



## Predicting the pyrolysis of single biomass particles based on a time and space integral method

Y. Haseli\*, J.A. van Oijen, L.P.H. de Goeij

Combustion Technology, Department of Mechanical Engineering, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

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### ABSTRACT

The objective of this paper is to present a simple pyrolysis model to capture the main characteristics of the decomposition of a thermally thin particle at high temperatures corresponding to those found in the furnace of coal/biomass power plants. To achieve this goal, it is assumed that pyrolysis begins soon after the surface of the particle has reached a certain pyrolysis temperature, and proceeds according to a shrinking (unreacted) core model with an infinitesimal reaction front. The formulation of various stages including initial heating, pre-pyrolysis heating, pyrolysis and post-pyrolysis heating is carried out based on a time and space integral method which allows one to describe the energy conservation equation in an algebraic form. Two different treatments are presented for the pyrolysis stage. The first formulation assumes separate temperature profiles for char and biomass regions (double-temperature profile), whereas in the second treatment only one profile is considered for the temperature throughout the particle (single-temperature profile). Of particular interest is the latter approach that leads to simple relationships for predicting the duration of various stages, enabling one to predict the mass loss history. The accuracy of both methods is examined by comparing their predictions with recent experimental data reported in the literature as well as the prediction of comprehensive pyrolysis models. Satisfactory agreement is achieved indicating that both pyrolysis models based on double- and single-temperature profiles can be used with sufficient accuracy for engineering purposes.

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### 1. Introduction

Thermochemical conversion of biomass is a topic of technological importance due to the increasing interest in the utilization of biomass as a renewable energy source. The main mechanism for chemically converting the biomass into other byproducts is heat from an external source. The energy from biomass can either be directly converted into heat, for instance, in the furnace of a power plant, or into the liquid fuel and biogas within a gasifier. The well-established methods of thermochemical conversion of biomass for engineering applications include combustion, gasification, torrefaction and pyrolysis. The key differences between these methods are related to the oxygen concentration in the surrounding fluid and the operating temperature.

A substantial amount of research has been conducted on the subject of biomass pyrolysis by means of experimental and numerical investigations to increase the knowledge of various physical and chemical processes involved in the biomass pyrolysis. The reader may access the recent state-of-the art in Refs. [1–12]. The

common feature of the models reported in these references is that the transport equations are usually described one-dimensionally and combined with a kinetic scheme representing chemistry of the virgin biomass decomposition. Two and three-dimensional models have rarely been reported; see e.g. Ghabi et al. [13]. The advantage of these models is that they allow calculating a variety of parameters such as solid and gas phase densities, temperature, pressure and velocity fields within the porous matrix and formation of main byproducts (light gases, tar and char) in space and time. Such advanced models enable one to get a deeper understanding of the physics and chemistry of the pyrolysis process on the scale of a single particle.

Because of the transient nature of the pyrolysis process, the transport equations are necessarily described in partial differential forms in order to capture the variation of key parameters along the particle and during the process. This would be at the expense of considerable amount of computational and programming efforts, in particular, when dealing with design of combustors and gasifiers, where a large number of particles undergo thermochemical conversion. For practical applications, designers are commonly interested in only a few parameters such as average temperature and/or temperature at the surface of the particle, rate and the amount of particle mass loss, ignition time at which a particle begins to

\* Corresponding author.

E-mail address: [y.haseli@tue.nl](mailto:y.haseli@tue.nl) (Y. Haseli).

**Nomenclature**

$c_p$	specific heat (J/kg K)
$h$	convective heat transfer coefficient (W/m <sup>2</sup> K)
$k$	thermal conductivity (W/m K)
$L$	thickness/Length of particle (m)
$L_{cr}$	minimum particle length for transition from thermally thin to thermally thick regime (m)
$\dot{m}''$	decomposition rate per unit surface area (kg/m <sup>2</sup> s)
$q''$	heat flux (W/m <sup>2</sup> )
$q''_{net}$	net heat flux at particle surface (W/m <sup>2</sup> )
$R$	particle radius (m)
$T$	temperature (K)
$T_p$	pyrolysis temperature (K)
$T_s$	surface temperature (K)
$T_{sL}$	surface temperature at the time $t_L$ (K)
$t$	time (s)
$t_L$	duration of thermal penetration movement from the front surface to the back face of the particle (s)
$t_{p,ini}$	time of commencement of pyrolysis at the surface of particle (s)
$t_p$	conversion/pyrolysis time (s)
$x$	spatial coordinate
$x_c$	char depth (m)
$x_t$	thermal penetration depth (m)

