RIGA TECHNICAL UNIVERSITY
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WOOD PELLETS CO-FIRING WITH GASEOUS FOSSIL FUEL

Dissertation Summary

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CONFIRMATION

I, the undersigned, hereby confirm that I have developed the PhD thesis submitted for consideration at the Riga technical University for obtaining a degree of Dr.sc.ing. The thesis has not been submitted to any other university for obtaining a scientific degree.

Vera Suzdalenko …………………………….
Date: ………………………

The dissertation is written in Latvian language and consists of an introduction, 4 chapters, conclusions, bibliography, 57 figures, 16 tables, and 94 pages. The bibliography contains 87 references.

CONTENTS

3. ANALYSIS OF EXPERIMENTAL RESEARCH RESULTS 17

Topicality of Thesis

Today, sustainability has become an issue of utmost importance due to fast development of the world. Consumption of natural resources and waste disposal volumes are growing and pollutants are emitted into the atmosphere. Sustainable development is important to all spheres: environment protection, economical, and social. Economical growth requests larger consumption of energy sources. Today, fossil fuels take the first place among other energy sources and comprise 74,6 % of the total energy consumption. Many important problems are related to the use of fossil fuels: first, the stock is limited, second, the stocks are geographically concentrated only in several states (Russian Federation, Saudi Arabia, United Arab Emirates, Venezuela, and others), third, combustion of fossil fuels produces emissions of greenhouse gases (CO_2, CH_4, SO_x, NO_x , and others).

European long-term development strategy is based on renewable energy sources (RES). On April 23rd, 2009 European Commission and Council Directive 2009/28/EC on the promotion of the use of energy from renewable sources was approved in order to promote use of RES. One of the main aims of the Directive is to achieve 20 % of the total European member state energy consumption to be produced from renewable energy sources. Latvian individual aim is one of the highest among the member states and equals 40 %. According to the EUROSTAT data specific amount of RES in total energy consumption of Latvia is 33% and this number has not changed since year 2004.

Topicality of the work is defined by the following factors:

- There is a relatively high potential of wood fuel use in Latvia. Amount of woodland has doubled during last 100 years and has reached 50,9 %.
- Despite the high potential, the specific weight of wood use in energy transformation sector is not sufficient and makes only 15 %.
- Relatively low efficiency ratio of the wood fuel use in boiler houses and cogeneration stations. For example, in year 2011 boiler houses powered with wood fuel had an efficiency of 65 %.
- Specific weight of gas in the transformation sector is approximately 80 %, but its continuously growing price provides conditions for partial natural gas substitution with wood fuel, simultaneously providing conditions for more efficient combustion of wood.

The goal and objectives of the work

The goal of the research described in the dissertation is to investigate the effect of wood pellets and gaseous fuel co-firing on emission production, efficiency, and produced energy volumes. The following objectives were set in order to achieve the aim of the research:

1. to perform experiment co-firing wood biomass of various moisture content with gaseous fuel – a mixture of propane and butane;
2. to make an analysis of the data obtained as the result of the performed experiments and develop empirical equations that describe influence of moisture content in the wood biomass and additional heat supply to the emission production (CO_2, CO, NO_x), temperature, efficiency, and produced heat energy;
3. to perform experiments in order to define influence of magnetic field on co-firing and combustion processes of wood biomass without additional heat input;
4. to make an analysis of a permanent magnet on the combustion process dynamics, e.g. development of cyclonic flow, emission production, and efficiency.

Methodology of the research

The research performed in the framework of the thesis can be divided into two parts. The first part contains experiment performed using an experimental equipment designed for this particular purpose. Wood pellets with various moisture contents (W = 8 %, 15 %, 20 % and 25 %) was combusted in this device without propane/butane and using propane/butane flame. Supply of propane/butane was being changed from 0,9 kJ/sec to 1,27 kJ/sec.

For the experiment on permanent magnet influence on combustion process the device was placed into applied magnetic field, which provided formation of axial and tangential magnetic field induction gradient in the flame combustion zone.

The second part was devoted to the regression analysis of the experiment results, where empirical equations were obtained. The equations describe influence of wood pellets moisture content and supply of propane/butane on emissions, efficiency, and produced heat energy volumes. It was checked using Student criteria at a definite significance level P and degree of freedom f, whether all parameters of the equation (moisture content in the wood and supply of propane/butane) are significant and are preserved in the equation. Also, adequacy of the equation was checked using Fisher criterion F.

Scientific novelty

The results of the experimental research achieved in the work and developed empirical equations allowed making a full analysis of influence on the combustion process produced both by wood pellets moisture content and supply of propane/butane, and magnetic field.

Supply of propane/butane to the wood pellets provide more intense development of volatile matters and ignition in the initial phase of combustion process, as well as more complete combustion of volatile matters, thus providing cleaner and more efficient heat energy production. A verification of the fact that magnetic field influences significantly creation of flame swirling flow.

Processes of magnetic field and flame interaction can be used to control flow dynamic, temperature of the flame, and composition of combustion products.

Practical significance of the work

The thesis has a high practical significance. The aim of it is to increase level of wood biomass use for energy production. The results of the work are meant for different target groups:

- heat energy producers – using moist wood for combustion with additional heat supply it is possible to provide more efficient and cleaner combustion of biomass;
- producers of biomass combustion equipment – for production of devices for biomass co-firing with gaseous fuels;
- society and state municipalities – rational and efficient use of wood biomass.

Approbation

The results of the research has been discussed and presented at the following scientific conferences:

1. seminar of the project CHP Goes Green with presentation „Biomasas un gāzes līdzdedzināšanas izpētes rezultāti" – 2013, 14th of May, Riga;
2. 53. RTU scientific conference, in section „ Environmental and Climate Technologies", with poster „The Regulation Possibilities of Biomass Combustion" – 2012, 11.-12. of October, Riga;
3. 10th International conference ICheaP with report „The Effect of Co-Gasification of Biomass Pellets with Gas on the Thermal Degradation of Biomass" – 2011, 8.-11. of May, Florence;
4. 69. LU scientific conference with poster „Degšanas procesu dinamikas kontroles iespējas virpuļplūsmā" – 2011, 9th of February, Riga;
5. 51. RTU scientific conference, in section „ Environmental and Climate Technologies", with report „The modification of wood pellets and propane co-firing in a magnetic field" – 2010, 12th of October, Riga;
6. 50. RTU scientific conference, in section „ Environmental and Climate Technologies", with report „The magnetic field effect on the swirling combustion of the renewable fuel" – 2009, 13th of October, Riga;
7. seminar "Current and future woody biomass for energy – Monitoring use and understanding technology" with poster "Co-firing of wood

pellets with propane for environmental friendly energy production” – 2009, 15th of September, Riga.

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1. EXPERIMENT EQUIPMENT AND MATERIALS

In the framework of the dissertation experimental researches were made on wood pellets with various moisture content co-firing with propane/butane mixture and on impact of magnetic field on the combustion process. All experiments were carried out at the laboratory of Heat and Mass Transfer Institute of Physics of the University of Latvia, where a special pilot device was constructed for this purpose. The layout of the pilot device is shown in the figure 1.1.

