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Multi-phase flow and drying characteristics in a semi-circular impinging stream dryer

X.L. Huai [a], X.F. Peng [b,*], G.X. Wang [c], D.Y. Liu [a]

[a] *Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100080, China*
[b] *Department of Thermal Engineering, Tsinghua University, Beijing 100084, China*
[c] *Department of Mechanical Engineering, The University of Akron, Akron, OH 44325-3903, USA*

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Abstract

A physical model was proposed to describe granular material drying in a semi-circular impinging stream dryer, and the multi-phase flow characteristics as well as the heat and mass transfer were numerically investigated. Specially, the influence of various factors (inlet air temperature, mass flow-rate ratio, initial moisture content etc.) on drying process was inspected. The results indicate that constant drying rate period does not exist in a semi-circular impinging stream dryer. Appropriate curvature radius, flow-rate ratio, air velocity and higher inlet air temperature should be chosen for improving the drying performance, and decreasing the energy consumption and operation cost. The numerical predictions were compared with the available experimental results, and they are in quite good agreement with each other.

Keywords: Semi-circular impinging stream drying; Multi-phase flow; Heat and mass transfer; Unsteady drying process

1. Introduction

Drying is a process of moisture removal from materials and can be performed by various methods and technologies, or using desiccants or chemical decomposition of the water in the substance, freeze-drying for water removal in liquids as well as solids [1–3], absorption from gases or solids by capillary action. Compression, centrifugal forces or gravity are often employed as mechanical technologies for drying. Thermal drying, on the other hand, is probably the method that is the most commonly employed in a wide variety of practical applications. The well known and probably most common technology is convective drying [4–6]. In these processes, air temperature decreases as a result of the uptake of water from the material. Hot air flows over the surface of the materials, and the thermal energy is transferred from the hot air to the drying material by convection. Evaporation takes place at the surface and the vapor is carried away by the air flow. Depending on the initial moisture content of the drying media, evaporation may also takes place in the media, and both moisture and vapor may be driven from the inside to surface. With the increasing demand for better and higher quality products and for efficient operation, minimizing product degradation and energy consumption are a current challenge for different applications.

Impinging stream drying (ISD) makes use of two or more streams, which have high temperature and high velocity with opposite moving directions to impinge, and at least, one stream contains wet materials. Wet particles are brought into oscillation by the impinging stream in an impinging chamber, and will be carried away from the impinging chamber after a few times oscillation. Owing to fast and unsteady motion of particles in the impinging chamber, the mean residence time of the particles in the impinging chamber is greatly prolonged, and the violent interaction accordingly enhances the heat and mass transfer between air stream and particles. Therefore, the impinging stream system has the

* Corresponding author. Tel.: +86-10-6278-9751; fax: +86-10-6277-0209.
E-mail addresses: hxl@mail.etp.ac.cn (X.L. Huai), pxf-dte@mail.tsinghua.edu.cn (X.F. Peng).

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Nomenclature

C_g	constant pressure heat capacity of dry gas (J/kg °C)
C_v	constant pressure heat capacity of water vapor (J/kg °C)
C_{gs}	constant pressure heat capacity of dry particle (J/kg °C)
C_s	constant pressure heat capacity of particle (J/kg °C)
C_w	constant pressure heat capacity of liquid water (J/kg °C)
D_s	moisture diffusion coefficient (m^2/s)
d_s	particle diameter (m)
f	resistance force coefficient
h_t	convection heat transfer coefficient (W/m^2 °C)
h_m	convection mass transfer coefficient (m/s)
m	particle mass (kg)
M_{si}	particle initial moisture content, dry basis (kg/kg)
M_s	particle moisture content, dry basis (kg/kg)
$\overline{M}_s$	particle mean moisture content, dry basis (kg/kg)
r_s	particle radius (m)
T_g	gas temperature (°C)
T_{gi}	inlet gas temperature (°C)
T_{go}	outlet gas temperature (°C)
T_{si}	particle initial temperature (°C)
T_s	particle temperature (°C)
$\overline{T}_s$	particle mean temperature (°C)
u_g	gas velocity (m/s)
u_s	particle velocity (m/s)
ΔX	water removal (%)
Y_g	gas absolute humidity (kg water/kg dry air)
Y_{gi}	inlet gas absolute humidity (kg water/kg dry air)
Y_{go}	outlet gas absolute humidity (kg water/kg dry air)

