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CONTROL OF THE DEVELOPMENT OF SWIRLING AIRFLOW DYNAMICS AND ITS IMPACT ON BIOMASS COMBUSTION CHARACTERISTICS

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The development of the swirling flame flow field and gasification/combustion dynamics at thermo-chemical conversion of biomass pellets has experimentally been studied using a pilot device, which combines a biomass gasifier and combustor by varying the inlet conditions of the fuel-air mixture into the combustor. Experimental modelling of the formation of the cold non-reacting swirling airflow field above the inlet nozzle of the combustor and the upstream flow formation below the inlet nozzle has been carried out to assess the influence of the inlet nozzle diameter, as well primary and secondary air supply rates on the upstream flow formation and air swirl intensity, which is highly responsible for the formation of fuel-air mixture entering the combustor and the development of combustion dynamics downstream of the combustor. The research results demonstrate that at equal primary axial and secondary swirling air supply into the device a decrease in the inlet nozzle diameter enhances the upstream air swirl formation by increasing swirl intensity below the inlet nozzle of the combustor. This leads to the enhanced mixing of the combustible volatiles with the air swirl below the inlet nozzle of the combustor providing a more complete combustion of volatiles and an increase in the heat output of the device.

Keywords: *combustion of volatiles, flame composition, heat output, mixing of reactants, swirling flow dynamics*

1. INTRODUCTION

Swirling flows, where a tangential flow velocity overlaps and interacts with the axial flow, are of importance in many technical and industrial applications, including gas turbines, furnaces and district heating boilers. The swirl enhances and controls the mixing of the flame components and provides flame stabilisation in combustion systems due to the formation of the central recirculation zone. Although the development of the swirling flow fields for non-reacting and reacting flows have relatively been well studied [1]–[7], a complete understanding of the inlet conditions and specific combustor configuration on the downstream swirling flow field formation and combustion characteristics has not been achieved. In fact, a wide variety of the flow structures can be obtained [4], which confirm that relatively small differences in combustor geometry and swirling flow inlet conditions can result in the formation of entirely different flow structure and it is difficult to predict the main flame characteristics. Meanwhile, improvement of the combustion dynamics and flame characteristics is important since the swirl-enhanced mixing of the flame components would lead to a more complete fuel combustion and cleaner energy production in jet engines, gas turbines and combustors. The results of experimental study and numerical modelling of the development of swirling flow dynamics for non-reacting and reacting flows, the formation of the flow field structure and flame stability confirm that the presence of swirl considerably increases the stability limits of most flames [9] with direct influence on the flame structure [9]–[12], mixing of the flame components and the development of chemical reactions [14]. The results of previous experimental study [9] on the development of confined isothermal swirling flow dynamics in a cylindrical tube with a swirling air inlet at the fixed distance from the bottom of the tube suggest that the formation of the swirling flow field and flow structure is highly influenced by the downstream and upstream swirling airflow formation. The propagation of swirling flow near the channel walls up to the bottom of the cylindrical tube leads to a decrease in gradual swirling airflow velocity and flow reversing from the bottom of tube. The airflow reversing correlates with an increase in the downstream flow velocity near the flow axis. Similar upstream swirling airflow formation is observed in a pilot device with a combined biomass gasifier and a combustor and swirling air input at the bottom of the combustor [9]. As a consequence of the upstream swirling airflow formation and flow reversing from the biomass layer, the swirl-enhanced axial mass transfer of the combustible volatiles (CO, H_2) with partial mixing of the reactants in the space below the swirling air nozzle leads to the formation of the fuel-rich primary reaction zone close to the flow axis entering the combustor. The further development of the flame reaction zone is influenced by mixing of the primary fuel-rich reaction zone with downstream swirling airflow, which predominately occurs along the outer shear layer of the flame reaction zone. Actually, the development of the reaction zone depends on the formation of the upstream and downstream swirling air flows. The results of recent experimental study aim at controlling the formation of the upstream and downstream swirling flows by varying the inlet conditions of the swirling airflow at the bottom of the combustor. The effects of inlet conditions on the development of swirling flow dynamics for non-reacting flows and the flame reaction zone are compared and analysed.

