Heat and mass transfer modeling of vacuum cooling for porous food material

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Vacuum cooling is afast cooling method in food chemistry industrial processes. A lot of modeling methods and simulation technologies has been used to reveal the heat and mass transfer process. Based on the theory of heat and mass transfer, a coupled model for a vacuum cooling process of porous food materialis constructed. The model is implemented and solved using COMSOL software. The effects of food materialinitial temperature, vacuum chamber pressure, chamber temperature and relative humidity on the vacuum cooling process were examined. The results showed that food materialinitial temperature and chamber temperature have little effect on the vacuum cooling process. The chamber pressure affected the core and surface temperature of the porous food material. The relative humidity affected the surface temperature. The vacuum cooling process of the porous medium is anoutside controlled process.

Key words:vacuum cooling,porous food material, heat and mass transfer, COMSOL.

INTRODUCTION

Vacuum cooling, as a rapid cooling process,has huge ability of cooling porous food materials [1-5]. Its heat and mass transfer is a complicated process, which has been investigated by many researchers [6-17]. Jin et al. [6-8] developed and validated a moisture movement model for vacuum cooling of cooked meat. The vacuumcooling of cylindrically shapedcooked meat was carried out to find out the effects of the variations of temperature, moisture content and evaporationrate. Sun et al. [9-13] developed a series of models of simultaneous transient heat and mass transfer with inner heat and mass generation for analyzingthe performance of vacuum cooling of cooked meat. In addition, a mathematical model is developed to analyze the performance of a vacuum cooler [14]. Dostal et al.[15] gave a simple mathematical model of the vacuum cooling process which enables to predict the temperature evolution considering the equipment size, vacuum pump parameters and properties of the cooled liquid. He et al. [16] developed a model for predicting the temporal temperature and the mass of spherical solid food materials during vacuum cooling. It discusses the effects of product thermophysical properties, convection heat transfer coefficient, latent heat of evaporation, as well as vacuum environmental parameters that govern the heat and mass transfer of the product. The temporal trends of total system pressure, product temperature

such as surface temperature, core temperature, mass-average temperature, and mass of product were predicted.

The vacuum cooling has been used for many kinds of food material, for example, ham[17], chicken breast [18,19], beef [20-23], potatoes [24], cherries [25], pork[26,27], mussels[28], carrots [29], roses [30],purslane[31], lettuce[32], etc. [1-4]. Compared with experiment, the simulation shows an excellent ability in time and economy. However, little research was performed on the effect on food materialinitial temperature, and vacuum chamber pressure, by modeling and simulation.

In this paper, heat and mass transfer of porous food material in a vacuum cooling process is implemented by using a non-equilibrium method. The effects of initialtemperature, vacuum chamber pressure, chamber temperature, and relative humidity were studied.

MODEL DEVELOPMENT

Aphysical two-dimensional axissymmetry model that explains the vacuum cooling process is shown in Fig.1. The total length of the porous food material is 310mm. The diameter is 130mm. In order to simplify the calculation, half of the food material was used.

The porous food material consists of a continuous rigid solid phase and a continuous gas phase considered as an ideal gas. For a mathematical description of the transport phenomenon in a porous medium, we adopted a continuum approach, wherein macroscopic partial differential equations are achieved through the volume averaging of the

microscopic conservation laws. The value of any physical quantity at a point in space is given by its average value on the averaging volume centered at this point.
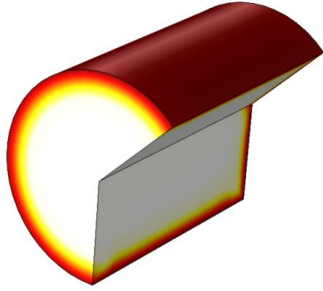

Fig.1. 2D Axissymmetry model of porous food material

The moisture movement of the inner porous medium is vapor movement; that is, the liquid H_2O could become vapor, and the vapor is moved by the pressure gradient. The heat and mass transfer theory could be found elsewhere [6-17].

