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Research Paper

A CFD-based comparative analysis of drying in various single biomass particles

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HIGHLIGHTS

- The geometrical shape of biomass and the external boundaries are investigated.
- Reducing moisture content decreases drying time about 83%.
- Non-uniform distribution of temperature increased drying time significantly.

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ABSTRACT

The understanding of the behaviour of biomass particles is important, therefore, modelling different sub-processes of biomass thermal conversion is derived during these years. This paper addresses a comparative CFD based analysis of different drying models. Several sub-models are simulated to investigate the evaporation process of different geometries based on standard densified wood pellets. In order to predict the transient evolution (moisture to dry wood) of the wood particles, transport equations (energy and moisture evaporation) are solved considering the reaction heat loss, effective thermal conductivity, specific heat capacity, and radiative and convective heat transfer. These models are compared with the previous experimental and numerical works. The Heat Sink model demonstrates the closest agreement with the reported data based on a cylindrical shape of biomass particle. This model is further analyzed by increasing the moisture content and decreasing the surface area exposed to radiative and convective heat taking into consideration the particle density, effective thermal conductivity and specific heat capacity. The results show a remarkable decrease in drying time when the particle is fully exposed to external radiative and convective heat with the lowest moisture content.

1. Introduction

Biomass fuel is regarded as an important renewable energy resource. Owing to the importance of this resource, a better understanding of its thermal conversion behaviour is needed in order to improve process efficiency and reduce pollutant emissions. Coupling the heat and mass transfer with the chemical processes involved in both packed and fluidised bed requires the development of a sophisticated CFD model. The complexity of such models is due to intra-particle reaction processes such as drying, devolatilization, char burning and oxidisation, interconnection conductivity and mass transfer between particles and its surrounds [1]. Convective heat exchange in packed-beds is not constant due to different counter-current air flow-rates and is calculated based on experimental correlation between the Nusselt and Sherwood numbers [2,3]. In addition, radiation models, geometry configurations, anisotropic shape of the fuel, phenomena like channelling and shrinkage and particles increase the level of complexity in CFD modelling [4]. This has resulted in focused attention on mathematical modelling and CFD analysis of single biomass particles.

Biomass contains water in three forms: bound water, free water and water vapour. Bound water is found in plant cell walls. The wood particle is occupied by free water, water vapour is found in cell lumina and compared to the other forms is negligible at atmospheric temperature and humidity [5]. Most manufacturers establish the limit for moisture content in the fuels due to the influence of moisture in the design and selection of burners. In the wood pel-

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Nomenclature

A_v	pre-exponential factor [s^{-1}]
A_s	surface area [m^2]
c_{pm}	moisture heat capacity [J/kg K]
$c_{p.p}$	Particle heat capacity [J/kg K]
E_v	activation energy [J/mol]
h	convective heat transfer coefficient [W/m^2 K]
k_v	kinetic reaction rate [s^{-1}]
l_{pore}	pore diameter [m]
LH_{moist}	evaporation enthalpy [J/kg]
q_g^{conv}	convective heat (gas phase) [W/m^2]
R	universal gas constant [J/mol K]
r_{dry}	evaporation rate [kg/m^3s]
S_s	depending source term
T	temperature [K]
t	time [s]
Δt	current time step [s]

Greek letters

$\rho_{moisture}, \rho_m$	moisture density [kg/m^3]
λ_{eff}	effective thermal conductivity [W/m K]
λ_{rad}	radiative thermal conductivity [W/m K]
$\sigma(5.67 \times 10^{-8})$	Stefan Boltzmann [W/m^{-2} K^{-4}]
ω	emissivity [–]
ε	solid mass fraction [–]

Subscripts

conv	convection
cond	conduction
dry	drying
evp	evaporation
eff	eeffective
g	gas
m	moisture
p	particle
reac	reaction
rad	radiation
s	solid
HS	Heat Sink
AR	Arrhenius
Cy	cylindrical geometry
Cb	cubic geometry
Sp	spherical geometry
*	mixed radiative temperature T = 800 K and natural convection is imposed on the half surface of the particles while the rest of the surfaces assume to be cooled by natural convection

let industry, a combination of low moisture content (8–10%) and high densified pellets (typically greater than 1000 kg/m^3) offer fuels with higher bulk energy densities. Moisture content influences the combustion behaviour, particularly pyrolysis and the adiabatic temperature of combustion and the volume of emitted gases. Conversely, longer resistance times for drying leads to a later occurrence of other sub-processes of thermal conversion like pyrolysis and char combustion [6]. From an energetic stand point, Minkova et al. [7] demonstrated that the liberated steam (water vapour) has a strong effect on the yield and properties of pyrolysis products from biomass fuels. In indirect bio-char reactors, increasing moisture contents and non-uniformity of temperature reduce the quality of bio-char and leads to lower efficient syngas combustion and higher emissions [8].

Different experimental studies are carried out to study thermal degradation of single biomass particles. The temperature and density profiles, outflowing water and volatiles analysis during pyrolysis of large biomass particles were performed by Chan et al. [9]. Alves and Figueiredo [10] investigated pyrolysis of cylindrical, wet and dried woods. Tran and White [11] calculated the burning rate in different thick wood particles by determining mass loss, average heat release and charring rate in a heat-release calorimeter. Gronli [12] investigated the pyrolysis of different wet biomass particles taking into account temperature profiles and chemical composition in order to describe thermal degradation in single biomass particles during drying and pyrolysis. Lu et al. [13] studied drying, devolatilization and char oxidisation of different spherical and cylindrical biomass woods. Their experimental facility provided mass loss and particle surface and centre temperatures as a function of time. However, widely varying property (density, specific heat, thermal conductivity, porosity, permeability) among different woods, expensive equipment and the problem of installation (uncertainty in thermal conductivity, specific heat capacity and combustion progress) introduce uncertainties in the experimental studies. Therefore, modelling is useful not only from an economical aspect but also to provide more data than experimental results.

The main advantage of single particle modelling is easy of implementation and assessment of essential physics. Saastamoinen and Aho [14] proposed a mathematical model of simultaneous drying and pyrolysis of single particle biomass pellets. They used temperature dependence functions based on experimental analysis and numerical approximations to express the phase change in evaporation and pyrolysis processes. They also determined that the Arrhenius model for larger particles is not accurate due to different wood varieties. The immediate outflow hypothesises used in the model was applied by Porteiro, Collazo et al. [15,16]. Based on this hypothesis, an outflow of gas species occurs in the reaction zone and moisture evaporated in the solid phase are incorporates into the gas phase domain. In fact, the time required for gases to travel through the outer layers of the particles is smaller than the simulation time step, therefore recondensation and moisture transfer in the liquid phase were not considered. This hypothesis is reinforced in the experimental study proposed by Gronli [12]. Porteiro et al. [17,15] investigated a one-dimensional model of a single wood particle incorporates sub-processes of thermal conversion. Mass loss and internal temperature were compared with the previous experimental studies. Yang et al. [18] applied a mathematical and experimental approaches to investigate the combustion characteristics of a single biomass particle for different sizes, taking into account volume shrinkage. The results demonstrated that assuming constant temperature for large particles appeared to be inadequate and more detail CFD modelling should be applied for those particles. Single particle studies have also been considered by several researchers [9,19–22] to introduce intra-particle and interactions between single particles in the packed-beds. Peters [23] employed the Thiele modulus to determine whether particle combustion was dominated by reaction or diffusion and then classified the combustion regime based on the Damkohler number (indicating where the bed behaviour is homogeneous) and the Thiele modules. The use of drying num-