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Modification of Wood Pellets and Propane Co-firing in a Magnetic Field

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***Abstract* – When burning fossil fuels and renewable energy resources, greenhouse emissions (GHG) are emitted into the atmosphere. One of the options to reduce GHG emissions is to apply a magnetic field. The effect of a gradient magnetic field on the gasification of renewable fuel and the combustion of volatiles by applying the field to the bottom part of the swirl flame with recirculation is studied for the conditions of field-enhanced reverse heat and mass transfer of paramagnetic flame species up to the layer of wood pellets. The aim of research to investigate the magnetic field effect on swirling flame dynamics for the conditions of self-sustaining wood fuel combustion and by co-firing with propane flow.**

***Keywords* – co-firing, magnetic field, swirling combustion, wood pellets.**

I. INTRODUCTION

For over one hundred years now it has been recognized that electric and magnetic fields can be used to affect the combustion behaviour of flames [1-6]. The AC and DC electric field effects on combustion have recently been studied extensively for different types of flames [1-3]. These studies show the field-enhanced improvements in combustion with a negligible energy consumption compared to the thermal power of flames. While early efforts considered that by analogy with electric field effects on flames this interaction to be due to the interaction between magnetic fields and ions in the flame, it is now acknowledged that the principal interaction is due to the paramagnetic and diamagnetic behaviour of the flame compounds [4-7]: the paramagnetic flame species (O_2) can be drawn toward the direction of increasing magnetic field strength, while diamagnetic flame species (CO, H_2, O, H, N_2, CO_2, H_2O, etc.) indicate a weak repulsion by magnetic field with direct impact on the combustion conditions. Experimental studies and numerical modeling of the magnetic field effects on the different types of diffusion flames indicate that the magnetic field effect on the flame depends on the volume magnetic susceptibility of paramagnetic and diamagnetic flame species (X_v), magnetic induction (*B)* and gradient (*dB/dz)*. Magnetic field effect can be mostly attributed to the field-induced mass transfer of paramagnetic oxygen (oxygen wind) towards the regions of stronger magnetic fields [6,7] because of higher magnetic susceptibility of paramagnetic oxygen ($\approx 2*10^{-6}$) in comparison with X_v for diamagnetic species that have X_v of order $(-0{,}2\text{-}0{,}5)*10^{-8}$. So far, the dominant experimental research of the magnetic field effects on combustion mostly refers to the magnetic control of combustion processes in diffusion flames, for which the dominant factors influencing combustion are the physical processes of diffusion and the mixing of the fuel flow with air. Research has not been carried out on the interaction between the magnetic field and the swirling flame flows with recirculation that have been used for the stabilization of combustion characteristics, reducing combustion length and producing higher rates of mixing close to the exit nozzle [8, 9]. The previous research on the combustion dynamics of renewable fuels downstream of the swirling flame channel flow have shown that the swirling flame structure and combustion efficiency of renewable fuel can be significantly improved and stabilized by using propane co-fire of volatiles [10, 11], increasing combustion efficiency and the total heat output downstream of combustor. Moreover, it is found that for a fixed rate of propane co-fire, additional improvement of combustion characteristics can be obtained using a magnetic field control of swirl flame dynamics [12].

The motivation of recent research was to get more detailed information about the applicability of a magnetic field for control of swirling combustion by comparing the field effect on the combustion characteristics for the conditions of self-sustaining wood pellets burnout and for the conditions of propane co-fire using different rates of propane co-fire with different thermal loads of the swirling flame flow. From the results of the complex experimental research of the magnetic field effect on combustion characteristics, the analysis of the mechanism of field effect on the combustion of renewable fuel (wood pellets) by co-firing with fossil fuel is carried out.

