COMBUSTION DYNAMICS AT BIOMASS THERMOCHEMICAL CONVERSION DOWNSTREAM OF INTEGRATED GASIFIER AND COMBUSTOR

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Abstract. Swirling flows are widely used to stabilize the flame reaction zone and to provide enhanced mixing of the axial fuel flow with air swirl. The goal of the present paper is to investigate the influence of the air swirl on the formation of the flame reaction zone at thermochemical conversion of the pelletized biomass. An experimental study of the swirl effects on the combustion dynamics is carried out providing the complex measurements of the formation of the flame temperature and composition profiles at different stages of thermochemical conversion of biomass pellets along with estimation of the effect of the swirl level on the mixing of the axial flow of volatiles with air swirl determining the thermochemical conversion of biomass. The numerical simulation of the swirl flow formation is used to analyze the results of the experimental measurements.

Keywords: thermochemical conversion, biomass, swirling flame, combustion dynamics.

Introduction

The present study has been performed to determine the effect of air swirl on the flow development and on combustion dynamics at thermochemical conversion of biomass pellets. In many combustion processes the flame is stabilized using swirling air supply that allows effective mixing of the flame compounds completing fuel combustion. The fundamental experimental and theoretical study of swirling flows has shown that the centrifugal force created by the air swirl motion plays an important role in the formation of the flame structure and stability with the peak values of axial and tangential mean velocities near the channel wall [1-3]. One of the most important features of the swirling flame is the formation of a recirculation zone inside of which the reverse axial mass transfer of the hot products helps heat and ignite the incoming fuel flow that makes it possible to stabilize the process of fuel combustion. In non-premixed combustors, where the fuel and air flows are injected separately the formation of the recirculation zone provides enhanced turbulent mixing of the axial fuel flow with the air swirl along the outer boundary layer of the recirculation region, where the turbulent shear stress achieves its maximum value [4]. In fact, despite the wide practical applications of swirl-stabilized combustors, the development of combustion dynamics of non-premixed flame flows is not clearly understood. Moreover, a lot of problems arise when providing control of combustion dynamics at thermochemical conversion of biomass because of a variety of processes developing at their thermochemical conversion which includes steps of biomass heating, drying, volatilization, ignition and combustion of volatiles depending on the swirling air supply rate and on the air excess ratio in the flame reaction zone. Analytical prediction of the combustion dynamics at thermochemical conversion of biomass pellets still is highly limited because of the complexity of the flow and many factors determining the swirl flow formation at biomass thermo-chemical conversion, whereas numerical simulation of the flow dynamics is quite difficult. Therefore, a detailed experimental study of the formation of swirl flow dynamics is highly important in order to understand the behavior of non-premixed combustor, predict combustion dynamics and provide active control of the swirl flow formation.

Because the main aim of the present study is to investigate the influence of the air swirl motion on the formation of the flame reaction zone at thermochemical conversion of pelletized biomass (wood pellets) detailed measurements of the formation of the flow structure and composition with specification of the inlet conditions of fuel and air determining the formation of the primary mixing region are required. To predict the formation of swirling flame dynamics with the specification of the inlet conditions, the formation of the primary isothermal mixing region was numerically simulated at different primary and secondary air supply rates providing comparison of the results of numerical simulation and experimental study of the swirl flow formation. The formation of the flow structure at thermo-chemical conversion of biomass pellets was investigated experimentally considering the effect of the air swirl motion on the formation of the recirculation zone induced by the swirling flow pattern in the vicinity of the fuel jet outlet that is produced due to the gasification of biomass pellets.

