

# STUDY OF BIOMASS PARTICLE COMBUSTION MODEL TO USE IN MULTI-PARTICLE SIMULATION CODES

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## Abstract

This paper presents an analyses of the modelling specifications required in the simulation of the conversion of a single biomass particle to be used in multi-particles computer simulation codes. It considers the transport and reaction of gases, the heterogeneous combustion and heat transfer within the biomass. The biomass conversion is described by a competitive reaction mechanism specifying the composition of the volatile species and tar properties. This approach can represent the influence of the heating conditions on biomass conversion and produce acceptable compositions for the final products. Tar decomposition is considered within the particle as well as combustion reactions for all combustibles: volatile, tar and char. The study of several approaches show the level of numerical approach required to simulate the thermal conversion of the biomass particle and further reactions such as tar decomposition and oxidation of the combustibles gases within the particle. The validation of the numerical code is accomplished with the conversion of a 50 mm trunk in a hot gas stream by measuring the mass loss and temperature along the combustion process. Parametric tests are carried out to investigate the conversion of tars and oxidation of gases within the particle and it is concluded that these can be neglected for particle diameters smaller than 20 mm with an error less than 1%. For combustible particles such as wood chips and pellets with 6 mm diameter, all intern gradients may be neglected.

*Keywords: Biomass combustion, tar conversion, large particles*

## 1. INTRODUCTION

Biomass combustion in several applications is carried out using different particle sizes, since large diameter wood logs, such as combustibles used in fireplaces as well as grate firing combustion systems till small particles used in pulverized systems like the use of wood in co-combustion with coal. With the objective of modeling grate fired combustion systems Thunman *et al.* [1] (2002) proposed the use of a particle layer model in the different conversion stages, e.g. drying, volatilization, char combustion and ash. In this model the reaction products are considered to be immediately released from the particle and the char combustion is only considered in the outer part of the particle.

Porteiro *et al.* [2] (2006) used a similar approach to calculate the conversion of biomass. The model is tested for the pyrolysis of a 50 mm

diameter dry birch sample in an inert atmosphere at 973K. The pyrolysis products released within the particle are considered to be immediately transferred for the surrounding atmosphere and no secondary conversion of tars is considered. The model is then used to calculate the conversion of a 180 mm diameter briquette of densified biomass. The application of the model allowed for the conclusion that the char burnout is delayed by the flow of volatiles, after it starts the increase of surface temperature leads to external diffusion controlled char combustion regime. In these circumstances considering the immediate release of gases without modelling gas phase combustion it is difficult to evaluate its effects on the particle. In the previous reference no comparison is done with particle temperature and the mass loss is observed to fit well to the conditions tested with the kinetic parameters for biomass decomposition of Thurner and Mann [3].

The primary products of biomass decomposition has been characterized by several authors leading to the definition of parallel reaction models that fit the results for specific biomass

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types under the test conditions considered, e.g. Nunn *et al.* [4] 1985), Yang *et al.* [5](2007) Miltner *et al.* [6] (2008) . The final yield of the components is specified from the test results and significant differences are observed depending on the biomass components and heating rates. The use of competitive reaction models were developed, e.g. Thurner and Mann [3] (1981), Font *et al.* [7] (1990) and Wagenaar *et al.*[8] (1993) that allow to estimate the yield of light gases, tars and char depending on the heating rate during biomass decomposition. Kinetic rates for tar decomposition into light gases and char by repolymerization was reviewed by Lu *et al.* [9] (2008). Boroson [10] (1987) characterized the light gas composition from tar decomposition and from elemental and energy balances can be estimated the heating value of the remaining tars.

Thunman *et al.* [11] (2001) presented a simplified model to address the composition of light gases and the heating value of oils formed during biomass conversion. These authors note that a comprehensive presentation of the thermo chemical properties of the fuel is still missing a situation that is still observed. Therefore the alternative is the use of empirical derived information that coupled with mass and heat balances provides a description of the biomass conversion.

The present paper is a contribution for the evaluation of this type of approach to represent the conversion of biomass particle during combustion and determine the level of detail required to represent the biomass conversion regarding the particle size.

Following this introduction, the model implemented is presented in section 2, including tests to evaluate the use of kinetic data from the literature. Section 3 presents the experimental characterization test carried out used to validate the numerical model. The results of different numerical approaches are discussed and addresses possible model simplifications. Section 4 presents conclusions and a general discussion on the obtained results.

## 2. MATHEMATICAL MODEL

This section presents a brief description of the model developed based on a one dimensional model presented in 2.1, where the local conversion

of biomass and tar is calculated as presented in 2.2.