II. EXPERIMENTAL

The digital image and sketch of the experimental pilot set-up for the experimental investigations on the magnetic field effect on the swirling combustion of volatiles released during the burnout of discrete doses of wood pellets (250-300 g) is shown in Figures 1.a,b. The main component parts of experimental device are: wood fuel gasifier (1), propane burner (2) and combustor (5) that can be composed of different numbers of water-cooled sections with local inlets (6) and outlets (7) of cooling water flow for calorimetric measurements downstream of the flame channel flow. The water-cooled sections are separated by the diagnostic sections (8) with orifices for the diagnostic tools. Four radial air nozzles (3) are used for a primary air supply below the wood layer to initiate the wood fuel gasification. The secondary swirling air supply is provided above the wood layer using two tangential inlets 3 mm in diameter (4). The diameter D of the combustor is 60 mm, while the total length L of the experimental device depends on the number of water-cooled sections and could be increased up to 700 mm. A propane flame burner (2) is used to initiate gasification of discrete doses of wood pellets (up to 365 g), which at the initial stage of the wood fuel gasification fill the gasifier up to the inlet of the propane flame flow.

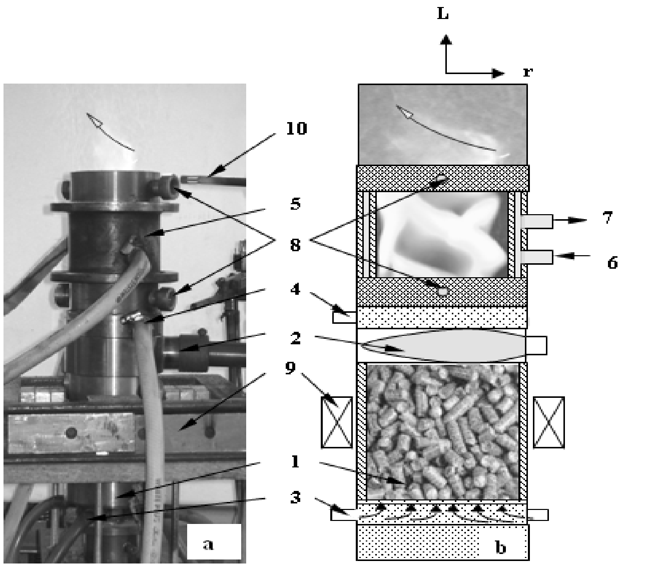


Fig. 1. The digital image (a) and sketch (b) of a pilot device for experimental study of the magnetic field effect on wood fuel combustion.

The experimental research of the magnetic field effect on the combustion characteristics of the wood fuel by co-firing with propane comprises complex research of the magnetic field effect on the flame dynamics, processes of heat production and combustion of the volatiles at different rates of propane co-fire, providing the local measurements of the flame velocity compounds (v_{ax}, v_{tg}), flame temperature and composition and different stages of the wood fuel burnout. The local measurements of the axial and tangential flame velocity, flame temperature and composition are carried out using the diagnostic sections with orifices (8) by introducing different diagnostic tools (Pt-Pt/Rh thermocouples, gas sampling probe and Pitot tube) into the flame reaction zone. The local measurements of the flame velocity and composition are provided using a gas analyzer Testo 350-XL with the time interval between measurements t = 1 s, determining the local average values from about 10 measurements of the flame velocity and composition.

To provide the experimental study of the magnetic field effect on the main characteristics of the flame reaction zone, a wood fuel gasifier is placed between the poles of the permanent magnet (9). The permanent magnet provides a relatively weak field with a peak value of a magnetic field induction (B) up to 0,18 T close to the poles at the bottom part of the permanent magnet and a mean axial field gradient up to dB/dz = 1,6-1,8 T/m. During the wood fuel burnout the upper part of the wood biomass and bottom part of the swirling flame flow gradually slows down towards the bottom part of the gasifier at the mean rate of 0,07-0,1 mm/s and approaches the poles of the permanent magnet at about t=800 s-1000 s after ignition of volatiles, when a more pronounced magnetic field effect on the swirling flame flow is detected.

