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EXPERIMENTAL STUDY AND NUMERICAL SIMULATION OF LOW CALORIFIC FUEL COMBUSTION AT DIFFERENT OXYGEN CONTENT IN THE OXIDIZER

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ABSTRACT
This study presents results of gas fuels combustion - propane and low calorific fuel. Low calorific fuel is produced during e.g. biomass gasification, which has got of 13% H_2, 4% CH_4, 30% CO, 13% CO_2, 40% N_2. This composition is very similar to composition of fuel obtained from wood pellets gasification. Investigations have been performed at room temperature and at conditions typical for High Temperature Air Combustion, i.e. high temperature of the oxidizer (above the level of auto-ignition) and low oxygen content (lower than 21 % as for conventional combustion). Such environment has been created on the base of exhaust gases coming from conventional gas burner in small scale single fuel jet furnace. The temperature of the exhaust gas as well as oxygen content has been adjusted in order to achieve test conditions. Experimental results show difficulties with burning of low calorific fuel at room temperature and stable combustion at high temperature.

INTRODUCTION
Combustion of hydrocarbon fuels, based on natural gas or oil, generates high emission of air pollutants. It forces the improvement of conventional technologies and the development of new ones. High Temperature Air Combustion (HiTAC) is new but already verified technology, used in recent years mainly in industrial furnaces. In this process high temperature of the oxidizer is combined with high flue gas recirculation. Apart from many other advantages it allows to achieve low emissions.

Typically, the combustion process uses fossil fuels, but they are limited. In this work combustion of low calorific fuel, produced in gasification process, is studied. The aim of this work is to verify possibilities of using HiTAC to burn such a low calorific fuel. The combustion of low calorific fuel has been compared to combustion of propane.

EXTERNAL SETUP
First stage of experiments was performed at room temperature. Combustion took place in combustion chamber with the use of ambient air as the oxidizer and test fuel from 0.5 mm nozzle.

In order to investigate combustion at conditions typical for HiTAC [1], i.e. high temperature of the oxidizer (above the level of auto-ignition) and low oxygen content (lower than 21 % as for conventional combustion), experimental single fuel jet furnace has been built Figure 1).

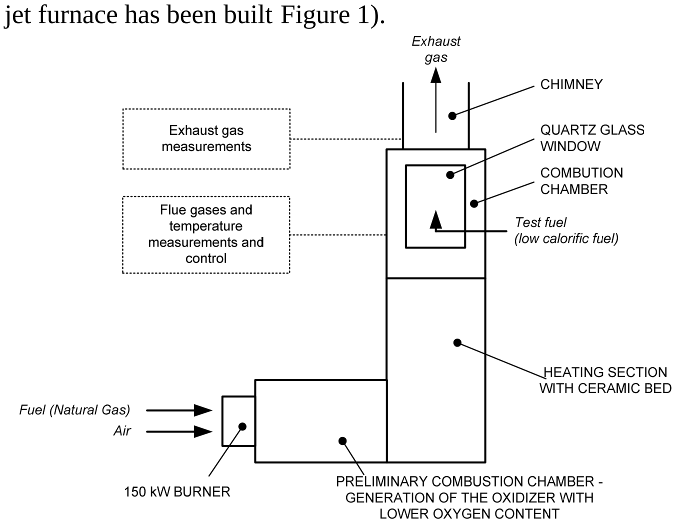

Figure 1 The scheme of experimental facility

Conventional burner with natural gas was used to create high temperature environment with various oxygen content in exhaust gases. The amount of oxygen was changed by changing the amount of natural gas provided to the burner. Test fuel was injected by 0.5 mm nozzle co-axially into exhaust gases in combustion chamber (Figure 2). The inner dimensions are: 0.46 m (hight), 0.2 m (width) and 0.15 m (depth). The chamber was equipped with quartz window, which enabled direct observation of the flame.

The temperature of the oxidizer was measured by S-type thermocouple located at fuel nozzle level. The National Instrument card and software was used to reading. The oxygen level was controlled by the use of Delta 2000 CD gas analyzer manufactured by MRU GmbH and confronted with JUNKALOR Infralyt 5000 analyzer. Test fuel was measured by mass flow meter produced by Bronkhorst High-Tech B.V. Direct flame photography was performed with the use of Sony DSR H5 digital camera.

