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Review

Simplified model and simulation of biomass particle suspension combustion in one-dimensional flow applied to bagasse boilers

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ABSTRACT

A simple numerical model is presented to simulate the combustion of a biomass particle in a vertical stream. Emphasis focuses on the trajectories of spherical and cylindrical particles in the furnace. Combustion is modeled in three sequential stages: drying, pyrolysis and char combustion. Biomass consumption is determined by correlations based on Arrhenius kinetics and mass transfer parameters. Pyrolysis is modeled using five first-order kinetic equations considering the following products: volatiles, char and tar. The char consumption rate is modeled by three first-order kinetic equations, considering that char reacts with oxygen, carbon dioxide and water. The model is validated by comparing the duration of each simulated stage against experimental data taken from the literature. It is validated for spherical particles of up to 5 mm in diameter using a shrinking core model and for cylindrical particles of up to 3 mm using an ash-segregated model. Particle trajectory results are presented in order to determine the geometry and functional parameters of the combustion chamber that ensure complete suspension-firing. The combustion chamber geometry and biomass distributor height are determined as a function of airflow velocity and biomass characteristics for the combustion of bagasse with moisture contents of 30%–50% and particle diameters of 0.5 mm–3.5 mm. This study also allows the airflow velocity to be determined based on the boiler dimensions and the biomass characteristics to ensure that no particle ends up on the grate. After establishing the velocity, it is possible to determine what particle size will reach the top of the chamber or burn completely in suspension.

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Nomenclature

A_p	Particle projected area, m^2
A_s	Particle surface area, m^2
c_p	Specific heat at constant pressure, $J\ kg^{-1}K^{-1}$
C_D	Drag coefficient
d_p	Particle diameter, m
D	Mass diffusivity, $m^2 s^{-1}$
E_a	Activation energy, $J\ mol^{-1}$
F_E	Buoyancy force, N
F_D	Drag force, N
$f_{p,i}$	View factor particle-surface i
G	Gravitational acceleration, $m\ s^{-2}$
H	Sensible specific enthalpy specie i, $J\ kg^{-1}$
h^l	Latent specific enthalpy, $J\ kg^{-1}$
h_j^q	Chemical specific enthalpy reaction j, $J\ kg^{-1}$
$\overline{h}$	Coefficient of thermal convection, $W\ m^{-2}K^{-1}$
$\overline{h}_m$	Coefficient of mass convection, $m\ s^{-1}$
k_c	Conductivity $W\ m^{-1}K^{-1}$
K	Kinetic coefficient
k_0	Arrhenius' Frequency factor
L_p	Particle length, m
M	Molecular mass, $kg\ mol^{-1}$
M	Mass, kg
m_0	Initial mass, kg
$\dot{m}$	Mass rate, $kg\ s^{-1}$
N	Reactant stoichiometric ratio
Nu_d	Nusselt's number based on particle diameter
Pr	Prandtl's number based on particle diameter
Pe_d	Péclet's number based on particle diameter
r_p	Particle radio, m
R	Universal gas constant, $J\ mol^{-1}K^{-1}$
Re_d	Reynolds' number
Sh_d	Sherwood's number
Sc	Schmidt's number
T	Absolute temperature, K
T_{ref}	Reference temperature, K
U_m	Global coefficient of mass transport, $m\ s^{-1}$
v	Velocity, $m\ s^{-1}$
Y_C	Initial fixed carbon in mass fraction
X	Molar fraction

Greek letters

α	Absorbance
ε	Porosity
λ	Air fuel equivalence ratio
μ	Dynamic viscosity, $kg\ m^{-1}s^{-1}$
ν	Cinematic viscosity, $m^2 s^{-1}$
ρ	Density, $kg\ m^{-3}$
σ	Stefan-Boltzmann constant, $W\ m^{-2}K^{-4}$
τ	Tortuosity

Subscripts

c	Char
b	biomass
g	Furnace environment gas
H_2O	Water
mix	Gas mixture
p	Particle
s	Surface
sp	Surrounding particles
tar	Tar
vol	Volatiles
i	specie i
j	reaction j

1. Introduction

The design of industrial boilers requires optimum understanding of the different phenomena that occur during the combustion of a biomass particle. Such knowledge contributes to improve constructive and functional parameters pertaining to biomass feed, air injection and combustion itself. In the earliest bagasse boiler models, the main combustion took place on the grate and involved large amounts of unburned residues that had to be removed from the boiler. Since then, biomass combustion systems have evolved continually to achieve suspension-firing of biomass, with a smaller fraction of grate-firing. This is possible because of secondary air injection heating, as shown in Fig. 1 [1]. The vast majority of bagasse boilers employed in Brazils sugar and alcohol industry use intermittently moving grates or water cooled pinhole grates. The bagasse is fed into the furnace mechanically or by gravity and the distribution of bagasse in the chamber is usually improved by means of air jets. The smaller particles are dragged by the gases and the combustion process takes place in suspension. However, larger particles settle onto the grate and the combustion process takes place in a fixed bed regime [2].

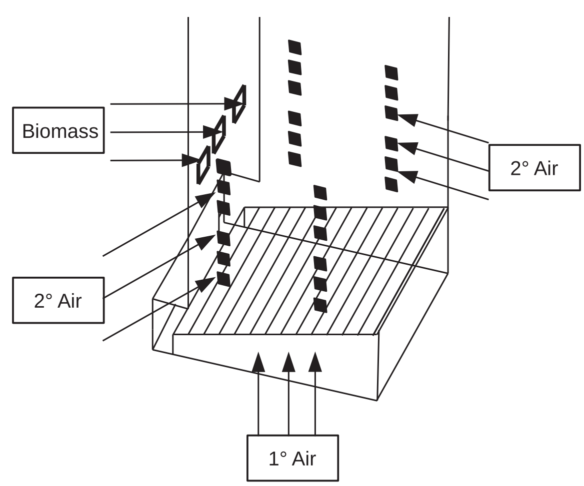

Fig. 1. Bagasse boiler - functional diagram.

Particle combustion begins when the bagasse comes into contact with the hot gases, and involves three main stages: drying, devolatilization and char combustion. In general, the devolatilization stage is modeled as pyrolysis. The stages can be simultaneous or sequential, depending on particle size and shape [3]. Most studies have used simultaneous-stage models in which drying and oxidation occur in infinitesimal layers, while pyrolysis takes place in a finite volume considering local thermal equilibrium. In those models, the biomass is divided into four different zones: unreacted wet biomass, pyrolytic zone, unburned char, and ashen zone [4,5]. Other models consider that the last two stages may be