Materials and methods

The formation of the swirl dynamics at the thermo-chemical conversion of wood pellets was studied experimentally using a compact experimental setup, which is an integrated system of a gasifier and a combustor with the total heat energy output (Q) up to 10-12 MJ·kg^{-1} at thermo-chemical conversion of wood pellets (Fig. 1). The primary thermal decomposition of batch-size wood pellets (230-260 g) develops in the gasifier (1) and is initiated by a premixed swirling propane/air burner with an additional heat energy supply into the upper part of the wood pellets at the average rate 1.2 kJ·s^{-1} (2). To support the gasification of the wood pellets the primary axial airflow is used, being injected into the bottom part of the gasifier, below the layer of the wood pellets at an average air supply rate of 0.58-0.6 g·s^{-1} and at an average air excess $\alpha \approx 0.4$-0.5. The average mass loss rate of wood pellets at thermal decomposition in the gasifier for the given system configuration can be varied in a range from 0.19 g·s^{-1} to 0.22 g·s^{-1} producing the axial mass flow of the volatiles (CO, H_2) at the average temperature 800-1000 K in the gasifier. To provide the thermochemical conversion of the volatiles, the axial mass flow of volatiles is injected into the bottom part of the combustor (3) downstream of which an enhanced mixing of the axial flow of the volatiles with the secondary air swirl develops completing the combustion of the volatiles. To produce an air swirl, the secondary air is injected in the bottom part of the combustor through two tangential air nozzles 5 mm in diameter. The average secondary mass flow rate in the combustor can be varied in a range from 0.6 g·s^{-1} up to 1.8 g·s^{-1}. The combustor of the diameter D = 60 mm and total length L = 600 mm is composed of the water-cooled sections. Between the water cooled sections of the combustor there are inserted the diagnostic sections with the orifices (4), which are used to put the diagnostic tools (Pitot tube, thermocouples and gas sampling probes) into the flame of the volatiles and provide local measurements of the flame flow velocity, flame temperature and composition at different stages of the thermochemical conversion of batch-size wood pellets.

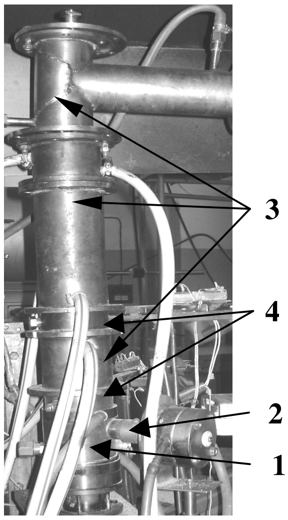

Fig. 1. **Digital image of the small-scale experimental device**

The swirling flame dynamics was experimentally studied providing local measurements of the flame velocity at different stages of the swirling flame flow formation using a Pitot tube with online data registration supported by Testo 454. The measurements of the flame temperature profiles at different stages of the swirling flame flow formation were made by Pt/Pt-Rh (10 %) thermocouples with an online data collecting and recording system using the PC-20TR plate. From the calorimetric measurements of the cooling water flow of the combustor the total heat energy produced at the burnout of volatiles downstream of the swirling flame flow was estimated. The local measurements of the swirling flame temperature, composition of the products (NO_x, CO_2, CO, H_2, and O_2) and combustion efficiency were made using a gas analyzer Testo 350XL.

Results and discussion

The experimental study of the formation of the swirling flame dynamics downstream of the combustor starts with the estimation of the effect of axial and swirling air supply on the inlet flow formation (L/D = 0.5). The results of the experimental measurements and numerical modeling of the flame velocity field formation have shown that at constant primary air supply (0.58 $g \cdot s^{-1}$) a typical feature of the swirling flow field close to the outlet of the swirling air nozzle (L/D = 0.5) is the formation of the peak values of the axial and tangential flow velocities close to the channel walls – at $r/R \approx$ 0.8-0.9 (r is the radial distance from the flame axis, R is the radius of the combustor) (Fig. 2, a) with the correlating linear increase of the average values of the axial and tangential flow velocity, as the secondary air supply rate increases (Fig. 2, b). The swirl intensity of the inlet flow was estimated using the swirl number (S) that can be approximately expressed as the relation between the axial flux of the swirl momentum (G_{tg}) and the axial flux of the axial momentum (G_{ax}) [1]:

$$S = \frac{2}{3}\frac{G_{tg}}{G_{ax}} \quad (1)$$

The evaluation of the swirl number for the isothermal inlet flow conditions at the primary stage of the swirling flame formation, when the processes of thermochemical conversion of biofuel can be neglected, has shown that the swirl flow intensity in the primary mixing region is relatively insensible to the variations of the secondary swirling air supply ($q_{air\text{-}2}$), while it is more sensitive to variations of the primary axial flow rate ($q_{air\text{-}1}$).