Figure 2 Combustion chamber

METHODOLOGY OF EXPERIMENTS

First stage of experiments was conducted at temperature equal 20ºC using air as the oxidizer. Second stage of investigations was performed at temperature between 1000 and 700ºC. The concentration of oxygen in the oxidizer has been changed from 21 % down to 10 %. This boundary was set because of very low visibility of the flame below 10% of O_2 and difficulty in using direct photography. The velocity of the oxidizer in combustion chamber was kept constant at around 0.45 m/s (small variations were present because of changes in fuel amount in conventional burner), which has been chosen in order to achieve the best working conditions of the furnace.

Two gas fuels was examined. Firstly, low calorific fuel, composition of which was: 13% H_2, 4% CH_4, 30% CO, 13% CO_2, 40% N_2, which is very similar to composition of fuel obtained from wood pellets gasification [2], although higher hydrocarbons were neglected. The lower heating value of this fuel was equal 5.8 MJ/kg. The combustion of low calorific fuel was compared with combustion of propane (LHV = 46.3 MJ/kg). The velocity of the test fuel was changed up to 110 m/s by changing the amount of test fuel. For low calorific fuel it was the highest velocity possible to achieve and determined by used flow meters.

Experimental results

The results of experiments show, that at room temperature the stable combustion of low calorific fuel is not possible without flame stabilization, when the velocity of fuel is high. At velocity over 40 m/s the flame was blown out. It was impossible to achieve lifted flame. Figure 3a shows this combustion with continuous ignition from additional source. The combustion of propane was stable at test velocity up to 110 m/s (and even higher) and gave lifted flame (Figure 3b). The low calorific fuel flame is small because of 8 times lower LHV.

a) b)

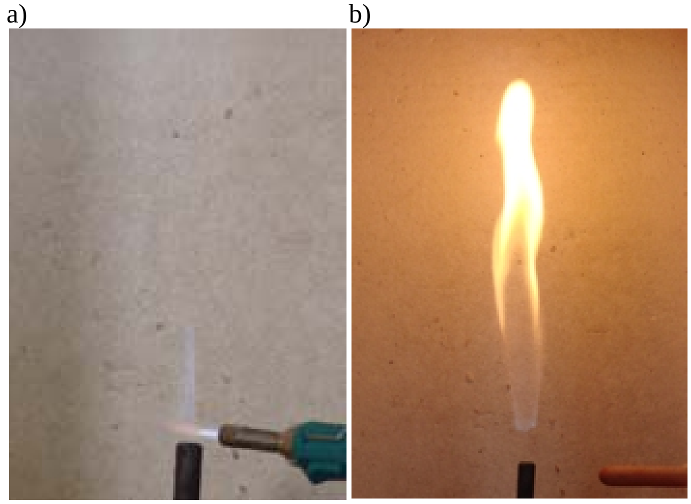

Figure 3 The direct photo of test fuel combustion at room temperature (20ºC) and 21% of O_2: a) low calorific fuel (80m/s, 0.11 kW), b) propane (100 m/s, 1.8 kW)

a) b) c) d)

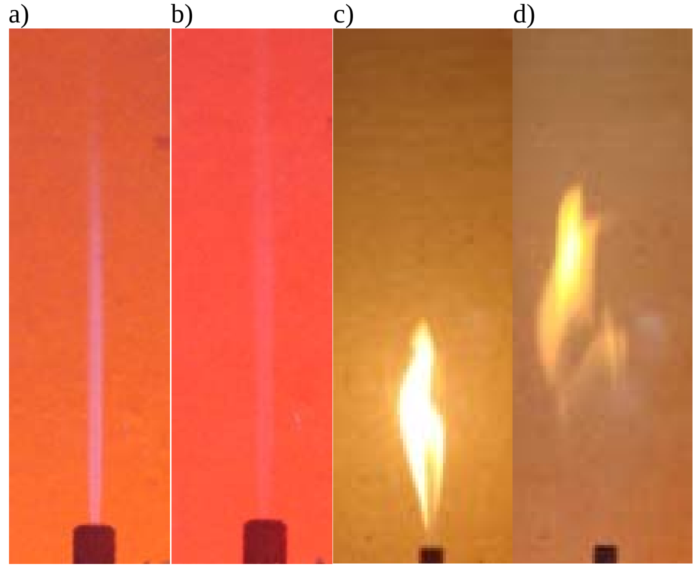

Figure 4 The direct photo of combustion in 800ºC oxidizer and different oxygen concentration: a) low calorific fuel at 18% O_2, b) low calorific fuel at 12% O_2, c) propane at 18% O_2, d) propane at 12% O_2; fuel velocity: 80 m/s for low calorific fuel and 50 m/s for propane

