Component Oriented Modeling of Biomass Incineration Plants

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Abstract: The thermal treatment of biomass in the so called incineration plants represents one of the most appealing ways for biomass treatment. It reduces not only the volume of the disposed biomass, but also it can convert the heat produced by the combustion into electrical energy or steam for the district heating. Any organic non-fossil fuel can be considered as a biomass such as industrial and municipal waste and any material that was created by a photosynthesis reaction. Hence, it can contribute considerably in the global energy supply, as it can be collected from different sources. However, the variability in biomass composition, the complex thermochemical reactions and heat transfer phenomena occurring during the combustion have justified the development of multiple mathematical models to investigate the process as precisely as possible. Usually, they aim to achieve a better combustion chamber design. Unfortunately, these models are very complex and very detailed, composed mainly of a set of partial differential equations that cannot be considered if the intent is the control of the plant. Hence, the goal of the proposed work in a first step is to reduce the present complexity by proposing a simplified mathematical model that captures the main dynamics present inside the incineration chamber. The model takes the heterogeneous solid phase and the homogeneous gas phase into account, and it considers the large unsteady variation in the biomass composition. The control part of the plant is also addressed by giving an overview on the current control schemes that are used in the context of biomass combustion control. Finally, the model is implemented using the object-oriented language Modelica in order to investigate the dynamic behavior of the system.

1 INTRODUCTION

In the last decades, the energy recovery from biomass took a special attention. The driving force for this is its availability in abundant amount, as it can be collected from different sources (ranked fourth as energy source after coil, oil, and natural gas. Any organic non-fossil fuel can be considered as a biomass fuel such as crop residues, industrial and municipal refuse or any material that was created by a photosynthesis reaction. Therefore, it contributes considerably to the global energy supply (over 14% of the total global energy) and can be more exploited than it has been so far (Van Loo and Koppejan, 2008).

One of the most appealing ways for energy recovery from biomass is via grate combustion which represents the state-of-art technology for the thermal treatment of biomass (Yin et al., 2008). It combines efficiency with low investment costs. Furthermore, grate combustion of biomass reduces the landfill volume and mitigates the environmental impact of active organic compounds which can leach and affect the underground water, or creates an odor nuisance otherwise. Due to the variability of the biomass composition such as the moisture content, its calorific value, and the intrinsic complexity of the combustion process which consists of heterogeneous and homogeneous reactions (Nussbaumer, 2003), this will lead to a variability in the operating conditions of the incineration plant, which would compromise the combustion efficiency (Rovaglio et al., 1998). Therefore, a need for suitable control is important to account for these variations.

The main emphasis of this work is to give a concise introduction to the biomass combustion process and to motivate the development of a simplified mathematical model which is simple enough to be used as a basis for an advanced model-based control strategy, as there is only few work that has been reported in the control part of the plant.

The paper is organized as follows: in Section 2, a

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brief description of the plant where the incineration of the biomass takes place is given followed by an introduction to the main thermal decomposition elements which the biomass undergoes in the moving grate. In Section 3, a mathematical modeling concept for the process is proposed along with a brief overview on the control part of the plant. Section 4 deals with the implementation and the simulation of a part of the system.

2 PROCESS DESCRIPTION

As already mentioned, an efficient way to convert biomass into a usable energy is through combustion that takes place in so called *incineration plants*. The biomass or the municipal waste is transported by means of a truck or a train to the plant where it is discharged into a storage unit called *Bunker*. Consequently, the disposal is gripped and moved to a large chute where it is thrown (see Figure 1).

At the bottom, the biomass, referred to as *fuel*, is fed into the incineration chamber by a horizontally moving ram and transported through the combustion chamber by a moving grate. The grate has in addition a rich oxygen air installation beneath, from which air is gradually added through existing holes in order to provide good stoichiometric combustion conditions inside the chamber.