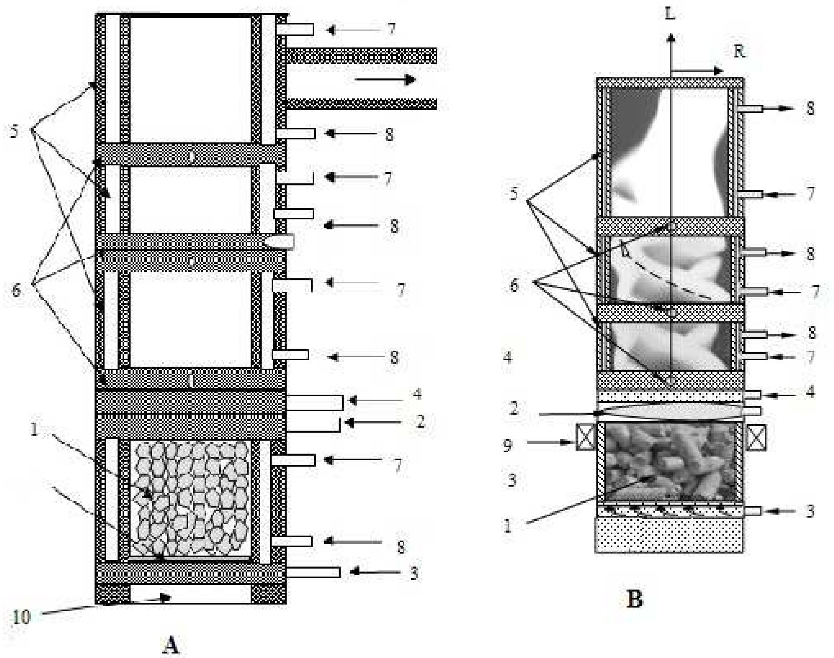

Fig. 1.1. Pilot device: A – Co-firing; B – application of magnetic field
1 – wood fuel gasifier; 2 – propane/butane/air burner; 3 – primary air supply; 4 – secondary air flow; 5 – cooled channel sections; 6 – diagnostic probe outlets; 7 – inlets of cooling water flow; 8 – outlets of cooling water flow; 9 – permanent magnets; 10 – steel riddle

The main parts of the device are wood fuel gasifier (1), propane/butane/air burner (2), as well as cooled channel sections (5), where volatile matters are produced, and ignition and combustion occur. The channel is comprised of three cooled sections and cooling water flow inlet (7) and outlet

(8). In order to secure gasification and full combustion of volatile matters air is supplied through 2 tangential inlets (∅ 5 mm) at the bottom of the gasifier (3) and at its upper part (4) above the wood biomass layer. Sections with outlets for diagnostic probes are located between the sections of the water cooling channel. The probes are meant for combustion zone temperature, gas composition, and axial and tangential velocity measurements. Propane/butane/air flame is forming when radial propane and butane flow and tangential air flow are mixed in the channel. Wood biomass, which has been inserted into the propane/butane flame provides faster heating and thermal decomposition and acceleration of volatiles and ignition.

The permanent magnet (9) with 4 pairs of poles, which height is 50 mm, was attached below the secondary air supply and propane/butane/air burner in order to produce axial and tangential transfer of paramagnetic oxygen molecules to the pellet layer surface, thus providing more complete mixing of volatiles and air at the primary stage of combustion process.

Magnetic induction (B) above the magnet poles reaches its maximal value of 120 mT at the outer wall of the channel. Directive 2004/40/EC of the European Parliament and the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) defines that maximum allowed radioation level for devices with frequency below 1 Hz can be 200 mT. This means that the permanent magnet used in the experiments complies with the safety standards.

Axial gradient of the magnetic field induction ($^{dB}\!/_{dL}$) at the wall of the channel, which causes oxygen transfer towards the pellet surface is equal to 1,56 T/m, but it is not higher than 0,8 T/m in the central part of the flame.

1.1. Characteristic parameters of the materials

In all of the experiments wood pellets were combusted simultaneously with propane/butane mixture without it. Wood pellets moisture content (%), volume (g), propane/butane supply (kJ/ses), and air supply (l/min) varied according to the experiment.

Wood pellets. In the experiments on the impact of magnetic field on the combustion process wood pellets with moisture content of 8% were used. In the experiments on the impact of propane/butane supply on the combustion of wood pellets the pellets were selected with different moisture content: 8 %, 15 %, 20 %, and 25 %. A discrete volume of wood pellets was used for combustion in the experiments: in co-firing experiments it was 500 grams of pellets, but in the experiments with permanent magnet – 320 grams.

Propane/butane mixture. During the experiment supply of propane/butane mixture varied from 0 till 1,55 kJ/sec.

Air supply. Primary air supply in the experiments was equal to 47 l/min. This value was meant for induction of wood pellet gasification. Secondary air supply was 69 l/min for co-firing and 71 l/min for application of magnetic field. The secondary air was supplied in order to secure full combustion of volatiles.

Table 1.1

Summary on the materials used in the experiments

	Co-firing	Magnetic field
Weight of the wood pellets, g	500	320
Moisture content (W), %	8; 15; 20; 25	8
Supply of propane/butane, kJ/sec	0,9; 1,03; 1,16; 1,27	1,27; 1,37; 1,46; 1,55
Primary air supply, l/min	47	47
Secondary air supply, l/min	69	71

Table 1.1 shows a summary on the materials used in two series of experiments: co-firing and application of magnetic field.

1.2. Description of the experimental research

During the experimental research, which was carried out in the Institute of Physics of the University of Latvia, a large number of experiments was carried out. Two possibilities of wood pellets combustion were analyzed during these experiments:

1. simultaneous combustion of wood pellets with different moisture content and propane/butane mixture;
2. combustion of wood pellets applying magnetic field.

Local flame temperature measurements ($T = f(t)$) were made during the experiment, measurements of the temperature and composition (O_2, CO_2, CO, NO_x), measurements of combustion efficiency, as well as local measurements of radial distribution of the axial and tangential flame velocity in the different stages of the combustion process. Also, measurements of the produced heat volumes were made to analyze the total produced heat volumes.

In order to obtain a valid data about the processes that take place on the combustion chamber, the measurement instruments, which were used – thermocouples, gas analyzer probe, and Pitot's tube were inserted at different height values depending on the series of experiment.

Table 1.2

Placement of the measurement instruments above the propane/butane burner

	Co-firing	Magnetic field
First thermocouple	157 mm	55 mm
Second thermocouple	187 mm	380 mm
Gas analyzer, Pitot’s tube	386 mm	145 mm

Thermocouples were placed in the center of the channel (R = 0), while the gas analyzer probe and Pitot’s tube were placed according to the aim of the experiment either in the center of the channel (R = 0) in case of making kinetic measurements of the flame composition, or were moved radially in the channel when making measurements of the flame composition and radial distribution of velocity in the steady combustion process. Measurements of the flame composition and radial distribution of velocity were made moving the probes with an interval of 30 second in the direction from the center of the flame to the channel wall and backwards. Diameter of the channel, where combustion process is developed, is 60 mm.

Length of each of the experiments was 2400 second or 40 minutes, thus providing full combustion of the wood pellets. In all of the experiments propane and butane were combusted first, but wood pellets were added at the 60th second of the experiment.

2. METHODOLOGY OF DATA PROCESSING AND CALCULATION

Data processing and different calculations had to be made in order to use the obtained data for carrying out an analysis.

The experimental data was obtained in two ways: using a computer program PC-20 for local flame temperature and colled water temperature measurements, and using gas analyzer TESTO 350-XL for defining temperature values for polluting substances, efficiency, and temperature of the combustion products.

2.1. Gas analyzer data processing

Gas analyzer Testo 350-XL uses two measurement units for the analysis of gas pollution: percents (%) for defining O_2 and CO_2 emissions, and ppm for CO and NO_x defining. ppm (*parts per million*) is a measurement unit, which does not depend on temperature or air pressure (1 ppm = 0,0001 %).