### 2.1 One dimensional model

The model considered is based on the definition of a coordinate along the direction perpendicular to the initial external surface, in the present case of a cylinder in a procedure similar to Thunmann *et al.* [1]. This model can also be extend to a parallelepiped geometry as shown in figure 1.

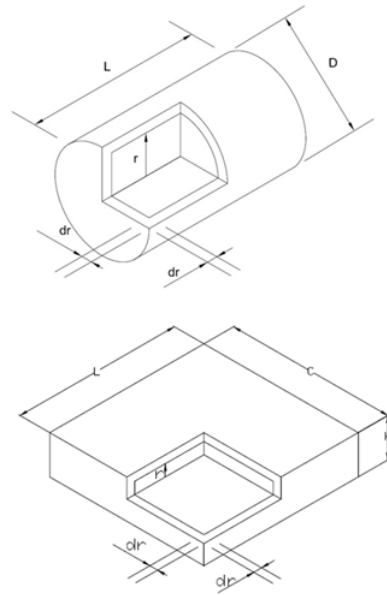


Figure 1: Layers model applied to parallelepiped and cylindrical geometry.

The area of each layer can be expressed as function of its radius and from the exterior particle dimensions.

$$A(r)_{cil} = 2\pi r(3r + L - D) \quad (1)$$

For parallelepiped particles, like wood chips, each particle layer is obtained from:

$$A(r)_{par} = 2(C'H' + C'L' + H'L') \quad (2)$$

Being:

$$C' = C - (H - 2r)$$

$$L' = L - (H - 2r) \quad (3)$$

$$H' = 2r$$

For spherical particles the area function is trivial. The main difference between the Thunman *et al.* [1] model and the present work is that the particle layers are considered with an initial fixed solid mass and their properties, namely the density may change along conversion due to shrinkage during drying, volatilization and chars combustion. Mass and energy balances are considered to describe the conversion of the particle. These balances include a transient term, diffusion and advection and sources. To define the advection resulting from the gas motion within the particle the velocity can be estimated assuming that all gaseous species flow immediately from the particle, or calculated more properly considering the biomass as a porous structure and from the Darcy equation, Eq.(4), achieve the velocity and pressure distribution:

$$u_g = \nabla P \frac{K}{\mu_g} \quad (4)$$

Where the permeability coefficient was considered an equivalent value based on the diameter/length ration with the biomass fiber parallel and normal coefficients suggested by Bellais [12]. With the char formation the particle permeability coefficient must be corrected. This value can also be revisited in the literature Yang *et al.* [13] and Bryden *et al.*, [14] with the reservation that the formation of cracks will increase drastically the gas permeability. Using this gas velocity in the continuity equation, Eq.(5), allow for the calculation of the pressure distribution within the particle, considering zero gradient at the centre and the outside pressure at the particle surface.

$$\frac{\partial(\varepsilon\rho_g)}{\partial t} + \frac{1}{A(r)} \frac{\partial}{\partial r} \left( A(r) \rho_g \frac{K}{\mu_g} \frac{\partial P}{\partial r} \right) = S_g \quad (5)$$

The gas density is calculated based on the local gas composition and the pressure. Based on the velocity distribution, the mass balance to individual species can be formulated as Eq.(6):

$$\frac{\partial(\rho_g Y_i)}{\partial t} + \frac{1}{A(r)} \frac{\partial}{\partial r} \left( \rho_g u_g Y_i A(r) \right) = \frac{1}{A(r)} \frac{\partial}{\partial r} \left( A(r) \mathcal{D} \rho_g \frac{\partial Y_i}{\partial r} \right) + S_{gi} \quad (6)$$

Where the individual mass sources of gas species are a result of biomass and gas phase conversion. The sum of the gas mass sources is used in the continuity equation. The mass balances are solved

for the light gas species, tar and oxygen. Boundary conditions are zero gradient at the centre and constant values outside the particle. These values have to be coupled to the conditions where the model is applied. In the present case the outside gas composition was set to the flue gas that surrounds the particle. This boundary condition is mainly important for oxygen once for the other species the outflow leads in general to the consideration of upwind scheme at the particle surface.