The compressibility effects of the solid phase are negligible, and the phase is homogeneous:

$$\bar{\rho}_m = cste \tag{1}$$

The gaseous phase is considered an anideal gas. This phase ensures that

$$\bar{\rho}_v = \frac{m_v \bar{P}}{R\bar{T}} \tag{2}$$

Mass conservation equations are written for each component in each phase. For arigid solid phase, the following is given:

For vapor,

$$\varphi \frac{\partial(\bar{\rho}_v)}{\partial t} + \nabla \cdot (\bar{\rho}_v \bar{V}_v) = \dot{I} \tag{3}$$

Where the gas velocity is given by

$$\bar{V}_v = -\frac{k_v}{\mu_v} \cdot \nabla \bar{P} \tag{4}$$

$$k_v = \frac{d^2}{32}$$

By considering the hypothesis of the local thermal equilibrium, the energy conservation is reduced to a unique equation:

$$\rho_m c \frac{\partial \bar{T}}{\partial t} - \nabla(k \cdot \nabla \bar{T}) = -\lambda \cdot \dot{I} \tag{5}$$

BOUNDARY AND INITIAL CONDITIONS

B.C. for Eq. (10) on the symmetric surface,

$$\frac{\partial \bar{P}}{\partial n} = 0 \tag{6}$$

B.C. for Eq. (10) on the outer surface,

$$P = \bar{P}_{vc} \tag{7}$$

B.C. for Eq. (5) on the symmetric surface,

$$\frac{\partial \bar{T}}{\partial n} = 0 \tag{8}$$

B.C. for Eq. (5) on the outer surface,

$$-k \frac{\partial T}{\partial n} = h_r (T_s - T_{vc}) - \lambda \cdot \dot{m}_s \tag{9}$$

$$hr = \sigma\varepsilon(T_s^2 + T_{vc}^2)(T_s + T_{vc}) \tag{10}$$

The initial pressure of vapor,
I.C. for Eq. (3):

$$\bar{P} = P_{sat,0} \tag{11}$$

The initial temperature of porous food material,
I.C. for Eq. (5):

$$\bar{T} = T_0 \tag{12}$$

PHASE CHANGE

The evaporation rate is a complex function of the drying process in the porous medium. The phase change can be formulated in two ways, equilibrium and non-equilibrium. Evaporation of liquid H_2O was implemented using an equilibrium formulation where liquid H_2O in the solid matrix is assumed to be in equilibrium with water-vapor in the surrounding air. However, recent studies have shown that evaporation is not instantaneous and non-equilibrium exists during rapid evaporation between water-vapor in gas phase and liquid H_2O in solid phase. Furthermore, the equations resulting from an equilibrium formulation cannot be implemented in any direct manner in the framework of most commercial software. The more general expression of non-equilibrium evaporation rate used for modeling of phase change in porous media that is consistent with studies on pure H_2O just mentioned, is given by [6-17]:

$$\dot{I} = 4\frac{\varphi}{d} h_m (a_W P_{sat} - P) \tag{13}$$

$$\dot{m}_s = h_m (a_W P_{sat} - RH \cdot P_{vc}) \tag{14}$$

Here I is a parameter signifying the rate constant of evaporation. The non-equilibrium formulation, given by equation (13), allows precisely this, i.e., it can express the evaporation rate explicitly and therefore would be preferred in a commercial software. Therefore itis used in our model.

NUMERICAL SOLUTION

COMSOL Multiphysics 3.5a was used to solve the set of equations. COMSOL is an advanced software used for modeling and simulating any physical process described by partial derivative equations. The set of equations introduced above was solved using the relative initial and boundary conditions of each. COMSOL offers three possibilities for writing the equations: (1) using a template (Fick Law, Fourier Law), (2) using the

coefficient form (for mildly nonlinear problems), and (3) using the general form (for most nonlinear problems). Differential equations in the coefficient form were written using an unsymmetrical-pattern multifrontal method. We used a direct solver for sparse matrices (UMFPACK), which involves significantly more complicated algorithms than solvers used for dense matrices. The main complication is the need to efficiently handle the fill-in in factors L and U.