Processing the experimental data CO and NO_x emissions (ppm) were translated into mg/nm^3. In this case normal conditions were used (temperature - 0 °C, pressure – 1013 mba). In order to compare data obtained in the different experiments, measured emissions were recalculated using reference conditions, applying oxygen content in the flue gases at the reference conditions ($O_{2ref.}$). This value changes depending on the fuel, which is used. For example, $O_{2ref.}$ for wood is 10%, for gas – (natural gas, propane, butane) – 3%. Considering the above mentioned facts, formula for CO and NO_x recalculation from ppm to mg/nm^3 is the following:

$$CO(mg/nm^3) = CO(ppm) \times 1{,}25 \times \left[\frac{21 - O_{2ref.}}{(21 - O_{2mer.})} \right] \qquad (2.1)$$

$$NO_x(mg/nm^3) = NO_x(ppm) \times 2{,}05 \times \left[\frac{21 - O_{2ref.}}{(21 - O_{2mer.})} \right] \qquad (2.2)$$

2.2. Calculation of the maximum CO_2 emission

Carbon dioxide (CO_2) is a product of full combustion. Its maximum value, which can be emitted during combustion depends on the type and composition of the fuel. It is calculated using the formulas shown below:

$$CO_{2\max} = \frac{21}{1+\beta} \qquad (2.3)$$

$$\beta = 2.37 \frac{H^d - 0{,}125 O^d}{C^d + 0{,}375 S^d}\ , \qquad (2.4)$$

where
H^d – hydrogen content in the as-fired fuel;
O^d – oxygen content in the as-fired fuel;
C^d – carbon content in the as-fired fuel;
S^d – sulphur content in the as-fired fuel.

When 1 kg of wood pellets is combusted, the maxumim CO_2 emission volume is 20,24 % irrespective of the moisture content. When 1 kg of propane/butane mixture is combusted, the maximum CO_2 emission volume is 13,93 %.

As it has been mentioned before, a discrete doze of wood pellets (500 or 320 grams depending on the experiment performed) was combusted. The pellets were inserted in the beginning of the experiment and never refilled. During the combustion process when wood pellet volume reduces, hydrogen, oxygen, and carbon volumes reduce, too, as the result of which maximum CO_2 emission volume reduces accordingly.

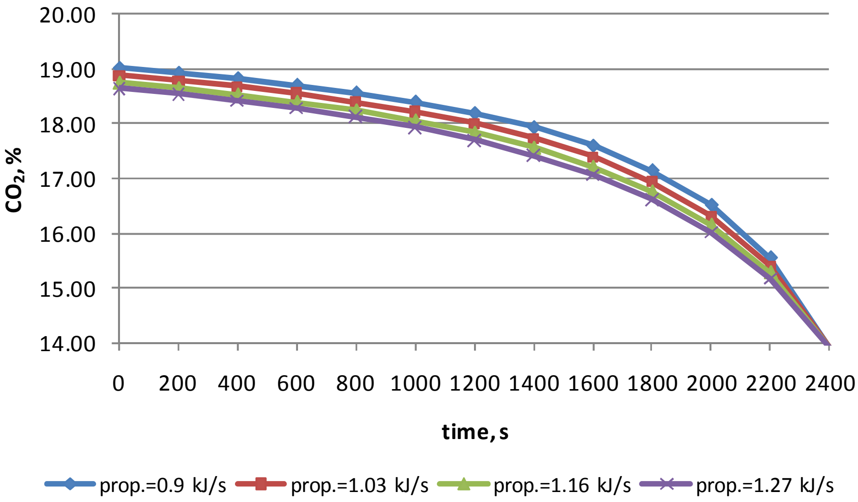

Fig. 2.1. Fluctuation of the maximum CO_2 emission volume depending on time and supply of propane/butane

Figure 2.1. shows a summary of the results that show how maximum CO_2 emission volume fluctuates during the experiment at supplies of additional heat. At the beginning of the experiment, when the weight of the wood pellets was 500 grams, the highest CO_{2max}:was observed: 19,02 %, 18,88 %, 18,75 % and 18,65 % at propane/butane mixture supply of 0,9 kJ/sec, 1,03 kJ/ sec, 1,16 kJ/ sec and 1,27 kJ/sec accordingly. After the wood pellets were fully combusted,

the maximum CO_2 emission volume reached 13,93 % irrelevant to the gas mixture supply velocity.

2.3. Methods of statistical data processing

During the experiments performed in the framework of the thesis development more than 20 000 data was obtained, of which an average values were calculated. The obtained data was processed using two statistical processing methods – correlation and regression analysis. The aim of these methods was to obtain graphical and analytical dependence between the variables.

Microsoft Office Excel program was used to develop several empirical equations with two independent variables: supply of propane/butane (kJ/sec) and moisture content (%) in the wood biomass. It was analyzed with the help of the developed empirical equations that these independent variables influence production of emissions (CO_2, CO, NO_x), efficiency, and produced heat energy volume. Statistical evaluation was made for each of these equations: obtained t criterion for each ratio with the value t_{tab}, found in Student's distribution tables according to the measure of significance $p = 0,05$ and f degrees of freedom. Adequacy of equations was checked using Fisher criterion.

3. ANALYSIS OF EXPERIMENTAL RESEARCH RESULTS

Current chapter contains summary of experimantal results of two experimental series:

a. The first series of experimental researches is related to co-firing of wood pellets and propane/butane mixture, evaluating influence of co-firing on emission production, efectiveness and produced heat energy.
b. The second series of experimental researches is related to usage of gradient of magnetic field to influence the combustion process and development of combustion product content. Researches on magnetic field influence on combustion process have been performed while wood granule combustion, as well as while co-firing wood granules with propane/butane mixture, changing its supply in wood pellets.

3.1. Results of biomass and gas co-firing investigations and its analysis

The process of wood pellets combustion starts with wood pellets endothermic heating, drying and thermal decomposition processes. Investigations with wood pellets of different moisture and different supply of propane/butane in the device confirm that in the term of the beginning of thermal decomposition stage essentially depends on content of moisture and supply of propane/butane to wood pellets.

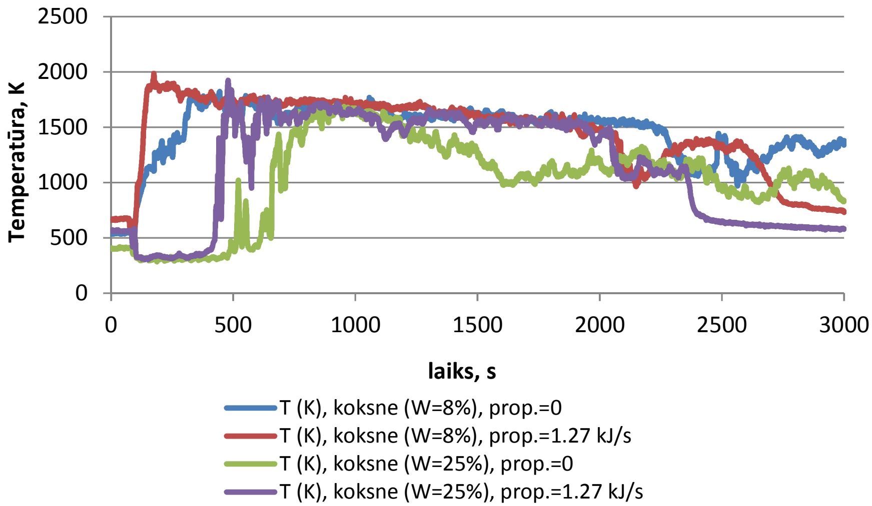

Fig. 3.1 Temperature changes (K) for wood pellets of different moisture content combustion with and without propane/butane supply

While combustion of wood pellets with 8% moisture content with propane/butane supply and without propane/butane supply to biomass, inflammation of volatile compounds has been noticed, comparing wood combustion with 25 % moist, faster reaching maximal temperature of combustion zone (Fig. 3.1). While increasing moisture content in wood pellets, temperature in the beginning of thermal decomposition process decreases (after 100th second), because endometrial processes of wood heating and drying dominate, thus limiting development of volatile compounds and inflammation.

Table 3.1

The influence of additional heat supply on maximal temperature during process of thermal decomposition in initial stage

Wood pellets	W = 8 %	W = 8 %	W = 25 %	W = 25 %
Supply of propane/butane	0 kJ/sec	1,27 kJ/sec	0 kJ/sec	1,27 kJ/sec
Maximal temperature	1821 K	1984 K	1699 K	1923 K
Time*	445 s	175 s	875 s	479 s

* Time period for reaching maximal temperature

Supply of propane/butane in wood pellets provided faster development of volatile compounds (Table 3.1): while wood pellets of 8% moist co-firing with propane/butane, maximal temperature has been reached already at 175th second after starting wood pellets gasification process, but when combusting wood pellets without propane/butane supply to biomass, maximal temperature at combustion zone has been reached after 445 seconds. Whereas pellets of 25 % moist with additional heat supply to biomass have reached maximal temperature at 479th second, but while combusting wood granules without additional heat supply to biomass, maximal temperature at combustion zone has been reached only in 875 seconds.