III. The Experimental Results and Discussion

As it is noticed above, the magnetic field effect on the formation of the swirling flame reaction zone is studied experimentally for the conditions of the self-sustaining wood fuel burnout and for the conditions, when the different rates of propane co-fire are used to provide stabilization of combustion conditions during the burnout of renewable fuel. For the conditions of self-sustaining wood fuel burnout (prop.=0), a shape of the undisturbed flame velocity profiles is influenced by the formation of the flame recirculation zone, extending up to the L/D≈3-4 with a minimum value of the axial flow velocity close to r/R≈0,7, where the recirculation of the hot products completely balances the axial flow of volatiles released during the wood fuel gasification (Fig. 2.a). The peak swirl motion of the undisturbed swirling flame flow is fixed close to the channel walls (r/R≈0,8) (Fig. 2.b). The propane co-fire with an increased rate of propane supply and correlating increase of the thermal load of the swirling flame reaction zone disturbs a shape of the flame velocity profiles.

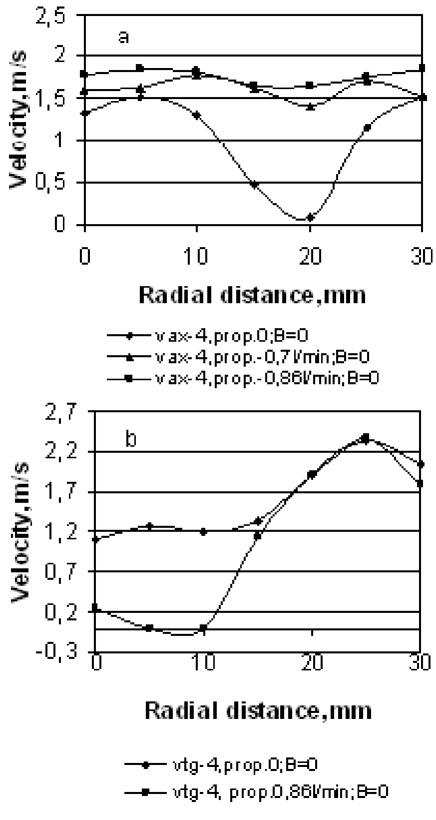


Fig. 2. The effect of propane supply on the formation of the velocity profiles of the flame reaction zone (L/D)=2,5.

As follows from Fig. 2.a, an increased rate of propane co-fire restricts the recirculation and slows down the swirl motion close to the flame axis.

The presence of gradient magnetic field that causes the reverse axial motion of the paramagnetic flame species (free oxygen) upstream to the wood layer results in significant changes of swirl flame behaviour and flow dynamics with a direct impact on the average values of flame velocity compounds. A dominant feature of the magnetic field effect on the flame velocity field is the magnetic field-induced brake of the axial flow velocity (Fig. 3.a,c) with a field-enhanced increase of the average value of the swirl velocity and swirl number of the flame reaction zone (Fig. 4.a,b), indicating that magnetic field variations of the swirl flow dynamic promotes an increase of the residence time of reactions ($t \approx L/v_{ax}$) with an enhanced mixing of the flame compounds.