2. EXPERIMENTAL PART

The experimental studies of the development of swirling cold airflow and swirling flame dynamics were carried out using the experimental setup (Fig. 1), which combined a biomass gasifier (1) and water-cooled combustor (2) of inner diameter D = 60 mm and of total length up to 600 mm [9]. The swirling air into device was supplied using the two tangential nozzles (3) of inner diameter 3 mm, which were attached to the channel walls, just below the annular inlet nozzle (4) located at the bottom of the combustor. The experimental studies of the flow field formation were made using the annular nozzles with inner diameter 20 mm, 40 mm and also without nozzles, when the inlet diameter of the combustor was equal to 60 mm. The average rate of the swirling air supply through the tangential nozzles varied from 30 to 90 l/min. The primary air at average rate 0–30 l/min was supplied at the bottom of the gasifier. The biomass thermal decomposition in the gasifier was initiated using the propane flame with an additional heat input into the biomass layer up to 1 kW [9]. Propane flame was switched off after ignition of volatiles.

The diagnostic sections with openings (6) for the diagnostic tools (thermoprobe, Pitot tube, thermocouples, gas sampling probes) were used for the local measurements of the flow velocity, flame temperature and composition. Local measurements of the flame temperature were made using Pt/Pt-Rh thermocouples with data online registration by a Pico logger. Local measurements of the flame composition – mass fraction of volatiles (CO, H_2), volume fraction of the main product (CO_2), air excess ratio (α), combustion efficiency – were conducted using a gas sampling probe and a gas analyser Testo 350 with measurement accuracy of ±1% for the volume fraction of O_2, CO_2 and of about ±0.5 % for the mass fraction of CO, H_2 and NO_x. Calorimetric measurements of the cooling water flow include the joint measurements of water flow temperature and mass flow rate. The water flow temperature was measured using thermal sensors AD 590 with online data registration by the Data Translation DT9805 data acquisition module and Quick DAQ program. The airflow supply rate was measured using flow meters and online data registration with Testo 454. To assess the impact of inlet conditions on the flame characteristics, heat output and average values of the produced heat energy at different stages of biomass thermo-chemical conversion, all measurements were carried out and compared for different inlet diameters of the annular nozzle (4).

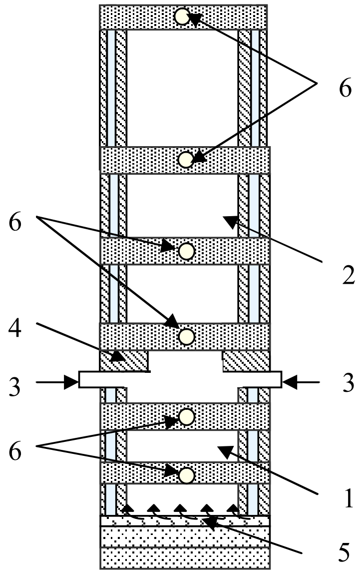

Fig. 1. A sketch of the experimental device: biomass gasifier (1), sections of the combustor (2), swirling air supply nozzles (3), annular inlet nozzle of the combustor (4), primary axial air supply (5), diagnostic sections with orifices for the diagnostic tools (6).

3. RESULTS AND DISCUSSION

3.1. *The Effect of Inlet Conditions on the Cold Non-Reacting Swirling Flow Field Formation*

The previous experimental study has shown [9] that the development of the cold non-reacting swirling flow field is highly influenced by the upstream swirling flow formation and flow reflection from the bottom of the gasifier by enhancing the formation of the downstream axial flow close to the centreline. This study aims at assessing the effect of inlet conditions on the upstream and downstream swirling flow field formation by varying the inlet diameter of the annular nozzle as well as the primary (q_1) and secondary (q_2) air supply rates. The development of the upstream velocity profiles below the annular inlet nozzle for constant secondary air supply and different rates of primary air supply is plotted in Fig. 2, a-e.