Stable combustion process of volatile compounds depending on moist content in wood fuel developed from 500th to 2000th second. The influence of propane/butane supply on combustion process of wood (W = 25 %) is observed also in the final stage of combustion process (t > 2000 s) (Fig. 3.1). After combustion of wood pellets of moist 25 % without supply of propane/butane to the device, in the final stage of combustion about 25–30 g of charred pellets are left in the gasifier, which continue glowing with slight increase of flame temperature in the end of the experiment.

After evaluating results of experimental measuring of the influence of wood fuel moisture content and additional heat supply on average temperature of combustion zone, the following empirical equation has been obtained:

$$T_{avg.} = 1715{,}23 - 27{,}15W + 117{,}83q\,, \qquad (3.1)$$

where
W – moisture content in wood fuel (biomass), %;
q – supply of propane/butane, kJ/sec.

Statistical evaluation of the coefficient gained from the empirical equation (3.1) is illustrated in Table 1 in Annexes.

As a result of experimental investigations it was stated that supply of propane/butane to wood pellets layer provides not only higher temperatures, but also increase of produced thermal energy.

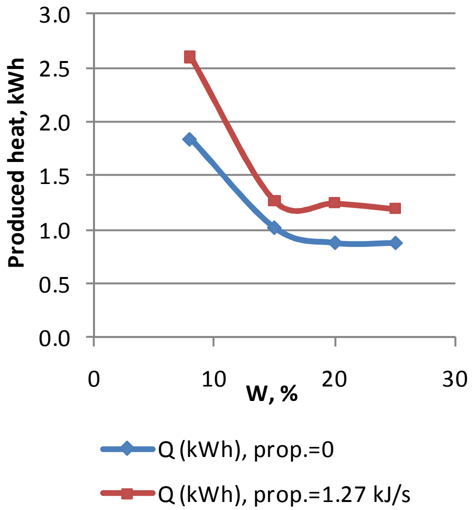

Fig.3.2 Produced heat dependence on moisture content in wood pellets and supply of propane/butane

Increase of wood pellets moisture reduces produced thermal energy, but, if propane/butane is supplied to the base of combustion zone, total produced heat increases (Fig. 3.2).

The evaluation of produced heat in the device depending on wood moisture and supply of propane/butane to the device revealed mutual interconnectedness of the parameters in the empiric equation:

$$Q = 2{,}42 - 0{,}08W + 0{,}35q \quad (3.2)$$

Statistical evaluation of the coefficient gained from the empirical equation (3.2) is illustrated in Table 1 in Annexes.

The influence of propane/butane and moisture content on CO_2 and CO emissions has been evaluated during the experiment by attributing average CO_2 and CO emisions to the maximal value. In case of CO it was maximal value, which was reached during the experiment, but maximal quantity of CO_2 was calculated depending on the speed of propane/butane supply (kJ/sec).

Wood pellets moisture content influences development of CO_2 emission during combustion, as well as its concentration in products. If the wood pellets moisture content is increased, CO_2 emissions decrease, but quantity of CO_2 emissions increases. Supply of propane/butane to combustion camera intensifies wood fuel combustion process, increasing CO_2 concentration, but decreasing CO concentration in products (Fig. 3.3).

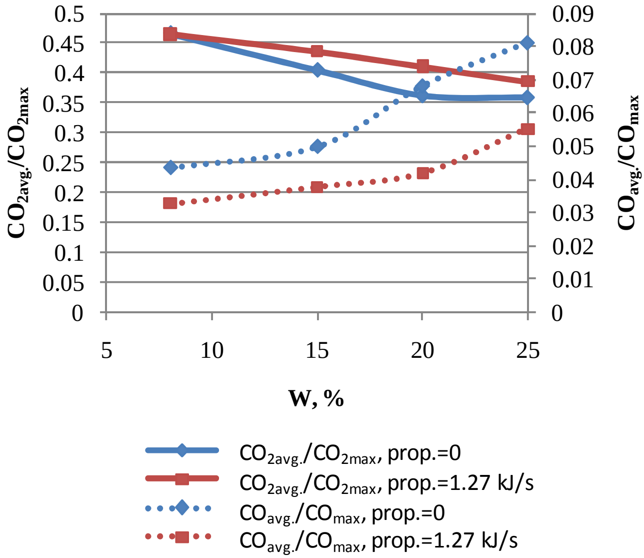

Fig. 3.3 The influence of propane/butane supply on relative changes in $CO_{2avg.}/CO_{2max}$ and $CO_{avg.}/CO_{max}$ of different moisture content wood fuel during combustion process

The results of experimental investigations confirm that current correlations can be described with empirical equations:

$$\frac{CO_{2avg.}}{CO_{2\max}} = 0{,}49 - 0{,}01W + 0{,}03q \qquad (3.3)$$

$$\frac{CO_{avg}}{CO_{\max}} = -0{,}001 + 0{,}006W + 0{,}039q \qquad (3.4)$$

Statistical evaluation of the coefficient gained from the empirical equations (3.3) and (3.4) is illustrated in Table 1 in Annexes.

For total combustion of wood pellets and gas mixture, sufficient air supply should be provided ($\alpha \geq 1$). With wood fuel moisture content increase, theoretically sufficient air volume for fuel combustion decreases, whereas during the experiments the same air volume has been supplied not depending on the wood pellets moisture content. Due to that reason coefficient of air excess increases from 2,5 to 3,07 with wood pellets moisture content increase from 8 % to 25 % and the process of wood pellets combustion develops at expressed odd air supply in the device.

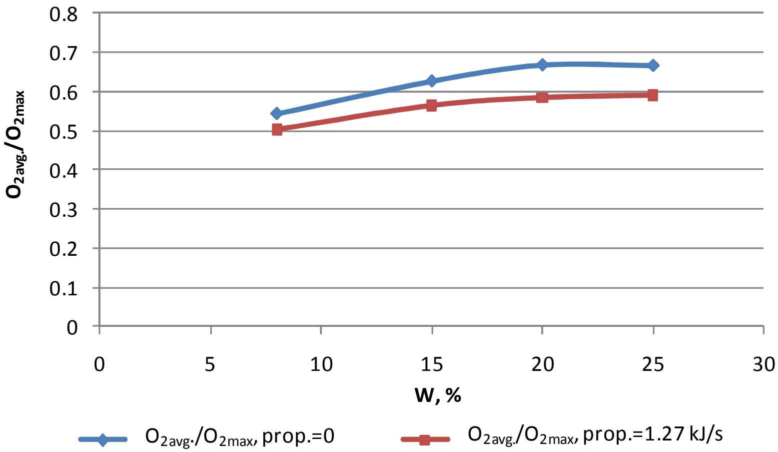

Fig. 3.4 $O_{2avg.}/O_{2max}$ changes in products depending on moisture content in wood fuel and supply of propane/butane in combustion zone

When the moisture content in wood pellets increases, $O_{2avg.}/O_{2max}$ (O_{2max} = 21 %) increases and average O_2 concentration in products increases, which confirms that in case of moisture increase in pellets, less air should be supplied for total burn-off of the fuel. At the same time combusting wood pellets with supply of propane/butane to the device, increase of relative $O_{2avg.}/O_{2max}$ volume concentration in products is slightly lower, because supply of propane/butane increases average temperature of combustion zone, providing complete combustion of volatile compounds (Fig. 3.3).