Increase of temperature of the oxidizer above 700ºC caused stable combustion of low calorific fuel for every velocity in wide range of oxygen concentration in the oxidizer. Figure 4a shows combustion of low calorific fuel at 800ºC oxidizer and 18% of oxygen in the oxidizer. Up to 80 m/s the flame was laminar and close to the nozzle for every velocity. At higher velocities the flame was lifted although combustion was stable. The colour of the flame is blue, because of presence of hydrocarbon in the fuel, and very intense at high oxygen concentration. When oxygen concentration was decreased (Figure 4b) the visibility of the flame was poor, although the length and volume of the flame was larger, and the basic shape was the same.

On the other hand the propane flame was lifted even et lower velocities (Figures 4c, d). Decreasing of oxygen cased higher lift-off and larger volume of the flame (Figure 4d). The shape of the flame has changed. The colour of the flame was yellow for lower velocities and changed into yellow-blue for higher velocities.

NUMERICAL MODELING

In this paper the calorific-oxidizer system is selected for modeling. The test HiTAC set up at Gdansk University of Technology in Gdansk, Poland has a combustion chamber with fuel jet nozzle (0.5 mm). The operating conditions in simulations are kept in the 0.45 m/s, 1273 K of main flow of oxidizer and 80 m/s, 300 K of low calorific fuel flow. Figure shows three-dimensional mesh of the test set-up combustion chamber. It has 1866165 unstructured tetrahedral cells to discrete the physical spaces of the chamber, Figure 5. CFD software ANSYS FLUENT 12.1 was used as the platform of simulations. The three-dimensional governing equations were employed to model the flow in the combustion chamber.

To be able to accurately simulate HiTAC, when using the full reaction mechanism it is indispensable to consider all the intermediates. However, a practical simulation of furnace including three-dimensional flow with full reaction mechanism is far beyond the capability of present computers. Therefore, the most realistic solution would be to adopt a set of greatly simplified reaction mechanisms covering some intermediates. Attention should be paid to the rate constant of a reaction during simulation of HiTAC. These constants are commonly obtained for normal combustion using ambient temperature air. The same problem exists when full reaction mechanism is used, even for the elementary reactions, since the accuracy of all the associated rate constants has not been confirmed. Therefore, the constants in models have to be optimized on the assumption that air temperature and oxygen concentration are variable.

The combustion process was simulated using the Finite Rate/Eddy Dissipation model. The finite-rate/eddy dissipation model is based on the Arrhenius finite rate chemistry and the eddy-dissipation concept of Magnussen and Hjertager. In the context of Magnussen and Hjertager model, the kinetic rates are deliberately set very high, so that turbulent mixing is guaranteed to be the controlling rate.

The solution of transport equations of chemical species with n-step chemical reactions under the influence of turbulence on the reaction rate is expected to describe the turbulent combustion taken place in a HiTAC furnace. In order to simulate the turbulence flow, the standard k-ε model is selected. In simulation two gases were calculated, propane and low calorific fuel.

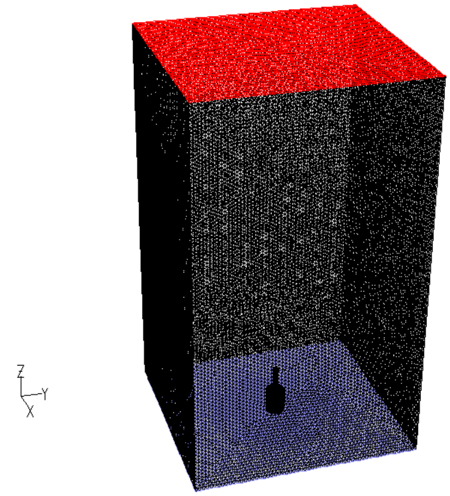

Figure 5 The 3D mesh of HTAC test furnace

For propane total five species were calculated and seven for low calorific fuel. These species for propane were C_3H_8, CO_2, N_2, O_2, H_2O and for low calorific fuel H_2, CH_4, CO, CO_2, N_2, O_2, H_2O respectively.