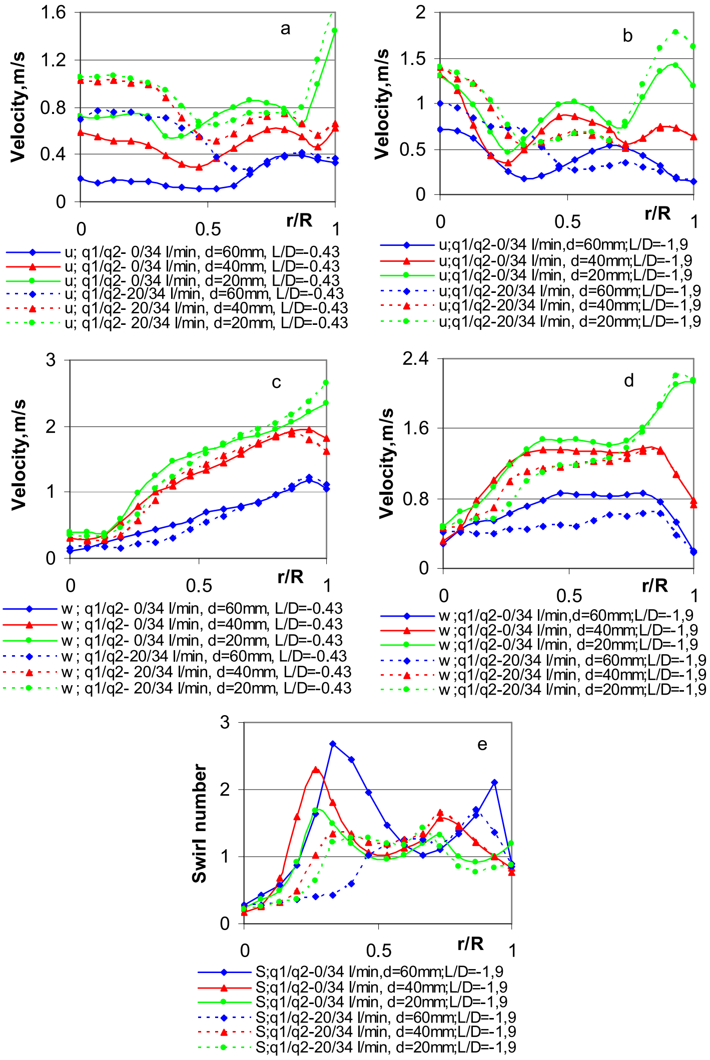

Fig. 2. The effect of primary air supply on the development of the upstream swirling flow velocity profiles.

The data show (Fig. 2) that for the same secondary air supply rate (34 l/min) the enhanced formation of the upstream swirling flow can be obtained by decreasing the diameter of the annular nozzle. In fact, the upstream swirl flow formation is observed for all flow cross sections up to bottom of the gasifier. The upstream swirling airflow formation correlates with the formation of the axial downstream flow at the bottom of the gasifier, which is observed even if the primary air is not supplied into the gasifier ($q_1 = 0$) (Fig. 2-a,b). Therefore, it can be concluded that the reflection of the upstream swirling airflow from the bottom of the gasifier is highly responsible for the formation of the axial downstream flow, which gradually diminishes with the increase in the distance from the bottom of the gasifier. Uneven distribution of the reflected flow at the bottom of the gasifier (Fig. 2-b) shows that the most intensive reflection of the swirling airflow occurs downstream of the flow axis (R < 0.3) and downstream of the channel walls (R > 0.8), where an increase in the axial downstream flow velocity correlates with a decrease in the upstream flow tangential velocity (Fig. 2-d) and swirl intensity (Fig. 2-e).

For the fixed diameter of the inlet nozzle (d = 40 mm) the upstream swirling airflow can be amplified by increasing the secondary air supply, which leads to the enhanced reflection of the swirling airflow from the bottom of the gasifier with a correlating increase in the axial velocity of the downstream flow (Fig. 3).