Analysis of experimental results confirms that influence of wood pellets moisture content and supply of propane/butane on changes in relative $O_{2avg.}/O_{2max}$ volume concentration can be approximately characterized using empirical equation (3.5):

$$\frac{O_{2\,avg.}}{O_{2\,\max}} = 0{,}52 + 0{,}01W - 0{,}06q \qquad (3.5)$$

Statistical evaluation of the coefficient gained from the empirical equation (3.5) is illustrated in Table 1 in Annexes.

NO_x emission during combustion process develops in accordance with Zeldovich's mechanism, which development is essentially influenced by the temperature at combustion zone, air supply in the device, as well as nitrogen content in the biomass. Slight increase (~ 20 %) of NO_x concentration in products is observed using supply of propane/butane in the combustion zone. Nevertheless maximal NO_x concentration in products at supply of propane/butane to the device does not exceed 70 ppm, which is provided by small nitrogen concentration in wood fuel (0,18 %), that provides ecologically pure combustion process.

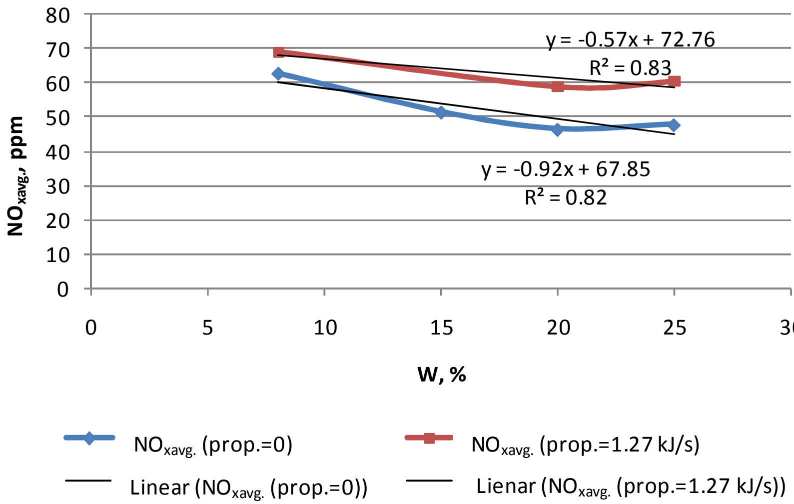

Fig. 3.5 The influence of propane/butane supply and moisture content in wood pellets on concentration of NO_x emission in products

Results of the experimental measuring show that influence of wood pellets moisture content and supply of propane/butane on relative changes of $NO_{xavg.}/NO_{xmax}$ can be described using equation (3.6). $NO_{xavg.}$ is an average value during the experiment, but NO_{xmax} – maximal value during the experiment.

$$\frac{NO_{x\,avg.}}{NO_{x\max}} = 0{,}65 - 0{,}01W + 0{,}12q \qquad (3.6)$$

Statistical evaluation of the coefficient gained from the empirical equation (3.6) is illustrated in Table 1 in Annexes.

While combusting the biomass it is important to arrange combustion process not only with limited exhaust of hazardous emission into atmosphere, but also higher heat production and effectiveness of combustion process should be provided. While proceeding experimental data on effectiveness of combustion, it is stated that supply of propane/butane and changes in wood fuel moisture content influence effectiveness of the combustion process (η), which increases with higher supply of propane/butane to the combustion zone and decreases with higher moisture content in wood pellets (Fig. 3.6).

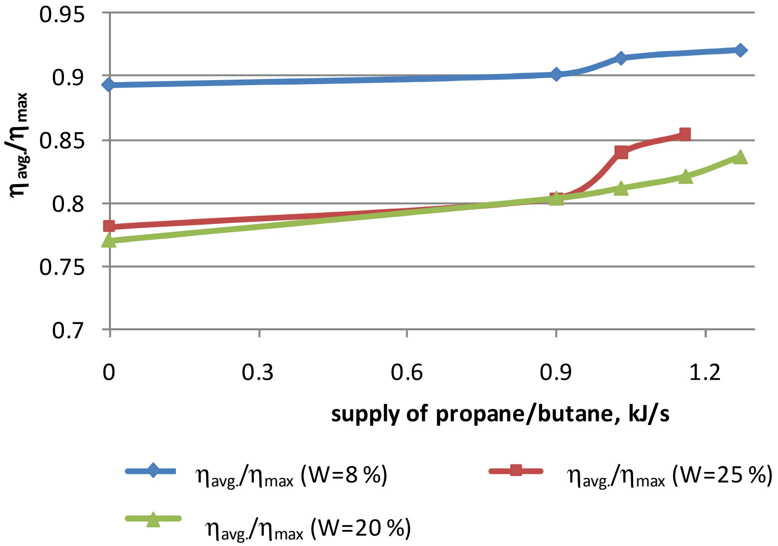

Fig. 3.6 $\eta_{avg.}/\eta_{max}$ at different velocity of propane/butane supply and at different moisture content in wood pellets

The influence of moisture content in wood biomass and additional heat supply on effectiveness can be described with linear equation:

$$\frac{\eta_{avg.}}{\eta_{\max}} = 0{,}93 - 0{,}008W + 0{,}04q \qquad (3.7)$$

Statistical evaluation of the coefficient gained from the empirical equation (3.7) is illustrated in Table 1 in Annexes.

3.2. Research of magnetic field impact on the combustion process

Number of researches that have been carried out previously confirmed that effects of interaction between flame and inhomogeneous magnetic field can be used in order to achieve additional impact on the combustion process. The effect is based on transfer of paramagnetic oxygen towards the gradient caused by the magnetic field gradient. It provides fluctuations of local oxygen concentrations in the air and in volatile mixtures with the following changes in combustion of volatiles. In order to evaluate impact of the magnetic field on the combustion formation the bottom of the combustion zone was placed into a magnetic field, thus providing formation of a magnetic field gradient at the bottom of the combustion zone, where an intense mixing of volatile flow with air swirling flow.

Influence of the magnetic field gradient (dB/dL) on the flow dynamics is mainly defined by the magnetic force (F_{mag}), which depends on the magnetic susceptibility of the oxygen (χ_v) and magnetic permeability (μ_0). Force generated by the magnetic field gradient defines fluctuations of the swirling flow dynamics, followed by fluctuations in volatile matter combustion process.

For evaluation of the magnetic field impact on the flow dynamics measurements of axial and tangential velocity distribution at the bottom of the combustion zone were made, making an evaluation of magnetic field impact on the formation of velocity distribution.

As the result of the interaction of the magnetic field gradient generated force and the flame fluctuations of swirling flow dynamics are observed with an evident reduction of axial and tangential velocity of the flame (Fig. 3.7). Considering this a forecast can be made that in the process of magnetic field and flame interaction length of volatile matter containment in the combustion zone will increase, providing more complete combustion of volatile matters.

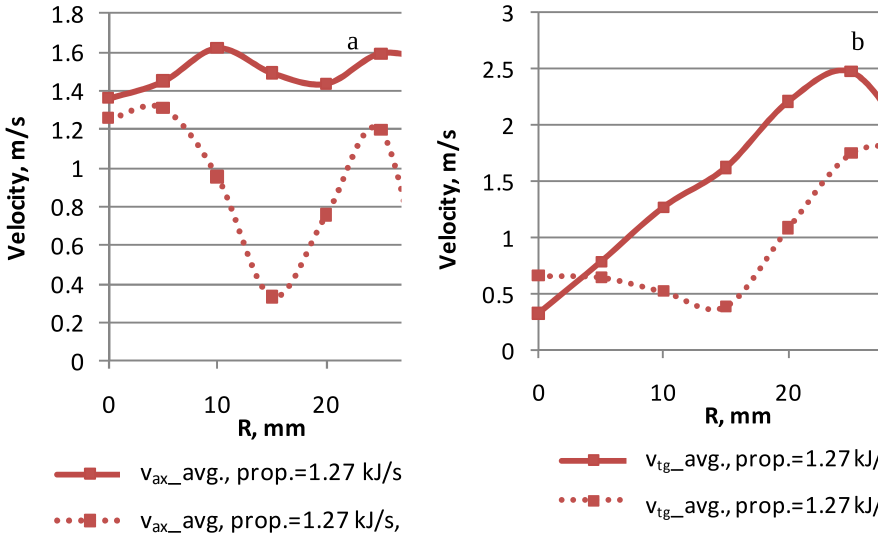

Fig. 3.7 The effect of magnetic field on formation of flame axial (a) and tangential (b) velocity distribution in the process of co-firing (L/D ~ 2,6)

Supply of propane/butane the combustion zone and impact of the magnetic field on formation of flame axial and tangential velocity distribution are related to the fluctuations of the swirling flow number (S), which defines the formation of recirculation zone and intensity of swirling flow (Fig. 3.8).