The energy balance within the particle. Eq.(7), considers also the four terms mentioned earlier. For the diffusion only conduction was considered with the conductivity values suggested by Bruch *et al.* [15].

$$\left( \rho_s c_{p,s} + \rho_g c_{p,g} \varepsilon \right) \frac{\partial T}{\partial t} + \frac{1}{A(r)} \frac{\partial}{\partial r} \left( \rho_g c_{p,g} T u_g A(r) \right) = \frac{1}{A(r)} \frac{\partial}{\partial r} \left( A(r) k \frac{\partial T}{\partial r} \right) + S_E \quad (7)$$

The energy source term is a result of the drying and reactions considered within the particle that are the oxidation of light gas species, tars and char. Biomass decomposition and secondary reactions are considered to occur without energy exchange. The kinetic rates for hydrocarbons and tar oxidation were adapted from Westbrook *et al.* [16] considering the reaction in two steps forming CO that is consumed by oxygen considering the kinetic rate proposed by Dryer *et al.* [17]. For char combustion the rate used by Porteiro *et al.* [2] was adopted but since the internal surface area was missing a value from Lu *et al.* [18] was considered.

During conversion is assumed that the particle size changes. First at the drying, where the moisture evaporation reduce significantly the particle size. For experiments performed with several types of biomass and found a linear reduction coefficient related with the water content as present on the next section.

Davidsson *et al.* [19] describes the formation of char with low temperature gradients, were the particle is submitted to a size reduction around 30%. Studies with other heating rates would be important to characterize the size reduction during volatilization. For the last stage of the particle combustion is admitted a typical density for the ashes of 548 kg/m<sup>3</sup>, Naik *et al.* [20] and recalculated the particle volume related to the char

combustion. At the end of the combustion, a particle of ash will remain.

## 2.2 Biomass decomposition

The application of the model requires the knowledge of the biomass drying and decomposition that leads to the release of gas products that evolve within the particle. The local description of the biomass is based on the calculated local temperature. For biomass drying three different approaches were tested and the procedure adopted was that proposed by Bryden *et al.* [21] that considers a kinetic rate, as presented in Eq. 8, and is the easiest to implement. In this equation  $\rho_w$  is the density of the moisture fraction, as the coefficients are in table 1. The index zero denotes the reaction that precedes the biomass decomposition as illustrated in figure 2.

$$r_0 = \frac{\partial \rho_w}{\partial t} = A_0 \exp(-E_0/RT) \rho_w \quad (8)$$

Biomass decomposition is considered from a competitive reaction model for which different kinetic parameters are tested.

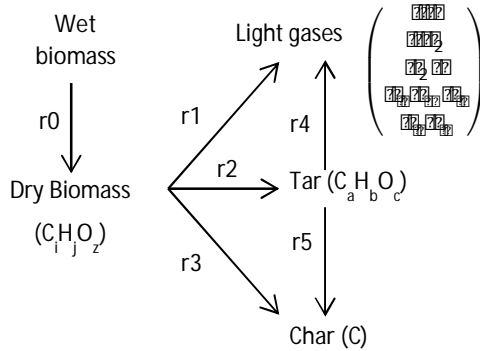


Figure 2: kinetic scheme for the biomass conversion used in this work

Like for the biomass drying, a similar expression is used to estimate the dry biomass conversion in light gases, tar and char. The coefficients are stated in table 1.

$$r_i = \frac{\partial \rho_b}{\partial t} = A_i \exp(-E_i/RT) \rho_b \quad (8)$$

Figure 3 presents the final yield of light gases, tar and char predicted by the application of different kinetic parameters compared with measurements

from other authors [22], [23], [4], [24] as a function of the heating rates considered.

