Effect of swirl intensity on the flow and combustion characteristics of pulverized biomass flame

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1 Introduction

Substituting traditional fossil fuel with biomass in large scale combustion facilities is not only of significant importance for meeting society's energy needs, but can also make a huge contribution towards the reduction of greenhouse gases emitted into the atmosphere.

Furthermore, the development of new technologies involving biomass induces new opportunities for economic re-vitalization and growth [1-3].

A comprehensive understanding of the physical and chemical processes involved in biomass combustion is important for any application in which biomass combustion is required, including stoves, boilers, and large-scale burners [4]. Indeed the combustion behavior of biomass is different from that of other solid fuels as coal, since biomass yields a much higher fraction of volatiles [5].

Swirl effect has proven to control and increase combustion efficiency [6,7]. Many types of swirl burners were developed, which employ complicated swirl gas/particle flow [8]. CFD is widely used in the design and optimization of practical combustion devices for efficiency improvement and emission reduction. Stone et al. [9] analyzed the impact of three swirl numbers (Sn = 0.56, Sn = 0.84 and Sn = 1.12) on the flame premixedstability of gas turbine combustor using CFD. For high values of Sn, they observed negative values of centerline axial velocity in the expansion plane which indicates the formation of the vortex-breakdown. Recently, Yilmaz [10] performed numerical study to investigate the effect of swirl number on combustion characteristics in a diffusion flame. He found that the combustion characteristics such as, flame temperature and species concentrations are strongly affected by the swirl number.

Mansouri et al. [11] studied numerically the swirl effects on the flow and flame dynamics in a lean premixed combustor. The investigation was done using five different swirl numbers Sn = (0, 0.35, 0.75,

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1.05, 1.4). The predictions were validated with available experimental data. Good agreement between numerical results and experiments is found. The results showed that increasing swirl number to an excessive value leads to the propagation of the inner recirculation zone (IRZ) upstream the combustion chamber, and consequently the flame is no more stable and the flashback appears.

Elorf et al. [12] investigated numerically the swirl motion effects on flame dynamics of pulverized biomass (olive waste) in a vertical furnace where air is introduced through two coaxial tubes. Three cases were analyzed: without swirl (Ja), with one swirl (Js1) and with double swirl (Js2). Results showed that the flame is more stabilized and close to the air inlet section for the swirling jet cases and the temperature of the burned gases reaches its maximum value of 1560 K.

The Js1 case is considered like most optimal case of pulverized olive waste (OW) in the previous study [12]. In order to more understand the effects of swirl in flame behavior of pulverized (OW) this paper present the Js1 case study with several swirl numbers.

The aims of this work is to study numerically the effect of swirl intensity on the flow behavior and flame characteristics to more clarifying the swirling pulverized biomass flames. The flow behavior, flame stability and combustion gases at each swirl number are analyzed. Four cases with different swirl numbers are studied (Sn=0.38; 0.95; 1.2 and 1.42). The results presented in this paper concern the influence of swirl number in flow topology, velocity contours, temperature distribution, and species concentrations profiles.

2 Configuration and numerical simulation

Combustion modeling of pulverized olive waste particles in vertical pilot scale furnace [12] is conducted using a commercial computational fluid (CFD) code ANSYS 14.

The computational domain is cylindrical tube with an internal diameter of 500 mm and total length of 1500 mm (Figure 1). The air is introduced into the furnace through two coaxial tubes, namely primary air stream and secondary air stream. The length of the coaxial tubes is 180 mm and the diameter of inner and outer tubes are 60 mm and 80 mm, respectively. The tertiary air is injected perpendicularly to the furnace axis from four injectors. Each injector has a square of 20 mm x 20 mm and a length of 100 mm. Primary air is swirled and the chosen swirl numbers are equal to 0.38; 0.95; 1.2 and 1.42, respectively. Swirl number being the ratio between the tangential and axial velocity *(w/u)*.