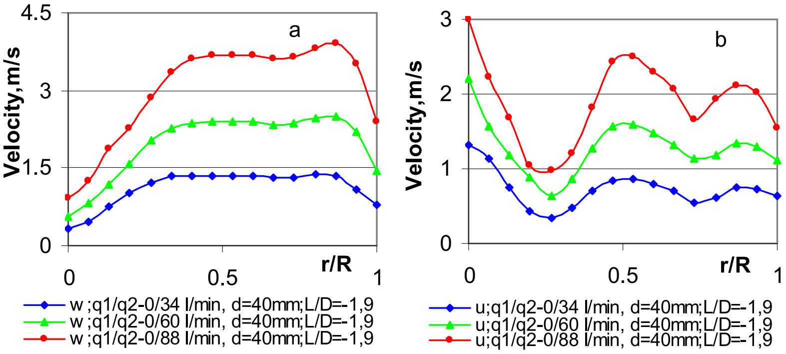

Fig. 3. The effect of the secondary air supply on the upstream swirling airflow (a) and downstream axial airflow formation (b).

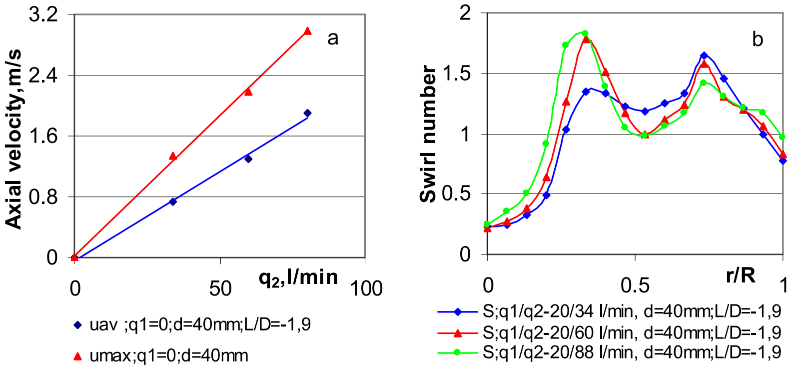

Fig. 4. The effect of secondary air supply on the average and peak values of the downstream axial airflow velocity (a) and local swirl intensity (b) of the upstream swirling airflow.

The appropriate estimation has shown that the average and peak values (R=0) of the axial velocity of the reflected downstream flow with high level accuracy ($R^2 \approx 1$) can be expressed with a linear dependence on the secondary air supply rate (Fig. 4-a). Moreover, the correlation between the average values of the tangential and axial velocities can be expressed as: $u_{av} = 0.63w_{av}$. This suggests that about 63 % of the upstream swirling airflow is reflected as axial downstream flow and about 37 % of the upstream flow is reflected as downstream swirling flow with peak value of swirl intensity at $r/R \approx 0.3$ (Fig. 4-a,b).