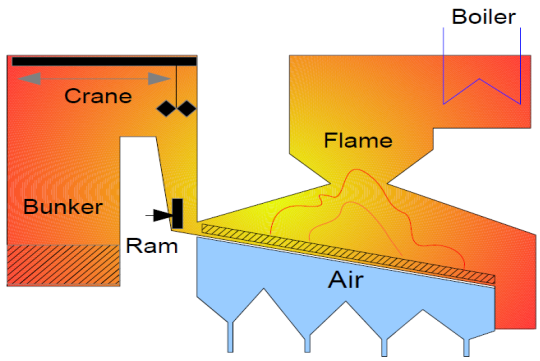


Figure 1: Incineration plant.

2.2 Biomass Thermal Decomposition Process

While the biomass is traveling along the combustion chamber by the moving grate, two main phases can be distinguished: *a solid phase* and *a gas phase*. The solid phase can be further divided into 4 steps: the drying, pyrolysis/gasification, char burning, and finally ash as an end product. In the gas phase, a secondary air is introduced above the grate in order to achieve good mixing conditions of the volatiles and unburned gases released in the previous step, i.e. the solid phase. The obtained hot gas, referred to as *flue gas,* is further transferred to a boiler where the steam is produced, that can be used as either in district heating or in electricity production by a turbine.

2.2.1 Drying

This step is very crucial and can have a strong influence on the overall behavior of the combustion in general and the temperature distribution inside the chamber in particular. Moreover, as the pyrolysis/gasification, char oxidation and ash take place at a predefined position on the grate, a biomass with high moisture content requires a longer time to be dried. As a consequence, they shift their position on the grate as reported in (Bauer et al., 2010). Therefore, it can be concluded that the moisture content in the biomass is an important variable.

The biomass moisture content evaporates at temperatures >100 °C. This can be achieved by radiation at the top of the fuel bed or by heat conduction through the grate bars. Other plant suppliers use a pre-heated primary air to speed up the drying process. Consequently, the evaporated water is transported by the primary air mass flux to the upper part of the waste bed. Lastly, it should be noted that the moist evaporation is an endothermic process in the sense that it absorbs heat from the chamber. (Van Loo and Koppejan, 2008) reported that for a moist content above 60% the flame cannot be maintained in the combustion chamber.

2.2.2 Pyrolysis/Gasification

After the wet biomass is dried in the previous step, the temperature in the chamber starts to rise considerably. As soon as the temperature reaches a certain level, another thermal degradation of the fuel takes place, namely the pyrolysis and its associate the gasification. The pyrolysis occurs under oxygen deficient conditions and high temperature levels, which break up the hydrocarbons of the form $CH_xO_yN_z$ into smaller species such as methane (CH_4), carbon monoxide (CO), hydrogen (H_2), nitrogen (N_2), and residual carbon called char.

In contrast to pyrolysis where no oxygen exists in order to oxidize the gasified hydrocarbons, the gasification takes place in the presence of a limited amount of oxygen, i.e. the thermal decomposition is kept under stoichiometric levels. The product of this phase is a combustible gas that will be burned in a

homogeneous reaction step above the fuel bed. Besides the difference in the oxygen amount used in these two thermo-chemical processes, the pyrolysis is maximized in terms of the char and tar produced, while the gasification phase is maximized in terms of combustible gas produced. Figure 2 shows the levels of the oxygen present during the thermo-chemical degradation of the biomass fuel as well as the obtained products from both the pyrolysis and gasification processes, and in the homogeneous gas phase, i.e. combustion.

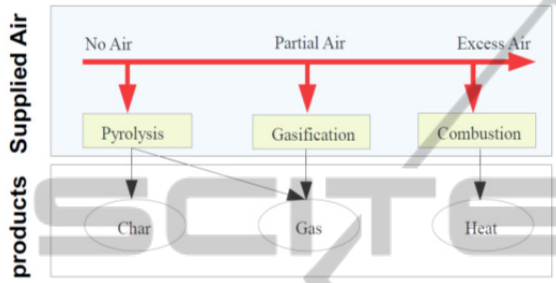


Figure 2: Oxygen levels during the thermo-chemical degradation of the biomass fuel and the associated products (Nussbaumer, 2003).