*Greek letters*

$\alpha$	thermal diffusivity (m <sup>2</sup> /s)
$\Delta h_p$	specific enthalpy of pyrolysis (J/kg)
$\varepsilon$	emissivity
$\rho$	density (kg/m <sup>3</sup> )
$\sigma$	Stephen–Boltzmann coefficient (W/m <sup>2</sup> K <sup>4</sup> )
$\varphi$	coefficient of Eqs. (3) and (17)
$\psi$	coefficients of Eq. (16)

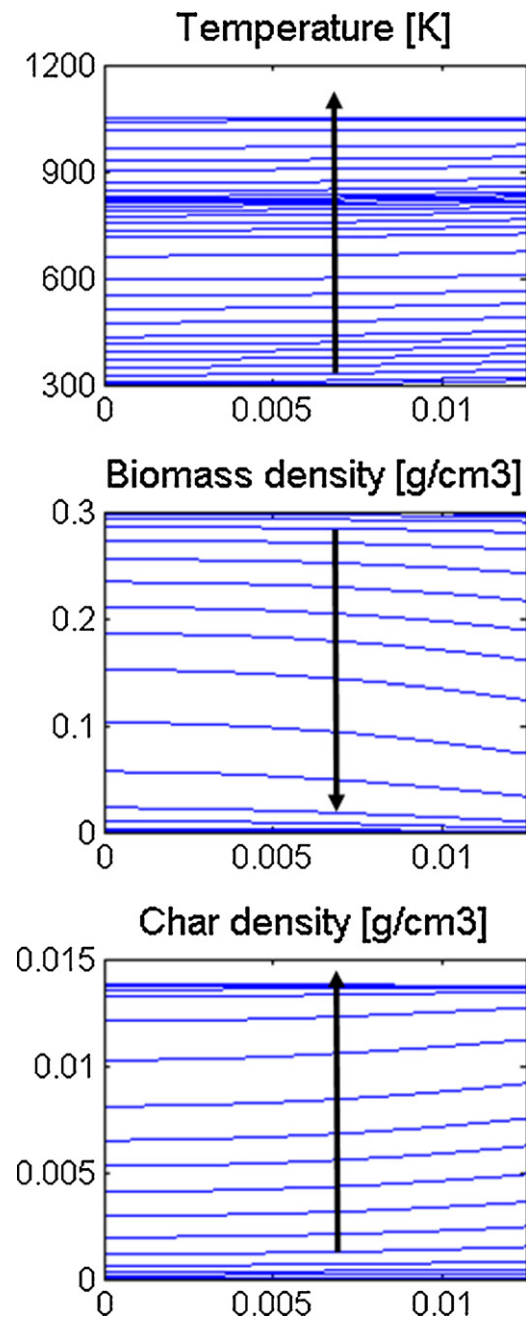
*Subscripts*

0	initial condition
$\infty$	surrounding condition
B	biomass
BC	boundary condition
C	char
ext	external
f	final
ph	post-pyrolysis heating up
r	reactor

decompose, and total duration of the conversion process. To capture the main characteristics of the pyrolysis of solid fuels with optimized computational efforts requires one to employ less complex models.

From a mathematical point of view, a key step towards simplified pyrolysis models is to describe the particle conversion process in the form of a set of ordinary differential equations (ODEs) rather than partial differential equations (PDEs). In principle, a chemically converting solid particle may ultimately decompose in the following two extreme limits: the regime of shrinking density, and the shrinking core regime. In the former limit, a particle undergoes an almost homogenous conversion in the absence of intra-particle gradients, whereas in the latter extreme limit the reaction takes place at a very thin layer, resulting in a reaction front that is created at the surface of the particle and moves towards its center.

For the case of pyrolysis of charring materials, e.g. wood, a particle may decompose homogeneously in the regime of kinetically controlled conversion. Our previous study [2] indicated



**Fig. 1.** Illustrative time and space evolution of intra-particle gradients of a biomass particle undergoing a homogenous pyrolysis (250  $\mu\text{m}$ ; 1050 K; 300 kg/m<sup>3</sup>). Different lines correspond to different times increasing in the direction of the arrows.

that homogenous pyrolysis of a wood particle may occur at low densities, small particles and low operational temperatures corresponding to (typically for a cylindrical beech wood)  $Bi < 0.1$  and  $Py' > 1.5 \times 10^{-3}$ , where  $Bi$  and  $Py'$  denote Biot and the external pyrolysis numbers, respectively. A typical time and space evolution of biomass and char densities as well as temperature of a particle undergoing a homogenous pyrolysis predicted by a comprehensive pyrolysis model [1,2] is depicted in Fig. 1.

It is however unlikely that pyrolysis of biomass in combustors and gasifiers occurs in the regime of kinetically controlled in the absence of intra-particle gradients, due to the high operational temperatures and relatively large particles. It is difficult to mill biomass due to its fibrous structure which results in particles of relatively large size (around 1 mm). Moreover, Lu et al. [14] and Bharadwaj

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