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Master curve behaviour in superheated steam drying of small porous particles

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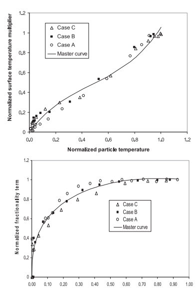
HIGHLIGHTS

- ► A new lumped model for superheated steam drying of porous particle was developed.
- ► Porous clay particles display a master drying behaviour under various conditions.
- ► Superheated steam drying resulted in significant mass transfer depression.

GRAPHICAL ABSTRACT



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ABSTRACT

A lump drying model was developed for superheated steam drying of porous particles. Using single particle drying data [1], a unique master curve drying characteristic was obtained for porous ceramic particles dried under different degree of superheating and relative velocities. Further analysis revealed that the mass transfer depression phenomenon is significant under such superheating condition, typically used in drying processes. This highlights the precaution required in the case of future model development. This approach can potentially be a versatile approach in modelling the drying of porous particles, such as brown coal, under superheated steam condition.

1. Introduction

Drying of porous particles has major practical applications. This can range from the drying of food materials to porous products in the particulate form. One major application in the energy industry, which is the motivation of this work, is in the drying of wet brown coal particles. The removal of moisture is essential to effectively use the brown coal for power generation [2]. A danger in the moisture removal of brown coals is the potential for spontaneous combustion during processing; indirectly posing a limitation on the drying environment and temperature. To obviate this, superheated steam provides an inert environment and can be introduced as the drying medium [3] to effectively remove the contained moisture.

The current predictive method for superheated steam drying of a single brown coal particle is to consider it as a porous particle. In order to capture this porous effect, a receding wet evaporating core is typically assumed, taking into account the formation of a dry outer crust. Detailed treatment on the transport of heat and vapour is often adopted in this approach; discerning the radial temperature, moisture and vapour distribution within the dry outer crust [1,4,5]. While such methods provide detailed description on the internal condition, albeit contrasting reports on the accuracy, they

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Nomenclature

m_p	mass of the particle (kg)
C_p	specific heat capacity of the particle (J/kg °C)
dT/dt	rate of change of the particle temperature (°C/s)
A_p	particle surface area (m²)
h	heat transfer coefficient (W/m² °C)
T_a	convective superheated steam temperature (°C)
T_{sat}	saturated temperature (°C)
T_p	particle temperature (°C)
X	moisture content in dry basis (kg moisture/kg dry solid)
k_s	thermal conductivity of the steam (W/m °C)
R_p	radius of the particle (m)
ρ_s	density of the superheated steam (kg/m³)
u	particle–steam relative velocity (m/s)
μ_s	viscosity of the steam (kg/m s)
R_p	particle radius (m)
$C_{p,s}$	specific heat capacity of the steam (J/kg K)
dm/dt	evaporation rate (kg/s)

involve non-trivial numerical solution and assumptions particularly on the transport and structural properties of the material being dried. In this respect, a lump model approach will offer a faster and simpler modelling approach. Extensive development of the lump modelling approach can be found in other particulate drying applications such as spray drying [24,25]. This facile approach has allowed implementation of the lump models in large scale simulation for industrial application [26–28]; an approach which can be used for the design of superheated steam dryer of porous particles. However, the key in such development for the current work is to ensure the approach captures the porous particle drying behaviour and at the same time capturing the superheated steam drying effect.

Some lump models on the drying of coal can be found in the literature. McIntosh [6] developed a lump model by assuming a constant wet bulb interface temperature. Bueno et al. (1993) proposed a purely empirical curve fitted lump model. However, these models were developed based on hot air drying of coal. It is noteworthy that superheated steam drying is significantly different from hot air drying on the mechanistic level [7] in terms of the driving force for moisture removal. For superheated steam conditions, a lump model by Chen et al. [8] was developed based on the distributed moisture approach. Complex integrals were included in the model to transform the distributed moisture approach to the lump approach. The model prediction exhibited significant deviation from the experimental results compared. Therefore, the aim of this study is to arrive at a simple semi-empirical lump model which can capture the superheated steam drying of such porous particles. At the moment, in the absence of reliable single coal particle superheated steam drying data, the developed model was compared with the experimental data of Hager et al. [1] for ceramic particle as a model for porous particles.

2. Theoretical development

The drying behaviour of porous brown coal particles under superheated steam condition is often modelled by a distributed diffusion approach in which the particle is internally 'discretized' [4,10,11]. While this approach provides very detailed information on the drying behaviour, it may not be practical to apply to larger scale analysis due to the high numerical requirements. In this respect a lumped modelling approach will be more practical. Along this line, Chen et al. [8] developed a lumped approach with complicated integration along the drying history. In this work, a simple semi-empirical master curve lump model was developed.

Following Ref. [4], heat transfer into the droplet during the initial heating up period takes the following form,

$$m_pC_p\frac{dT}{dt} = A_ph(T_a - T_p), \quad T_p < T_{sat} \tag{1}$$

This form assumes that evaporation occurring within the heating up period is negligible until the particle (simultaneously with the evaporating front) reaches the saturated temperature corresponding to the ambient pressure. Specific heat capacity was approximated by mass weighting between the properties of water and the bone dry material,

$$Cp = xCp_{ceramic} + (1 - x)Cp_w \tag{2}$$

With x as the mass fraction of dry ceramic (kg/kg total) given as,

$$x = \frac{1}{1+X} \tag{3}$$

The heat transfer coefficient can be computed from typical droplet or particle Nusselt correlations. A well-known one is the Ranz–Marshall correlation,

$$h = \left(2 + 0.6Re^{1/2}Pr^{1/3}\right)\left(\frac{k_s}{2R_p}\right) \tag{4}$$

The Reynolds and the Prandtl number is computed as follow,

$$Re = \frac{\rho_s u 2R_p}{\mu_s} \tag{5}$$

$$Pr = \frac{C_{p,s}\mu_s}{k_s} \tag{6}$$

At the instance that the particle temperature reaches the saturated condition, heat transfer then takes the form,

$$m_pC_p\frac{dT}{dt} = A_ph(T_a - \psi T_{sat}) - \frac{dm}{dt}\Delta H_{evap} \tag{7}$$

A unique ψT term is introduced into the convective heat transfer driving force term. Following the receding evaporating front concept, a significant temperature gradient could exist across the particle. The lower boundary of this gradient is the saturation temperature while the upper boundary would then be the particle surface temperature. If convective heat transfer is considered to be the sole mechanism in which energy is transferred into the particle, this mechanism would be driven by the temperature difference between the surface temperature and the ambient steam temperature. Therefore, if the mean temperature is used to capture the convective heat transfer into the particle, it can be deduced that over-prediction will occur. In order to account for this effect coupled with the impact of temperature gradient within the particle, the term ψ is incorporated as a surface temperature multiplier term delineating how much the surface temperature increases from the saturated temperature as the evaporating front recedes. In effect, the combined term ϕT_{sat} denotes the effective surface temperature. This form of empiricism was introduced as to avoid assumptions on any internal gradient or profiles (temperature or moisture) within the material [12]. It will be shown later that having knowledge of such a parameter can be advantageous in predicting surface temperatures. Rearranging Equation (7), the multiplier term can be obtained experimentally from each stage of drying under various external conditions,