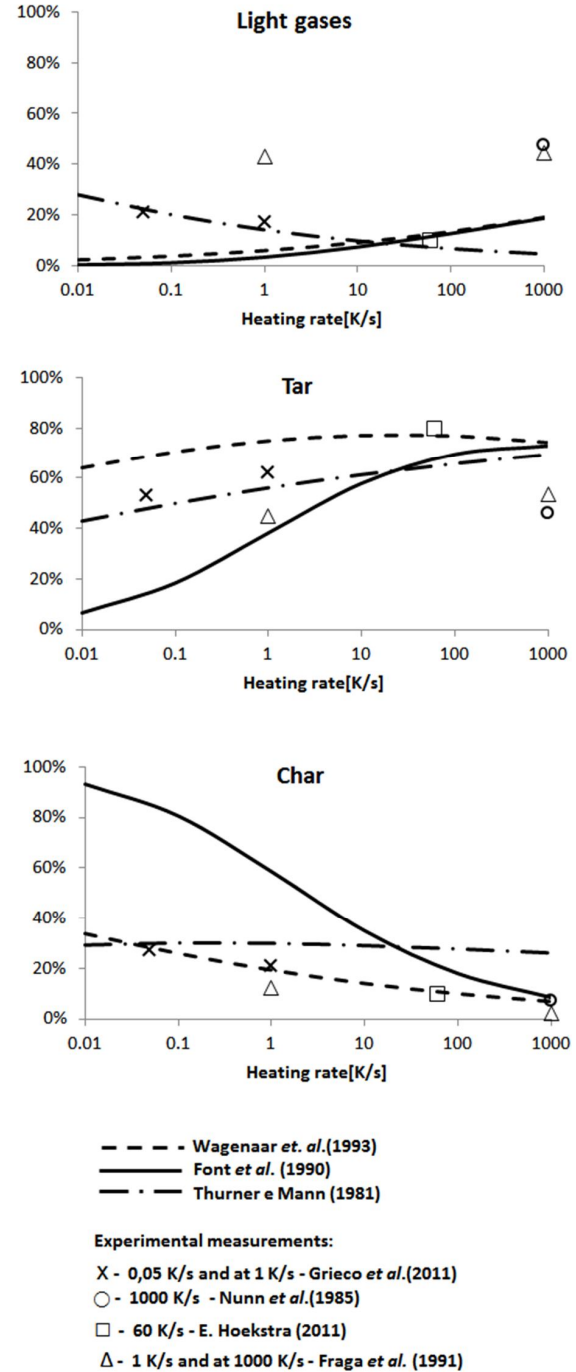


Figure 3: Percentage by weight of light end gases, tar and char for the primary reactions depending on the heating rate of the biomass. Comparison on the kinetics reported in the literature and comparison with experimental results.

The competitive reaction models were developed initially by Thurner and Mann [3] and Font *et al.* [7] for heating rates from 10 to 70 K/min in Thermo Gravimetric Analyzers (TGA) with particle sizes from 300 to 600  $\mu\text{m}$  while the work of Wagenaar *et al.* [8] with particle sizes from 100 to 200  $\mu\text{m}$  including data from an Entrained Flow Reactor allowed to extend the heating rate to 650 K/s.

Table 1: Kinetic parameters used on the reaction illustrated on figure 2

Reaction	A [s <sup>-1</sup> ]	E [kJmol <sup>-1</sup> ]	Ref.
r <sub>0</sub>	$5,13 \times 10^{10}$	88	Bryden <i>et al.</i> [21]
r <sub>1</sub>	$1,11 \times 10^{11}$	177	Wagenaar <i>et al.</i> [8]
r <sub>2</sub>	$9,28 \times 10^9$	149	Wagenaar <i>et al.</i> [8]
r <sub>3</sub>	$3,05 \times 10^7$	125	Wagenaar <i>et al.</i> [8]
r <sub>4</sub>	$4,48 \times 10^6$	107,5	Liden <i>et al.</i> [25]
r <sub>5</sub>	$1,00 \times 10^5$	107,5	Di Blasi [26]

This may explain the best qualitative behavior of the later kinetic rates compared with experimental results. Nevertheless the Wagenaar *et al.* [8] leads to an over predicted value of tar yield and lower values of light gases an effect that may be corrected by the consideration of secondary reactions.

Figures 4 and 5 presents the calculated mass loss from the competing reaction models compared with experimental results obtained at two very different heating rates. It can be confirmed that the final yield is correctly predicted as expected from Figure 3 but the mass loss is also predicted at the temperature range when it is observed, namely 900°C and 1200°C, respectively for the slow (10°C/min) and fast (1000°C/s) heating rates. These results enhance confidence on the use of the competing reaction model with the kinetic parameters of Wagenaar *et al.* [8].

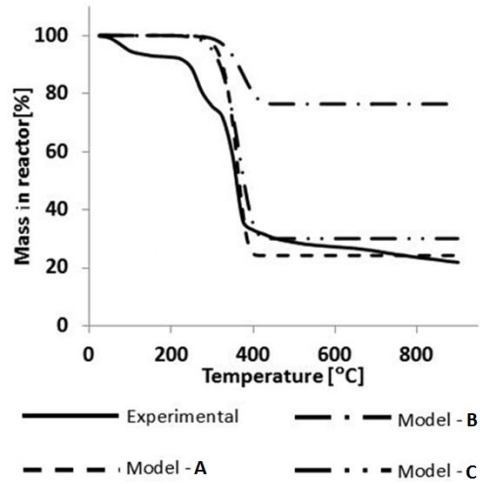


Figure 4: Comparison between experimental data and the models on the literature for the conversion of biomass. It was taken a heating rate of 10 °C/s and a maximum temperature of 900 °C.

