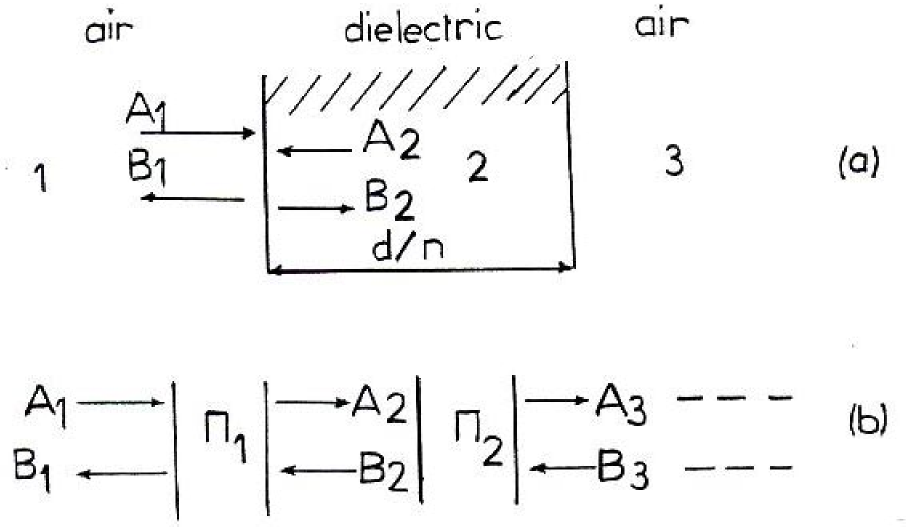

Fig. 4 Incident and reflected wave (a) for section number 1 and the chain (b) of the cub of the treated material.

IV. SIMULATION RESULTS

Due to the temperature rise caused by the microwave power $P_{m.W}$ the values of both m^n and T^n can be known. Then by iteration and use of equation (3), the new iterated values could be determined. Iteration process is repeated until the required object is reached. The profile of the dissipated microwave power (Fig.5) is calculated and it is contained in the main program with the help of sub – program (Hyper).

To get rapid drying the cub is exposed to microwave power radiations from its two sides (i.e +ve and –ve directions of its longitudinal axis z), and this is called bilateral radiation. The obtained profile of the total used microwave power as a function of z has oscillating shape and this is due to standing wave phenomena which occurs with the bilateral radiation (more details exist in reference [1]).

Simulation is done for drying of solid cub of sand with length equals to 30 cm and other data given in table 1. The evolution of temperature (Fig.6) as a function of the coordinates X and Y of the material is illustrated for drying time equals 1.5 hours , ambient temperature $T_a = 90^0$C, with hot air and without microwave power.

Simulation is carried out for hybrid drying (i.e. drying with hot air and microwave power) of the same mentioned specimen. Evolution of temperature T (^{0}C) is given as a function of coordinate system as shown in Fig.7 with hot air and microwave power.

The obtained results displayed on the temperature surfaces of Fig.6 and 7 assure that microwave energy is dissipated in the regions where the humidity is higher and so temperature rise occurs.

 ISSN 1516-7399

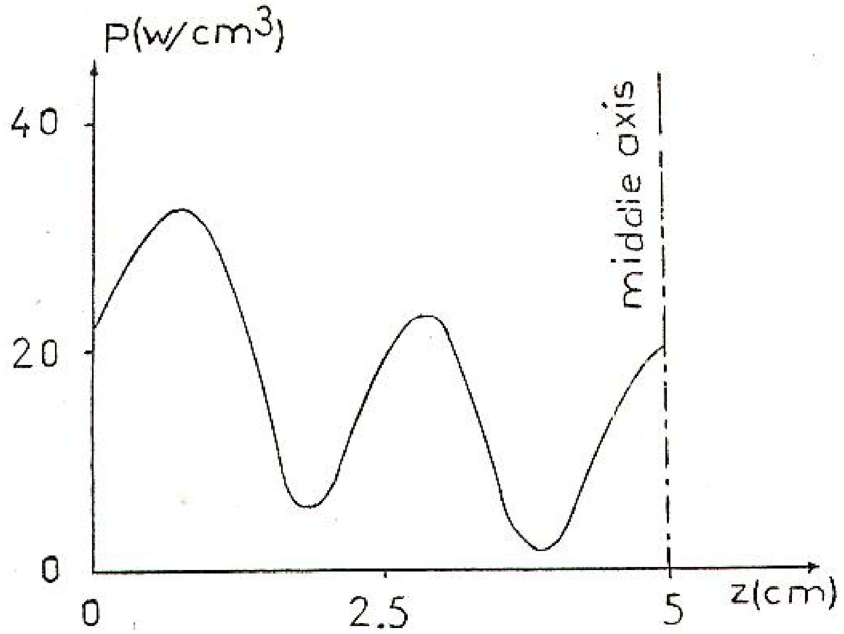

Fig. 5 Microwave drying power profile as a function of the thickness of the processed material for m = 15 %.

