THE ANNALS OF "DUNĂREA DE JOS" UNIVERSITY OF GALAȚI
FASCICLE V, TECHNOLOGIES IN MACHINE BUILDING,
ISSN 1221- 4566, 2014

NUMERICAL SIMULATION OF BIOMASS COMBUSTION IN A DOWNDRAFT BOILER

Răzvan MAHU[1], Florin POPESCU[2], Ion V. ION[3]

[1] Tensor s.r.l.,
[2,3] "Dunarea de Jos" University of Galati
razvanmahu@yahoo.com

ABSTRACT

The present work meets some problems related to crop residues combustion in a small heating boiler. When the biomass is burned in small boilers, emissions from incomplete combustion such as volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NOx) tend to increase. Modeling and numerical simulation synergistically complement the experiments and they represent a low-cost approach to design, allowing combustion optimization. Modeling helps us understand the fundamental processes occurring during biomass combustion and it can substantially reduce the time required for design optimization.

KEYWORDS: wood sawdust, crop residues, combustion, downdraft boiler, modelling, simulation

1. INTRODUCTION

The purpose of this study consists in applying an original numerical model for solving a highly complex case of combustion modelling and simulation. The chosen case is modelling and simulating the combustion of cylindrical briquettes made from a mixture of hardwood sawdust and crop residues in a 40KW heating boiler.

The combustion stages that we modelled are:

1. biomass drying – the water vapour inside the wood are eliminated and mixing with the combustion by-products forms the tar;
2. pyrolysis (devolatilisation) - wood gas is produced while dried wood is transformed into charcoal through the distillation process;
3. primary combustion – the combustion of the resulted fuel and the heat transfer to previous and next level;
4. the main combustion – the fuel mixture is blown through the refractory nozzle in the secondary chamber where it self ignites at 560° C mixed with secondary air;
5. the final combustion – the combustion of wood gas occurs in the main combustion chamber mixed with secondary air at a temperature of 1200° C.

2. THE NUMERICAL MODEL

The numerical modelling of the combustion was done using the same techniques and methodologies as during the validation process of the combustion model. The only difference is the complexity of the geometry, which involves a significantly greater effort in the process of grid generation for the computational domain, plus an increase in the time required to define the numerical model.

The CAD model of the boiler geometry is a simplified one compared to the real geometry. The considered elements are strictly relevant to the combustion problem, if neglecting the heat transfer to outside. However, even in this configuration, the simplified model can be extended by imposing conditions on the external borders to approximate to some extent the heat transfer to the water chamber (Fig. 1).

As it can be seen in Fig. 2, the grid was carefully generated, every effort being made to obtain a grid nodes distribution as close to ideal and concentrating their density in areas of interest (for example in the fuel briquettes' region or in the walls' vicinity). The grid is completely consistent, to eliminate any numerical instability and deformation of the volume, control is reduced to minimum, the standard deformation degree being: max. = 0.446, med. = 0.0496, (ideal is 0 while 1 means degenerated volume).

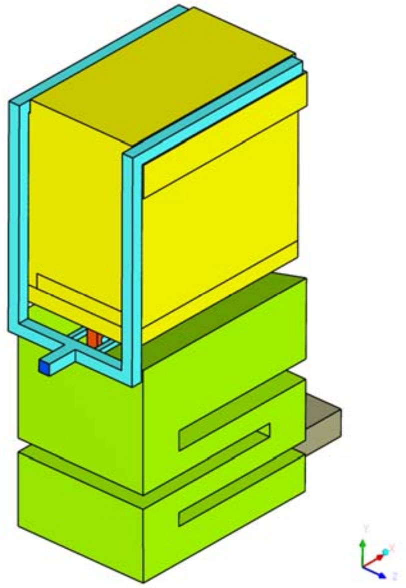

Fig.1. *3D view of the boiler CAD model used in the pre-processing phase of the CFD numerical model*

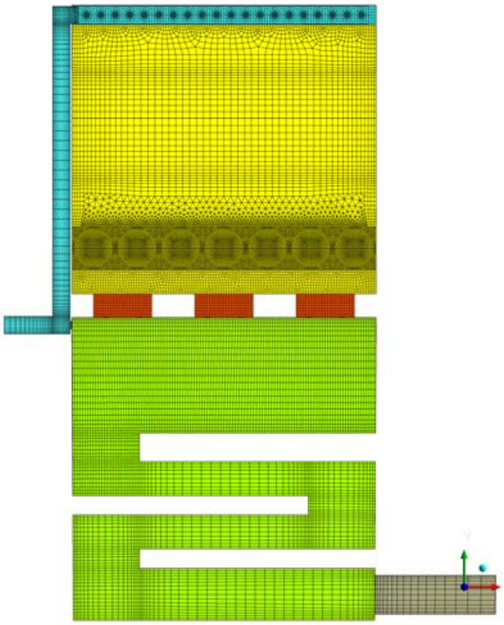

Fig. 2. *Generated grid (side view).*

3. MODELING THE BIOMASS COMBUSTION

The biomass briquettes are cylinders with a diameter of 70 mm and a length of 320 mm. The briquettes are evenly distributed across the primary combustion chamber. The total mass of the raw fuel is 6.44 kg (the average density being 747 kg/m^3).