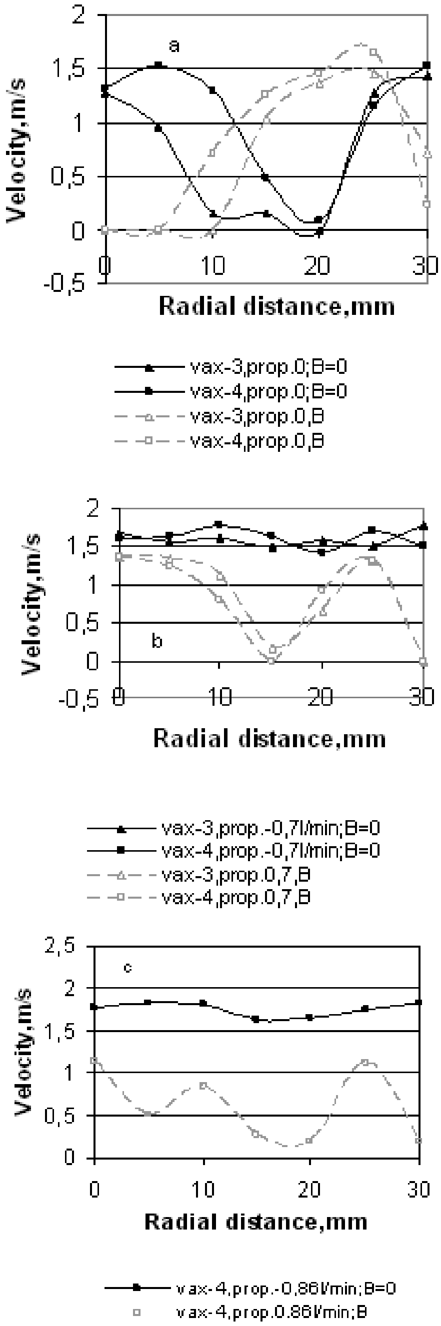


Fig. 3. The magnetic field-induced variations of a shape of the flame velocity profiles at different rates of propane co-fire at different stages of the wood fuel burnout (3: t = 600-800 s, 4: t = 800-1000 s).

As follows from Figures 3 and 4, the field effect on the flow dynamics is very sensitive to the variations of propane co-fire – an increased rate of propane co-fire and increased thermal load of the swirling flame flow results in a more pronounced decrease of the axial flow velocity with enhanced swirl motion of the flame reaction zone.

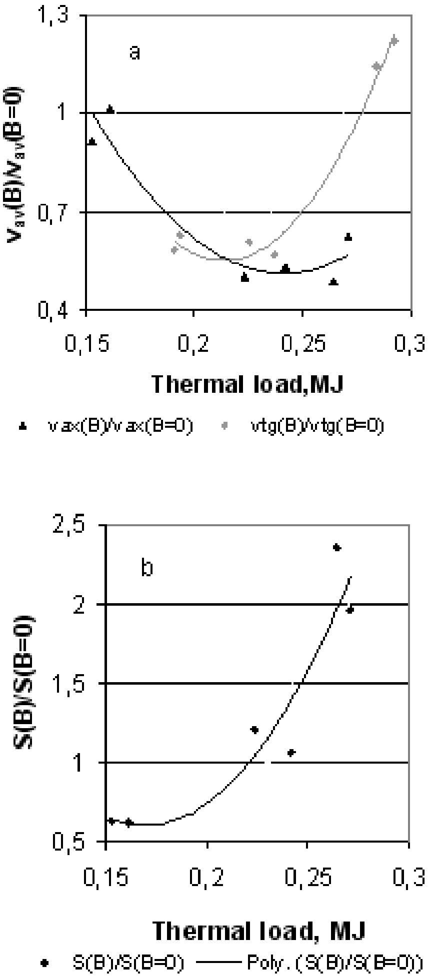
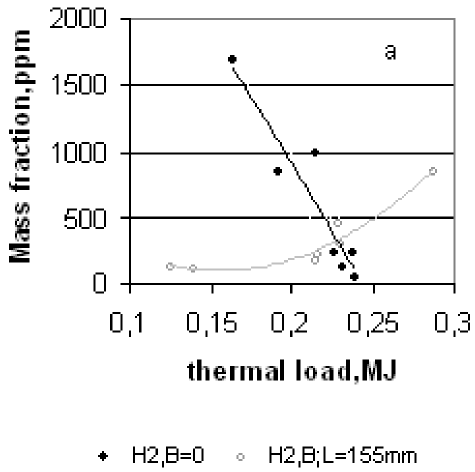


Fig. 4. The variations of the magnetic field effect on the average values of the axial and tangential velocity compounds and swirl number of the flame reaction zone at different rates of propane co-fire and thermal load of the flame channel flow.