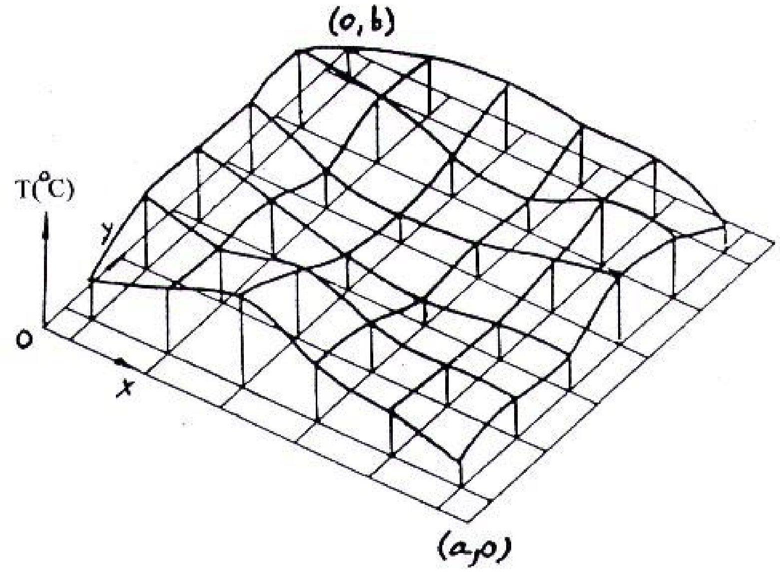

Fig. 6 Evolution of temperature T (^{0}C) as a function of the system coordinates x and y for the case of conventional drying.

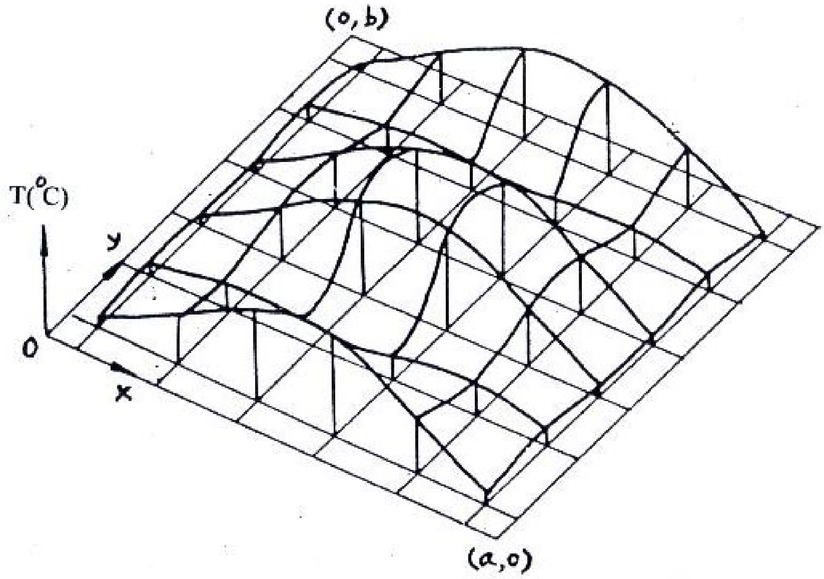

Fig. 7 Evolution of temperature T (^{0}C) as a function of the system coordinates X and Y for the case of hybrid drying.

Table 1. Data Used in Simulation.

Initial Profile of Humidity, m	15%
Initial Profile of Temperature, T	293 ^{0}K
Ambient Air Temperature, T_a	363 ^{0}K
Humidity of Drying Air,	0.1 m_{sat}
Frequency of Operation, F	2.45 GHz
Step Length in X direction, HX	0.75 cm
Step Length in Y direction, HY	0.75 cm
Step of Time, HT	30 sec
Saturated Humidity, m_{sat}	0.4
Heat Capacity of Dry Body, CP_0	5 J/gk
Heat Capacity of Water,, CPE	4.18 J/gk
Bulk Density of the Material, ρ_0	1 g/cm^3
LATENT HEAT GENERATION SOURCE, L	2200 W/M^3
Biot Number, NB	0.5
Transformed Biot Number, NBT	1000
Velocity of Light, C	3x10^{10} cm/sec
Loss Tang δ of Water	0.1
Loss Tang δ of Dried Sand	0.013
Relative Dielectric Constant Of Dried Sand, ε_{r1}	2.4
Relative Dielectric Constant Of Water, ε_r	40
Step Length in z Direction, HZ	0.5 cm

 ISSN 1516-7399

V. CONCLUSIONS

Hybrid drying is faster than conventional one, besides it gives products, which meet the user requirements. Standing wave phenomena has been occurred due to bilateral radiation. Microwave energy permits more and rapid migration of humidity from the heart to the surface of the product and therefore more water are obtained on the surface of the material.

REFERENCES

[1] M.A.Saber " Microwave drying of cylinderic Products " 37 th Microwave Power conference, Atlantic City, New Jersey, USA, July 24-26, 2002.

[2] Presi.A."Etude de l`amelioration du rendement des techniques de Sechage des materiaux epais par apport d`energie electromagnetique conception d`applicateur" These I.N.P, Toulouse, French 1998.

[3] J.Crank, "Numerical Solutions of Partial Differential Equations-Finite Difference Methods" 2nd edition, ch.5. Oxford, 1978.

[4] Bruce W.Arden "Numerical Algorithms: Origins and Applications", Addison Wesley Comp, 1970.

 ISSN 1516-7399