A two-dimensional (2D) axis symmetry grid was used to solve the equations using COMSOL Multiphysics 3.5a. The mesh consists of 4224 elements (2D), and time stepping is free taken by the solver. Several grid sensitivity tests were conducted to determine the sufficiency of the mesh scheme and to ensure that the results are grid-independent. A backward differentiation formula was used to solve time-dependent variables. Relative tolerance was set to 1×10^{-4}, whereas absolute tolerance was set to 1×10^{-6}. The simulations were performed using a Tongfang PC with Intel Core 2 Duo processor with 3.0 GHz processing speed, and 4096 MB of RAM running Windows 7.

INPUT PARAMETERS

The detailed parametersare given in Table 1.

Table1. Parameters used in the simulation process

Parameter	Value	Source	Unit
ρ_v	Ideal gas		kg m^{-3}
ρ_m	1072	[13]	kg m^{-3}
c	3439	[13]	J kg^{-1} K^{-1}
k	0.59	[13]	W m^{-1} K^{-1}
μ_v	1.8×10^{-5}		Pa s
h_m	8.4×10^{-7}	[13]	KgPa^{-2}m^{-2} s^{-1}
λ	2791.2×10^3	[8]	J kg^{-1}
φ	6	[13]	%
T_0	74+273.15	[13]	K
T_{vc}	25+273.15	[13]	K
d	2.5×10^{-3}	[13]	m

RESULTS AND DISCUSSION

Fig. 2 presents the simulation result using the parameters of Table 1. It is compared with the result from Ref [14]. The temperature of the surface agrees well, while the core temperature does not agreewell. The difference is because the liquid H$_2$O activity a_w has changed, but our parameter $a_w = 0.66$ is used and *RH* is 0.53 at the end. The temperature is lowered when the pressure is lowered until core temperature is higher than 0 ℃ and surface temperature is lower than 0 ℃. According to

Eq.(14), surface liquid H$_2$O could be evaporated by the vapor pressure difference[14].

Fig.3. shows the total, core and surface weight loss.The results show that the inner weight loss is the major part of the temperature cooling function. The pressure difference is given by the vacuum system between the vacuum chamber and the inner porous medium that enhances the mass transfer and heat transfer. It is the vacuum cooling method superiority.

Fig.4. shows the initial temperature effect on the vacuum cooling process. The initialtemperature is 74, 84 and 94ºC, respectively. The vacuum cooling temperature is almost the same. It should be concluded that the initial temperature has little effect on the vacuum cooling process if the vacuum is high enough. That is why the vacuum system including the condenser is sufficient, the pressure, especially the vapor pressure in the vacuum chamber is not affected by the vacuum cooling process. In our simulation process, the chamber pressure is given by Eq.(7) that is not changed in all simulations. The vacuum cooling process is controlled by the vacuum chamber conditions, i.e.,the outside conditions controlled the porous food material.
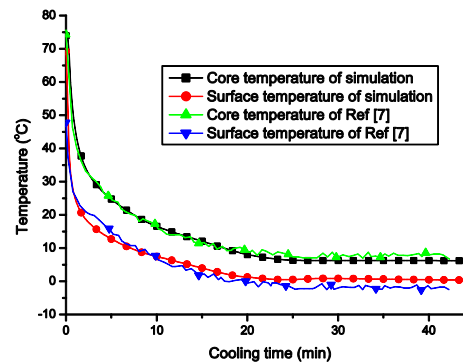

Fig.2. The simulation and experimentalresults compared with Ref [7] for porous food material.