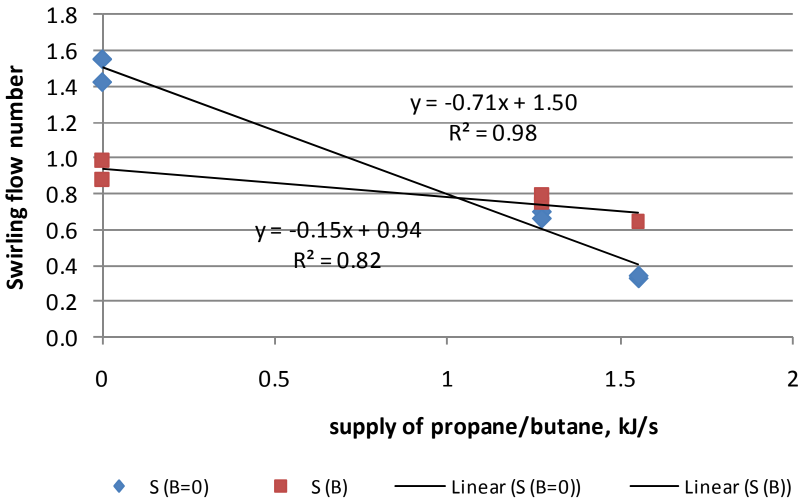

Fig. 3.8. Influence of magnetic flow on fluctuations of the swirling flow number at different capacities of propane/butane supply

The results of the experimental measurements prove that increase of propane/butane supply to the combustion chamber gradually reduces the swirling flow of the flame. Accordingly, axial increase of velocity caused by the supply of propane/butane limits formation of the recirculation flow.

Influence of the magnetic field on combustion process emissions, temperature, and produced heat energy was investigated and evaluated also in the process of wood pellet combustion with supply of propane/butane at the bottom of the combustion zone, while changing supply of propane/butane from 1,27 kJ/sec till 1,55 kJ/sec. These experimental data was compared with the process of wood pellet and gaseous mixture co-firing process, where magnetic field was not applied (B = 0). Average parameter values were calculated for the data analysis. These average values obtained from the experiments with magnetic field (B) were divided by the average values obtained from the experiments without magnetic field (B=0).

Figure 3.9 shows how $O_2(B)/O_2(B = 0)$ ratio depending on supply of propane/butane during the experiment.

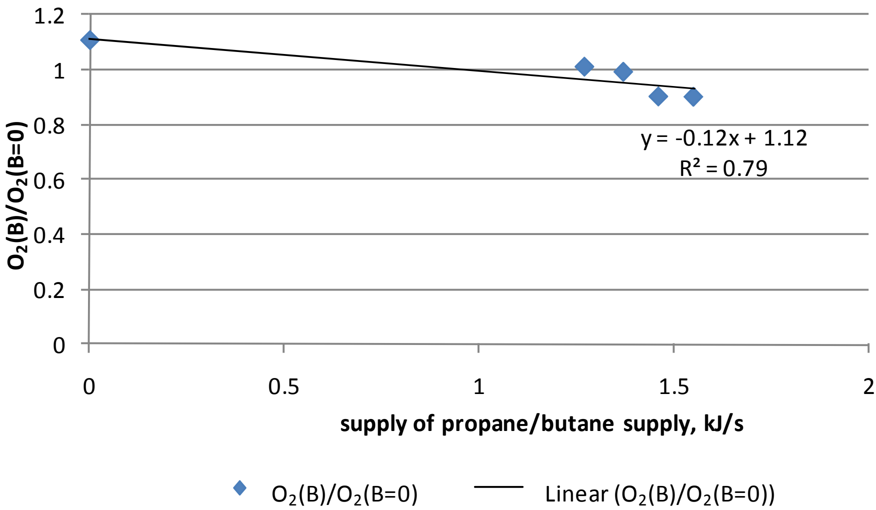

Fig. 3.9 Influence of propane/butane supply on O_2(B)/O_2(B=0)

When wood pellets are combusted without supply of propane/butane in the bottom of the combustion zone, O_2(B)/O_2(B=0) ratio is greater than 1. It means that average amount of oxygen at the bottom of combustion zone increases if paramagnetic oxygen transfer is intensified along the magnetic field. At the same time if wood pellets are combusted with supply of propane/butane in the bottom of the combustion zone, O_2(B)/O_2(B=0) ratio reduces, which indicates reduction of the average amount of oxygen. Basically this can be explained with the fact that in case if wood pellets are combusted with supply of propane/butane additional heating of paramagnetic oxygen is provided, ensuring transfer of hotter heat flow to the pellet surface. This improves gasification of the wood pellets and provides more intensive formation of volatiles.

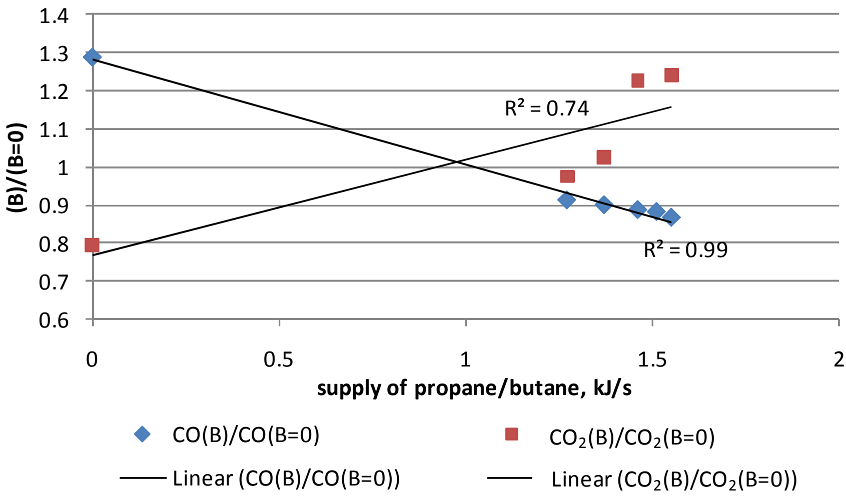

Fig. 3.10 Influence of propane/butane supply on CO_2(B)/CO_2(B=0) and CO(B)/CO(B=0)

In contrast to the changes of oxygen concentration, a higher CO_2(B)/CO_2(B=0) ratio for wood pellet combustion process is observed when supply of propane/butane to the bottom of the combustion zone is increased. More intensive combustion process with CO_2 emission increase if formed without supply of propane/butane to the bottom of the combustion zone if paramagnetic oxygen transfers towards the bottom of the combustion zone if not intensified. More complete volatile combustion can be achieved by combining supply of propane/butane at the bottom of combustion zone with magnetic force produced paramagnetic oxygen transfer. Influence of propane/butane supply is describes by the following linear equation:

$$\frac{CO_2(B)}{CO_2(B=0)} = 0{,}25q + 0{,}77 \qquad (3.8)$$

After influence of magnetic field and supply of propane/butane on concentration of CO emissions was stated that supply of propane/butane ensures reduction of CO(B)/CO(B=0) ratio (Fig. 3.10).