Experimental: Yang *et al.* [5]; Model A: Wagenaar *et al.* [8]; Model B: Font *et al.* [7]; Model C: Thurner and Mann [3]

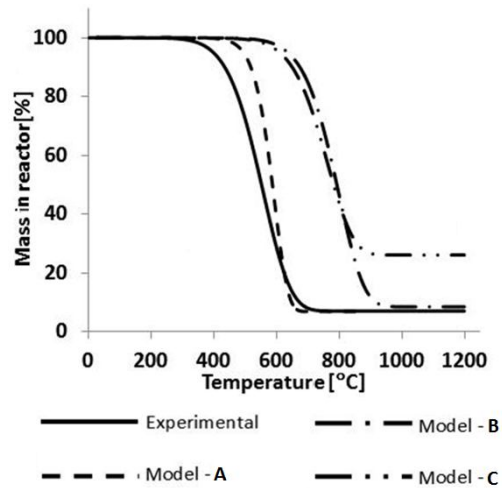


Figure 5: Comparison between experimental data and the models on the literature for the conversion of biomass. It was taken a heating rate of 1000 °C/s and a maximum temperature of 1200 °C.

Experimental: Nunn *et al.* [4]; Model A: Wagenaar *et al.* [8]; Model B: Font *et al.* [7]; Model C: Thurner and Mann [3]

The competitive reaction models developed do not identify the light gas species nor identify the properties of the tar evolved. To complement the kinetic biomass decomposition model, data from other sources was considered to characterize the process. The composition of the light gases, CO, CO<sub>2</sub>, H<sub>2</sub>O and an equivalent C<sub>n</sub>H<sub>m</sub>O<sub>k</sub> representing a lump of other light gases, was fixed with the values observed by Nunn *et al.* [4]. Other approach on this can be found in Thunman *et al.* [11] and Neves *et al.* [27].

The high heating value of the light gases as a whole is 10.5 MJ/kg and since the Wagennar model parameters under predicts the value of light gas yield over predicts the yield of tars, the high heating value for these are estimated as 20.7 MJ/kg compared with the value of 25.7 MJ/kg obtained by Nunn *et al.* [4]. Based on the composition of the tar calculated from the elemental balances the high heating value can also be estimated, e.g. by a correlation from Manson e Ghandi [28] and the results are consistent with better agreement for the higher heating rates from which the light gas composition was taken.

Another important aspect is that combining the use of competitive and parallel reaction models allows the estimate of the modification of the heating value of tars that for a low heating rate of 1°C/s was estimated as 17 MJ/kg.

For the secondary reactions was used the kinetics parameters from Liden *et al.* [25] and from Di Blasi [26], presented in table 1, to simulate the competitive decomposition reaction in the tar, reactions 4 and 5 represented in figure 2. To estimate the light gas production in this reaction were studied the results from Boroson [10] that include 2.34% of char and a mixture of gases with a mass composition (59.77 % CO; 12.93 % CO<sub>2</sub>; 1.75% H<sub>2</sub>O and 25.55% C<sub>x</sub>H<sub>y</sub>) where the later was characterized with x=1.46; y=5.46 and the high heating value was estimated as 57 MJ/kg. This data was derived from results obtained at 800°C and heating rate of 10°C/min. Based on this data and the results from the primary decomposition the remaining tars from the secondary reactions have high heating values from 22 to 45 MJ/kg.

### 3. MODEL TESTING AND DISCUSSION

#### 3.1 Test results and numerical comparison

To test the model developed and to further document the combustion of a biomass particle, a test section, shown in figure 6, was prepared consisting of a square section channel (110 cm<sup>2</sup>) where hot gas was supplied from the bottom from a matrix of nine burners with a total capacity of 20 kW. The wood sample was a cylinder with vertical axis 50 mm of diameter, 150 mm long made of dried acacia trunk with an initial density of 510 kg/m<sup>3</sup>.

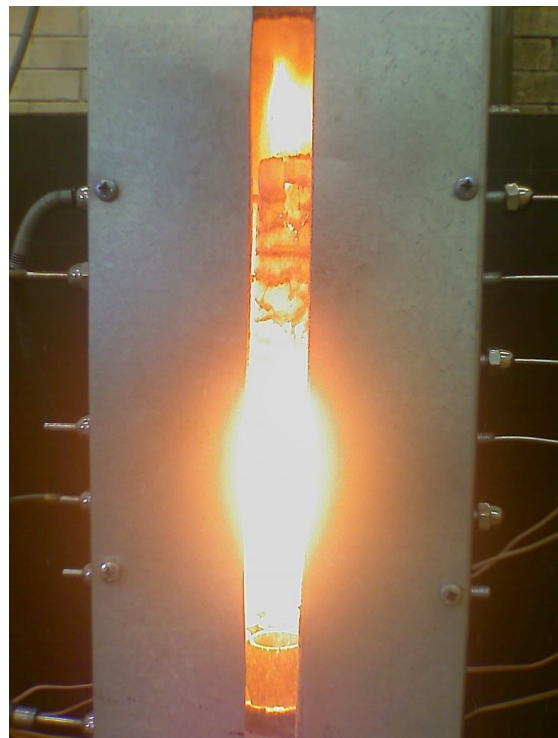


Figure 6: Test section, with an observation window. Image collected 300 s after the test beginning.