Greek symbols

ξ	drag force coefficient
β	particle concentration
γ	heat of vaporization (J/kg)
μ	mass flow-rate ratio ($\mu = W_s/W_g$)
μ_g	gas viscosity (kg/m s)
ρ_g	gas density (kg/m^3)
ρ_s	particle density (kg/m^3)

advantages of great drying intensity, short time, high efficiency, good quality, and low energy consumption and is expected to have a wide application foreground and one of the most prospective drying for engineering application.

In formal Soviet Union, ISD was successfully used in drying metal particles, chemical products, medicines and urban sludge. Some experimental studies were performed to understand the drying performance of different agricultural products, such as rice, millet and potato granules, at the China Agricultural University [7]. Most of previous studies available in open literature focused on the horizontal or vertical impinging stream systems [8–12], besides fast and unsteady motion of materials in the impinging zone, the semi-circular impinging stream drying makes use of the effect of centrifugal force increasing transverse flow turbulence and enhancing heat and mass transfer rate [13]. However, there is still a solid shortage in understanding the flow, heat and mass transfer characteristics of semi-circular impinging stream drying. In last a few years, a series of experimental investigations were conducted on the drying performance of several distinct semi-circular impinging streams including one-stage semi-circular impinging stream drying and two-stage semi-circular impinging stream drying, as well as the combined system of vertical and semi-circular impinging stream drying [14–18]. The particle velocities along the radial and circular direction, the mean residence time were determined from the experiments. The emphasis was made on exploring the influences of inlet air temperature, mass flow-rate ratio, initial moisture content of particles and air velocity on drying characteristics. Structural and operational parameters, which affect the performance of impinging stream dryer, were analyzed and a number of important conclusions were obtained. This paper aims at further revealing the flow and drying characteristics of granular materials drying in a semi-circular impinging stream dryer by numerical simulation, providing credible foundation of drying equipment and technology design for improving drying quality, decreasing energy consumption and operation cost.

2. Physical and mathematical description

2.1. Particles dynamic model

As shown in Fig. 1, after entering a semi-circular dryer, the multi-phase flow with particles separates into two streams, and is accelerated along each semi-circle tube. On the exit end, two streams form opposite impingement. Particles get into opposite gas stream and decelerated gradually. After one or a few times of for-

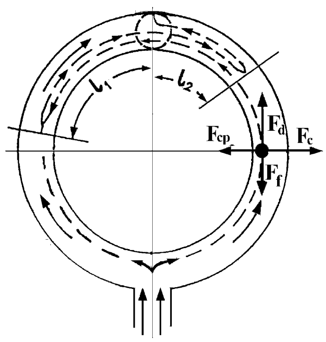

Fig. 1. Semi-circular impinging stream. l_1, particle's first (maximum) penetrating depth, l_2, particle's second penetrating depth.

ward-and-back movement, particles are carried away from the impinging zone. Obviously, particle movement can be divided into two periods/regions: acceleration and deceleration.

No questionably, velocity and residence time of a particle in a semi-circle are of critical importance for the drying characteristics. For convenience, following assumptions are introduced to simplify the mathematical description.

(1) The particles are homogeneous spheres with identical properties, and volume shrink of particles during drying is neglected.
(2) Particle velocities in the same cross-section are uniform.
(3) The interaction among particles is taken into account by resistance force coefficient F_f.

