Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2013, 5(12):1429-1439

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Intrinsic permeability effect on vacuum drying process of porous medium

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ABSTRACT

Drying is the key process in chemical, food and other related industry process. Corns, fruits, and vegetables are usually used as porous medium in drying process. The parameters of modeling are very important because the simulation results are decided by them. The intrinsic permeability is the property of the porous medium that is should be gotten by accurate method. Based on the theory of heat and mass transfer, a coupled model for the porous medium vacuum drying process is constructed. The model is implemented and solved using COMSOL software. The parameter sensitivity analyses of intrinsic permeability were then examined. The temperature, pressure and moisture characteristics were shown.

Key words: heat and mass transfer; porous medium; sensitivity analyses; vacuum drying; COMSOL

INTRODUCTION

Drying is the key process in chemical, food and other related industry process. The vacuum drying has been used to corn in china [1–3]. However, the corn vacuum drying theory remains unclear. Hypothesized that corn is a porous medium, the vacuum drying of corn is a complicated heat and mass transfer process that has been the subject of intensive research [4–7]. All vacuum drying models have to address the water phase change during numerical solving. In one method, the vapor pressure is equal to its equilibrium value [8–11]. Another method is non-equilibrium method [12–16]. As the porous medium, the heat and mass transfer in vacuum drying process has been studied with non-equilibrium method by us [17, 18]. In fact, the parameters of modeling are very important because the simulation results are decided by them. The intrinsic permeability is the property of the porous medium that is should be gotten by accurate experiment. But most of the modeling is gotten by the reference [8-11]. It must be clarify the impact of model parameters on the model predictions [19].

In this paper, heat and mass transfer of porous medium in the vacuum drying process is implemented by using a non-equilibrium method. The parameter sensitivity analyses of intrinsic permeability were then examined.

EXPERIMENTAL SECTION

Problem descrisption

A physical one-dimensional (1D) model that explains the drying process is shown in Fig. 1. The heat and mass transfer is considered only in the *y* direction. The heat transfer is through the bottom surface of medium and mass transfer is through the top surface of medium. The total height of the porous medium is 1 cm.

Assumption

The porous medium consists of a continuous rigid solid phase, an incompressible liquid phase (free water), and a continuous gas phase that is assumed to be a perfect mixture of vapor and dry air, considered as ideal gases. For a mathematical description of the transport phenomenon in a porous medium, we adopt 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.

The moisture movement of the inner porous medium is liquid water and vapor movement; that is, the liquid water could become vapor, and the vapor and liquid water are moved by the pressure gradient. The heat and mass transfer theory could be found in everywhere [8].

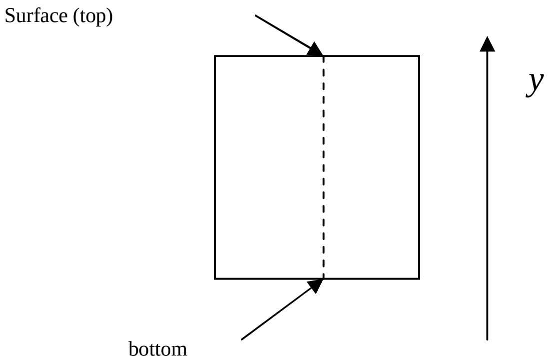

Figure 1. 1D model of porous medium with cortex

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

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

The solid phase is rigid and homogeneous:

$$\bar{\rho}_s = cste \tag{2}$$

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

$$\bar{\rho}_a = \frac{m_a P_a}{R\bar{T}} \tag{3}$$

$$\bar{\rho}_v = \frac{m_v \bar{P}_v}{R\bar{T}} \tag{4}$$

$$\bar{P}_g = \bar{P}_a + \bar{P}_v \tag{5}$$

$$\bar{\rho}_g = \bar{\rho}_a + \bar{\rho}_v \tag{6}$$

The assumption of the local thermal equilibrium between the solid, gas, and liquid phases involves

$$\bar{T}_s = \bar{T}_g = \bar{T}_w = \bar{T} \tag{7}$$

Governing equations
Mass balance equation

Mass conservation equations are written for each component in each phase. Given that the solid phase is rigid, the following is given:

$$\frac{\partial \bar{\rho}_s}{\partial t} = 0 \tag{8}$$

The averaged mass conservation of the dry air yields

$$\frac{\partial(\varepsilon \cdot S_g \bar{\rho}_a)}{\partial t} + \nabla \cdot (\bar{\rho}_a \bar{V}_a) = 0 \tag{9}$$