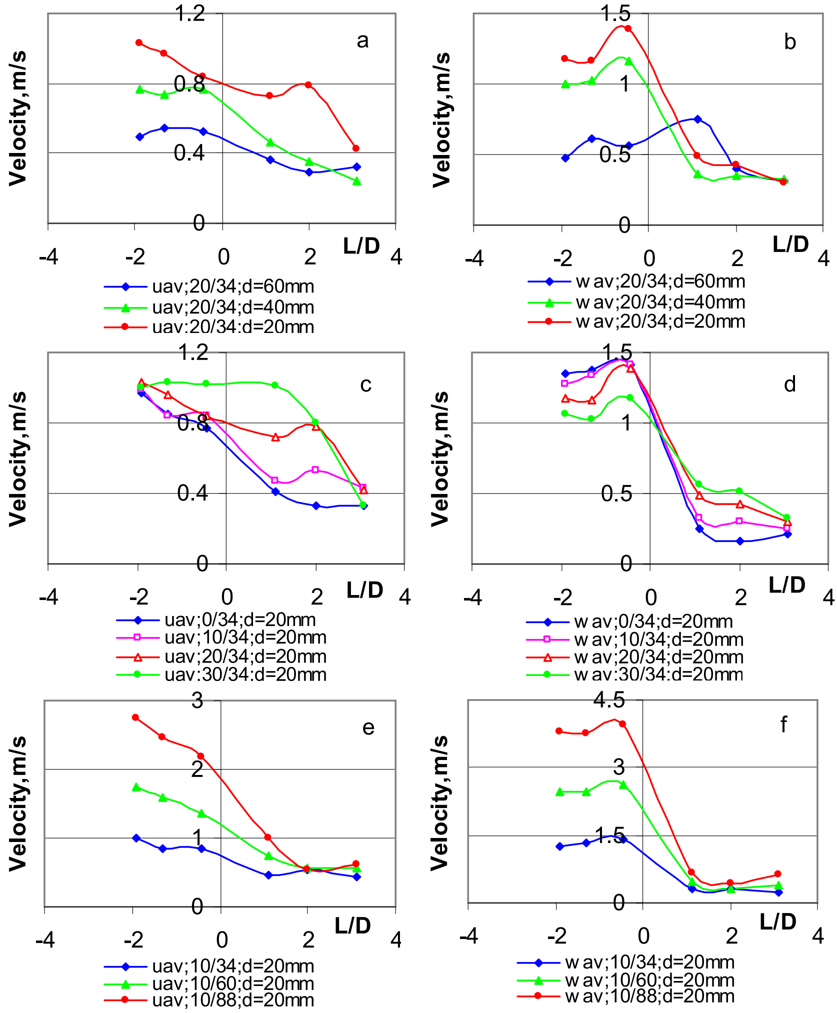

Fig. 5. The effect of inlet conditions on the development of the velocity profiles downstream of the device.

The variation of the annular nozzle diameter, as well primary and secondary air supply rates show the influence on the development of the flow dynamics not only below the annular nozzle, but also downstream of the combustor (Fig. 5, a-f). For the constant primary and secondary air supply rates, a decrease in the inlet nozzle diameter at the bottom of the combustor results in enhanced upstream swirling flow motion of the airflow with enhanced formation of the axial airflow and faster decrease of the air swirl motion downstream of the combustor (Fig. 5-a,b). For the constant diameter of the annular nozzle and constant secondary air supply rate, an increase in the primary air supply rate results in a decrease in the tangential velocity and swirl intensity of the upstream flow (Fig. 6-c,d). A marked increase in the axial flow velocity close to a correlating increase in the tangential flow velocity at nearly constant swirl intensity is observed downstream of the combustor, above the annular nozzle. Finally, for the constant diameter of the annular nozzle and constant primary air supply rate an increase in the secondary air supply rate results in an enhanced upstream swirl motion and flow reflection from the combustor with fast decay of the flow velocity components and swirl intensity downstream of the combustor (Fig. 5-e,f).

3.2. The Effect of Inlet Conditions on the Swirling Flame Flow Formation and Main Combustion Characteristics

The development of the swirling non-reacting airflow dynamics and flow velocity profiles downstream of the combustor is confirmed to be dependent on the inlet conditions at the bottom of the combustor, which are responsible for the upstream and downstream swirling airflow formation. Knowledge obtained in this study is applied to provide control of the gasification/combustion characteristics at thermo-chemical conversion of biomass pellets and the swirling flame flow formation downstream of the combustor (Fig. 1). The experimental study of the swirling flame formation, first of all, demonstrates that a decrease in the diameter of the annular nozzle significantly affects the free flame shape through the influence of the inlet conditions on the formation of the upstream and downstream flow fields (Fig. 6).

