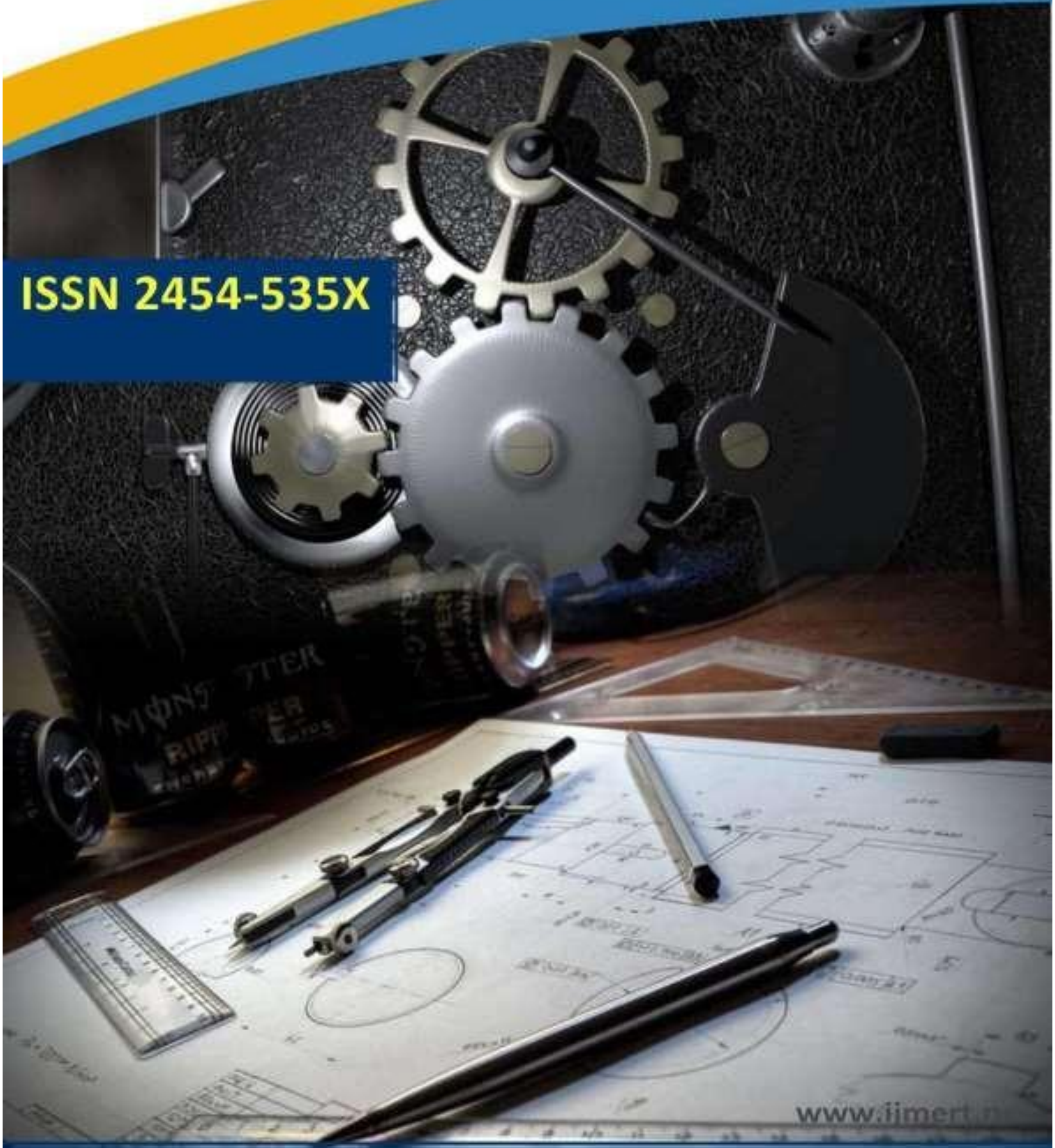
International Journal of
Mechanical Engineering Research and Technology

ISSN 2454-535X



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Int. J. Mech. Eng. Res. & Tech 2017