Fig.5. presents the effect of vacuum chamber pressure on the vacuum cooling process. The end pressure is 650, 725 and 825 Pa, respectively. The vacuum pressure before the end pressures is the same. The temperature of core and surface is the same at different simulations until the end pressure is achieved. The temperature of core and surface has little effect at the end pressure stage. The higher the end pressure, the higher is the temperature including the core and surface. It shows that the vacuum cooling process is affected by the end pressure before the end pressure stage. So the vacuum cooling process is controlled by outside conditions of porous food material.
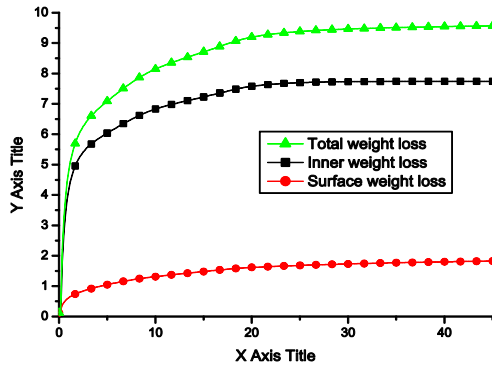
Fig.3. The total weight loss, inner weight loss and surface weight loss in the vacuum cooling process of porous food material.
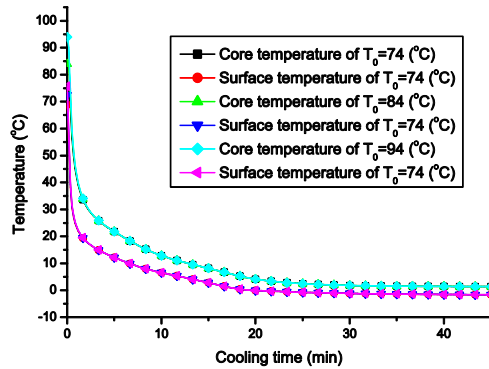

Fig.4. The initial temperature efffect on the vacuum cooling process of porous food material.

Fig.6. illustrates the effect of vacuum chamber temperature on the vacuum cooling process. The chamber temperature T_{vc} is 35, 25 and 15 ℃, respectively. The effect of vacuum chamber temperature could be shown by Eq.(9). But in fact the chamber temperature does not affect the vacuum cooling process. It is controlled by $\lambda \cdot \dot{m}_s$ in Eq.(9), evaporating rate and evaporating latent heat.

Fig.7. shows the effect of relative humidity on the vacuum cooling process. The relative humidity *RH* is 0.75, 0.65 and 0.55, respectively. The inner temperature is not affected by the relative humidity *RH* that agreeswith Eq.(13). But the surface temperature is affected by therelative humidity *RH* that agrees with Eq.(14).
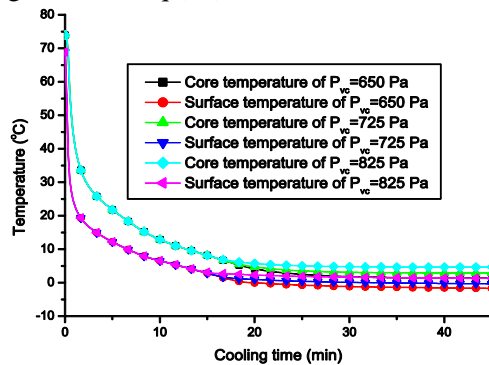

Fig.5. The vacuum chamber pressure effect on the vacuum cooling process of porous food material.
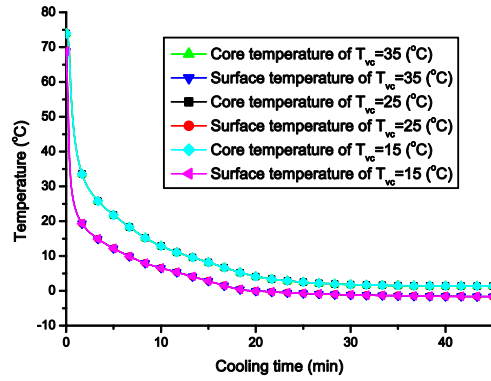