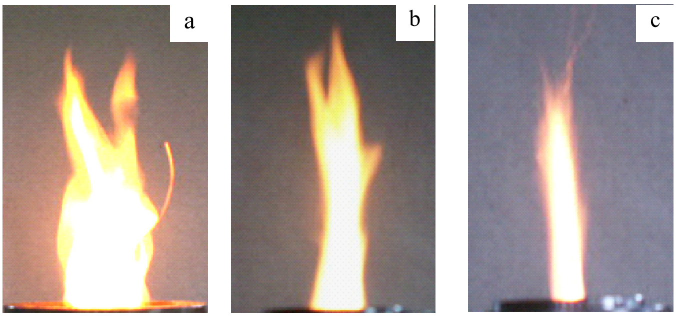

Fig. 6. The variation of the free flame shape by decreasing the inlet diameter of the annular nozzle: a-d = 60 mm; b-d = 40 mm, c-d = 20 mm.

The measurements of the flow velocity profiles below the inlet nozzle confirm that by analogy with the formation of non-reacting swirling flow dynamics a decrease in the inlet nozzle diameter provides enhanced upstream swirling airflow formation inside the gasifier towards the surface of a biomass layer. For constant primary and secondary air supply in the device a decrease in the inlet nozzle diameter leads to enhanced mixing of the upstream air swirl with the axial flow of combustible volatiles (H_2, CO) determining enhanced formation of the primary reaction zone near the flow axis with correlating increase in the heat output during the flaming combustion stage of volatiles (Fig. 7-a) and total amount of the produced heat energy at thermo-chemical conversion of biomass pellets (Fig. 7-b).

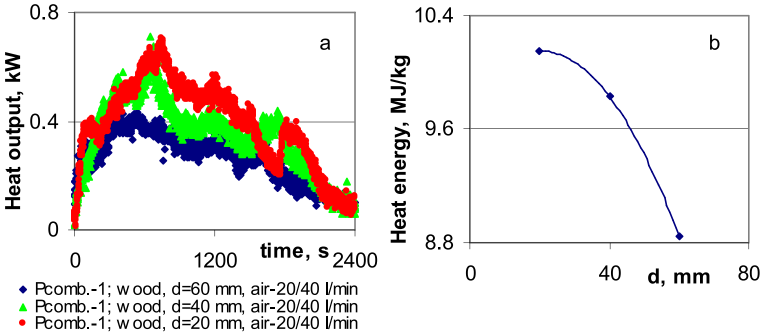

Fig. 7. The effect of decrease in the annular nozzle diameter on heat output and produced heat energy per mass of wood pellets during their thermo-chemical conversion.

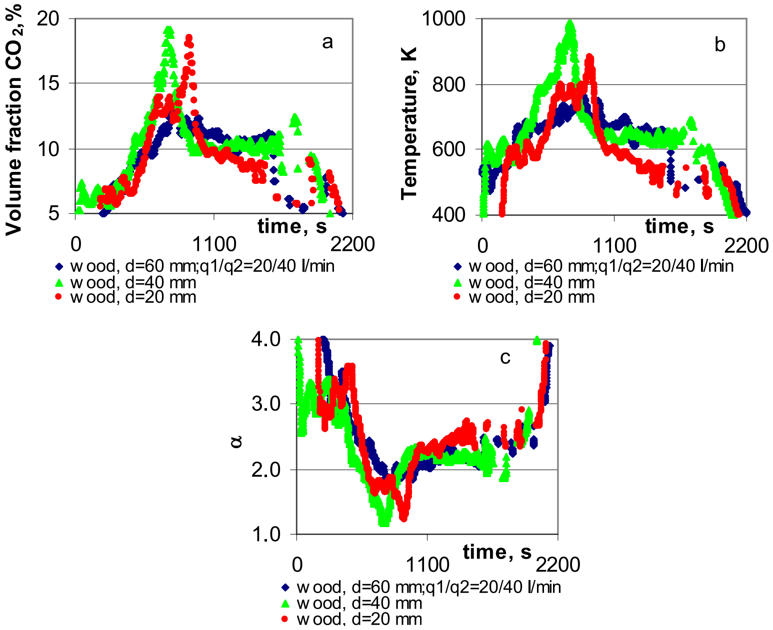

Fig. 8. The effect of decrease in the annular nozzle diameter on the volume fraction of CO_2 (a), temperature (b) and air excess ratio in the products (c).