International Journal of Mechanical Engineering Research and Technology

ISSN 2454 – 535X
www.ijmert.com
Vol. 2 Issue. 1, March 2014

Modeling of Wood Particle Drying by Superheated Steam

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ABSTRACT: In this study, an experimental investigation of the superheated steam drying behavior of individual wood particles at high temperatures (i.e. 120°C, 140°C, 160°C, and 180°C) is conducted utilizing a magnetic suspension balancing system. A coupled heat and mass transfer drying model is built to explain the experimental drying behavior. While other thermo-physical characteristics are assessed, an inverse analysis is used to calculate the moisture diffusivity in the wood particles. The moisture transport in the particles is described by two different forms of effective diffusivities: moisture-dependent effective diffusivity and temperature-dependent effective diffusivity. Utilizing the finite volume element approach, this mathematical model is built and resolved. The experimental findings serve as a standard for the numerical results using temperature-dependent effective diffusivity and moisture-dependent effective diffusivity. It suggests that

INTRODUCTION

Both daily living and industrial operations need wood, which is a significant material. Wood must be dried to a safe moisture content level for storage and production in order to maximize its durability and resistance to being damaged by fungi. Superheated steam drying (SSD) with/without microwave or ultrasound assistance has recently been shown in many applications to be more suited than hot air drying (HAD) procedures due to its primary benefits in energy savings and reduced carbon dioxide emission [1-7]. Comparing the SSD technique to HAD, experimental research have shown that the SSD technique can aid to raise the caliber of wood products [8–10].To describe the SSD, several theoretical investigations of heat and mass transmission inside porous media have been conducted.

MODEL DESCRIPTION

To develop the continuous model for SSD of single wood particles, several following assumptions are made.

(1)M_t eff where (kg dry solid/m^3) is the apparent density of the dry porous medium, X M_l

The drying product is preheated up to the boiling temperature prior to drying, the surface condensation andevaporation periods are not accounted for.

Although porous wood is anatomically complex and heterogeneous, the transport properties of solid and fluidphases are averaged in a representative elementary volume by mean of volume averaging technique.

Heat and mass conservation equations

Mass conservation of water is written as the change of water concentration in the medium is caused by waterdiffusion flow $\frac{0X}{\quad}$ D X 0

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$_0V$ ... M_s (kg water/kg dry solid) is the moisture content of the solid. M_l and M_s (kg) are the mass of water and solid, respectively. D_{eff} (m^2/s) is the effective diffusivity of moisture in the medium. To describe the reduction of magnitude of this moisture diffusivity when the moisture removes further, the moisture diffusivity is classically expressed by the Arrhenius equation

$$D_{eff} = D_0 \exp\left(-\frac{E_A}{RT}\right) \quad (2)$$

where D_0 is the maximal diffusion coefficient, E_A is the activation energy for diffusion (J/mol), T is the absolute temperature (K), R is the universal gas constant, 8.314 J/(mol·K) [16]. The Arrhenius equations is often referred astemperature-dependent effective diffusivity (TDED).

Recently, Khan et al. [16] reported that the moisture diffusivity can be described as a function of moisture content,the so-called temperature-dependent effective diffusivity (MDED), as

$$D_{eff} = D_{ref}\left(\frac{(1+X_0)\rho_l(1+X)+\rho_0 X}{(1+X)\rho_l(1+X_0)+\rho_0 X_0}\right)^2 \quad (3)$$

where D_{ref} (m^2/s) is the reference diffusivity.

By minimization of the sum of square of difference between numerical and experimental moisture content evolutions over time, the reference diffusivity D_{ref} and maximal diffusivity D_0 are determined by using an optimization procedure, i.e. *fminsearch* function in MATLAB software.

The energy conservation equation is written as the change of total energy due to the enthalpy flow of water diffusive flow and the conductive heat flow can be computed as

$$\frac{\partial}{\partial t}\left(\rho_0\left(h_s + h_l X\right)\right) - \nabla\cdot\left(\rho_0 h_l D_{eff}\nabla X\right) - \nabla\cdot\left(\lambda_{eff}\nabla T\right) = 0 \quad (4)$$

In Eq. 4, h_s and h_l (J/kg) denote the specific enthalpy of solid and liquid water, respectively. Assuming a constant value for the specific heat capacity, the specific enthalpy of the solid and of the liquid can respectivelybe calculated from temperature as

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h_s □ $c_{p,s}$ □T □ T_{ref} □ and h_l □ $c_{p,l}$ □T □ T_{ref} □(5)

with the reference temperature T_{ref}□ 0 °C. □ $_{eff}$denotes the effective thermal conductivity of the porous grain.