Differential momentum equation for a single particle can be expressed as:

$$m\frac{d\vec{u}_s}{d\tau} = \vec{F}_d + \vec{F}_f \quad (1)$$

where traction force is given as

$$F_d = \xi\frac{\pi d_s^2 \rho_g}{4}\frac{(u_g \pm u_s)^2}{2}$$

and resistance force

$$F_f = f\frac{m u_s^2}{R}$$

In acceleration and deceleration segments, Eq. (1) evolves to

$$m\frac{du_s}{d\tau} = \xi\frac{\pi d_s^2 \rho_g}{4}\frac{(u_g - u_s)^2}{2} - f\frac{m u_s^2}{R} \quad (2)$$

$$-m\frac{du_s}{d\tau} = \xi\frac{\pi d_s^2 \rho_g}{4}\frac{(u_g + u_s)^2}{2} + f\frac{m u_s^2}{R} \quad (3)$$

The velocity, residence time, maximum penetrating depth and time of a particle for all three flow modes (laminar: $Re = 1$–13, $\xi = 26.3Re^{-0.8}$; transition: $13 < Re < 800$, $\xi = 12.3Re^{-0.5}$; turbulent: $Re > 800$, $\xi = 0.43$) can be obtained by solving the above equations.

2.2. Heat and mass transfer

Drying is a very complicated transport process coupling heat with mass transport. In conducting mathematic description of the problem, the following assumptions are considered.

(1) The initial temperature and moisture content are uniform.
(2) Water diffuses from the interior to the surface of particle and the evaporation only takes place at the surface.
(3) Heat transfer from the airflow to the particle surface by convection and is conducted to interior.
(4) Heat transfer between multi-phase flow and tube wall is neglected.

The mass and energy equations in the semi-circular impinging stream drying system are derived as the followings, respectively.

$$\rho_g u_g (Y_{go} - Y_{gi}) = -\beta\rho_s u_s \delta\tau \frac{d\overline{M}_s}{d\tau} - (1-\beta)\rho_g u_s \delta\tau \frac{dY_g}{d\tau} \quad (4)$$

$$\begin{aligned}\rho_g u_g (C_g + C_v Y_g)(T_{go} - T_{gi}) &= -\beta\rho_s u_s \delta\tau (C_{gs} + C_w \overline{M}_s)\frac{d\overline{T}_s}{d\tau} \\ &\quad - (\gamma + \Delta\gamma)\cdot\left[\rho_g u_g (Y_{go} - Y_{gi}) + (1-\beta)\rho_g u_s \delta\tau \frac{dY_g}{d\tau}\right] \\ &\quad - (1-\beta)\rho_g u_s \delta\tau (C_g + C_v Y_g)\frac{dT_g}{d\tau}\end{aligned} \quad (5)$$

as $\delta\tau \to 0$, Eqs. (4) and (5) evolve to

$$[\rho_g u_g + (1-\beta)\rho_g u_s]\frac{dY_g}{d\tau} = -\beta\rho_s u_s \frac{d\overline{M}_s}{d\tau} \quad (6)$$

$$\begin{aligned}\rho_g (C_g + C_v Y_g)[u_g + (1-\beta)u_s]\frac{dT_g}{d\tau} &= -\beta\rho_s u_s (C_{gs} + C_w \overline{M}_s)\frac{d\overline{T}_s}{d\tau} \\ &\quad - (\gamma + \Delta\gamma)\cdot[\rho_g u_g + (1-\beta)\rho_g u_s]\frac{dY_g}{d\tau}\end{aligned} \quad (7)$$

The corresponding dynamic equation of the drying process is expressed as:

$$\frac{d\overline{M}_s}{d\tau} = \frac{\rho_g(C_g + C_v Y_g)[u_g + (1-\beta)u_s]}{\beta\rho_s u_s(\gamma + \Delta\gamma)} \frac{dT_g}{d\tau} + \frac{C_{gs} + C_w \overline{M}_s}{\gamma + \Delta\gamma} \frac{d\overline{T}_s}{d\tau} \tag{8}$$

where average particle temperature, $\overline{T}_s$, and moisture content, $\overline{M}_s$, can be obtained by solving the mass and heat transfer model for a single particle, described as the following.