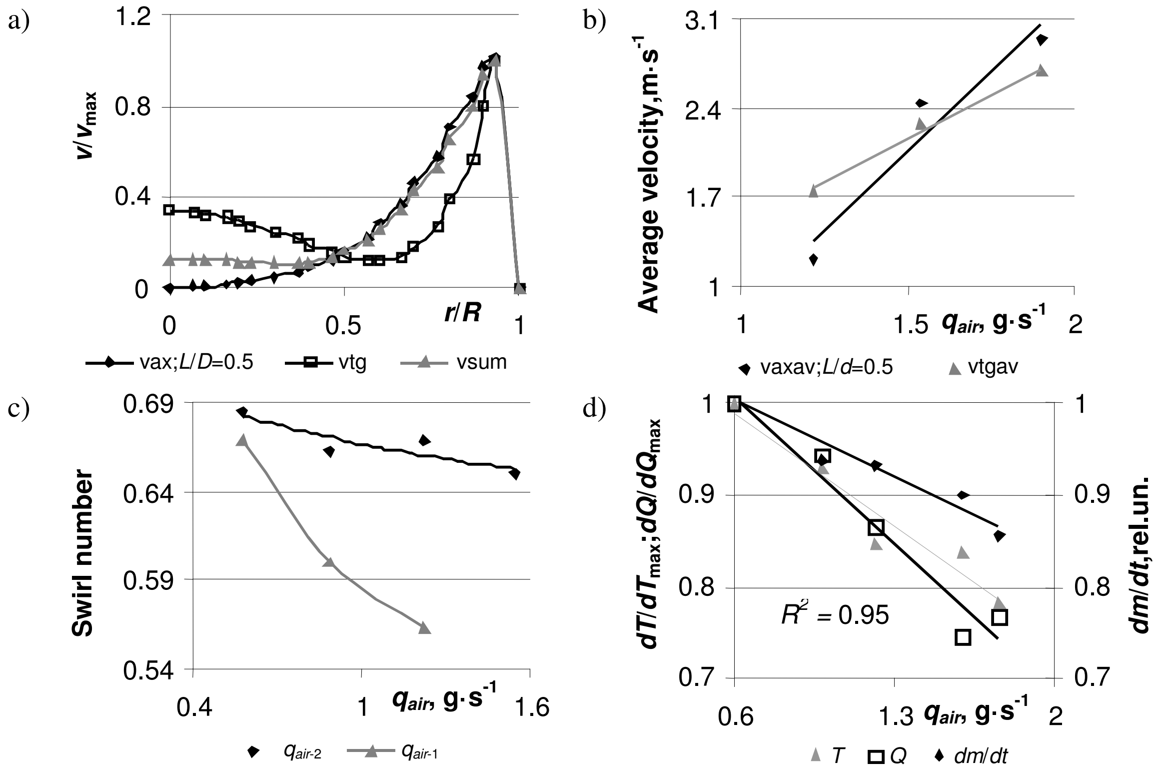

Fig. 2. **Numerical estimation of the formation of the isothermal inlet flow velocity profiles (a); the effect of secondary air supply on average values of the axial and tangential velocity (b); the effect of primary and secondary air supply on the swirl number (c); the effect of secondary air supply on swirl-induced variations of the rate of thermal decomposition of wood pellets and on the main characteristics of swirling flame at thermochemical conversion of wood pellets (d)**

If the secondary air supply increases from 0.6 to 1.2 $g \cdot s^{-1}$, the swirl number of the inlet flow slightly decreases – from S = 0.68 to S = 0.66 (by $\approx$ 4 %) (Fig. 2, c). The experimental study of the formation of the tangential velocity profiles at different rates of secondary air supply has shown that the observed decrease of the swirl number for the inlet flow can be related to the cold upstream air swirl formation with the swirl flow reversing from the wood layer downstream of the flame axis (Fig. 2, a). A similar swirl flow reversing along with the upstream swirl flow formation was observed by the authors of [5] for the conditions, when the number of local swirls exceeded the critical value ($S > 0.6$). At equal variations of the primary flow rate in a range from 0.6 $g \cdot s^{-1}$ up to 1.2 $g \cdot s^{-1}$, the swirl number of the inlet flow decreases from $S = 0.66$ to $S = 0.56$ (by ≈15 %) (Fig. 2, c). Hence, it is obvious that the primary air supply rate increase at a fixed secondary air supply rate can result in a more pronounced decrease of the swirl level of the inlet flow with direct influence on the mixing rate of the flame compounds and combustion conditions downstream of the combustor.