Initial and boundary conditions

A wet spherical wood particle of radius r_p is surrounded by superheated steam flowing at a constant temperature of T_b and pressure of p_b . Initially, this porous grain is at uniform temperature T_0 and moisture content X_0 (kg water/kg dry solid). For the mass and heat transfer at the interface between the porous sample and the externalbulk gas, the following boundary conditions are applied j_e □ n □ □ □ □$T_{g,b}$ □ T□ □ □ □ h_{evp} □ $c_{p,v}T$□ □ □ $_{,surf}$ □ □ $_{v,b}$ □(6)j_w □ n □ □ □ □ □ $_{v,surf}$ □ □ $_{v,b}$ □5) In Eqs. 5-6, n denotes the outward unit normal vector pointing out of sample surface,j_w andj_e are the water and energy fluxes transferred from the sample surface toward the bulk steam, respectively. The vapor density atthe particle surface is calculated from the particle surface temperature and the bulk steam pressure. The heat transfer coefficient is calculated by using the modified Ranz - Marshall correlation proposed in Hager et al. [17]

Nu □ 2 □ 0.616 $Re^{0.52}$ Pr^{3}(7)

whereNu □ □d_p ,□ $_v$$Re$ □ $v_b\,d_p$ □ $_v$and Pr □ $c_{p,v}$ □$_v$ □$_v$

are the dimensionless Nusselt, Reynolds and Prandtlnumbers, respectively. The thermo-physical properties of steam used in dimensionless number calculation are determinedat T_b and $p_{v,b}$. The mass transfer coefficient is obtained by using an empi rical correlation [18]

□d_p1

Sh □ 0.144 □ 0.579 $Re^{0.5}$ Sc(8)

where Sh □~~and~~ δ Sc □ _□$_v$are the Sherwood and Schmidt numbers, respectively. □$_v$is the self-diffusivityof vapor, at atmospheric pressure it can be empirically computed as [14 □ □ □ 1.057□ $10^{□4}$ □ 3.35□ $10^{□7}T$9)

SUPERHEATED STEAM DRYING EXPERIMENTS

The superheated steam drying experiments of the single wood particles are performed in an apparatus shown in Fig. 1. Beechwood particles (provided by Holz-Allerlei GmbH, Germany) are consistent in shape and neither drilled nor waxed. Before commencing a drying experiment, the wood particles are moistened by soaking in liquid water attemperature 20 °C for 16 hours. This has led to an average initial moisture content of about 0.752 ± 0.023 (kg water/kg dried solid). Other thermo-physical properties of wood material are measured directly in the frame of thiswork and has been published in our previous article where the detail measurement procedures are presented in detail. These parameters are summarized in Table 1.

This drying system is comprised of three main components: a micro-evaporator, a drying chamber and a magneticsuspension balance. The liquid water is pumped and injected into the micro-evaporator. In this evaporator, liquidevaporates, and the generated vapor is superheated. By using a controllable micro-pump and temperature controller, the mass flow rate and temperature of superheated steam can be adjusted. The superheated steam flows into drying chamber, interacts with wood particle and is released at the top of chamber. The mass evolution of particles is recorded by using a magnetic suspension balance (Rubotherm GmbH, Germany). The balance operates in a massrange up to 10 g with a measurement resolution of ± 1 µg. The sample mass measurements are recorded by the Rubotherm system control software (RSCS), whereas temperature and pressure of the drying chamber are loggedby using a data acquisition system (Omega, USA). The drying conditions and initial conditions used in drying experiments are listed in Table 2.