2.2.3 Char Oxidation

After the pyrolysis step is finished and the amount of carbon yield, called char, is maximized, the oxidation process of char begins. The char oxidation is undergone under high temperature levels and oxygen-rich conditions. It is useful to illustrate this process by a particle which is heated from the outer surface surrounded by a high oxygen pressure in order to allow for the oxygen diffusion to the inner core of the char particle. This thermal process releases a considerable amount of the remaining energy. Hence, it is an exothermic reaction. The gases released in char oxidation consist mainly of carbon monoxide (CO), and carbon dioxide (CO_2).

2.2.4 Ash

This is the last step of the biomass thermo-chemical decomposition. It consists of the remaining residues from the combustion process, such as unburned matters, or the by-product from the char combustion called *ash*. This residue is generally collected at the output of the plant in a collection pit.

3 PROCESS MODELLING AND CONTROL

In order to build the set of the mathematical equations used in the model, two common modelling approaches in the context of combustion process modelling are mainly presented: *lumped modeling*, and distributed *modeling*. In the lumped modelling approach the governing equations are merely based on first-order principles, i.e. mass and energy balances. As a result, the equations will be a set of ordinary differential equations (ODE's). In contrast to the lumped model, the distributed modeling approach, referred to as two-dimensional modeling, depends not only on time, but also on space leading to partial differential equations (PDE's) (Yang et al., 2004).

The former approach is used if the intent of the model is to be deployed in model-based control strategies (Rovaglio et al., 1996), (Bauer et al., 2011), (Van Kessel and Van Loo, 2011), (Paces and Kozek, 2011). The latter approach is largely used to simulate the phenomena present in a combusting fuel bed (evaporation, pyrolysis/gasification, char burring and ash) leading to a model with set of equations of a high complexity that prohibit its use as a basis for a model-based design of control systems. Nevertheless, the distributed modelling is a commonly adopted approach to simulate the gas phase and to optimize the design of the incineration chamber in order to achieve better combustion efficiency by using Computational Fluid Dynamics software (CFD).

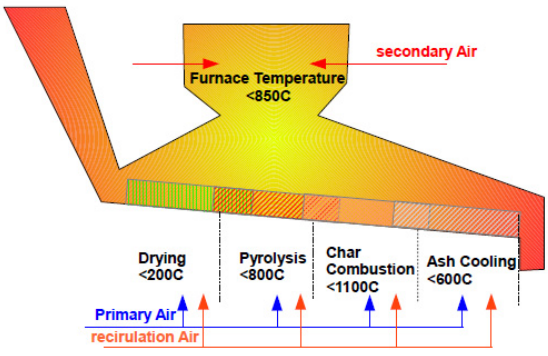


Figure 3: Biomass thermal decomposition processes occurring on the moving grate.

3.1 Mathematical Modeling Concept

The main core of this work is the development of a mathematical model for the combustion process in a biomass incineration plant, which is simple and

accurate enough to capture the main dynamics occurring during the thermal decomposition of the biomass on the moving grate, as well as in the gas phase. As a consequence, the elaborated model can be used as a basis for a model-based control strategy and to investigate the influence of the control parameters on the combustion process. Hence, the temperature inside the chamber and the amount of steam delivered to the turbines for electricity generation.

The combustion process of biomass on the moving grate is divided into different zones depending on the individual thermal decompositions occurring on the grate, i.e. drying, pyrolysis/gasification, char oxidation, and ash. These steps occur at distinct positions on the grate and might overlap with each other to some extent (see Figure 3). Therefore, in the building of the mathematical model concept, it is advantageous to represent each of these zones by a number of the well-known Continuous Stirred Tank Reactors (Schmidt, 1998) arranged with each other in cascade as shown in Figure 4.