The test section, was installed over a weighting scale and temperature measurements were made for the gases surrounding the wood sample from which the temperature was 1200 K. A thermocouple was also inserted at the center of the trunk. Others thermocouples were installed to control the hot gas temperature after the burner reaction zone and near the particle surface. The average composition of the hot gases surrounding the particle was measured. In a dry basis was measured 5% O<sub>2</sub>, 14% CO<sub>2</sub> and 0.2% CO. These conditions were used in the numerical modelling.

Figure 7 and figure 8 show the evolution of the

mass of the particle over time and temperature measured at the center of the particle via a thermocouple. The figure includes the results obtained in the numerical model considering 30 layers and a step time of 0.05s.

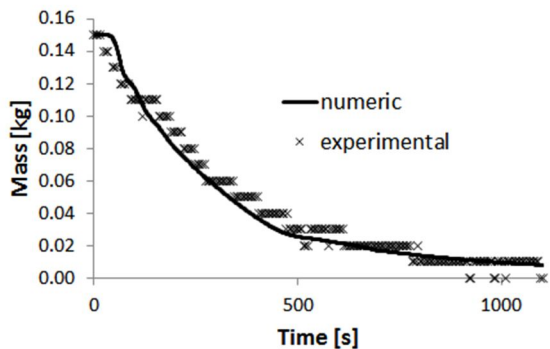


Figure 7: Variation of the particle mass during the conversion.

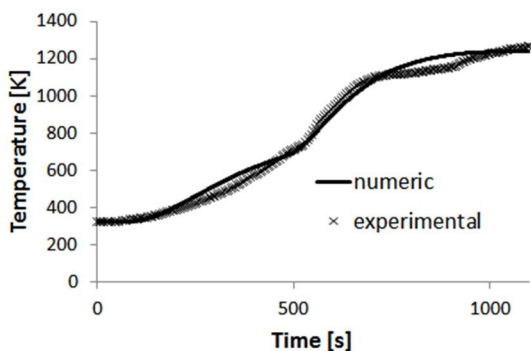


Figure 8: Temperature evolution within the particle throughout the conversion.

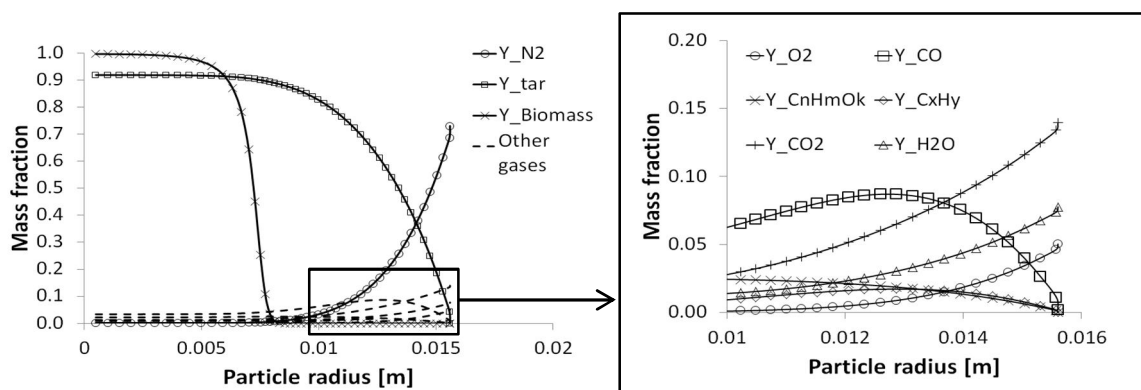


Figure 9: Mass concentration of gaseous species within the particle obtained with the model after 400 s

Much of the computational effort results from modeling the flow of gases and their conversion into the particle. This modulation must be performed in order to know the effect of diffusion of oxygen and residence time of the tars in the particle, thus knowing whether the contribution of the intrinsic combustion in the gaseous species and the secondary reactions inside the particle is substantial or not.