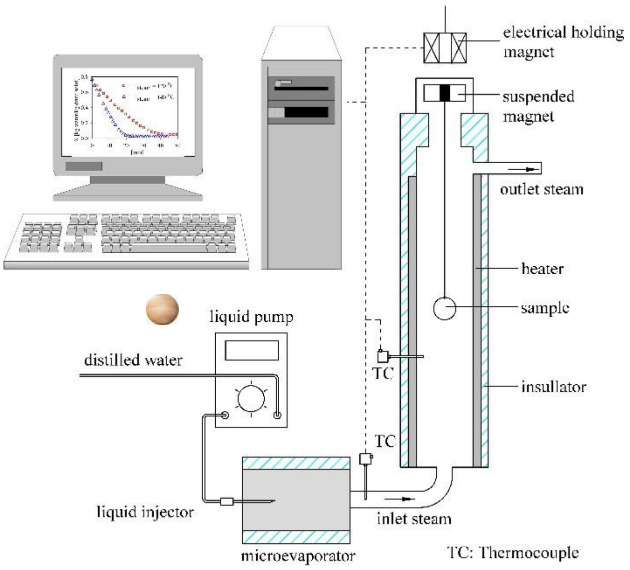


Figure 1. Schematic of the experimental setup used for drying of single wood particles.

Table 1. Thermo-physical properties of wood particles used in simulations.

Property	Value
Particle diameter d_p, mm	6.2 ± 0.3
Apparent solid density ρ_b, kg/m^3	743
Sorption isotherm $p_v/p_{v,sat}$, -	$a_w = \begin{cases} 1 & \text{with } X \geq X_{irr} \\ \frac{X}{X_{irr}}\left(2 - \frac{X}{X_{irr}}\right) & \text{with } X < X_{irr} \end{cases}$ X_{irr} = 0.256 kg water/kg dry solid
Thermal conductivity λ_{eff}, W/mK	$\lambda_{eff} = 0.138\left(\frac{X \rho_b}{\rho_l}\right)$

Specific heat capacity of dry solid cp,s, J/kgK	770 ± 3.6

Table 2. The drying conditions and initial conditions used in simulation.

Tb, °C	vb, m/s	$X0$, kg water/kg dry solid
120	0.015	0.758
140	0.015	0.765
160	0.015	0.729
180	0.015	0.756

RESULTS AND DISCUSSION

The wood particles before soaking, after soaking and after drying are presented in Fig. 2. It can be seen that the colorand shape of the particles are optically prevented, it favors the application of SSD for wood material.


Before wetting Wetted After drying

Figure 2. Wood particles before soaking, after soaking and after superheated steam drying.