For vapor,

$$\frac{\partial(\varepsilon \cdot S_g \bar{\rho}_v)}{\partial t} + \nabla \cdot (\bar{\rho}_v \bar{V}_v) = \dot{I} \tag{10}$$

For free water,

$$\frac{\partial(\varepsilon \cdot S_w \bar{\rho}_w)}{\partial t} + \nabla \cdot (\bar{\rho}_w \bar{V}_w) = -\dot{I} \tag{11}$$

For water, the general equation of mass conservation is obtained from the sum of the conservation equations of vapor (v) and free water (l). The general equation is written as follows:

$$\frac{\partial W}{\partial t} + \nabla \cdot \left\{ \frac{1}{\bar{\rho}_s} (\bar{\rho}_w \bar{V}_w + \bar{\rho}_v \bar{V}_v) \right\} = 0 \tag{12}$$

$$W = \frac{\varepsilon \cdot S_w \bar{\rho}_w + \varepsilon \cdot S_g \bar{\rho}_v}{(1-\varepsilon)\bar{\rho}_s} \tag{13}$$

For the Darcy flow of vapor,

$$\bar{\rho}_v \bar{V}_v = \bar{\rho}_v \bar{V}_g - \bar{\rho}_g D_{eff} \cdot \nabla \bar{\varpi} \tag{14}$$

For the Darcy flow of air,

$$\bar{\rho}_a \bar{V}_a = \bar{\rho}_a \bar{V}_g + \bar{\rho}_g D_{eff} \cdot \nabla \bar{\varpi} \tag{15}$$

The vapor fraction in mixed gas is given by

$$\bar{\varpi} = \frac{\rho_v}{\rho_g} \tag{16}$$

The saturation of free water and gas is

$$S_g + S_w = 1 \tag{17}$$

Momentum balance equation
Where the gas and free water velocity is given by

$$\overline{V}_g = -\frac{k_{in,g} \cdot k_{r,g}}{\mu_g} \cdot (\nabla \overline{P}_g - \rho_g \vec{g}) \tag{18}$$

$$\overline{V}_w = -\frac{k_{in,w} \cdot k_{r,w}}{\mu_w} \cdot (\nabla \overline{P}_w - \rho_w \vec{g}) \tag{19}$$

The pressure moving the free water is given by

$$\overline{P}_w = \overline{P}_g - \overline{P_c} \tag{20}$$

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

$$\frac{\partial \overline{\rho} \overline{T}}{\partial t} + \nabla \cdot (\overline{\rho}_a \overline{V}_a C_a \overline{T}_a + \overline{\rho}_v \overline{V}_v C_v \overline{T}_v + \overline{\rho}_w \overline{V}_w C_w \overline{T}_w) = \nabla (k_e \cdot \nabla \overline{T}) - \lambda \cdot \dot{I} \tag{21}$$

$$k_e = (1-\varepsilon)k_s + \varepsilon(S_w + S_g(\omega k_v + (1-\omega)k_a)) \tag{22}$$

$$\overline{\rho}\overline{T} = \overline{\rho}_s \overline{T}_s + \varepsilon \cdot S_g \overline{\rho}_a \overline{T}_a + \varepsilon \cdot S_g \overline{\rho}_v \overline{T}_v + \varepsilon \cdot S_w \overline{\rho}_w \overline{T}_w \tag{23}$$

Boundary and Initial Conditions
The model was run for different parameters. It was heated from the bottom, and the air and vapor was escaped from the top surface. The other boundaries of the model are insulated and impermeable. The boundary conditions are then given as:

B.C. for Eq. (9):

$$\rho_{a,top} = \rho_{a,dryer} \tag{24}$$

B.C. for Eq. (10) [15]:

$$n_{v,top} = -h_m \varepsilon S_g (\rho_{v,top} - \rho_{v,dryer}) \tag{25}$$

B.C. for Eq. (15):

$$n_{w,top} = -h_m \varepsilon S_w (\rho_{v,top} - \rho_{v,dryer}) \tag{27}$$

B.C. for Eq. (21) in bottom:

$$T_{bottom} = T_h \tag{29}$$

B.C. for Eq. (21) in top:

$$q_{top} = h(T_{ext} - \overline{T}) + (\lambda + C_w \overline{T}) n_{w,top} + C_v \overline{T} n_{v,top} \tag{30}$$

The initial moisture of the porous medium is represented by the liquid water saturation. And other initial condition is as follows.

I.C. for Eq. (9):

$$\rho_a = \rho_{a,0} = \frac{P_{amb,0} M_a}{R T_0} \tag{31}$$

I.C. for Eq. (10):

$$\rho_v = \rho_{v,0} = \frac{P_{sat,0} M_v}{R T_0} \tag{32}$$

I.C. for Eq. (11):

$$S_w = S_{w,0} \tag{33}$$

I.C. for Eq. (21) :

$$\bar{T} = T_0 \tag{34}$$

The detail value of boundary and initial condition is show in Table 1.

Table 1. Boundary and initial condition

Parameter	Symbol	Value 1	Unit	Source
Initial temperature	T_0	273+25	K	
Initial air pressure	$P_{atm,0}$	101325	Pa	
Initial saturation	$S_{w,0}$	0.3		
Vapor pressure of dryer	$P_{v,dry}$	2720	Pa	
Air pressure of dryer	$P_{a,dry}$	$P_{a,dry} = \begin{cases} (101325 - 1700t - 2720) & t < 58s \\ 5 & t >= 58s \end{cases}$	Pa	
Temperature of dryer	T_{ext}	273+28	K	

Numerical solution

A two-dimensional (2D) grid was used to solve the equations using COMSOL Multiphysics 3.5a. Given the symmetry condition setting at the left and the right sides, the 2D is applied to the 1D model shown in Fig. 1. The mesh consists of 2 × 100 elements (2D), and time stepping is 0.1 (0 s to 10 s of solution), 1 (10 s to 100 s of solution), 10 (100 s to 10000 s of solution), 20 (10000 s to 20000 s of solution), 50 (20000 s to 20000 s of solution). Several grid sensitivity tests were conducted to determine the sufficiency of the mesh scheme and to ensure that the results are grid-independent. The maximum element size was established as 1e^{-4}. A backward differentiation formula was used to solve time-dependent variables. Relative tolerance was set to 1e^{-6}, whereas absolute tolerance was set to 1e^{-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 Parameter

The parameter is listed in Table 2. The most parameter is gotten from the reference. The Intrinsic permeability is input for four groups in order to study the sensitivity.

Table 2. Parameters used in the simulation process

Parameter	Symbol	Value 1	Unit	Source
Density			kg m^{-3}	
Water	ρ_l	998	kg m^{-3}	[12]
Vapor	ρ_v	Ideal gas	kg m^{-3}	
Air	ρ_a	Ideal gas	kg m^{-3}	
Solid	ρ_s	476	kg m^{-3}	[8]
Specific heat capacity				
Water	C_w	4187	J kg^{-1} K^{-1}	[12]
Vapor	C_v	1840	J kg^{-1} K^{-1}	[12]
Air	C_a	1000	J kg^{-1} K^{-1}	[12]
Solid	C_s	1400	J kg^{-1} K^{-1}	[8,12]
Thermal conductivity				
Water	k_w		W m^{-1} K^{-1}	[15]
Vapor	k_v	0.026	W m^{-1} K^{-1}	[15]
Air	k_a	0.026	W m^{-1} K^{-1}	[15]
Solid	k_s	0.21	W m^{-1} K^{-1}	
Intrinsic permeability				
Water	$k_{in,w}$	4×10^{-13}, 4×10^{-14}, 4×10^{-15}, 4×10^{-16}	m^2	
Vapor and air	$k_{in,g}$	4×10^{-13}, 2×10^{-14}, 4×10^{-15}, 4×10^{-16}	m^2	
Relative permeability				
Water	$k_{r,l}$			[11]
Vapor and air	$k_{r,g}$			[11]
Viscosity				
Water	μ_l	0.988×10^{-3}	Pa s	[15]
Vapor and air	μ_g	1.8×10^{-5}	Pa s	[15]
Heat transfer coefficient	h	2.5	W m^{-2} K^{-1}	[11]
Mass transfer coefficient	h_m	0.2	m s^{-1}	[15]
Latent heat of vaporization	λ	2.26×10^{6}	J kg^{-1}	[15]
Porosity	ε	0.615	m^2	[8]
Effective diffusivity of gas	D_{eff}		m^2 s^{-1}	[8]
Capillarity Pressure	P_c		Pa	[8]
Critical Saturation of free water	S_r	0.08		[14]
Bound water diffusivity	D_b		m^2 s^{-1}	[8]
Molar mass of air	M_a	29×10^{-3}		[12]
Molar mass of air	M_v	18×10^{-3}		[12]