The variations of the magnetic field effect on the flow dynamics at different rates of propane co-fire is closely linked to the variations of combustion conditions in the flame reaction zone. There are several factors that show the influence on combustion conditions. First, by increasing a rate of propane co-fire and a thermal load of the swirling flame flow, the field-enhanced reverse axial mass transfer up to the wood layer is associated with interrelated heat transfer promoting the field-enhanced wood fuel gasification. Next, in accordance with the Arrhenius reaction rate equation, the rates of reactions are very sensitive to the local variations of the flame temperature and composition. Therefore, the field-enhanced heat/mass transfer up to the wood layer with field-enhanced wood fuel gasification promotes the faster combustion of the volatiles downstream of the swirling flame flow. Moreover, the field-induced swirl motion promotes the enhanced mixing of the axial flow of volatiles with a reverse axial flow of free oxygen with direct impact on the rates of reactions. Finally, the field-enhanced variations of the axial flow velocity show a direct impact on the residence time of reactions ($t \approx L/v_{ax}$), completing combustion of the volatiles for the conditions, when the field-enhanced flow reversing slows down the axial flow of volatiles.

The kinetic study of the field-induced variations mass fraction of volatiles (H_2) in the products during the wood fuel burnout (with appropriate estimation of the field effect on the average values of the mass fraction of volatiles in the flame reaction zone (L/D=2,5) at different thermal loads of the swirling flame flow) confirms that the field-enhanced reverse axial heat/mass transfer up to the wood layer results in an enhanced wood fuel gasification. The resulting gasification is increasing the average values of the mass fraction of the volatiles (H_2) in the flame reaction zone (Fig. 5.a), completing combustion of the volatiles downstream of the flame channel flow.



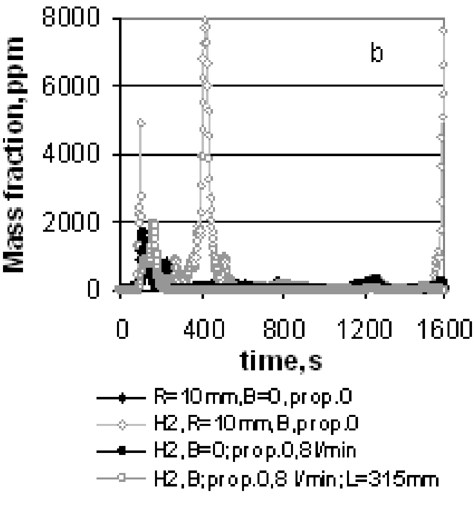


Fig. 5. The field-enhanced variations of the average value of H_2 in the flame reaction zone and time-dependent variations of the H_2 mass fraction in the products during the burnout of volatiles.

As follows from (Fig. 5.b) the mass fraction of volatiles (H_2) in the products due to the field-enhanced wood fuel burnout (t>800 s) can be reduced below 100 ppm. Similar field-enhanced increase of the mass fraction at the primary stage of the wood fuel gasification (t < 500 s) and reduction below 100 ppm during the field-enhanced burnout of volatiles is observed for CO. It indicates that magnetic field promotes cleaner combustion of the wood fuel with correlating increase of the average values of the volume fraction of CO_2 and temperature of the flame reaction zone (Fig. 6).

The magnetic field-induced variations of the flame characteristics show the impact on the local rates of NO formation and the average values of temperature-sensitive thermal NO in the flame reaction zone (Fig.6). The principal source of NO formation via the Zeldovich mechanism is the oxidation of molecular air nitrogen through two-stage reactions ($O+N_2 \leftrightarrow NO+N$ and $N+O_2 \leftrightarrow NO+O$). In accordance with this mechanism, a rate of NO formation is highly limited by the first-step reaction, determining a break-up of the nitrogen triple-bond with high energy of activation (E/R=38000) and low-rates of reactions $k=A\exp(-E/RT)$ below 1600K [13]. Moreover, it should be noted that NO formation in the flame reaction zone is a result of competing thermodynamic, chemical and fluid dynamic factors, depending on the fuel-air equivalence ratio, degree of fuel-air premixing the inlet air temperature, the residence time in the flame reaction zone and flow velocity. For the conditions of swirl-enhanced mixing of the flame compounds with air excess in the flame reaction zone the main factors, determining the rate of NO formation and average value of NO in the flame reaction zone are the flame temperature and the residence time in the flame reaction zone ($t \approx L/v_{ax}$). Both of these factors show the influence of the average value of NO in the flame reaction zone, when the magnetic field is applied to the flame promoting the variations of the flame flow dynamics (Fig. 3, 4) and flame temperature (Fig. 6.). It should by noted that for the conditions of low-temperature staged combustion downstream of the flame reaction zone, the peak values of NO are relative low (80 ppm) and do not exceed acceptable limit for wood fuel combustion (300-350 ppm).