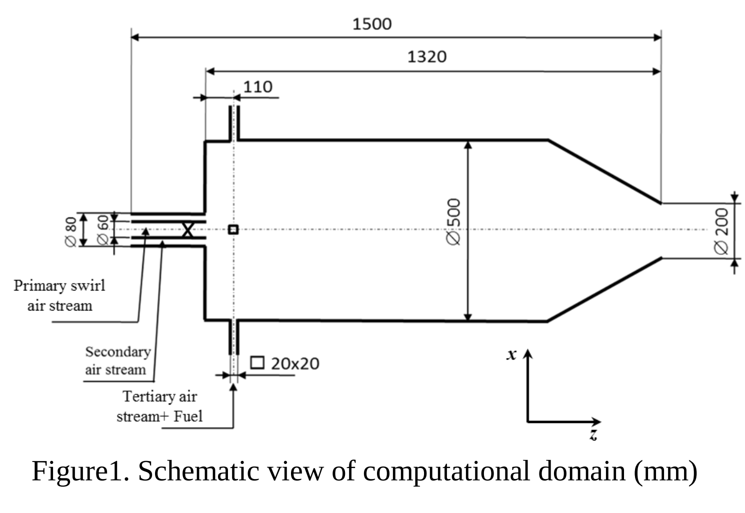

Figure1. Schematic view of computational domain (mm)

The application of a tangential velocity component to the flow, gives the flow a rotating component, represented by the non-dimensional swirl number (S_n) defined as the ratio of the tangential momentum flux to axial momentum flux. We introduce the value of this ratio in the inlet boundary conditions. The expression of swirl number depends on the injector geometry and flow profiles as follows [13]:

$$S_n = \frac{\int_{R_n}^{R_h} \bar{u}\bar{w}r^2 dr}{\int_{R_n}^{R_h} R_n \bar{u}^2 r dr} \qquad (1)$$

Where, R denotes the swirler radius and $\bar{u}$ and $\bar{w}$ are respectively the mean axial and tangential (swirl) velocity.

The numerical approach is based on Reynolds averaged Navier–Stokes (RANS) method using the k–ε turbulence model. The mixture fraction/probability density function (PDF) approach is used for turbulence-chemistry interactions of the non-premixed combustion. The P-1 model is used to simulate the radiation model.

The biomass particles are modelled as spheres using discrete phase model (DPM). A Rosin-Rammler distribution pattern, with a maximum diameter of 100 µm and mean diameter of 70 µm is applied. Owing to large amounts of gas production, the influence of pyrolysis on the drag coefficients for particle diameters less than 100 µm is minimal [14]. Such influence becomes important at large particle diameters.

The biomass thermal characteristics and proprieties are determined experimentally by the thermogravimetric analysis [12]. The calorific value is calculated also in the laboratory using the bomb calorimeter. The experimental lower heating value of OW is 20 MJ/kg. The fuel proprieties are summarized in table 1.

Table1. Proximate and ultimate analysis of the biomass (OW)

Proximate Analysis (Wt%)		**Ultimate analysis(Wt %)**	
Volatile Matter	64	Carbon	59
Fixed Carbon	23.2	Hydrogen	8.5
Ash	6.5	Nitogen	1.5
Moisture	6.3	Sulphur	0
		Oxygen	31

The biomass mass flow rate $\dot{m}_{biomass} = 2.55$ g/s is used to generate a power of 50 kW. The flow parameters and details of all cases are given in table 2 were λ is the excess air ratio and $\dot{m}$ correspond to air mass flow rate for each entry.

Table2.Flow parameters and cases details

Cases	S_n	w/u	λ	$\dot{m}_{primary-air}$ $[g/s]$	$\dot{m}_{secondary-air}$ $[g/s]$	$\dot{m}_{tertiary-air}$ $[g/s]$
Js1	1,2	0,9	1,3	15,08	8.1	2,62
Case 2	0,38	0,288	1,3	15,08	8.1	2,62
Case 3	0,95	0,714	1,3	15,08	8.1	2,62
Case 4	1,42	1,06	1,3	15,08	8.1	2,62

3 Results and discussion

The results of mesh validation was presented and discussed in previous work [12] where grid convergence study has been conducted for three meshes. The validation of the numerical model used in this work was performed by the comparison with the experimental and numerical data of Toporov et al. [12].