Fig.6. The vacuum chamber temperature effect on the vacuum cooling process of porous food material.
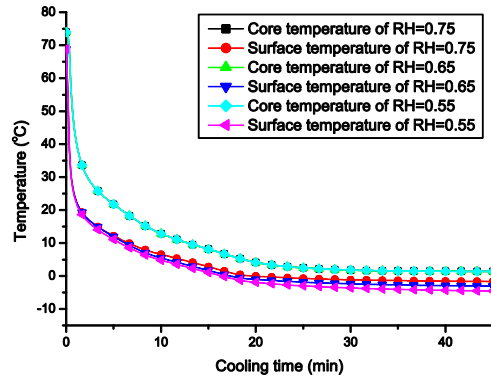

Fig.7. The relative humidity effect on the vacuum cooling process of porous food material

CONCLUSION

A coupled model of porous food material vacuum cooling based on the theory of heat and mass transfer was implemented in this paper. The effects ofinitialtemperature, vacuum chamber pressure, chamber temperature and relative humidity on the vacuum cooling process were examined. The temperature characteristics of the porous food material core and surface wereobtained. The results show that initial temperature and chamber temperature have little effect on the vacuum cooling process, but the chamber pressure affected the core and surface temperature of the porous food material. The relative humidity affected the surface temperature. The results showed that the vacuum cooling process of the porous medium is an outside controlled process. The results are meaningful for vacuum cooling of porous food material.

NOMENCLATURE

a_w - liquid H_2O activity

c - specific heat (J kg^{-1} K^{-1})

d - -diameter of pores (m)

h_m - evaporation rate (kg Pa^{-1} m^{-1} s^{-1})

h_r - heat transfer coefficient (W m^{-2} K^{-1})

i - liquid H_2O phase rate (kg s^{-1}m^{-3})

k - thermal conductivity (W m^{-1} K^{-1})

k_v - permeability (m^2)

m_v - vapor molecular mass (g mol^{-1})

m_s - mass transfer coefficient (kg m^{-2} Pa^{-1} s^{-1})

n - outer unit normal to the product

$\bar{P}$ - pressure (Pa)

P_{sat} - vaporisation pressure (Pa)

$P_{sat,0}$ - initial vapor saturation pressure (Pa)

R - universalgas constant (J kmol^{-1}K^{-1})

RH - relative humidity

t - time (s)

$\bar{T}$ - food materialtemperature (K)

T_0 - initial temperature (K)

T_{vc} - vacuum chamber temperature (K)

T_s - surface temperature of food material (K)

$\bar{V}_v$ - vapor velocity (m s^{-1})

φ - porosity (%)

μ_v - viscosity (kg m^{-1} s^{-1})

λ - latent heat of evaporation (J kg^{-1})

$\bar{\rho}_m$ - food materialdensity (kg m^{-3})

$\bar{\rho}_v$ - vapor density(kg m^{-3})

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МОДЕЛИРАНЕ НА ТОПЛО - И МАСОПРЕНАСЯНЕТО ПРИ ВАКУУМНО ОХЛАЖДАНЕ НА ПОРЬОЗНИ МАТЕРИАЛИ

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(Резюме)

Вакуумното охлаждане е най-бързия метод за охлаждане на хранителни материали и при процесите в химическата промишленост. Множество математични методи на моделиране и симулиране са използвани за изучаване на топло и масообменните процеси. В настоящата работа на основание теорията на топло и масопренасянето е създаден модел, описващ вакуумното охлаждане на порьозни хранителни материали. Моделът е приложени решаван със софтуер COMSOL. Изследвани савлияннията на началната температура на материала, налягането, температурите на вакуумната камера, на камерата на сушилнята и на относителната влажност. Резултатите показват, че началната температура на материала и температурата на сушилната камера имат слаб ефект върху процеса на вакуумно охлаждане. Налягането в камерата влияе значително върху температурата във вътрешността и по повърхността на порьозния материал. Относителната влажност влияе на повърхностната температура. Вакуумното охлаждане на порьозни среди се контролира от процесите извън материала.