Finally it should be noted that the dominant field-induced increase of the average values of the main products and flame temperature correlates with a decrease of the air excess in the flame reaction zone (Fig. 6). The local measurements of the flame composition have shown that the more pronounced decrease of the air excess occurs close to the channel walls, where the peak values of the air excess with minimum value of the flame temperature correlates with a peak value of the volume magnetic susceptibility of paramagnetic oxygen and magnetic force, acting on the swirling flame flow.

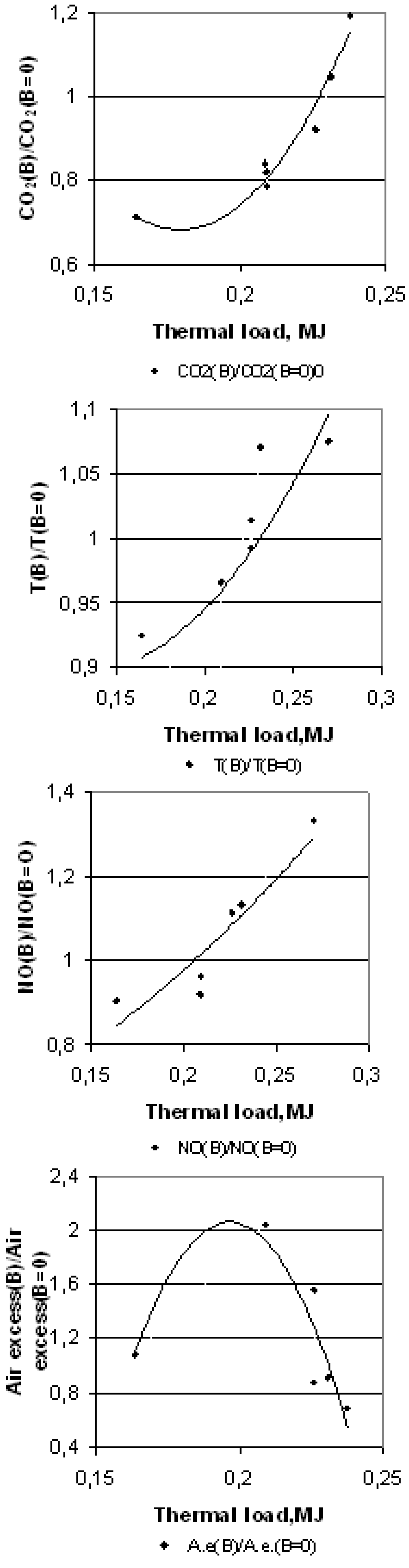


Fig. 6. The magnetic field effect on the average values of the swirling flame temperature and composition by varying a thermal load of the flame reaction zone.

IV. Conclusions

The present study has revealed that the gradient magnetic field-enhanced reverse axial mass transfer of paramagnetic oxygen results in interrelated variations of combustion dynamics indicating that the magnetic field effect on the swirling flame formation can be used to provide control of the flow dynamics, flame temperature and composition. Based on the results of experimental investigations at different rates of propane co-fire, the following conclusions have been drawn:

- the field-enhanced reverse axial heat/mass transfer of paramagnetic oxygen up to the wood layer with an increased the thermal load of the flame reaction zone for the conditions of propane co-fire promotes the field-enhanced wood fuel gasification with enhanced release of the volatiles (CO, H_2) during the primary stage of the swirl flame formation. Moreover, the magnetic field-enhanced variations of flame recirculation zone increase release of CO emission from 2500 ppm up to 8000 ppm and H_2 from 2500 ppm up to 10000 ppm;
- the magnetic field-enhanced variations of the flame velocity compounds with field-induced brake of the axial flame velocity and enhanced swirl motion results in field-induced variations of the residence time of reactions and swirl-enhanced mixing of the flame compounds, completing combustion of the volatiles with intensive releases of CO_2, NO_x. (CO_2 increase from 14% up to16%, NO_x from 80 ppm up to 90 ppm).