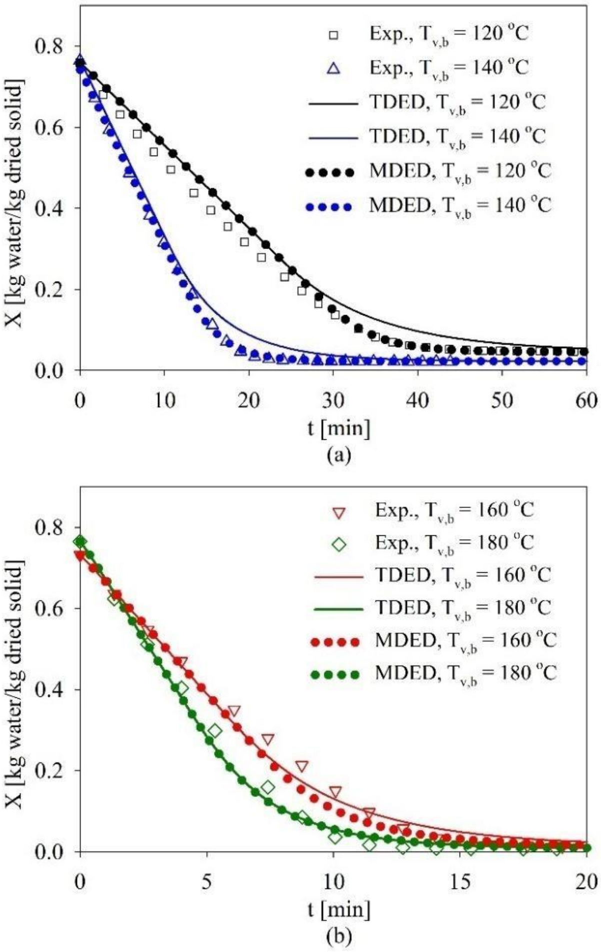
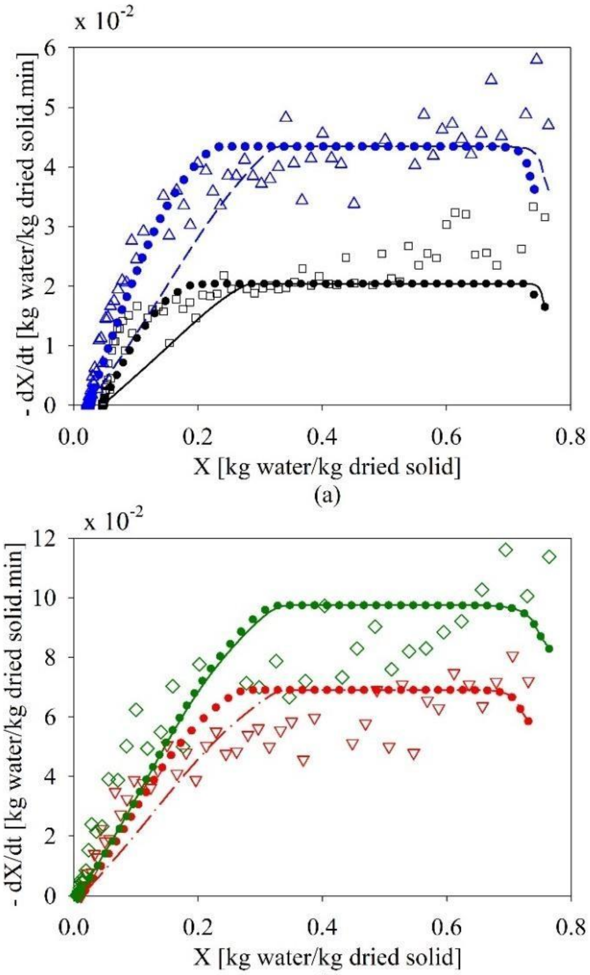


Figure 3. Experimental and numerical moisture content evolutions over time with different drying temperature:

(a) 120 °C and 140 °C, (b) 160 °C and 180 °C.

The experimental moisture content evolutions over time are presented in Fig. 3. Based on the experimental data, thediffusivity of medium is calculated by running the optimization procedure. For MDED model, a reference diffusivity of 7.13×10^{-9} m^2/s is obtained. For TDED model, the diffusivity varies in range from 1.67×10^{-9} m^2/s to 5.76×10^{-9} m^2/s when the drying temperature increases from 120 °C to 180 °C, respectively. Based on these data, maximal diffusivity of 1.72×10^{-5} m^2/s and activation energy for diffusion 30138.25 J/mol are obtained. The range of diffusivity and activation energy values determined in this study closely agreed with the literature data [3,10-12].Thenumerical observations obtained from the diffusion model with both MDED and TDED are also plotted in Fig. 3together with experimental data. It can be seen; the experimental data can be fairly reflected by the diffusion modelwith both MDED and TDED models of moisture diffusivity. This result is in close agreement with the previousstudies.

A better agreement between experimental data and numerical observations obtained with MDED model is seen compared to TDED model. The moisture content generated with TDED model reduces slower than the experimental data and numerical data obtained with MDED model. Moisture content profile considering MDED agrees more closely, compared to experimental data, than that of TDED. At the end of drying process, when the falling dryingrate period commences, the difference between moisture content evolutions obtained with MDED and TDED models becomes pronounced. It can be explained by the drying rate curve evolutions presented in Fig. 4. The numerical results obtained with MDED fits better to with experimental data therefore, it can be concluded that MDED is the more accurate approach for wood drying than TDED.