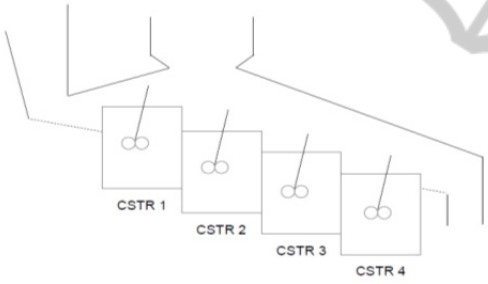


Figure 4: The proposed modeling concept of biomass combustion process.

Such a representation of the combustion model enables a simplified mathematical description of the process leading to a first-order principle based model, since the governing equations describing the dynamics on the firing grate will be based solely on mass and energy balances.

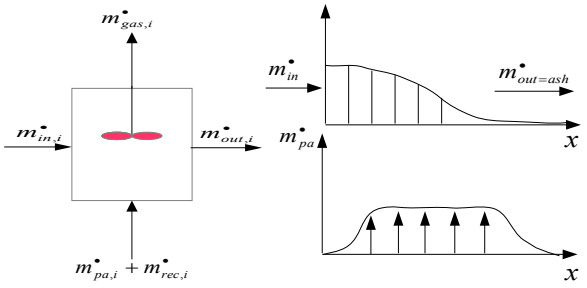


Figure 5: Mass entering a zone (i) of the fuel on a moving grate.

Figure 5 represents the mass entering a zone (i), which is represented by a CSTR, at time t+Δt. It should be noted that the mass $m_{in,0}$, given in [kg], is mainly composed of moisture, volatile matters, carbon and ash.

$\dot{m}_{pa}$ and $\dot{m}_{rec}$ represent the primary air and recirculated gas mass flow respectively given in [kg/s]. The amount of primary air as well as the recirculated gas can vary depending on each zone air requirement. Hence, they can be formulated as follows:

$$\dot{m}_{pa,i} = \Omega_{pa,i} \cdot \dot{m}_{pa} \tag{1}$$

$$\dot{m}_{rec,i} = \Omega_{rec,i} \cdot \dot{m}_{rec} \tag{2}$$

$$\dot{m}_{tot1,i} = \dot{m}_{pa,i} + \dot{m}_{rec,i} \tag{3}$$

Where $\Omega_{pa,i}$ and $\Omega_{rec,i}$ are the air distributions at a zone (i).

From Figure 5 it is clear that the mass balance equation can be formulated as:

$$\frac{dm_{s,i}}{dt} = \dot{m}_{in,i} - \dot{m}_{out,i} - \dot{m}_{gas,i} \tag{4}$$

and

$$\dot{m}_{out,i} = \frac{m_{s,i}}{\tau_i} \tag{5}$$

$\dot{m}_{gas,i}$ represents the mass substance which is converted from solid to gas phase, that can be presented by an Arrhenius type reaction rate. τ_i represents the time which the mass spends inside a given reactor (residence time).

The overall residence time of the biomass inside the system τ_{total}[s] can be modeled by the following approach:

The horizontal grate is assumed to be moving with a velocity V_{grate}[m/s] and has a length D [m], whereas the biomass moves along the incineration chamber with a velocity $V_{biomass}$ [m/s].

α [deg] is the inclination angle of the moving grate relative to the horizon which can be obtained from the plant construction data (see Figure 6). Hence, $V_{biomass}$ is related to V_{grate} by:

$$V_{biomass} = \frac{1}{\cos(\alpha)} \cdot V_{grate} \tag{6}$$

with

$$V_{grate} = D \cdot Freq \tag{7}$$

Finally,

$$\tau_{total} = \frac{L}{V_{biomass}} = \frac{L \cdot \cos(\alpha)}{V_{grate}} \quad (8)$$

where L [m] is the total length of the grate system, *Freq* [1/s] is the frequency with which a given grate moves.