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Inese Barmina, Maija Zaķe, Vera Kriško, Mārtiņš Gedrovičs. Koksnes granulu un propāna līdzsadedzināšanas procesa izmaiņas magnētiskajā laukā
Ir veikti kompleksi nehomogēna magnētiskā lauka ietekmes pētījumi uz kombinētu atjaunojamā kurināmā (koksnes granulu) un fosilā kurināmā (propāna) degšanas procesiem liesmas virpuļplūsmā pie lauka konfigurācijas, kas veicina paramagnētiskā skābekļa pārnesi virzienā uz gazificējamās biomasas virsmu. Pētījumi apvieno liesmas dinamikas, degšanas produktu temperatūras un sastāva izmaiņu mērījumus magnētiskā lauka un liesmas mijiedarbības procesā, mainot propāna un papildus siltuma padevi liesmas virpuļplūsmā ar mērķi noskaidrot iespējas izmantot magnētiskā lauka un liesmas mijiedarbības efektus kombinētā degšanas procesa kontrolei un regulēšanai. Pētījumu rezultātā ir konstatēts, ka magnētiskais spēks izraisa savstarpēji saistītus siltuma/masas pārneses procesus virzienā uz gazificējamo koksnes granulu virsmu, intensificējot paramagnētiskā skābekļa aksiālo masas pārnesi lauka gradienta virzienā, uzlabojot koksnes granulu gazifikāciju un gaistošo savienojumu veidošanos degšanas procesa pirmajā stadijā. Magnētiskā spēka izraisītā virpuļplūsmas aksiālā ātruma samazināšanās ar vienlaicīgu plūsmas virpuļa skaitļa palielināšanos nodrošina pilnīgāku gaistošo savienojumu sajaukšanos un sadedzināšanu. Intensificējot gaisa un gaistošo savienojumu sajaukšanos, nedaudz palielinās temperatūras recirkulācijas zonas ārējā daļā, kurā vērojams neliels slāpekļa oksīdu koncentrāciju pieaugums.

Инесе Бармина, Майя Заке, Вера Крышко, Мартиньш Гедрович. Изменения комбинированного процесса горения древесных гранул и пропана в магнитном поле
Были произведены комплексные исследования о влиянии неоднородного магнитного поля на комбинированный процесс горения возобновляемого источника энергии (древесных гранул) вместе с невозобновляемым источником энергии (пропана) в закрученном пламени. Магнитное поле обеспечивает движение парамагнитного кислорода к поверхности биомассы. Во время взаимодействия магнитного поля с пламенем, меняя подачу пропана в вихревом потоке пламени, были произведены замеры по изменению динамики пламени, температуры и состава продуктов горения. Цель данного исследования изучить возможности использования эффектов взаимодействия магнитного поля с пламенем для контроля и регулирования комбинированного процесса горения. В ходе исследования было констатировано, что магнитная сила вызывает взаимосвязанные тепловые/массовые процессы переноса в направлении газифицируемой поверхности древесных гранул, таким образом ускоряя аксиальный перенос парамагнитного кислорода в направлении действия градиента магнитного поля, улучшая газификацию древесных гранул и образование летучих веществ на начальной стадии горения. В свою очередь, уменьшение аксиальной скорости вихревого потока с одновременным увеличением параметра закрутки, вызванное влиянием магнитного поля, обеспечивает улучшенное смешивание и горение летучих веществ. Ускоряя смешивание воздуха и летучх веществ, немного увеличивается температура внешней стороны зоны рециркуляции, в ходе чего наблюдается небольшое повышение концентрации оксидов азота.