The composition of both types of biomass within the briquettes’ composition is shown in Table 1. This information, along with the briquettes average density constituted the input for the chemical kinetic model used to define the functions implemented in the dynamic model (external function + CFD numerical model). The equivalent composition of the mixture, based on the wet mass is: CL = 0.398, HCl = 0.267, LG = 0.194, ash = 0.070, water = 0.072. The type of lignin considered is a proportional mixture of LG-HW and LG-G.

Table 1. *The biomass technical analysis*

Components	Biomass type [50%/50%]	
	Sawdust	Agricultural residues
Cellulose (CL)	0,424	0,371
Hemicellulose (HCl)	0,292	0,242
Lignin (LG)	0,205	0,182
Ash	0,015	0,125
Water	0,064	0,080

3.1. Computing resources

The numerical modeling and simulation cases solved during the verification and validation phase of the combustion numerical model were run using conventional computer systems (multiprocessor workstations). The combustion inside the downdraft boiler was solved by means of the HPC system from the "Dunărea de Jos" University of Galați (Fig. 3). The system has 60 processors and 144 GB RAM and benefits from an ANSYS CFD™ academic license for parallel multiprocessing.

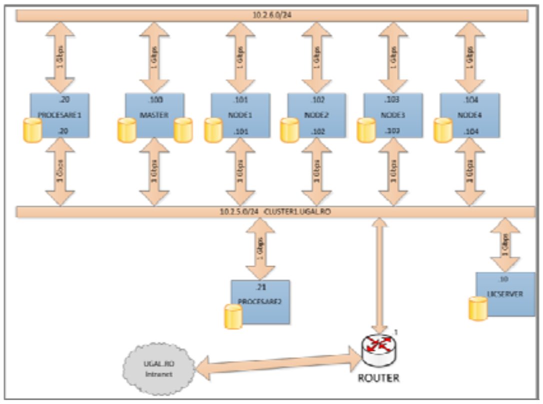

Fig. 3. *Structured diagram of the HPC system used for the numerical simulation of the combustion inside the downdraft boiler*

The case was run during a four week period of time – two runs of 18,000 [hours/CPU], each of 300 hours, with a time step Δt = 0.1 s and a mean computational time of 90 s/step.

3.2. Analysis of biomass combustion simulation results

This chapter contains some of the numerical results obtained during the simulation of combustion. From the 20 minutes of simulated operation the first 10 minutes were the fuel ignition phase, combustion stabilization, and combustion air flow modification, followed by the next 10 minutes of operation. For each of these periods of operation the achievement of a quasi-stationary operating state was observed. However, looking carefully at the evolution of chemical species or carbon monoxide in the same point, it is noted that in terms of chemical transformations that occur during fuel conversion the process is not stationary as the species concentrations are continuously changing.

As shown by numerical results, the boiler operational parameters of the two air supply regimes are very different, airflow rate proving to be a critical factor for this problem.

Figures 4 - 7 present various data calculated during the numerical simulation. We can appreciate comparatively the combustion process characteristics between the reference airflow rate of 0.04 kg/s and the flow rate of 0.02 kg/s. For most cases, excepting the radiation intensity, we used the same value scale, in order to facilitate difference identification between the two cases. In all figures, the values and the units' size are represented and displayed together with the value scale.

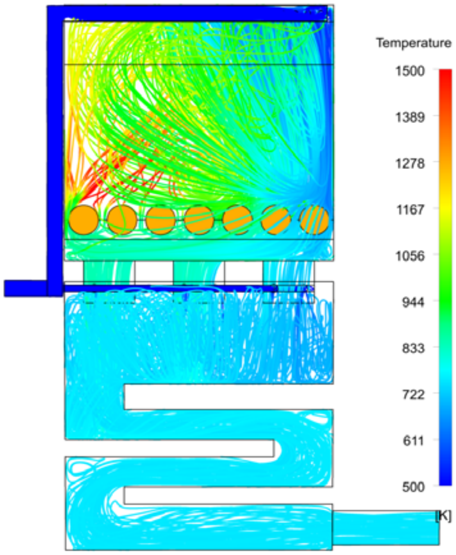

Fig. 4. *Streamlines coloured according to local temperature; air flow rate = 100%*