From the data presented in [1] it follows that the variations of the inlet flow swirl number evidence of direct impact on the swirling flow structure. At the high swirl level of the inlet flow ($S > 0.6$) the swirl-induced formation of the recirculation zone at the bottom part of the combustor can be obtained determining enhanced mixing and more complete combustion of the flame compounds. With account of this, an experimental study of swirl flame dynamics is carried out at the average rate of primary air supply 0.58 $g \cdot s^{-1}$ and average rate of secondary air supply 1.22 $g \cdot s^{-1}$, when the swirl number of the inlet flow exceeds 0.6 and the swirl-induced formation of the recirculation zone controls the mixing of the flame compounds and the combustion characteristics. The experimental study of the formation of swirling flame dynamics at the swirl level of the inlet flow $S > 0.6$ confirms the formation of the central recirculation zone at the bottom part of the combustor, extending from $L/D = 1$ up to $L/D = 3$, inside of which the axial flow of the volatiles (CO, H_2), which are produced at the thermal decomposition of wood pellets, is completely balanced by the reverse axial flow of the hot products (Fig. 3, a).

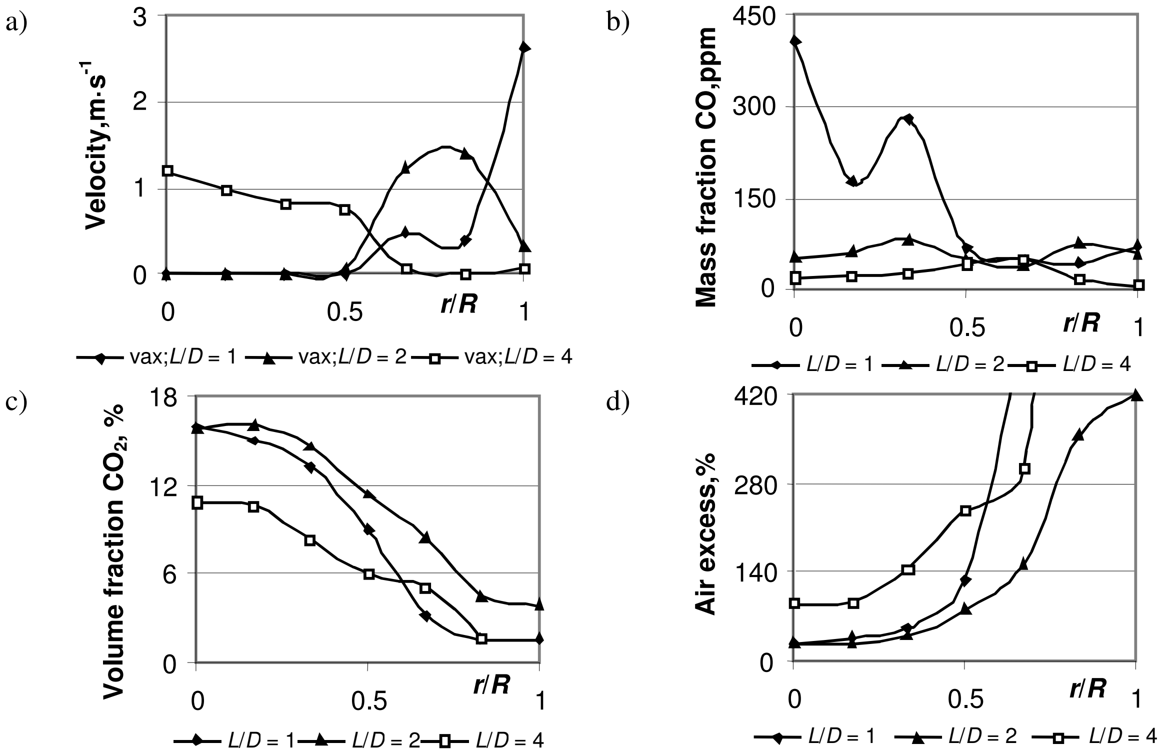

Fig. 3. **Development of the flame velocity (a) and composition (b-d) profiles downstream of the swirling flame flow at swirl-induced formation of the recirculation zone at the bottom part of the combustor**