RESULTS AND DISCUSSION

The moisture curve of different intrinsic permeability is shown in Figure 1.The intrinsic permeability $k_{in} = 4\times10^{-13}$ and $k_{in} = 4\times10^{-14}$ m^2 is quickly gotten the drying end time. It just is taken less than 3.5 hours and 7 hours respectively. When the $k_{in} = 4\times10^{-15}$ m^2, the drying time is too long. It is taken more than 28 hours. But when the $k_{in} = 4\times10^{-15}$ m^2, the drying is not gotten the end until more than 56 hours that just gotten the 0.5 d. b.. The effect of intrinsic permeability on moisture is so obviously.

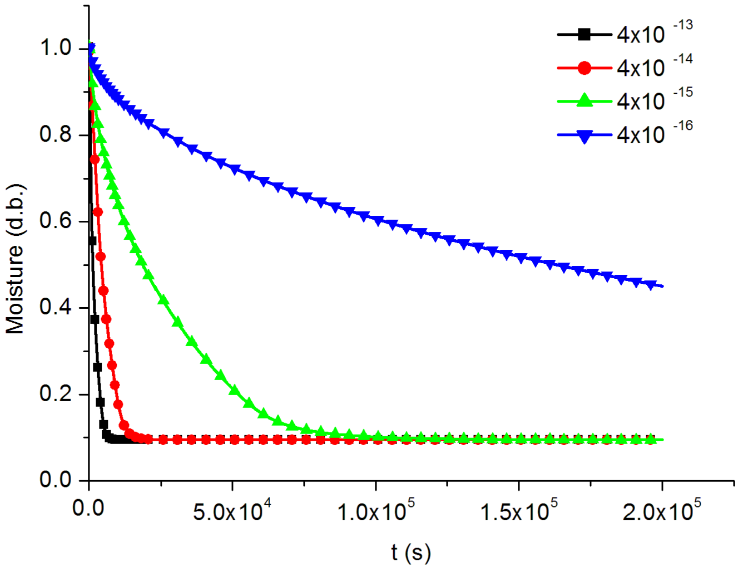

Figure 2. Moisture curve (d. b.) of different intrinsic permeability

The temperature curve of different intrinsic permeability at different height (5mm, 7.5mm and 10 mm) was shown in Figure 3. Figure 4, Figure 5 and Figure 6. When the $k_{in} = 4\times10^{-13}$ m^2, the temperature is lift up and maintain some time, and then slowly down. At last, the temperature is slowly lift up and gotten the end temperature. But when $k_{in} = 4\times10^{-14}$ m^2, the temperature is just lift up and maintain long time, and then lift up until gotten the end temperate. When the $k_{in} = 4\times10^{-15}$ m^2, and $k_{in} = 4\times10^{-16}$ m^2, the temperature is just lift up until gotten the end time.

The difference is because the mass transfer is decided by the intrinsic permeability k_{in}. It also the energy transfer is decided by intrinsic permeability k_{in}.