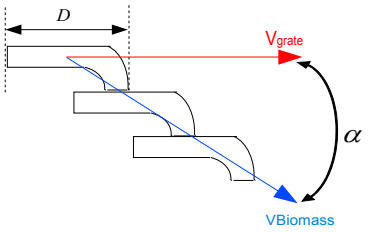


Figure 6: The grate system.

Consequently, the residence time τ_i can be directly computed by dividing the total residence time by the number of the CSTRs used as follow:

$$\tau_i = \frac{\tau_{total}}{\#CSTR} \quad (9)$$

Similar to the solid phase, a mass balance for the gas phase can be drawn. It should be noted that in the gas phase, a secondary air mass flow rate $\dot{m}_{sec}$ [kg/s] is injected together with the amount of primary air blown under the grate.

$$\frac{dm_{gas}}{dt} = \dot{m}_{gas,in} + \sum_i \dot{m}_{tot1,i} + \dot{m}_{tot2} - \dot{m}_{gas,out} \quad (10)$$

Where

$$\dot{m}_{tot2} = \dot{m}_{sec} + \dot{m}_{rec} \quad (11)$$

$\dot{m}_{tot2}$ [kg/s] is the sum of the mass flow rate of the secondary as well as the recirculation gas.

To enclose the proposed modelling approach, the energy balance for both solid and gas phases are derived. For simplicity, it is assumed that the main heat exchange process is the radiation between the gas cloud on top of the combusting bed and its surface, since it is the most dominating heat transfer mechanism inside the combustion chamber.

The energy balance equation for both mass and energy balance are given by:

$$C_{p_s} \sum_i m_{s,i} \cdot \frac{dT_{s,i}}{dt} = \dot{Q}_{in,i} - \dot{Q}_{out,i} + \dot{Q}_{rad} \quad (12)$$

$$C_{p_g} \cdot m_g \cdot \frac{dT_g}{dt} = \dot{Q}_{gas,in} + \dot{Q}_{sec} + \dot{Q}_{pa} + \dot{Q}_{rec} - \dot{Q}_{gas,out} - \dot{Q}_{wall} - \dot{Q}_{rad} + \dot{Q}_{combustion} \quad (13)$$

where

$$\dot{Q}_{combustion} = \dot{m}_{biomass} \cdot H_{LHV} \quad (14)$$

and

$$H_{LHV} = H_{HHV} - h_{H_2O} \cdot \left(\frac{K \cdot \omega}{V_n}\right) \cdot M_{H_2O} \quad (15)$$

$\dot{m}_{biomass}$ is the mass flow rate of the solid biomass fed into the incineration chamber [kg/s], H_{LHV} and H_{HHV} are the lower and higher heating value of the feed fuel [kJ/kg] that can be determined from the approximate or the ultimate analysis of the biomass (see Figure 7), h_{H_2O} is the evaporation enthalpy of water (2443kJ/kg).

```
model Enthalpy
 extends Components.Constants;
  Connectors.RealInput C, H,O,N,S,W,A" Ultimate
analysis";
  Connectors.RealInput K;
  Connectors.RealInput Omega;
  Connectors.RealOutput H_HHV;
  Connectors.RealOutput H_LHV;
  equation
  // Lowe Heating Value LHV
 H_HHV=32.79*C+120.9*(H-(O/8))+9.28*S-
2.443*W;
  // Upper Heating Value HHV
 H_HHV=H_LHV+Enthalpy_H2O*((K*Omega)/V_n)*
M_H2O;
end Enthalpy;
```

Figure7: Modelica code for computing the lower heating value of biomass.

For the following exemplary ultimate composition of the biomass (see Table 1), some valuable results can be extracted from the global combustion model (see Figure 8):

Table 1: Biomass ultimate analysis composition [%].

	C	H	O	N	S	W	A
Biomass	38.25	5.49	29.95	1.22	0.30	10.00	13.78

Lower and Higher biomass heating values:

	Value	Unit
H_{HHV}	1465.97	MJ/kg biomass
H_{LHV}	14.5838	MJ/kg biomass

Air quantity L_{min} and L:

	Value	Unit
L_{min}	3.9106	m^3 Air/kg biomass
L	6.6481	m^3 Air/kg biomass

L_{min} is the minimum required air quantity to burn one kilogram of the biomass fuel.