It should be noted that by analogy with heat output kinetics the enhanced thermal conversion of the volatiles by decreasing the diameter of the annular nozzle and enhancing the formation of the upstream air swirl is also confirmed by the kinetic study of product composition, temperature and air excess ratio (α), causing a correlating increase in the volume fraction of CO_2 and temperature, and a decrease in the air excess ratio in the products (Fig. 8, a-c). As seen in Fig. 9, the most pronounced increase in the CO_2 volume fraction and temperature is observed during the flaming combustion stage of the volatiles and a decrease during the post-combustion smouldering stage of biomass pellets.

4. CONCLUSIONS

The research includes the modelling experimental study and analysis of the main factors determining the cold non-reacting swirling airflow field formation in a device, which combines the biomass gasifier and combustor by varying the inlet conditions at the bottom of the combustor with estimation of their impact on the kinetics of thermo-chemical conversion of biomass (wood) pellets.

The experimental study of dynamics of cold non-reacting swirling airflow dynamics has shown that a decrease in the annular nozzle diameter leads to the enhanced formation of the upstream swirling airflow, whereas the upstream swirling airflow reflection from the bottom of the combustor results in the enhanced axial downstream flow formation near the flow axis, depending on the primary and secondary air supply in the device.

At thermal decomposition of biomass pellets, the enhanced upstream swirling flow formation up to the surface of biomass pellets results in the intensified mixing of the upstream air swirl with the axial flow of combustible volatiles promoting enhanced formation of the primary reaction zone near the flow axis. The enhanced formation of the flame reaction zone is confirmed by the experimental study of the main combustion characteristics indicating a correlating increase in the heat output, produced heat energy, volume fraction of CO_2 in the products, and decrease in the air excess ratio in the products.

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GAISA VIRPUĻPLŪSMU DINAMIKAS VEIDOŠANĀS UN TĀS IETEKME UZ BIOMASAS DEGŠANAS PROCESU RAKSTUROJOŠIEM PARAMETRIEM

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Kopsavilkums

Ir veikti aukstu nereaģējošu gaisa virpuļplūsmu dinamikas veidošanās eksperimentālie pētījumi pie mainīgiem tās veidošanās sākuma nosacījumiem, izvērtējot galvenos faktorus, kas nosaka virpuļplūsmu dinamikas veidošanās specifiku iekārtā ar apvienotu biomasas gazifikatoru un degšanas kameru un to ietekmi uz granulētas biomasas degšanas procesa raksturojošiem parametriem liesmas virpuļplūsmā.

Auksto nereaģējošo virpuļplūsmas dinamikas veidošanās pētījumu rezultātā ir konstatēts, ka, samazinot gredzenveidīgās sprauslas atveres diametru degšanas kameras pamatnē, tiek intensificēta reversās gaisa virpuļplūsmas veidošanās virzienā uz gazifikatora pamatni, veidojot atstarotu aksiālo plūsmu kanāla centrālajā daļā, kuras intensitāte ir atkarīga no sprauslas atveres diametra, kā arī primārā un sekundārā gaisa padeves iekārtā.

Reversās gaisa virpuļplūsmas intensifikācija gazifikatorā būtiski ietekmē gaistošo savienojumu aksiālās plūsmas sajaukšanos ar reverso gaisa virpuļplūsmu un granulētas biomasas degšanas procesu dinamikas veidošanos degšanas kamerā, intensificējot gaistošo savienojumu degšanas procesa veidošanos ar sekojošu iekārtas siltuma jaudas un saražotā siltuma daudzuma pieaugumu, vienlaikus palielinot CO_2 koncentrāciju, bet samazinot gaisa padeves pārsvaru dūmgāzēs.

15.12.2016.