1. INTRODUCTION
European Union energy policy leads to the increase of renewable energy sources (RES) energy market share. Unfortunately, currently available RES technologies cause lots of operational problems and have relatively low electricity generation efficiencies. The use of known and highly manageable processes (e.g. combustion) with an alternative fuels seems to be reasonable midgoal in energy technologies transfer to RES. Gaseous fuels, especially natural gas, have became one the basic energy sources in power generation and transportation. Gaseous fuels have lots of advantages: no need for storage, relatively low impact on the environment and simplicity of the automation of the combustion process (comparing to solid fuels). Gas units are often used to cover the peak demands for electric energy because of their short start-up time. On the other hand, natural gas is expensive and the users are dependent on the strategic suppliers. The way for gaseous fuels supply diversification is the use of low-calorific value gases.

The low-calorific value gases (LCV gases) may be derived from very different sources. A significant percentage of LCV gases are waste gases form technological processes. Coke oven gas or converter gas are by-products but also the valuable fuels with a lower heating value (LHV) 17-18 MJ/m³ and 7-8.5 MJ/m³ respectively. Technological processes-derived gases may be characterized by fluctuations in their calorific
Another type of the LCV gases are gases produced in the gasification process (syngas). The very significant feature of these gases is the possibility of changing the gas composition by changing the feedstock or using different gasification agents. Gasification gases show a significant potential as an additional fuel for co-combustion processes.

The aim of the work presented in the article was the experimental investigation of the reburning process using sewage sludge-derived syngas in a small-scale coal-fired boiler and analysis of the nitrogen oxides emission as a function of the gaseous fuel stream added to the boiler.

2. THEORETICAL INFORMATION

2.1. Low-calorific value gases

Low-calorific value gases, in most cases, are mixtures of a few flammable gases, e.g. CO, H₂, CH₄ with diluents such as N₂, H₂O. The examples of syngas compositions taken from literature [2, 3] are presented in Table 1.

<table>
<thead>
<tr>
<th>dry composition, % vol.</th>
<th>wood-derived syngas</th>
<th>wood-derived syngas</th>
<th>lignite-derived syngas</th>
<th>blast furnace gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>8.8</td>
<td>33.4</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>CO</td>
<td>6.9</td>
<td>8.8</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>CO₂</td>
<td>19.2</td>
<td>21.8</td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>CH₄</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>N₂</td>
<td>60</td>
<td>35.5</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>5.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>gasifying agent</td>
<td>air</td>
<td>steam</td>
<td>air/steam</td>
<td>-</td>
</tr>
<tr>
<td>LHV [MJ/m²n]</td>
<td>6.47</td>
<td>4.9</td>
<td>4.13</td>
<td>2.59</td>
</tr>
</tbody>
</table>

Composition of LCV gases, especially the dominance of carbon monoxide and hydrogen as flammable components and significant share of the inert gases, causes that the LCV gases combustion becomes a challenge. Despite the way of utilization (boiler, gas turbine, gas piston engine), an important aspect of the use of gasification gases is the examination of its properties [3,4]. Authors [2, 3] point out that main problems is the stability of the flame, reduced temperature of combustion and narrow flammability limits.

The problems mentioned earlier are connected directly with the composition of gas and the reactions between individual components during the combustion process. The analysis carried out in [5] shows that the interpretation of investigations and calculations conducted with an available methane or carbon monoxide combustion mechanisms is not clear. Generally, the presence of carbon dioxide slows down methane combustion, but the hydrogen accelerates it. It turned out that carbon monoxide's influence is variable – with high CO concentration and high temperature, it increases laminar flame speed but with low CO concentration it inhibits the combustion process. Considering the influence of H₂O also shows the behavior dualism – in lean mixtures it increases the combustion speed, but with high concentration of oxidizer, the laminar flame speed is decreased [4, 5]. The authors of [3] suggest that the negative impact of small amount of hydrocarbons in gas may be neutralized by increasing the substrates temperature.

Using of the reactions mechanism that actually fits the process is vital for mathematical modeling [6, 7] which usually precedes the designing process of e.g. gas burners. The necessity of numerical calculations of gas mixtures with similar composition to gasification gases and their experimental verification are postulated. They are vital for combustion process optimization which leads to satisfying effectiveness of turbomachinery.

Authors of [4] point out that realization of the full potential of low-calorific value gases is dependent on redesigning power systems and machinery. Although, the industry responds to the market needs and some of the manufacturers declare the compatibility of certain series of the machines with alternative fuels such as biogas, syngas or pyrolytic gas [8].