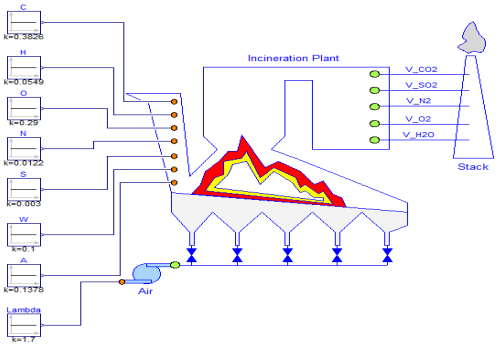


Figure 8: A global biomass combustion model implemented in Modelica.

3.2 Plant Control: Overview

The control of an incineration plant is a complex, multi-objective and elaborative task due to the intrinsic complexity of the combustion process, as well as the fuel components and its calorific value variation. This is further complicated by the stringent environmental laws on the allowed gaseous emissions (Rovaglio et al., 1998). Such concerns have strong consequences on the operating conditions of the process leading to disturbances and fluctuations in the temperature inside the chamber if the process is not stabilized by an appropriate control action. This calls for the implementation of a reliable control system that is robust enough to reject the aforementioned disturbances and to maximize the energy recovery from the biomass, in the meantime assuring acceptable levels of emission (Bardi and Astofli, 2010).

Clearly, the process control system should integrate both environmental and energy production aspects, and its efficiency should be evaluated based on (El Asri and Baxter, 2004):

-The achieved burnout in the solid and gas phases.
-The achieved plant throughput and energy recovery.
-The achieved emission control of the gaseous gases.

The associated indicator for this is the amount of oxygen concentration in the flue gas which should be limited to 8% for the case where the emission level has to be controlled. For the plant throughput and consequently the energy recovery, the main indicator to be controlled is the steam temperature and the steam flow rate. These two indicators, i.e. the oxygen concentration and the steam flow are referred to as the controlled variables, which are the variables that have to be influenced by the control action in order to achieve constant and uniform operating conditions. The following manipulated as well as the controller variables in an incineration plant are reported in Figure 9.

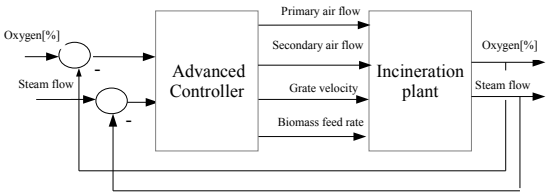


Figure 9: Control scheme of a biomass incineration plant.

The present situation indicates that the control systems present in an incineration plant are a network of the classical PID controllers, which allows the plant operators to intervene by parameter tuning of these controllers (Pirouti et al., 2010). As a matter of fact, the plant can be run in sub-optimal operating conditions due to the non-optimized structure of aforementioned control scheme, which can contradict the economical objective imposed by the plant managers, i.e. maximizing the revenue of the plant by increasing the throughput. Hence, generating more steam for electricity generation or for district heating.

Therefore, the classical control schemes turn out to be inferior in comparison to existing advanced control techniques such as model predictive control (MPC) (Leskens et al., 2005), (Paces and Kozek, 2011), Neural Networks and Fuzzy logic. A detailed discussion of these techniques would be out of the scope of this paper. These three control strategies are so far the most appealing advanced control strategies that would assist the plant operators and compensate the sub-optimal operating conditions generated by the classical PIDs.

