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Numerical analysis of heat-mass transport and pressure buildup of unsaturated porous medium in a rectangular waveguide subjected to a combined microwave and vacuum system

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ABSTRACT

This paper presents two-dimensional numerical analysis of heat-mass transport and pressure buildup inside an unsaturated porous packed bed which is filled in a rectangular waveguide and subjected to a combined microwave and vacuum system. A microwave system supplies a monochromatic wave in a fundamental TE_{10} mode. The unsaturated porous media is composed of glass beads, water and air. The finite difference time domain method is used to determine the electromagnetic field distribution in the rectangular waveguide by solving the transient Maxwell's equations. The finite difference method together with Newton–Rephson technique is employed to predict the heat, multiphase flow and pressure buildup. The influences of vacuum pressure and operating microwave frequency on temperature, microwave power absorbed, saturation and pressure buildup distribution, and movement of fluid inside the unsaturated porous media are investigated during microwave vacuum drying process.

1. Introduction

Microwave technology has been applied to many drying processes for several decades. In microwave drying, that heat is generated by directly transforming the electromagnetic energy into kinetic energy, thus heat is generated deep within the material to be dried. Some of the successful examples of microwave drying are in a ceramics process for drying and sintering, drying of paper, freeze drying and vulcanization of rubber. Furthermore, excellent reviews of microwave drying are presented by Mujumdar [1], Metaxas and Meridith [2] and Datta and Anantheswaran [3]. In vacuum drying processes can offer reduced drying times and higher end-product quality in comparison with a conventional drying [4–5]. Indeed, operating at low pressure reduces the boiling point of water, and provides low temperature to treat product throughout drying process. Vacuum drying is well known in the metallurgical industries for processing of high purity alloys. It is apparent that microwaves can provide a substantial increase rate of heating in a vacuum environment compared with other methods. However it may be limited not only by the usual restraint of mass transfer but also by the onset breakdown electric filed. Fundamental to the operation of a vacuum drying system is the operating pressure to control the temperature of the product below a prescribed limit. Fig. 1 shows the boiling point temperature of water versus pressure range of 1–133 kPa (about 0.1–1000 torr). For vacuum drying, the pressure range of 1.33–26.6 kPa (about 10–200 torr) is more successful application to dry heat sensitive materials such as pharmaceutical products and other chemicals. The critical breakdown electric field should be also carefully selected to avoid breakdown electric field responses causing the effect of breakdown in gas such air or water vapor [2].

Microwave vacuum drying provides higher product qualities and an improved drying rate compared to conventional drying processing by experimentally investigated of many researchers. Some of the successful researches of experimental microwave vacuum drying are as followings. Drouzas and Schubert [6] investigated experimentally microwave vacuum dying of banana slices that dehydrated products of excellent quality as examined by taste, color, aroma, smell and rehydration tests compared to conventional drying. Drouzas et al. [7] used a laboratory microwave vacuum drier to investigate drying kinetics experiments with model fruit gel, simulating orange juice concentrate that drying rate constant of the thin-layer drying model is increased with increasing microwave power output and decreasing absolute pressure in vacuum drying. Péré and Rodie [8] presented experimental results obtained by microwave vacuum drying of a packing of initially water saturated glass beads and a packing of initially unsaturated pharmaceutical granules. Sunjka et al. [9] investigated two drying methods of cranberries such microwave-vacuum and

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Nomenclatures

C	velocity of light (m/s)
C_p	specific heat capacity (J/kg K)
D	binary mass diffusion (m^2/s)
D_m	effective molecular mass diffusion (m^2/s)
E	electromagnetic field intensity (V/m)
f	frequency of the microwave (Hz)
g	gravitational constant (m/s^2)
H_v	specific heat of evaporation (J/kg)
h_c	Heat transfer coefficient (W/m^2 K)
h_m	mass transfer coefficient (m/s)
J	Leverett functions
K	permeability (m^2)
M	molecular weight (kg/mol)
$\dot{n}$	phase change term (kg/m^3 s)
P	microwave power (W)
p	pressure (Pa)
p_{vs}	partial pressure of the saturation vapor (Pa)
Q	microwave power absorbed term (W/m^3)
R	universal gas constant (J/mol K)
S	water saturation
S_e	effective water saturation
S_{ir}	irreducible water saturation
T	temperature (°C)
t	time (s)
u, w	velocity (m/s)