2.2. Gasification

Gasification is a thermo-chemical conversion of solid feedstock into a gaseous fuel. It is also called “half-combustion” because of partial oxidation of the solid fuel for heat generation for endothermic gasification reactions. Gasification is often mentioned as a proper process to utilize alternative fuels (e.g. microalgae) [9, 10] or waste fuels (e.g. sewage sludge) [11]. Because of the low amount of the oxidizer used in the process and the reducing atmosphere, gasification prevents sulphur and nitrogen oxides emission, also it is possible to accumulate part of the contaminants in the solid residues [12]. Biomass gasification gases, as
a fuel that might be received from local energy sources shows a great potential as fuel for CHP plants.

Gasification is characterized by the possibility of varying the gas composition. The type of gasification agent has significant influence on the flammable components share of the gas composition which determines possible ways to utilize the syngas [3]. The example of such agent is steam – using steam as a gasifying medium increases hydrogen share in the gas despite the type of biomass used as feedstock [13]. It results with better combustion parameters e.g. increased laminar flame speed.

Integration of gasification system with power boiler has lots of advantages, especially compared to direct co-combustion of biomass or waste with coal. There are lots of problems that can be avoided e.g. reduced quality of ash, corrosion, slagging and fouling of heating surface. Co-combustion of the low-calorific gas with coal is not trouble-free either but using gasification integrated system allows to solve that problems in the gasifier or gas-cleaning unit. Modification of the power boiler may generate significant costs.

2.3. Reburning

Gasification gases are classified as proper reburning fuel. Reburning is a method for reducing the nitrogen oxides emission by reorganizing the combustion process. It is implemented in the combustion chamber therefore it is one of the primary reduction methods.

Reburning consists of three stages. It strongly depends on the air excess ratio in the particular stage. The air excess ratio ($\lambda$) is a ratio of an actual air to stoichiometric air needed for complete combustion of the fuel. During the first stage, the main part of the fuel is combusted with stoichiometric conditions. During the second stage an additional fuels is added to provide a reductive atmosphere with the local air excess ratio lower than 1 ($\lambda < 1$). The final stage with $\lambda > 1$ is vital to provide burnout of the incomplete combustion products [14]. Figure 1 shows the scheme of the process.

Reburning, as a NOx emission reduction method is applied mostly in older systems. It is connected with significant investment costs of catalytic methods and installation modifications. The authors [15] pointed out that reburning provide 70% effectiveness of NOx emission reduction. As the environmental protection requirements constantly increase, it seems necessary to use the combination of the reburning with another denitrification method [16].

The most important part of the reburning is the reduction zone where the $\text{--CH}_i$ radicals decompose the nitrogen oxides. The main factors determining the reburning effectiveness are: type of additional fuel, air excess ratio, time of reaction in the reduction zone, the local temperatures in the combustion chamber [14]. Fuel considered as a proper reburning fuel should be highly-reactive with significant share of volatile matter. It also should be able to produce lots of $\text{--CH}_i$ radicals. Considering mentioned features, the natural gas is the first choice. Because of its high price, alternative fuels are constantly investigated. Gasification gases also meet the requirements of the reburning fuel. It is confirmed by authors [13, 17] who carried out numerical calculations with sewage sludge-derived syngas and suggest that it shows a great potential as an additional fuel for three-stage combustion. The reburning effectiveness reached 90%. The authors assumed the emission of NO only, however, according to [14] NO is up to 95% of the standard volume fraction of NOx and there is no significant influence of this assumption on the results.

Figure 1.
The scheme of the reburning process.
3. EXPERIMENTAL INVESTIGATION

The experimental investigation of the reburning process in small-scale coal-fired boiler using sewage sludge-derived syngas was carried out. The analysis of nitrogen oxides emission as a function of an additional fuel stream was conducted.

The apparatus consists of the automatic retort coal-fired boiler (25 kW) with the coal storage and fan supplying air for the combustion process. The boiler was manufactured to combust only one fuel. The boiler modification was obligatory because the experimental study required supplying syngas into the combustion chamber. The boiler was equipped with a new firing door that enabled to connect gas supply nozzle. The nozzle was placed concentrically with the burner, between the burner and deflector. The nozzle location allowed to provide a rapid and thorough mixing of gas with exhaust gases what significantly influences the reburning effectiveness. The boiler modification scheme is presented in Figure 2.

Mole fraction of exhaust gas components was measured. The ABB AO2020 Advanced Optima series analyzer was used. It is a modular on-line analyzer that may be upgraded depending on the requirements of the investigation. For the purpose of presented work the Uras 14 infrared absorptive method module was applied. This method, combined with a good quality detector provides highly-selective measurements with a syngas stream in a range 20-100 dm³/h. The measurement of oxygen fraction was carried out using electrochemical method.

The measurements were carried out in two stages. The first stage was the coal combustion – the referential measurements. The second stage involved the analysis of exhaust gases during the combustion of the same stream of coal with an additional stream of syngas. Syngas stream was gradually increased. The composition of combusted low-calorific value gas is presented in Table 2.

The dependence of relative nitrogen oxides emission on syngas share in the chemical energy of combusted fuel is presented in Figure 3.