4 SIMULATION

In a first step of the proposed model (see Figure 10), only one continuous stirred tank reactor has been tested to investigate the assumptions done on the modeling concept of the plant. The Modelica® model of the CSTR is simulated using Dymola®, which is an objected-oriented language for modeling complex physical systems (Tiller, 2004), where the overall model is broken down into sub models, referred to as *components*. A component has a predefined set of connectors that determine the interaction between other components sharing the same type of connectors. Since the developed mathematical model in the previous section consists merely of mass and energy balances for the different material composition of the fuel, i.e. water, volatile matters, carbon and ash, the connectors can be defined as follows:

```
connector MultiplePort_In/Out "Multiple In/Out Port Interface"
 import Modelica.SIunits.*;
 parameter Integer nConnector=1
flow MassFlowRate mdot[nConnector] ;
Temperature Temp;
end MultiplePort_In/Out;
```

and

```
connector HeatPort "HeatPort"
  extends Interfaces.HeatPort;
end HeatPort;
```

These are the two kinds of connectors that are present in the illustrated concept for modeling an incineration plant. The waste flow components between the different zones, i.e., reactors, is implemented as an array of size nConnectors where nConnectors is equal to 4 in this case. Finally, The *HeatPort* connector allows the heat exchange between gas phase and solid phase.

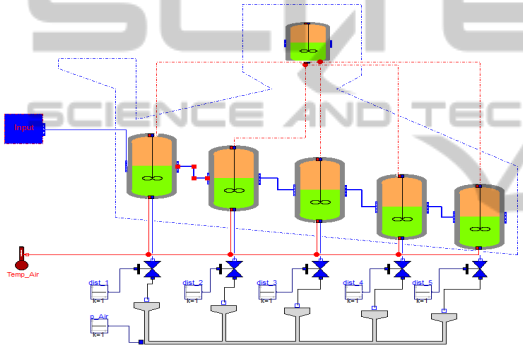


Figure 10: Overall Process.

Since the different sub models can be tested individually in Modelica, and for simplicity, the reactor model has been tested for the case of moisture drying and volatile matters. The mass flow rate of both the water and volatiles is set to a given reference value, and the temperature of the reactor was set initially to the ambient temperature of the incoming fresh fuel (25 ^{o}C). The radiation was dynamically varied from 500 ^{o}C to 1000 ^{o}C for a duration of 50 seconds (see Figure 11). Lastly, the kinetic data for the Arrhenius parameters are illustrated in Table 2, where A [s^{-1}] is the pre-exponential factor and E [$kJ.mol^{-1}$] is the activation energy.

Table 2: Kinetics data for water evaporation and volatiles.

	A	E
Water →Vapour	$5.13x10^{10}$	88
Volatile→Gas	$5.16x10^{6}$	84

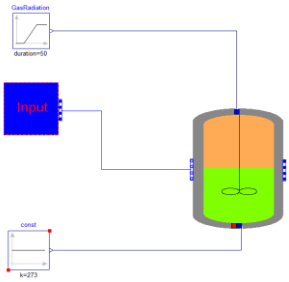
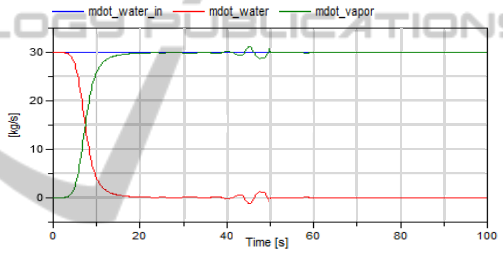


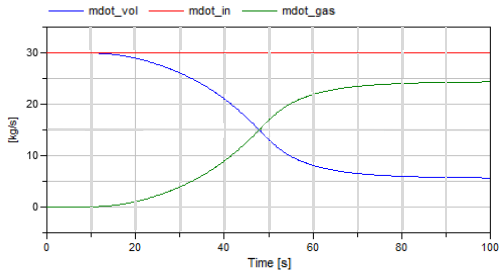
Figure 11: Testing scheme of the CSTR model.

```
model Input " reference Mass Flow"
parameter Integer N=2 ;
 Interfaces.MultiplePort_Out multiplePort_Out1(nConnector=N)
equation
 multiplePort_Out1.mdot[1]=30 "Water";
 multiplePort_Out1.mdot[2]=30 "Volatiles";
end Input;
```