Heat and mass transfer differential equations for a single particle are as

$$\rho_s C_s \frac{\partial T_s}{\partial \tau} = \frac{\partial}{\partial r}\left(\lambda_s \frac{\partial T_s}{\partial r}\right) + \frac{2}{r}\cdot\lambda_s \frac{\partial T_s}{\partial r} \tag{9}$$

$$\frac{\partial M_s}{\partial \tau} = \frac{\partial}{\partial r}\left(D_s \frac{\partial M_s}{\partial r}\right) + \frac{2}{r}\cdot D_s \frac{\partial M_s}{\partial r} \tag{10}$$

with initial conditions

$$\tau = 0 \quad T_s = T_{si} \quad M_s = M_{si} \tag{11}$$

and boundary conditions

$$\tau > 0 \quad r = 0 \quad \frac{\partial T_s}{\partial r} = 0 \quad \frac{\partial M_s}{\partial r} = 0 \tag{12}$$

$$r = r_s \quad D_s \frac{\partial M_s}{\partial r} + h_m(M_s - M_e) = 0 \tag{13}$$

$$\lambda_s \frac{\partial T_s}{\partial r} - h_t(T_g - T_s) - \rho_s \cdot \frac{V_s}{A_s}[\gamma + C_v(T_g - T_s)] \cdot \frac{\partial M_s}{\partial \tau} = 0 \tag{14}$$

The average moisture content and temperature of a particle after time τ are obtained by integrating the entire sphere,

$$\overline{M_s} = \frac{1}{v_s}\int_0^{r_s} 4\pi r^2 M_{sj}\,dr = \frac{3}{r_s^3}\int_0^{r_s} r^2 M_{sj}\,dr \tag{15}$$

$$\overline{T_s} = \frac{3}{r_s^3}\int_0^{r_s} r^2 T_{sj}\,dr \tag{16}$$

It can be seen from Eq. (8) that factors affecting the drying rate are gas velocity, material velocity and density, and temperature rising rate and moisture content of material etc. Both temperature rising rate and moisture content of material are dependent upon the convective heat and mass transfer coefficients.

2.3. Numerical technique

Simple integral method was employed to solve the particle dynamic model, finite difference method to calculate the heat and mass transfer of a single particle. The mean temperature and moisture of a particle were calculated using complex simple integral method. Gas temperature and moisture content were calculated using Numerical Alternate. Here, the simulation was conducted only for the experiment of millet drying in a semi-circular impinging stream drying [15].

3. Results and discussion

3.1. Physical parameters

The physical properties were obtained from open literature and are summarized as followings.

Heat conduction coefficient [19]

$$\lambda_s = 0.14 + 0.68M_s \quad (\mathrm{W/m\,^\circ C})$$

Mass diffusion coefficient [19]

$$D_s = a\cdot\exp(b\cdot T_s) \cdot \exp\{c\cdot\exp[d\cdot(T_s - 77.2)^2]\cdot M_s\} \quad (\mathrm{m^2/s})$$

where,

$$a = 0.32\times10^{-12} \quad b = 4.35\times10^{-12}$$
$$c = 17.1 \quad d = -1.8\times10^{-4}$$

Specific heat of particles [19,20]

$$C_s = C_{gs} + C_w\cdot M_s \quad (\mathrm{J/kg\,^\circ C})$$

Convective heat transfer coefficient [21]

$$h_t = \frac{Nu_{i,i+1}\cdot\lambda_g}{d_s} \quad Nu_{i,i+1} = \frac{Nu_i + Nu_{i+1}}{2}$$

$$Nu_i = 2 + 1.05Re_i^{0.5}\cdot Pr^{0.33}\cdot Gu^{0.175},$$
$$Nu_{i+1} = 2 + 1.05Re_{i+1}^{0.5}\cdot Pr^{0.33}\cdot Gu^{0.175}$$

Convective mass transfer coefficient

$$h_m = \frac{D_s'}{d_s}(2.0 + 0.552Re^{0.5}Sc^{0.33})$$

where, Reynold number $Re = (\rho_g(u_g \pm u_s)\cdot d_s)/\mu_g$ Schmidt number $Sc = \mu_g/\rho_g D_s'$ particle moisture content at equilibrium [19]:

$$M_e = 0.272 - 0.996\cdot\log(1-\varphi_g) - 0.0544\cdot\log(T_g)$$

3.2. Results and discussion

Fig. 2 illustrates predicted results of particle velocity and gas–solid relative velocity along the flow direction. For comparison, the experimental measurements [15] are illustrated in Fig. 2. Obviously, the gas–solid relative velocity is higher in the impinging zone than in other zones, which is favorable for enhancing semi-circular impinging stream drying.