Greek letters

α	attenuation constant
$\tan\delta$	loss tangent coefficient
δ_s	skin depth
ε	complex permittivity (F/m)
ε'	permittivity or dielectric constant
ε''	dielectric loss factor
ϕ	porosity
λ_{eff}	effective thermal conductivity (W/m K)
μ	magnetic permeability (H/m) or Dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	gas–liquid interfacial tension

Subscripts

0	free space
a	air
c	capillary
g	gas
l	liquid
p	particle
r	relative
v	water vapor
x, z	Cartesian coordinate

microwave-convective that microwave vacuum drying exhibited to enhance characteristics in almost all observed parameters (color, textural characteristics, organoleptic properties) and was more energy-efficient when compared to microwave-convective drying. Hu et al. [10] compared the characteristics of hot air and microwave vacuum combination drying using edamame as the raw material, it was found that combined hot air and microwave vacuum is enable to increase drying rate and enhance product quality.

In a theoretical analysis of heat and mass transfer in porous materials has been studied for several decades and it can be classified into three difference fundamentals as following details.

(1) The single variable model: one diffusion equation of moisture content is used for simple configuration.
(2) The two variables model: two dependent variables as temperature and moisture content are employed, and effect of pressure buildup can be neglected.
(3) The three variables model: three dependent variables as temperature, moisture content, and pressure buildup are used; this model provides better transport phenomena details than other models.

The single variable and two variables model are mostly applied to investigate for a conventional drying because they are not complicated to manipulate numerical scheme. However, a few studies used the three variables model are Datta and Anantheswaran [3], Perré and Turner [11], Rattanadecho [12], and Ni et al. [13].

A few of researchers have numerically studied heat and mass transport phenomena of porous material under microwave drying processing, and most previous works have not mentioned pressure buildup within porous material [14–19]. Some of previous researches [20–21] revealed pressure buildup by using the three variables model for microwave drying of an unsaturated porous media. However, the studies in case of numerically microwave vacuum drying of unsaturated porous material in a rectangular waveguide of a microwave system supplies a monochromatic wave in a fundamental mode (TE_{10} mode) with operating frequency of 2.45 GHz have not been investigated before. Therefore, this research studies the influence of vacuum pressure and operating microwave frequency to affect internal phenomena of unsaturated porous medium when apply microwave energy.

The objective of this study is carried out to predict temperature, microwave power absorbed and pressure buildup distribution, moisture profile, and movement of fluid inside the unsaturated porous media at vacuum and atmospheric pressures. Furthermore, the influence of material properties is investigated.

2. Experimental apparatus

Fig. 2 shows the experimental apparatus is used. The microwave system is a monochromatic wave of TE_{10} mode at operating frequency of 2.45 GHz. Microwave energy is generated by magnetron, and it is transmitted along z-direction of the rectangular waveguide with inside dimensions of 110 mm × 54.61 mm toward water load that is situated at the end of the waveguide. In addition,

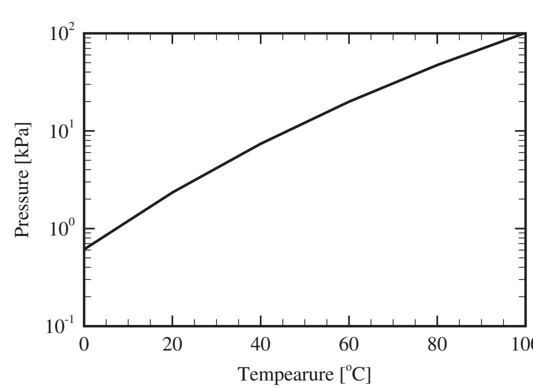

Fig. 1. Saturation vapor pressure of water as a function of temperature.