3.1 The influence of the swirl number (S_n) on the flow structure

Figure 2 illustrate the contours of the axial velocity and the streamlines along the combustion chamber for the four studied cases. The choice of minimum and maximum speeds in the legend of this figure corresponds to the highest minimum and maximum speeds encountered in simulated cases.

The intensity and the axial position of principal recirculation zone (PRZ) are strongly influenced by the swirl number values (S_n). As the swirl number increases, the PRZ becomes more intense and closer to the burner outlet. Contraction of the passage section of the principal jet, due to the size of the PRZ, requires a smaller flare of the jet for the low values of Sn (see red dotted lines, where U_z = 0, 2 m/s). Concerning the intensity of PRZ, it can be seen that when the number of swirl is small (S_n = 0.38), the recirculation zone takes its place at a higher level in the combustion chamber. This zone is closer to the burner outlet when the swirl number is high (S_n = 1.42). Blue dotted line in figure 2 presents the position of the maximum longitudinal velocity (swirled jet lobe). We can see that the position of this maximum increases when S_n increases.

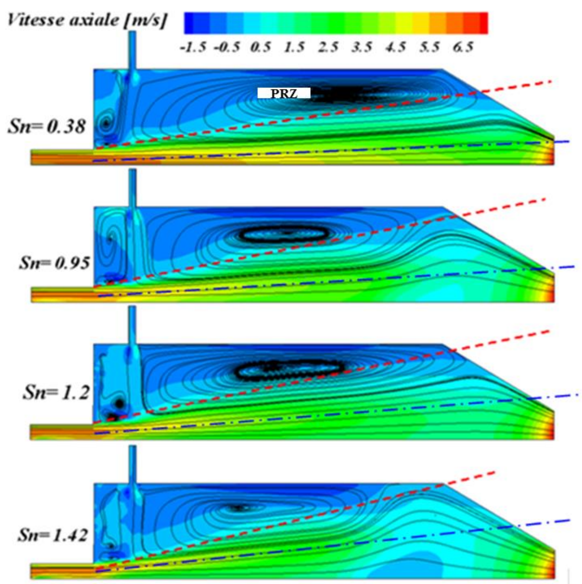

Figure 2. Streamlines and average axial velocity for different swirl numbers (S_n) (plan x-z)

3.2 Gas temperatures and species concentration profiles

Figure 3 shows the spatial distribution of mean temperature in the combustion chamber for the different swirl numbers S_n. It can be noticed that the flame develops in the boundary zone between the main jet and the PRZ. The flame position moves towards the lower base of the combustion chamber with S_n increase. This is the reason why, for low swirl numbers (S_n = 0.38), the temperature on the chamber axis increases less rapidly than for flows with high swirl number (S_n=1.42).
Figure 4 shows the radial profiles of the mass fraction of CO_2 and CO in several longitudinal sections. The maximum values of the mass fraction of CO_2 are located near the burner inlet (z / D = 3.125) for the four different Sn cases.The value of this mass fraction of CO_2 is CO_2max = 0.250. In this section z/D=3.125,

the production of CO_2 takes place extremely rapidly, unlike the other sections z/D. In this region, the share of CO_2 is made up of CO_2 resulting from devolatilization, and CO_2 resulting from the combustion of the flame.

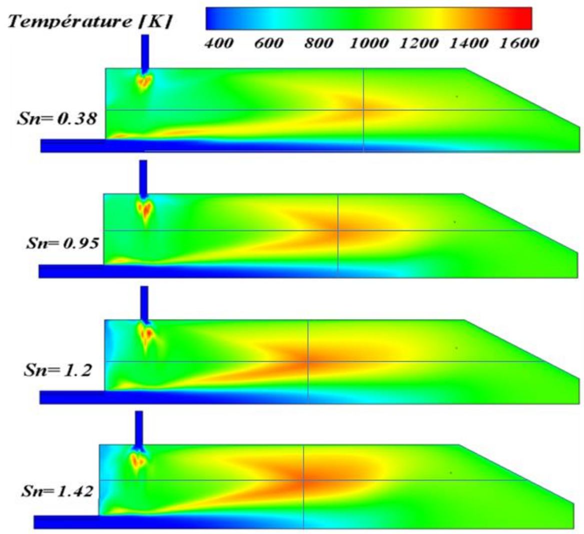

Figure 3. Gas temperature for different swirl numbers (S_n) (plan x-z)