The particle shrinkage is simulated using shrinkage coefficients characterized in this study by drying the particle at 105 °C, presented in Eq.(8). For different types of biomass, acacia and pine wood, as well with densified biomass in pellets and briquettes was found that the volume reduction is approximatively linear with the water content in the solid biomass  $Y_{W,s}$ . A similar shrink coefficient is found in Wood Handbook [29].

$$(8)$$

While the biomass conversion occurs, the gaseous species are transported by advective and diffusive mechanisms. The numerical results predicts that the species gradient occur from the biomass conversion front to the exterior boundary, figure 9. The gas composition at the particle center is expected to be similar to the gas species produced in the volatilization. At the beginning of the volatilization the gas transport is mainly advective with Peclet numbers around 10, decreasing to values less than one during the char combustion.



For bigger particles the biomass conversion is more time consuming and the converted gas remains inside the particle more time. With big particles the gas flow resulting from the conversion in the center of the particle can be as small that it can't prevent the diffusion of oxygen to the exterior layers of the particle. In this situation the char combustion begin at the particle exterior while the interior still in conversion, so the resulting gas species may combust.

The same analysis can be performed with the tar decomposition. As the tar flows to the particle exterior it encounters the exterior layers at high temperature and, with the required time, will convert to other species. For small particles, say bellow 20 mm, as can be observed in figure 10, the tar decomposition by the secondary reaction is residual.

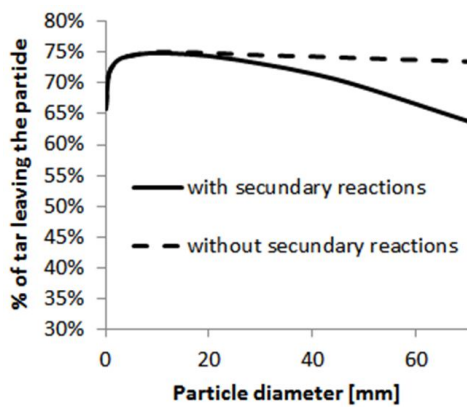


Figure 10: Mass of tar released as a function of particle diameter, with and without secondary reactions.

The numerical study shown in figure 11, estimate that, in typical combustion conditions, the oxidized gases is significant for particles with a diameter more than 50 mm

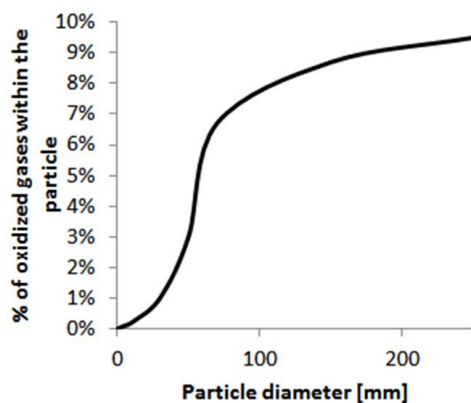


Figure 11: Percentage of combustible gases oxidized within the particle in function of its outer diameter.

### 3.2 Discussion and model simplifications

The results presented above leads to the possibility of a simplification in the numerical modelation to be used with small particles, with a diameter bellow 20 mm. The simplification neglets all homogeneous reactions inside the particle, i.e., the secondary reaction of tar decomposition and the combustion inside de particle. Doing this, the computational effort is reduced being the results similar to obtained in the detailed model. In figure xx is shown a comparison between the detailed model (model 1) and the simplified model (model 2) for a wood pellet with 6 mm diameter and 24 mm length. The small differences observed in figure 12 may be justified by some combustion of the gas inside the particle.

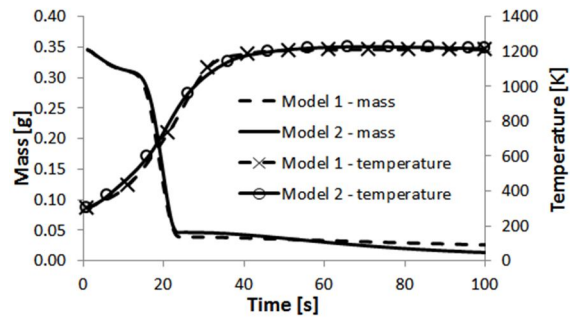


Figure 12: Comparison of the evolution of mass consumption and temperature at the center of the particle during the conversion between the detailed model (Model 1) and the simplified model (Model 2).

The next consideration to make is whether or not the temperature gradients inside the particle must be considered. Using the simplified model, was analyzed the particle conversion process in two particles, with the same conditions, maintaining the same diameter/length relation but with different sizes. For a particle with 50 mm diameter and 200 mm length, the temperature gradients cannot be neglected, as can be observed in figure 13. Nevertheless, for a small particle, like a wood pellet with 6mm diameter and 24 mm length the differences between the simulation performed with some layers and only one layer are less significant than the obtained for the larger particle, as can be observed in figure 14.