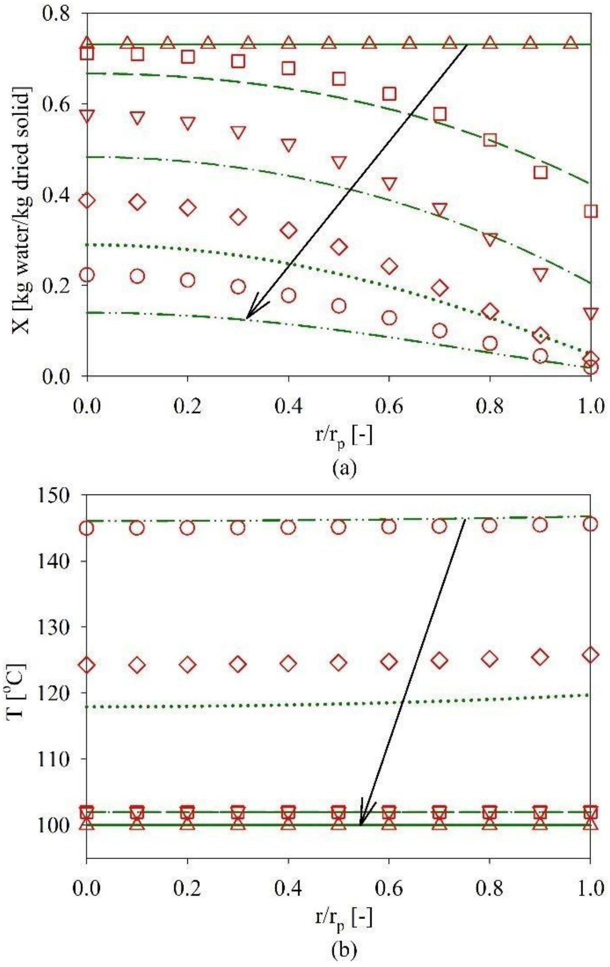


(a)

(b)

Figure 4. Experimental and numerical drying rate curves with different drying temperature: (a) 120 °C and 140 °C, (b) 160 °C and 180 °C.

Exemplarily, the internal moisture content and temperature distribution obtained with MDED and TDED with drying temperature of 160 °C are plotted for a time of t = 12 min with an interval of 3 min are plotted in Fig. 5. As can be seen, during the constant drying rate period, the temperature generated numerically with MDED and TDED are identical, the mass transfer is solely controlled by the moisture diffusion. Since the diffusivity of TDED model at 160 °C is smaller than the reference diffusivity of MDED, the moisture at the surface in TDED simulation reduces faster than the MDED simulation (e.g. time of 2 minute and 4 minute). Therefore, the falling drying rate of TDED simulation commences sooner compared to MDED model. As a result, the moisture content of TDED simulation reduces slower compared to MDED model at the end of drying process as can be seen in Figs. 3 and 4. In light of these findings, it can be claimed that the moisture has more influence than the temperature in case of wood drying. In the next section, the influence of drying conditions on the drying kinetics is investigated by a MDED model-based sensitivity analyses.



(a)

(b)

Figure 5. Simulated moisture content (a) and temperature (b) profiles of the wood particles obtained with MDED (line) and TDED (symbol). The surface of the particle is located at r/rp = 1. The profiles are plotted for a time period of t = 12 min with an interval of 3 min. Parameters used in simulations are: Tv,b = 160 °C, vv,b =

0.015 m/s and X_0= 0.73 kg water/kg dry solid.

The diffusion simulations are made with MDED model with different values of bulk steam velocity and of initialmoisture content. The numerical evolutions of moisture content over time are presented in Figs. 6-8. As can be observed in Fig. 6, with the increase of bulk vapor velocity, the drying time reduces significanlty. However, in high velocity range (i.e. 0.5 m/s and 1 m/s), the time saving is not remarkable. It implies that in high velocity range, the water removal is controlled by the internal mass transfer resistance and the increasing of velocity is not meaningful. Additionally, a low initial moisture content is only helps to shorten the constant drying rate period, the falling drying rate seemingly remains unchanged (c.f. Figs. 7 and 8).