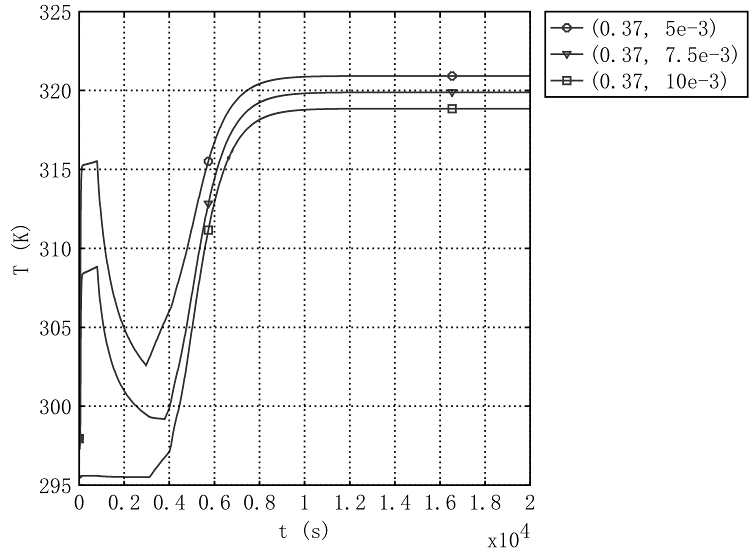

Figure 3.Temperature curve of different position with k_{in} = 4×10^{-13} (height of 5mm, 7.5 mm and 10mm)

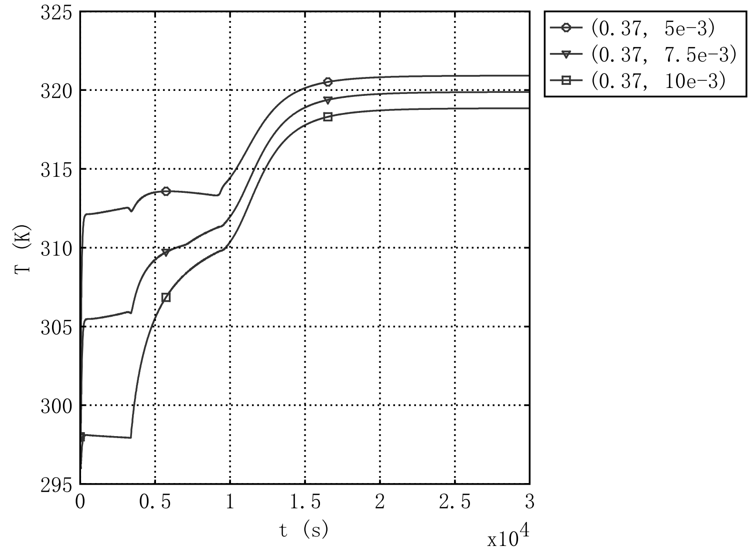

Figure 4.Temperature curve of different position with k_{in} = 4×10^{-14} (height of 5mm, 7.5 mm and 10mm)

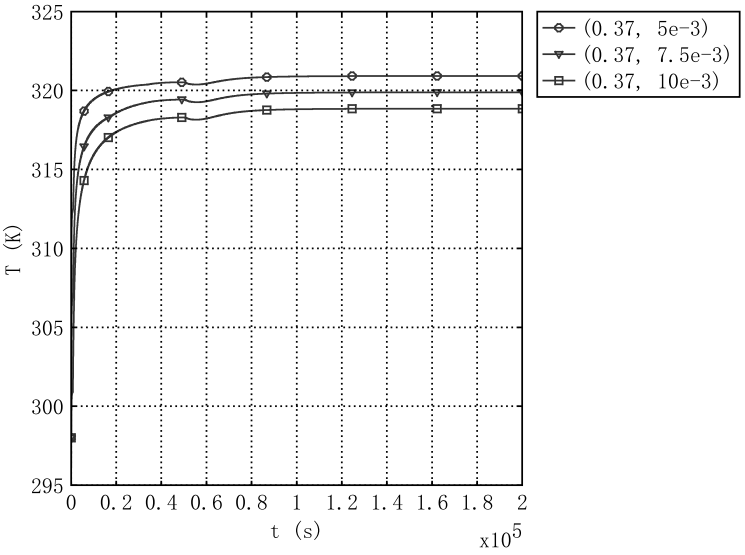

Figure 5.Temperature curve of different position with k_{in} = 4×10^{-15} (height of 5mm, 7.5 mm and 10mm)