Fig. 3 presents the predicted time of a particle first accelerating and decelerating at various gas velocities. The time initial to accelerate and decelerate decrease as

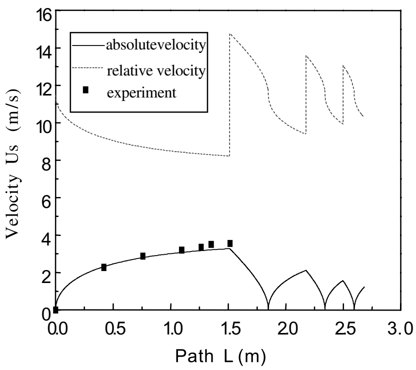

Fig. 2. Particle velocity profile.

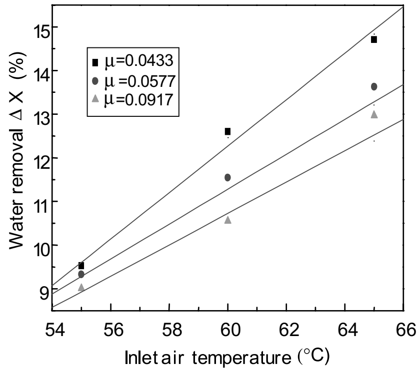

Fig. 4. Effect of inlet air temperature on water removal.

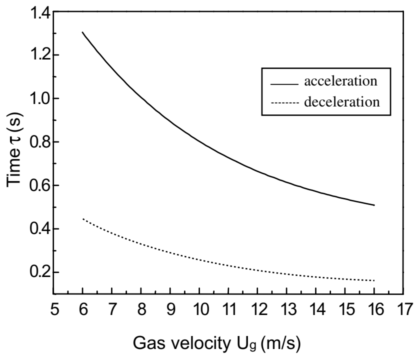

Fig. 3. Effect of gas velocity on acceleration and deceleration time.

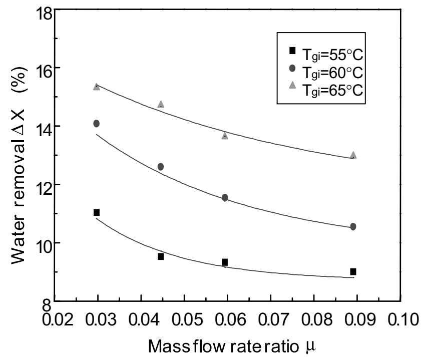

Fig. 5. Effect of mass flow-rate ratio on water removal.

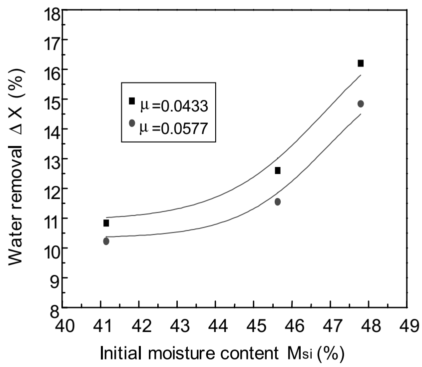

Fig. 6. Effect of initial moisture on water removal.

gas velocity increasing. Meanwhile, mean particle residence time decreases with the increase of gas velocity, which has negative effect on material drying. However, the increasing in relative velocity between gas and solid particles and decreasing of gas humidity improve the drying performance. Obviously, there is a favorable gas velocity improving drying performance and decreasing energy consumption and operation cost.

The effect of inlet air temperature on water removal is illustrated in Fig. 4. These predictions and experiments were for the mass flow-rate ratios of 0.0433, 0.0577 and 0.0917, respectively, and moisture content 45.63%. The water removal increases as inlet air temperature increasing.

The predicted water removal is also compared with the experimental results at different mass flow-rate ratios, as shown in Fig. 5. The water removal monotonously decreases with the increasing of the mass flow-rate ratio. In practical processes the mass flow-rate ratio should be kept at a lower value. However, very low mass flow-rate ratio would limits dryer capacity, and increase energy consumption and operation cost.