Considering the used fuels in calculations, whose composition is listed above, the reactions were as follows:

- for low calorific fuel

$$H_2 + 0.5\,O_2 \rightarrow H_2O$$
$$CH_4 + 2\,O_2 \rightarrow CO_2 + H_2O$$
$$CO + 0.5\,O_2 \rightarrow CO_2$$

- for propane

$$C_3H_8 + 3.5\,O_2 \rightarrow 3\,CO + 4\,H_2O$$
$$CO + 0.5\,O_2 \rightarrow CO_2$$

Numerical modeling results

Figures below present numerical modeling results of turbulent jet combustion. Figure 6 shows profiles of turbulent jet thermal fields in conditions of 12 % and 18 % oxygen concentration at 1173 K during low calorific combustion. Figure 7 shows profiles of turbulent jet thermal fields in conditions of 12 % and 18 % oxygen concentration at 1173 K during propane combustion.

a) b)

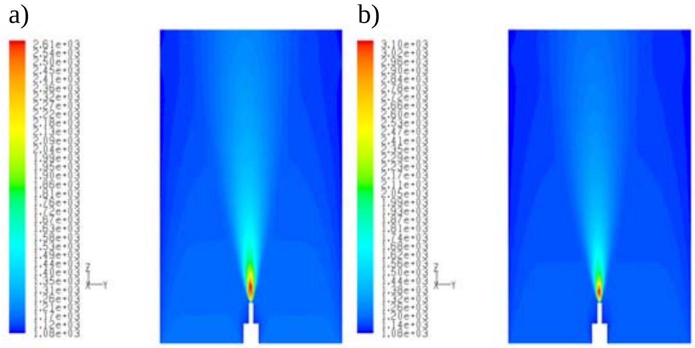

Figure 6 Results of numerical simulations of temperature field of low calorific fuel combustion at 800ºC oxidizer's temperature and different oxygen concentration: a) low calorific fuel at 12% O_2, b) low calorific fuel at 18% O_2.

a) b)

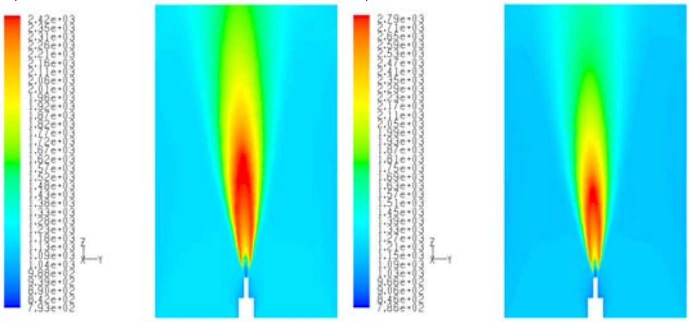

Figure 7 Results of numerical simulations of temperature field of propane combustion at 800ºC oxidizer's temperature and different oxygen concentration: a) propane at 12% O_2, b) propane at 18% O_2

It can be noticed that under the conditions of high temperature, the lower oxygen concentration of main combustion flow leads to a more uniform temperature. Higher values of temperature were for 18 % oxygen concentration in both cases. For low calorific fuel combustion this phenomenon doesn't exist. Flame is kept by nozzle at its outlet even when concentration of oxygen was high, about 18% in flue gases. For propane combustion it is easy to see lift off phenomena.