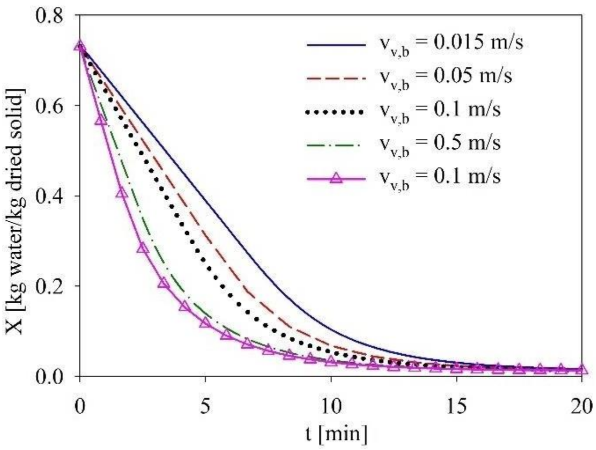


Figure 6. Simulated moisture content evolution of the wood particles obtained with MDED model withdifferent bulk vapor velocity. Parameters used in simulations are: $T_{v,b}$ □ 160 °C andsolid.X_0 = 0.73 kg water/kg dry

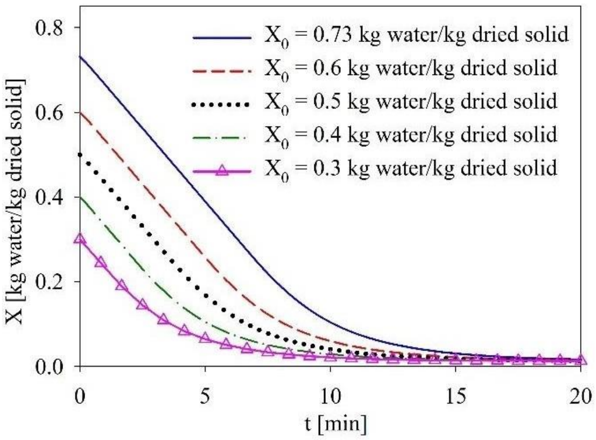


Figure 7. Simulated moisture content evolution of the wood particles obtained with MDED model withdifferent initial moisture content. Parameters used in simulations are: $T_{v,b}$ □ 160 °C and $v_{v,b}$ □ 0.015 m/s.

CONCLUSIONS

In this work, a diffusion model is developed to describe the heat and mass transfer inside single wood particles subjected to superheated steam drying. The model is validated successfully by benchmarking against experimental data obtained by mean of magnetic suspension balance system. By analysis the experimenal and numerical data, several conclusions can be drawn.

The superheated steam drying can be applied for wood materical since the color of the particles is prevented.

The superheated steam drying of wood particles can be describe by diffusion model. The moisture-dependent effective diffusivity is more appropriate to be used in diffusion model of wood particle superheated steam drying.

The impact of vapor veloctity on drying kinetic is significant in low value range of velocity, it become insignificant in high value range.

With initial moisture content values higher than the irreducible moisture content, the initial moisture content influences only on the constant drying period.

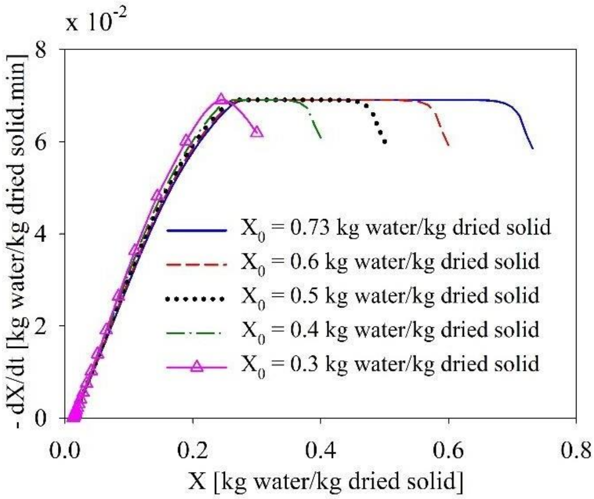


Figure 8. Simulated drying rate curve of the wood particles obtained with MDED model with different initialmoisture content. Parameters used in simulations are: $T_{v,b}$ □ 160 °C and $v_{v,b}$ □ 0.015 m/s.

In the future, the diffusion model can be extented to describe fully superheated steam drying process, i.e. including condensation period. The inversed method used in this work to determine moisture diffusivity can be applied to estimate moisture diffusivity of other porous products.

ACKNOWLEDGEMENTS

This research is funded by the Hanoi University of Science and Technology (HUST) under project number T2018-TT-004.

International Journal of Mechanical Engineering Research and Technology
ISSN 2454 – 535X
www.ijmert.com
Vol. 2 Issue. 1, March 2014

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