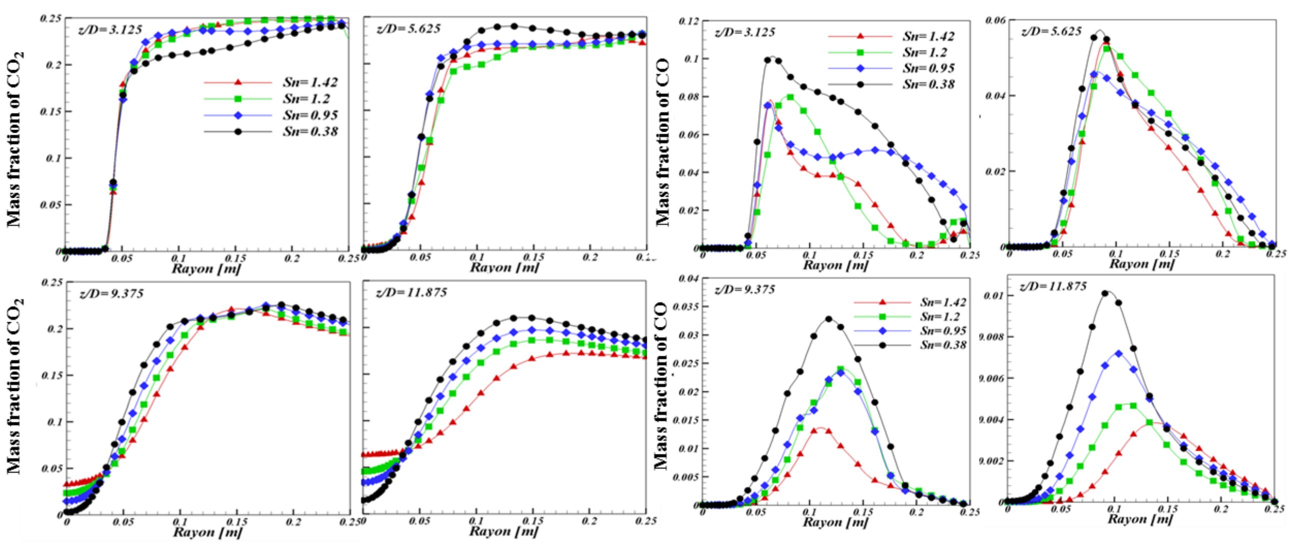

Figure 4. $CO_2$and CO mass fraction radial profiles in several locations for all cases

In the other z/D sections, the trend is reversed since the mass fraction of CO_2 is higher for the low S_n. On the other hand, the CO_2 level in these sections is lower than its level in the section z/D = 3.125. This can be explained by the fact that in z/D = 9,375 and z/D = 11,875 the CO_2 is due only to combustion.

The portion of CO_2 resulting from the devolatilization or conversion of CO to CO_2 by oxidation is low. Concerning CO mass fraction, the maximum values are located near the burner inlet (z / D = 3.125) for the four different cases. Beyond this section, the CO mass fraction values are divided by a factor of 10 in z/D= 11.875. This decrease in CO in these other sections can be explained by the fact that CO has been oxidized and converted to CO_2. We think that the share of oxidized CO and its conversion to CO_2 is low compared to CO_2 produced by combustion or by devolatilization. Finally, we can also observe in two lasted section (z/D=9.3757 and 11.875) that the CO_2 and CO masse fraction decrease with swirl number (Sn) increase.

4 Conclusions and perspective

This paper summarized a 3D numerical simulation study of the effect of swirl number on combustion characteristics such as temperature, velocity, species concentrations of a pulverized biomass flame. The results showed that increasing swirl number decrease both axial position of PRZ and flame location. The mass fractions of CO and CO_2 decrease with swirl number (S_n) decrease. The combustion chamber and the burner are, currently, installed at ICARE laboratory. Measurements campaign is planned to start soon.

Acknowledgements

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