The highest value of the mass fraction of the main volatiles (CO, H_2) is observed at the bottom part of the recirculation zone ($L/D = 1$), close to the flame axis (Fig. 3, b). Inside of the recirculation zone the fast mixing of the flame compounds promotes enhanced combustion of the volatiles. As a result, the mass fraction of the volatiles downstream of the flame axis rapidly decreases with the correlating increase of the volume fraction of CO_2 and with radial expansion of the reaction zone (Fig. 3, c), whereas the air excess in the reaction zone decreases to the minimum value (Fig. 3, d), confirming that the formation of the recirculation zone at the high swirl level of the inlet flow ($S > 0.6$) promotes enhanced thermochemical conversion of the volatiles. Further downstream, above the recirculation zone (L/D > 4), a gradual flame extinction is observed with the correlating decrease of the mass fraction of volatiles, volume fraction of the main products and flame temperature that falls below 1000 K (Fig. 3, b, c), whereas the air excess in the reaction zone rapidly increases (Fig. 3, d).

Finally it should be noted that the complex experimental study of the interrelated processes of thermal decomposition of wood pellets in the gasifier and thermo-chemical conversion of volatiles downstream of the combustor has revealed that increase of the secondary air supply rate promotes a gradual decrease of the mass loss rate at thermal decomposition of wood pellets with the correlating decrease of the temperature in the flame reaction zone and produced heat energy at thermo-chemical conversion of the volatiles (Fig. 2, d). In fact, there are two main factors determining the observed variations of the combustion characteristics. First, the increase of the secondary swirling air supply promotes a gradual decrease of the swirl number of the inlet flow (Fig. 2, b) by limiting the hot product recirculation and swirl-induced mixing of the flame compounds downstream of the combustor. Second, as shown above, the increase of the secondary air swirl supply promotes the cold upstream air swirl formation with swirl-induced cooling of the wood layer and correlating decrease of the mass loss rate (dm/dt) at thermal decomposition of wood pellets [6]. At constant secondary air supply rate, the mass loss rate variations result in the correlating variation of the air to fuel supply rate in the flame reaction zone. Hence, the air excess increase in the reaction zone promotes the correlating decrease of the flame temperature (Fig. 2, d) by limiting the process of thermochemical conversion of the volatiles and heat energy production downstream of the combustor (Fig. 2, d).

Conclusions

1. A system of small size integrated gasifier and combustor has been developed to provide thermochemical conversion of biomass (wood) pellets along with the estimation of the effect of primary axial and secondary swirling air supply on the swirl level of the inlet flow determining the development of the flow dynamics and the processes of biomass thermochemical conversion of the biomass depending on the mass loss rate at thermal decomposition of wood pellets. The results of the experimental study are compared with the results of the numerical simulation to determine the effect of primary and secondary air supply on the isothermal inlet flow formation and flow dynamics.
2. The measurements of the flow patterns demonstrate that the variations of the primary and secondary air supply rates determine the variations of the flow dynamics depending on the swirl number of the isothermal inlet flow. At $S > 0.6$, the formation of the flame dynamics is influenced by the formation of swirl-induced recirculation of the hot products and by secondary air with an enhanced mixing of the flame compounds in the flame recirculation zone completing the combustion of the volatiles.

Acknowledgments

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References

1. Gupta A.K., Lilley D.D., Syred N., Swirl Flows, Abacus press, UK, 1984, 588 p.
2. Linck M., Armani M. and Gupta A.K. Effect of swirl and fuel pulsation on flame dynamics, flame structure and droplet dynamics in swirl stabilized spray flames, Proceedings of the 6th Annual ASME Power Conference, Baltimore, 2004, paper PWR 2004-52048.
3. Huang Y., Yang V., Effect of swirl on combustion dynamics in a lean-premixed swirl-stabilized combustor, Proceedings of the Combustion Institute, vol. 30, 2005, pp. 1775-1782.
4. Tang G., Yang Z., McGuirk, J.J. Large eddy simulation of isothermal confined swirling flow with recirculation, Engineering Turbulence Modelling and Experiments-5, ed. Rodi, W. and Fueyo, N., Elsevier Science Ltd, 2002, pp.875-901.
5. Physics of Swirling flow. [online][20.12.2012] Available at: http://www.personal.psu.edu/yxw145/physics%20of%20swirling%20flow.htm.
6. Gasparovic L., Labovsky J., Markos J., Jelemensky L. Calculation of Kinetic Parameters of the Thermal Decomposition of Wood by Distributed Activation Energy Model (DAEM), Chem. Biochem. Eng., 2012, vol. 26 (1), pp. 45-53.