The highest CO(B)/CO(B=0) ratio is observed if wood pellets are combusted without supply of propane/butane at the bottom of combustion zone, when paramagnetic oxygen transfer stimulates formation of air excess and temperature reduction. When supply of propane/butane is provided at the bottom of combustion zone, this ratio decreases and provides more complete combustion process as well as decreases release of harmful CO emissions into the environment. Influence of propane/butane supply on CO(B)/CO(B=0) is described with the following linear equation:

$$\frac{CO(B)}{CO(B=0)} = -0{,}28q + 1{,}28 \qquad (3.9)$$

Paramagnetic oxygen transfer caused by the magnetic field and supply of propane/butane at the bottom of combustion zone influence also formation of NO_x. The results of the experimental research on influence of this factor on fluctuation of NO_x(B) /NO_x (B=0) are summarized in Figure 3.11.

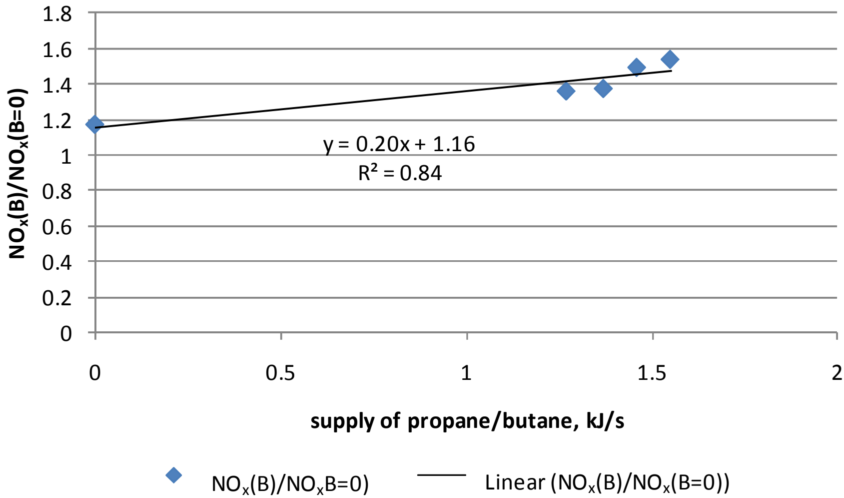

Fig. 3.11 Influence of propane/butane supply on NO_x(B)/NO_x(B=0)

As it is seen from Figure 3.11. in the process of wood pellet combustion NO_x(B)/NO_x(B=0) ratio increases, thus increasing supply of propane/butane at the bottom of combustion zone. The figure shows that in all cases NO_x(B)/NO_x(B=0) ratio is greater than 1, which means that application of magnetic field intensifies formation of NO_x with higher NO_x emission release into the atmosphere. This should be evaluated as a negative result of the interaction between the field and the flame.

One of the most significant factors that influence formation of NO_x emissions is fluctuations of combustion zone temperature and air excess (α), which is generated by supply of propane/butane and the magnetic field. These fluctuations are shown in Figure 3.12.

α(B)/α(B=0) ratio reduces when supply of propane/butane at the bottom of combustion zone is increased (similar to O_2(B)/O_2(B=0) ratio). This relation is shown in Figure 3.12 and is described with the following linear equation:

$$\frac{\alpha(B)}{\alpha(B=0)} = 0{,}35q + 1{,}43 \tag{3.10}$$

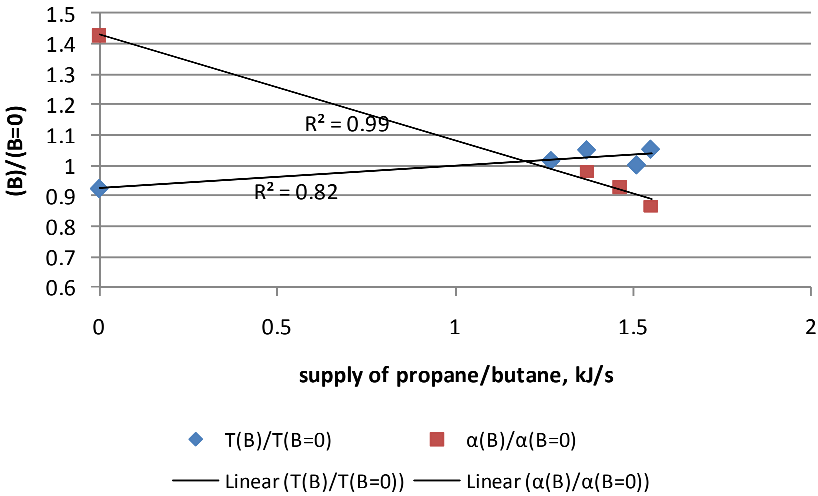

Fig. 3.12 Influence of propane/butane supply on α(B)/α(B=0) and T(B)/T(B=0)

Figure 3.12 shows that fluctuations of T(B)/T(B=0) ratio depends on supply of propane/butane at the bottom of combustion zone. Temperature increases when supply of propane/butane is provided to the bottom of combustion zone. Considering that oxygen transfer provided by the magnetic field simultaneously increases concentration of oxygen, combustion of the volatiles gets intensified.

Influence of propane/butane supply on the temperature is described by the following linear equation:

$$\frac{T(B)}{T(B=0)} = 0{,}07q + 0{,}93 \tag{3.11}$$

After influence of propane/butane supply and magnetic field on the formation of combustion process has been analyzed, influence of these factors on efficiency of combustion process and amount of produced heat energy was evaluated. The results of these analyzes are shown in Figure 3.13.

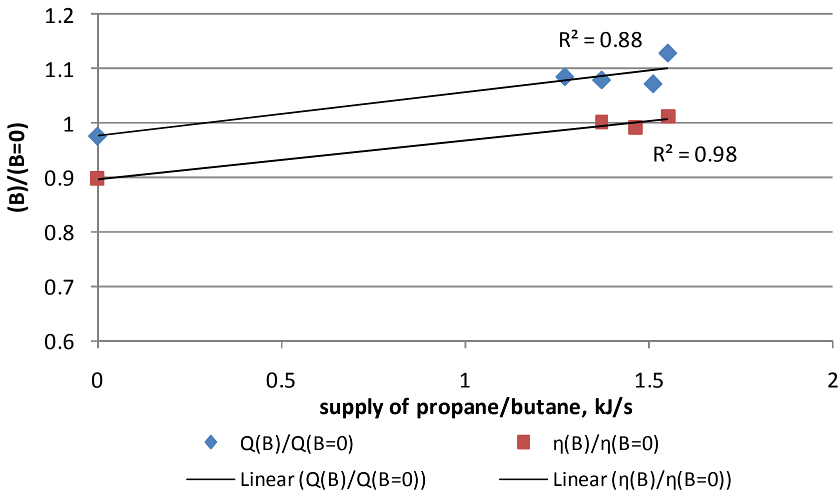

Fig. 3.13 Influence of propane/butane supply on η(B)/η(B=0) un Q(B)/Q(B=0)

As it results from the figure 3.13 – influence of propane/butane supply on the process of interaction between the flame and magnetic field η(B)/η(B=0) is described with the following linear equation:

$$\frac{\eta(B)}{\eta(B=0)} = 0{,}07q + 0{,}90 \qquad (3.12)$$

If wood pellets are combusted and provide increase of propane/butane supply at the bottom of the combustion zone, efficiency of the combustion process also increases. In the result of interaction between the flame and magnetic field average efficiency of combustion process is higher than its efficiency in those cases, when magnetic field has not been applied and paramagnetic oxygen transfer towards gradient of the field has not been intensified.

Figure 3.13 shows influence of propane/butane supply on Q(B)/Q(B=0) ratio, comparing produced heat energy (kWh) in the experiments with and without application of magnetic field. Influence of propane/butane supply on the ratio Q(B)/Q(B=0) is described with the following linear equation:

$$\frac{Q(B)}{Q(B=0)} = 0{,}08q + 0{,}98 \qquad (3.13)$$

In the result of interaction between the flame and magnetic field increase of produced heat energy is observed. It increases when supply of propane/butane to the device is increasing.