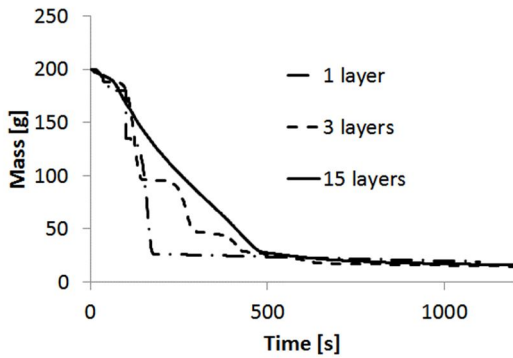


Figure 13: Mass consumption during the conversion of a particle with 50 mm diameter and 200 mm length using the simplified model with different number of layers.

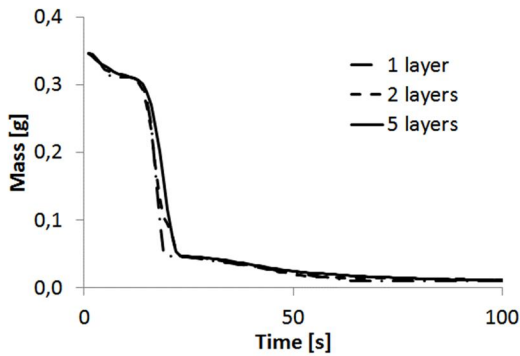


Figure 14: Mass consumption during the conversion of a particle with 6 mm diameter and 24 mm length using the simplified model with different number of layers.

The temperature gradient exists inside both particles, being less steeply in the smaller particle. The smaller particle heats faster and with more homogeneity. Performance an average for the evolution of the mean temperature in all particle, for the simulation parameters is obtained in the simulations that the smaller particle has a heating rate around 20 °C/s during the volatilization period, while the bigger particle as a much smaller heating rate, around 1 °C/s.

Simulating for different particle sizes, from 1 mm to 50 mm diameter, using for the small particles at least five layers, is shown that the heating rate during the volatilization of the particle, as an all, follow an power function stated as Eq.(9).

$$\text{---} \quad (9)$$

#### 4. CONCLUSIONS

The numerical simulation of biomass conversion has been present by several authors with different approaches and level of detail. In the biomass conversion four processes were identified to modulate: particle heating, thermal decomposition, gas species flow through the particle and gas and char combustion. The thermal decomposition can be modelled by structural models like the CPD and FG-DVC or by simple kinetic models that predicts the product formation using an Arrhenius equation. In the last case the models can be divided into two classes, global models were the final products of the biomass conversion are prescripts and competitive models were the final products depend on the particle heating rate. Wagenaar [8] present kinetic expressions for the competitive model that reproduce the experimental results of other authors (Grieco, *et al.* [22], E.Hoekstra [23], Fraga *et al.* [24]) but needs a more comprehensive analysis to quantify the light gas species and tar composition. In this work, the analysis of different kinetic parameters was performed studying values from the literature and confirmed with the evaluation of the mass loss in a converting particle in laboratory. Since the biomass decomposition depends on the particle temperature, the thermal modulation is other issue that must be analyzed.

The shape of the biomass particles may be approximated by simple spheres, cylinders or parallelepipeds. A tridimensional discretization would produce a more correct temperature distribution results, but is not acceptable when a simple and less time consuming model is required. The particle discretization in concentric layers produced good results, confirmed by the temperature evolution in the performed tests. Nevertheless, the temperature distribution is not so important with the conversion modulation on small particles.

For particles such as wood pellets, although the temperature gradient exists inside the particle, their effect on the biomass decomposition, depending on the level of accuracy, may be neglected. For large particles, beside the temperature gradient, the residence time of the gas species produced during the volatilization allow further homogeneous reactions, such as the decomposition of tars, known as secondary reactions, and the oxidation of combustible species as they may react with the

oxygen diffused from the exterior. The detailed model present in this work performs the simulation inside the particle as a porous medium solving the Darcy equation together with the continuity equation. For particles smaller than 20 mm, with an error less than 1%, the homogeneous reactions inside the particle may be neglected, and so, in this condition can be assumed that all the gas species flow immediately to the particle exterior without the need to solve the velocity distribution.

Removing from the detailed model the velocity distribution and the homogeneous reactions, the particle intern gradients depend mainly from the temperature distribution. At last was analyzed the effect of the number of layers needed to simulate the conversion of a small biomass particle like a wood pellet with 6 mm of diameter. The numerical results show that, depending on the needed accuracy, one single layer can produce good results. It can be justified by the smaller temperature gradients inside the particle and higher heating rate.

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