Figure 8 shows profiles of CO_2 mass fractions in conditions of 12 % and 18 % oxygen concentration at 1173 K during low calorific combustion. Figure 9 shows profiles of CO_2 mass fractions in conditions of 12 % and 18 % oxygen concentration at 1173 K during propane combustion.

a) b)

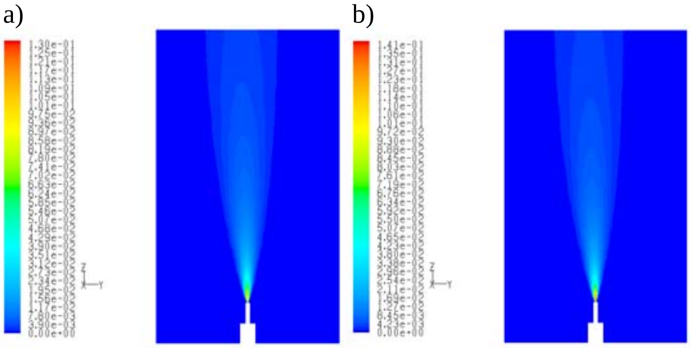

Figure 8 Results of numerical simulations of CO_2 mass fractions of low calorific fuel combustion at 800ºC oxidizer's temperature and different oxygen concentration: a) low calorific fuel at 12% O_2, b) low calorific fuel at 18% O_2

Carbon dioxide concentration during low calorific fuel combustion is almost the same for 18% and 12% oxygen cocentration in oxydizer. For propane combustion concentration of CO_2 is significantly different. It is easily to notice end of reaction zone, because beyond this zone CO_2 concentration is equal to zero and fuel doesn't react with oxygen.

a) b)

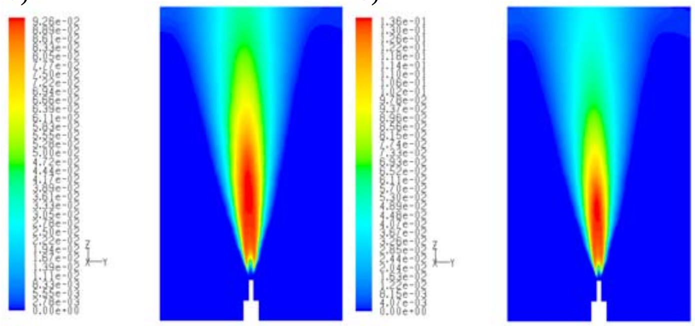

Figure 9 Results of numerical simulations of CO_2 mass fractions of propane combustion at 800ºC oxidizer's temperature and different oxygen concentration: a) propane at 12% O_2, b) propane at 18% O_2

Figure 10 shows comparison of low calorific fuel combustion with result of numerical modeling in conditions of 21% oxygen concentration and temperature 293 K.

a) b)

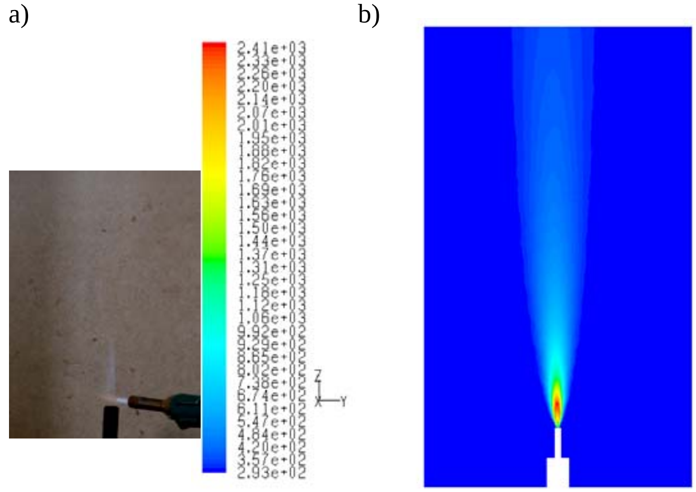

Figure 10 Comparison of low calorific fuel combustion at 20ºC oxidizer's temperature and 21% oxygen concentration: a) direct photo, b) numerical result of temperature field

CONCLUSION

The High Temperature Air Combustion appears to be useful technology to burn very low calorific fuels, coming from e.g. biomass gasification. It is difficult to achieve stable combustion of such a fuel at ambient temperature. Blow out occurs even at low fuel velocities (for which combustion of propane is stable). Increase of the oxidizer temperature above 700ºC improves the flame stability at wide range of fuel velocity and oxygen concentration in the oxidizer. Under the conditions of high temperature, the lower oxygen concentration of main combustion flow leads to a more uniform temperature. Higher values of calculated temperature were for 18 % oxygen concentration in both cases.

ACKNOWLEDGMENT

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