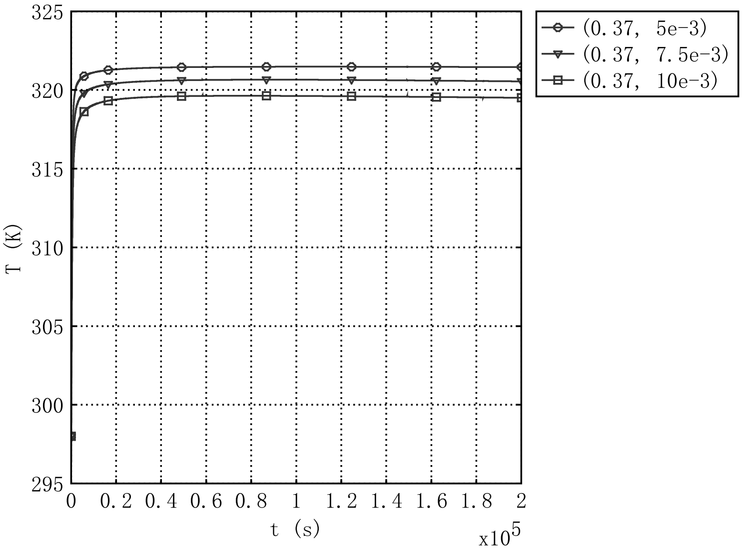

Figure 6.Temperature curve of different position with k_{in} = 4×10^{-16} (height of 5mm, 7.5 mm and 10mm)

In Figure 3, Mass and heat transfer is higher inner porous medium from the bottom to up when bigger k_{in} at drying startup. Then the temperature is near to bottom temperature. But because the mass transfer and heat transfer is also higher from porous medium to outside. When the heat transfer from bottom is less than the heat transfer to top surface, the temperature is then slowly down. At last, the heat transfer from bottom is more than the heat transfer to top surface, the temperature is slowly increased.

In figure 4 and figure 5, heat transfer is higher the heat transfer from bottom is more than the heat transfer to top surface, the temperature is slowly increased until equilibrium.

CONCLUSION

A coupled model of porous medium vacuum drying with cortex effect based on the theory of heat and mass transfer was implemented in this paper. The parameter sensitivity analyses of intrinsic permeability were then examined. The moisture and temperature characteristic is gotten. The results are shown that the intrinsic permeability has obviously effect on drying process. It would be affect the mass and heat transfer, and then the temperature curve is shown obviously different. The results has some meaningful for vacuum drying of food and chemical material for heat sensitivity.

Nomenclature

B	*diagonal tensor*
D	*diffusivity (m^2s^{-1})*
D_{eff}	*diffusion tensor (m^2s^{-1})*
g	*gravity vector ($m\ s^{-2}$)*
h	*intrinsic averaged enthalpy ($J\ kg^{-1}$)*
I	*water phase rate ($kg\ s^{-1}m^{-3}$)*
k	*intrinsic permeability (m^2)*
k_r	*relative permeability*
m	*mass (kg)*
n	*outer unit normal to the product*
P	*pressure (Pa)*
P_c	*capillary pressure (Pa)*
R	*universal Gas constant ($J\ kmol^{-1}K^{-1}$)*
S	*saturation*
t	*time (s)*
T	*temperature (K)*
W	*moisture content (in dry basis)*
Greek letters	
ΔH	*latent of phase change ($J\ kg^{-1}$)*
λ_{ef}	*effective thermal conductivity tensor ($W\ m^{-1}\ K^{-1}$)*
μ	*viscosity ($kg\ m^{-1}\ s^{-1}$)*
ρ	*density ($kg\ m^{-3}$)*
ω	*vapor fraction*
Subscripts	
a	*dry air*
g	*gas*
w	*water*
s	*solid*
v	*vapor*
sat	*vapor saturation*
in	*intrinsic*
r	*relative*
Mathematical operators	
Δ	*gradient operator*
$\nabla \cdot$	*divergence operator*

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant No. 31000665, No. 51176027, No. 31371873).

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