From Fig. 6, for inlet air temperature of 60 °C, and mass flow-rate ratios 0.0433 and 0.0577, respectively, the water removal sharply increases with the increasing of the materials initial moisture content, which strongly support that a semi-circular impinging stream drying is

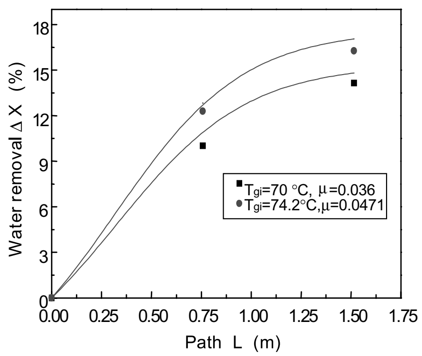

Fig. 7. Variation of water removal along direction.

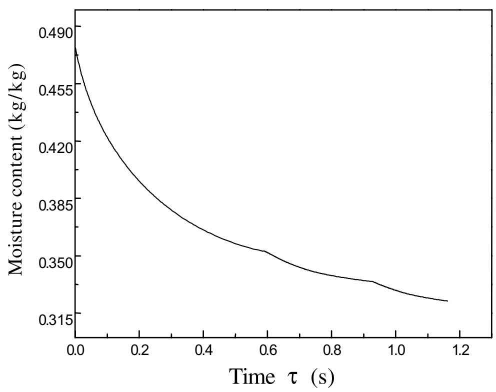

Fig. 9. Variation of moisture content.

favorably suitable to handle materials with high moisture content.

For initial material moisture content 45.63%, and inlet air temperatures of 70 and 74.2 °C, with corresponding mass flow-rate ratios of 0.036 and 0.0471, respectively, the increment of water removal along flow direction goes very fast in the entrance end of the circle and then turns slower, as shown in Fig. 7. So, the key for enhancing the semi-circular impinging stream drying is to improve the drying intensity of the downstream, especially exit end of the circle. Adding fresh air in downstream region of the circle can enhance drying performance. Increased the circular diameter, the friction between a particle and the wall would decrease and accelerating zone of particles would prolong. Accordingly, water removal increases. However, the questions, such as "how much of the fresh air should be added" and "how big of the circular diameter should be used" need to be considered combining drying rate, energy consumption, operation cost and equipment size etc.

Figs. 8 and 9 show the predicted variation of drying rate and moisture content with time for mass flow-rate ratio 0.0433, initial moisture content 47.8% and inlet air temperature 60 °C. The results indicate that the constant drying rate period does not exist during material drying in a semi-circular impinging stream dryer.

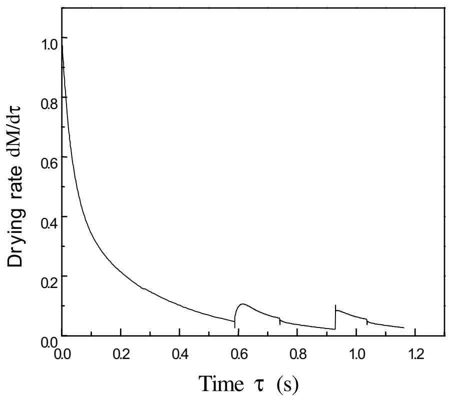

Fig. 8. Variation of drying rate.

4. Conclusions

- A physical model and associated mathematical formula were established to describe granular materials drying in a semi-circular impinging stream dryer and investigate the influence of operating parameters, such as inlet air temperature, mass flow-rate ratio and initial moisture content etc. on drying process. The calculated results show a quite good agreement with the experimental results.
- Higher inlet air temperature can be used to greatly enhance the drying rate, and water removal increase with the decreasing of mass flow-rate ratio and the increasing of initial moisture content.
- Adding the fresh air in the downstream of circle and properly increasing the circular diameter can enhance the drying performance. Gas–solid relative velocity has a higher value in the impinging zone, which enhances semi-circular impinging stream drying.
- Different from conventional drying processes, constant drying region does not exist in a semi-circular impinging stream dryer.

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