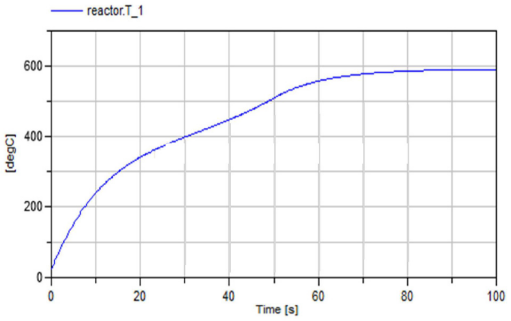
The results obtained from the CSTR for moisture evaporation and volatiles gasification are illustrated in Figure 12.



(a)



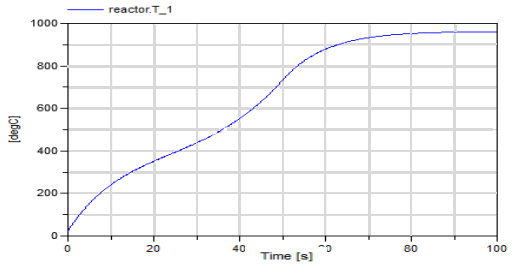
(b)



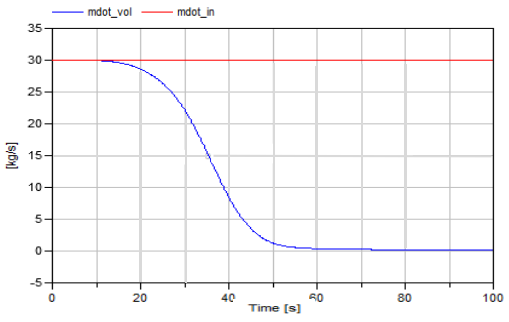
(c)

Figure 12: Simulation results.

Figure 12.a represents the evolution of the water content in the liquid phase (red curve) and in the gas phase, i.e. vapor, (green curve). Clearly as depicted in the figure, the water starts to vaporize as soon as the temperature in the reactor reaches 100 °C at 2.8 seconds, whereas the water in liquid phase decreases until it is totally consumed as expected. Similarly, the Figure 12.b illustrates the gasification of the volatile matters. It should be noted that the gasification of volatiles is activated at higher temperature, here about 266 °C after 12 seconds for rate parameters which are in agreement with the parameters used for a faster devolatilization in (Yang et al., 2004). But compared to the water vaporization case, the devolatilization is not completed; this can be checked from the offset present between the reference input in red and the green curve which represents the gasified volatiles. This is in accordance with the reported results on the gasification of volatile matters, which state that the gasification of volatiles is accomplished at higher temperatures. Here, the maximum achieved reactor temperature is 600 °C as shown in Figure 12.c. This remark can be validated by increasing the radiating temperature of the gas phase to 1500 °C as shown in Figure 13.a, which represents the gasified volatiles over time.



(a)



(b)

Figure 13: Effect of temperature on the volatile matters.

5 CONCLUSIONS

In this work, a rudimentary introduction to the process of energy recovery from biomass was presented. The process consists merely of different thermo-chemical reactions for the degradation of biomass on the moving grate. Furthermore, two main phases can be distinguished: a heterogeneous solid combustion (solid phase) followed by secondary homogenous combustion (gas phase).

Secondly, a simplified mathematical modeling concept was proposed, that is based on the well-known continuous stirred tank reactor (CSTR). Hence, the governing mathematical equations are merely based on energy and mass balances, which are suitable for the simulation of the process using the component-oriented Modelica modelling scheme. The motivating reason for this work is that the incineration process is run sub-optimally due to the currently used classical control techniques. The developed model will be the basis for testing more advanced control schemes in order to increase the process efficiently and reduce the emitted levels of exhaust gases.

Future work will include the implementation of the overall component-based model of the plant, and to test its robustness against the variation of biomass composition.

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