Table 2. Chemical composition of sewage sludge-derived syngas

<table>
<thead>
<tr>
<th>component</th>
<th>fraction, % vol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>5</td>
</tr>
<tr>
<td>CO</td>
<td>28.5</td>
</tr>
<tr>
<td>CO₂</td>
<td>15</td>
</tr>
<tr>
<td>CH₄</td>
<td>1</td>
</tr>
<tr>
<td>N₂</td>
<td>50.5</td>
</tr>
</tbody>
</table>
The analysis of presented results shows that the NO$_x$ emission decreased. According to figure 3 NO$_x$ emission depends on the stream of an additional fuel in the reburning zone. The highest value of the reduction – 30% was noticed with 11% of gas energy in chemical energy of both fuels supplied to the boiler. The reburning effectiveness strongly depends on the construction of investigated boiler. The gas injection position was determined by a relatively small distance between the burner and deflector. What is more, the temperature over the deflector was too low for the reburning process. According to [17], the optimum temperature for the reburning process using sewage sludge-derived syngas oscillates about 1200 K. Therefore, significant reduction of the temperature caused NO$_x$ reduction reactions occurred in a short period of time. The results presented in [18] confirm that generally, the reburning effectiveness decreases with decreasing temperature in boiler.

The combustion conditions in coal-fired boiler used in the experimental study was not reburning favorable. However, the results clearly present that sewage sludge-derived syngas may be considered as a reburning fuels because of its potential to maintain the reductive atmosphere in boiler. The increase of nitrogen oxides emission reduction potential is expected using syngas produced with different gasifying agents. According to [13], steam is considered as a gasifying agent proper for production of a reburning fuel.

4. THE RESULTS AND LITERATURE DATA COMPARISON

The experimental study on reburning process in coal-fired boiler (25 kW) is presented in [18]. As an additional fuel, the alder wood chips-derived syngas was used. The conditions in boiler was similar to conditions in boiler presented in this work. The lack of afterburning zone is important. The heat input of the reburning fuel was 63%. The authors pointed out that the proportions of heat input was not proper to evaluate the effectiveness of the reburning process, however, the ability of maintaining the reductive atmosphere by biomass syngas was presented.

In the work [19] the conventional reburning in a coal fired boiler using biomass gasification gas was simulated. Author used syngas produced out of the paper from a paper mill. The effectiveness of the nitrogen oxides emission reduction reached 46% with syngas as 23% of the overall heat input to the boiler. The paper rejects-derived syngas is a low-calorific value fuel as gas from sewage sludge gasification. It is characterized by a small fraction of CH$_4$ and authors of [19] pointed out significant role of CO and H$_2$ in the reduction zone. The authors rightly underline that syngas, thanks to its high concentration of inert components, does not require the use of transport medium to provide the right penetration of combustion chamber and mixing with the exhaust gas.

In the work [3] the experimental investigation of low-calorific value gas co-incineration with coal was carried out. The OPG-230 power boiler was used, which is a modification of the popular OP-230, adapted to combust two types of fuel: gas and pulverized coal. The analysis was focused on the influence of LCV gas combustion on the boiler operation conditions. Despite the partial change of fuel, the thermal input was maintained. This assumption caused great stream of LCV gas supplied to the boiler and significant increase of the exhaust gas stream. The changes in exhaust gas stream caused the increase of convective heat transfer and decrease the radiation. This may be a reason for expensive modifications of the heat exchange part of the power boiler. Co-combustion of the LCV gases has also positive aspects: the amount of ash is reduced and there is no need for simultaneous work of the boiler and the gasifier. In addition, integration of the gasification installation with the power boiler provides the ability of the system to utilize many different fuels. If the gas share in thermal input is up to 20%, it does not influence significantly the power boiler operation conditions. It may even be recommended if the gas is injected above the main coal flame because of the reburning process. The authors pointed out that all of the negative aspects of the LCV gas (2 MJ/m$^3$) co-firing are not applicable for 8.5 MJ/m$^3$ gas co-firing. Results of the analysis present that composition and quality of the LCV gas is especially important if the utilization in power generation industry in considered [3].
5. CONCLUSIONS

Low-calorific value gases may be a valuable fuel for the power generation industry if the installation is modified and adapted for its specific properties. The proper use of the LCV gas should be preceded by the experimental and numerical study of operational conditions of the particular LCV gas.

The experimental investigation of the reburning process using sewage sludge-derived syngas was carried out. The analysis of the nitrogen oxides emission reduction as a function of the syngas stream supplied to the boiler showed its high application potential as a reburning fuel. The boilers with automatic screw feeder are characterized by 40% higher NOx emission than traditional domestic boilers [18] so the results of the experiment may be promising for the reducing the small scale boilers emission. The use of the alternative and waste fuels should be determined by their availability and ecological and economic effectiveness.

REFERENCES