CONCLUSIONS

1. It was investigated in the framework of the developed dissertation that moisture content in the wood pellets influences combustion process – formation of emissions, temperature, efficiency, and produced amount of heat energy. A research on how combustion process can be improved by co-firing wood pellets with gaseous fuel was made. To perform the scientific research, an experimental device was designed for co-firing wood biomass and gaseous fuel.
2. The following conclusions were made in the result of co-firing of wood pellets with different moisture content with supply of propane/butane:
   2.1. Duration of thermal decomposition of wood pellets substantially depends on moisture content and supply of propane/butane. Moisture in the wood biomass delays formation and ignition of volatiles, as well as its combustion, in the process of which the highest temperature in the combustion zone is reached. When wood pellets with moisture content of 8% is combusted, the maximum temperature in the combustion zone is reached already at the 445th second after beginning of gasification process. In case of wood pellets with 25 % moisture content formation and ignition of volatiles is significantly delayed and the maximum temperature in the combustion zone is reached at the 875th second only. Experimental research carried out in the framework of the confirms that endothermic processes that are connected to warming up and drying of wood pellets with moisture content 25 % can be compensated applying supply of propane/butane to the wood pellets – e.g.co-firing wood pellets with supply of propane/butane of 1,27 kJ/sec, thus intensifying formation and ignition of volatiles. Maximum temperature in the combustion zone is reached significantly faster – already at the 479th second;
   2.2. It was stated as the result of experimental research that supply of propane/butane to the wood pellets layer provides amount of produced heat energy. Combustion of wood pellets with moisture content of 25 % without supply of propane/butane produced 0,87 kWh of heat energy during the experiment. Co-firing this wood with gaseous fuel of 1,27 kJ/sec generated 36 % greater amount of heat energy;
   2.3. Analysis of combustion product composition fluctuations was made in order to evaluate impact of co-firing on the composition. It was made by evaluating relative changes of the combustion product composition in the process of co-firing. The analysis showed that formation of CO_2 emissions in the process of wood pellets combustion is significantly influenced by the moisture content in the wood pellets: CO_2 emission formation is reduced if moisture content increases, while CO emission

volume increases. For example, in combustion of wood pellets with moisture content of 8 % $CO_{2avg.}/CO_{2max}$ ratio was equal to 0,47, $CO_{avg.}/CO_{max}$ ratio – 0,04. Meanwhile during combustion of wood pellets with moisture content of 25%, relative amount of CO_2 was reduced by 23%, while relative amount of CO increased by 70%. During combustion of wood pellets with moisture content of 25 % with supply of propane/butane relative amount of CO_2 increased by 8 %, CO – reduced by 31 % in comparison with combustion of wood pellets without supply of propane/butane. This proves that using supply of propane/butane to the wood fuel formation, ignition, and combustion of volatiles in intensified, as well as formation of CO_2 emissions, but concentration of CO emission in combustion products is reduced;

2.4. When wood pellet moisture content increases from 8 % to 25 % average volume of O_2 concentration in products increases from 11,41 % till 13,97 %. This shows that increase of moisture content s in the wood fuel provides increase of average O_2 concentration in the products, which means that increase of moisture content in the biomass limits combustion of volatiles and air supply has to be reduced in order to provide complete combustion of the fuel. Simultaneous combustion of wood pellets with supply of propane/butane in the device provides slightly lower increase of relative $O_{2avg.}/O_{2max}$ volume concentration by 11% in comparison with wood pellets combustion without supply of propane/butane, because supply of propane/butane increases average temperature in the combustion zone, hence providing more complete combustion of volatiles;

2.5. Increase of moisture content in wood pellets limited formation of NO_x emissions, which is related to increase of oxygen concentration. At the same time, during wood co-firing with supply of propane/butane a moderate NO_x emission increase by 21 % in average, was observed, which was related to the increase of average temperature;

2.6. Processing the experimental data on combustion efficiency showed that supply of propane/butane and changes of moisture content in the wood pellets influence efficiency of combustion process. It increases when supply of propane/butane in the combustion zone is increased and reduces when wood pellets moisture content is increased;

2.7. Analyzing impact of wood pellets moisture content and supply of propane/butane on $T_{avg.}$, Q, $\frac{CO_{2avg.}}{CO_{2\max}}$, $\frac{CO_{avg.}}{CO_{\max}}$, $\frac{O_{2avg.}}{O_{2\max}}$, $\frac{NO_{xavg.}}{NO_{x\max}}$,

$\frac{\eta_{avg.}}{\eta_{\max}}$, empirical equations were developed using regression analysis. Statistical evaluation of the equation ratios and verification of equation adequacy allowed concluding that the applied parameters – wood pellets moisture content and supply of propane/butane – are significant and application of the equations is correct.

3. It was stated in the result of the experimental research that it is possible to use flame and nonhomogeneous magnetic field interaction effect for additional control of combustion processes. This effect is based on magnetic field gradient caused paramagnetic oxygen transfer in the direction of field gradient, causing the changes of local oxygen concentration in air and volatiles mixture with following changes of volatiles combustion process. The following conclusions were made after the experimental device was placed into a permanent magnetic field and wood pellets were combusted with and without supply of propane/butane:
   3.1. As the result of the interaction of the magnetic field gradient generated force and the flame fluctuations of swirling flow dynamics are observed with an evident reduction of axial and tangential velocity of the flame. Considering this a forecast can be made that in the process of magnetic field and flame interaction length of volatile matter containment in the combustion zone will increase, providing more complete combustion of volatile matters;
   3.2. When wood pellets were combusted without supply of propane/butane it was stated that magnetic field causes paramagnetic oxygen transfer to the outer part of the flame, reducing formation of CO_2, reducing temperature of the combustion zone and efficiency if the combustion process;
   3.3. $O_2(B)/O_2(B=0)$ ratio reduced 19 %, while T(B)/T(B=0) increased by 16 %, when supply of propane/butane to the wood pellet layer was increased from 0 kJ/sec till 1,55 kJ/sec, providing increase of $CO_2(B)/CO_2(B=0)$ ratio by 56 % but reduction of CO(B)/CO(B=0) ratio by 33 %. This means that combination of propane/butane supply to the bottom of the combustion zone with paramagnetic oxygen transfer caused by the magnetic force can ensure more complete combustion of volatiles. Supply of propane/butane and application of magnetic field caused increase of the temperature, thus increasing formation of NO_x emissions by 30%;
   3.4. Application of magnetic and co-firing of wood pellets with propane/butane provided increase of efficiency by 8% in average and increase of produced amount of heat energy by 6%.

Annexes

Annex 1

Statistical evaluation of empirical equation ratios

	Arguments	**Coefficients**	**t statistic**	**P value**	**R**
$T_{avg.}$	b_0	1715,23	25,1	0,000	0,94
	b_1	-27,15	-8,42	0,000	
	b_2	117,83	2,42	0,036	
$Q_{avg.}$	b_0	2,42	10,38	0,000	0,88
	b_1	-0,08	-6,81	0,000	
	b_2	0,35	2,31	0,035	
$\frac{CO_{2avg.}}{CO_{2\max}}$	b_0	0,49	26,43	0,000	0,85
	b_1	-0,01	-5,74	0,000	
	b_2	0,03	2,5	0,026	
$\frac{CO_{avg.}}{CO_{\max}}$	b_0	-0,001	10,38	0,004	0,86
	b_1	0,006	-6,81	0,008	
	b_2	0,039	2,31	0,019	
$\frac{O_{2avg.}}{O_{2\max}}$	b_0	0,52	20,97	0,000	0,84
	b_1	0,01	5,22	0,000	
	b_2	-0,06	-3,53	0,003	
$\frac{NO_{xavg.}}{NO_{x\max}}$	b_0	0,65	16,11	0,000	0,87
	b_1	-0,01	2,32	0,036	
	b_2	0,12	-6,39	0,000	
$\frac{\eta_{avg.}}{\eta_{\max}}$	b_0	0,93	44,77	0,000	0,92
	b_1	-0,008	-6,99	0,000	
	b_2	0,04	3,34	0,007	