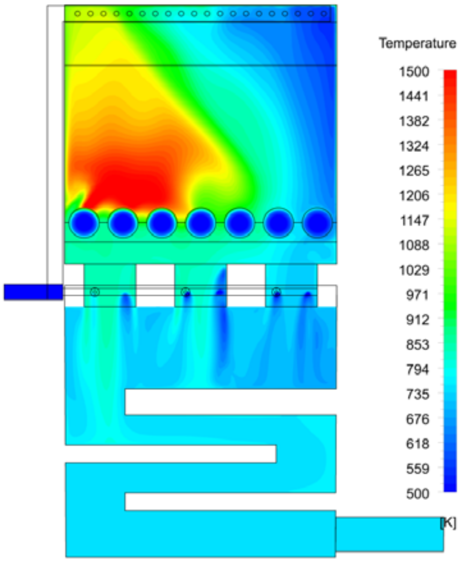

Fig. 5. *Temperature distribution in longitudinal centreline section; airflow rate = 100%*

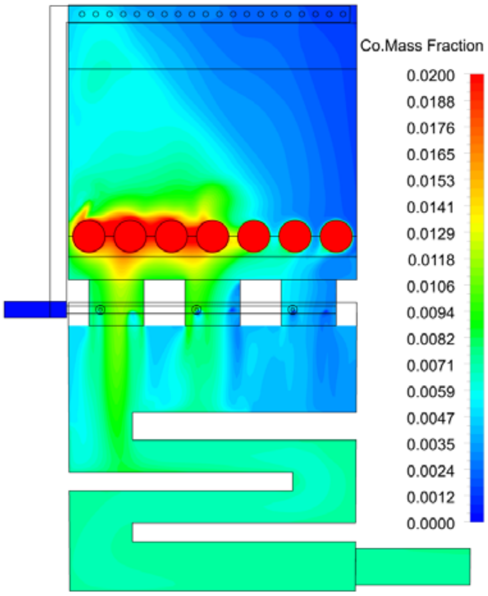

Fig. 6. *CO concentration; air flow rate = 100%*

One of the first characteristics that stand out for both values of air flow rate is the distorted flow in the primary combustion chamber. This effect can be seen in almost all images.

First, stricto-senso, we do not observe the biomass gasification. For both airflow rates, the volatiles and air mixture burns almost entirely in the boiler upper chamber. As shown in Fig. 5 the gas mixture does not burn in the secondary chamber, gas temperature remaining practically constant.

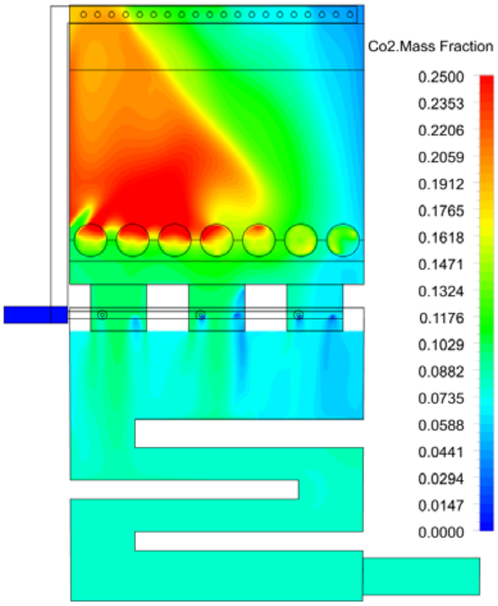

Fig. 7. *CO_2 concentration; air flow rate = 100%*

4. CONCLUSIONS

The computational results are valuable given that under the existing circumstances, numerical modeling and simulation are the only methods for achieving in depth research, with a degree of information detail inaccessible to experimental methods.

Comparing some calculated quantities with the experimental measurements, e.g. emissions of carbon monoxide or carbon dioxide, oxygen concentration in the flue gas, or the temperatures inside the combustion chambers is mostly informative as accurate experimental conditions could not be reproduced, due to the lack of experimental necessary data. This problem is compounded by the model simplifications, which did not include the problem of heat transfer from the combustion chambers to outside, which may have had a decisive impact on the numerical results. The values are still acceptable, even good in some cases, which encourages improving the model and eventually rerunning the calculations in a future study to assess the model ability to correctly estimate the whole phenomenon.

REFERENCES

[1] Mahu, R., *Modelarea numerică a proceselor fizico-chimice associate combustiei biomasei*, Teză de doctorat, Universitatea “Dunărea de Jos” din Galați, 2013

[2] *,** *ANSYS CFD 14.0, 2011. User Guide and Tutorial Guide*

[3] Miller, R. S., Bellan, J., *A generalized biomass pyrolysis model based on superimposed cellulose, hemicellulose and lignin kinetics*, Combustion Science and Technology, vol. 126, pp. 97-137, 1997

[4] C. Di Blasi, *Modeling chemical and physical processes of wood and biomass pyrolysis*, Progress in Energy and Combustion Science, vol. 34, pp. 47-90, 2008.

[5] Mehrabian, R et al., *A CFD model for thermal conversion of thermally thick biomass particles*, Fuel Processing Technology, vol. 95, pp. 96-108, 2012.