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Experimental Research and Numerical Modelling of Low Calorific Fuel Combustion Process at Different Oxygen Concentration in Oxidizer

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Abstract. The article presents the results of combustion of low calorific fuel as a product of biomass gasification process. Composition of the burned fuel 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 gasification such as pellets. Investigations have been performed at room temperature and at conditions typical for High Temperature Air Combustion Technology, i.e. high temperature of the oxidizer (above the auto-ignition temperature level- from 800°C to 1100°C) and low oxygen concentration (below 21 % of O_2 as for conventional combustion - from 21 % by volume to 10 %). The experiments were supplemented and compared with numerical calculations performed using CFD ANSYS Fluent package. Experimental results show stable combustion process at high temperatures.

1 Introduction

One of the biggest challenges of the 21st century is to harness clean, efficient and sustainable energy production for any application and mainly for power generation. The continuously increasing standards of environmental protection, saving primary energy sources and the drive to reduce energy costs results in the development of new combustion technologies for many purposes. Besides air pollution and climate control issues, fuel flexibility is another important motivation towards technology innovation in the area of energy conversion.

Nowadays several different combustion technologies have been developed to meet new and more stringent demands on energy consumption, environment impact and production expenditure. Modern technologies for thermal conversion of low calorific fuels are expected to simultaneously meet the requirements in terms of reliability, economy and environmental protection.

One of the different available combustion techniques the FLOX (**Fl**ameless **Ox**idation) known also as HiTAC (**Hi**gh **T**emperature **A**ir **C**ombustion), MILD (**M**oderate or **I**ntense **L**ow oxygen **D**ilution) or CDC (**C**olourless **D**istributed **C**ombustion) offers significant advantages of ultra-low pollutants emission, stable operation and improved, uniform temperature distribution in combustion chamber. The inlet oxidizer temperature is higher

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than the self-ignition temperature of the fuel and oxygen concentration is low due to high recirculation that results in relatively small flame temperature during combustion. The differences include increasing thermal field uniformity in the combustion zone leading to high efficiency and low fuel consumption. The term colourless is accredited to very low visible flame signature as compared to the conventional flames due to distributed combustion. Furthermore, low heating value fuel can be utilized without any auxiliary fuel. This technology has created a significant impact on the design and development of an advanced industrial furnaces and offers possibility of application for gas turbines, internal combustion engines, boilers or industrial furnaces.

2 State-of-the-art

Significant development of HiTAC technology began with its implementation in industrial furnaces [1]. Systematic studies of combustion in highly preheated and low oxygen content oxidizer started about two decades ago. Research focused on single flame combustion or combustion in semi-scale furnaces, mainly with high calorific fuels. Effect of oxidizer temperature and oxygen content on flame characteristics, its visibility, volume, lift-off distance, emission spectrum and radicals distribution were investigated [2-20]. Numerical simulations were also conducted [21-24]. PIV and light emission spectroscopy were widely used in experiments, for example [25]. The use of high temperature and low oxygen contend air in regenerative burners in semi-industrial furnace equipped with radiant tube was also investigated [26-27]. Significant improvement in temperature distribution along the tube as well as higher efficiency of the process was reported in comparison with conventional combustion with recuperative burner. More recently presented results of flame structure and emission signature under colorless distributed combustion regime using different gaseous hydrocarbon fuels with a swirl-stabilized combustor can be found in [28-32]. The flame lift-off heights were measured to explore the nature of different flames when approaching CDC condition. The location and global structure of swirl-stabilized flame at different O_2 concentration corresponding to different flow dilution levels were determined from the OH chemiluminescence signature. The influence of fuel properties (including hydrogen enriched fuels) on colourless distributed combustion was also investigated [33]. Although HiTAC started with industrial furnaces, other applications were also proposed and investigated by different researchers. The possible use of high temperature air combustion in utility boilers were considered, among the others, in [34]. A few review articles presenting possibility and potential of adaptation of HiTAC in gas turbines were given recently in [35-37]. High preheating air has been used with success also in gasification process called high temperature air/steam gasification (HiTAG/HiTSG). Some of the results are presented in [38-40] and they show favourable influence of high temperature agent on gasification product quality from renewable fuels, such as biomass, Fig. 1.

Fig. 1. The types of renewable fuels utilized for gasification process to obtain low calorific gas fuel: a) wood chips, b) wood pellets, c) straw pellets, d) miscanthus pellets.

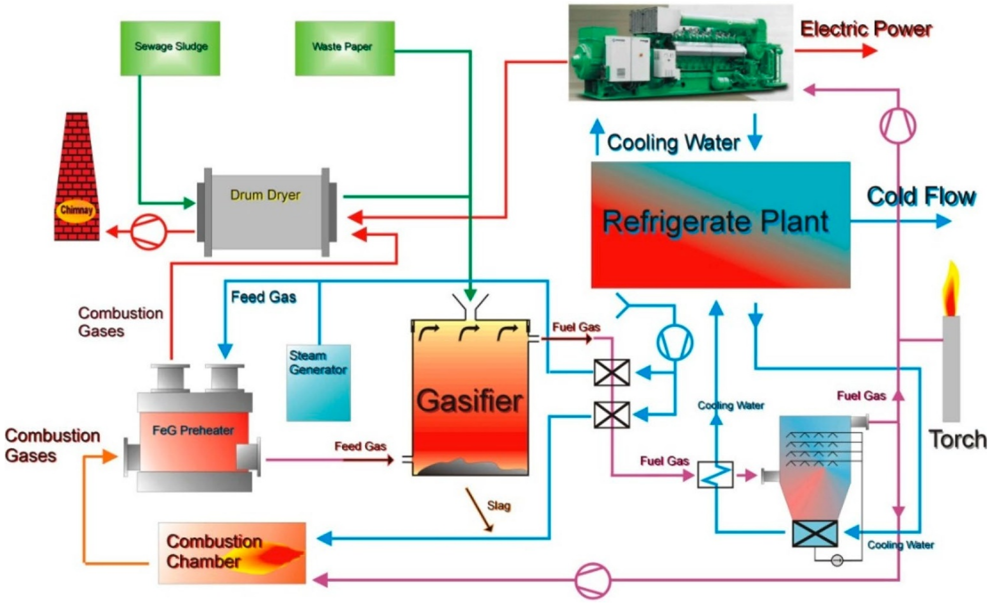

Fig. 2. The example of low calorific fuel utilization after gasification process of different types of biomass [35].

3 Experimental rig

The combustion experiments of low calorific fuel at conditions for HiTAC, [1], with high temperature of the oxidizer (above the auto-ignition temperature level - from 800°C to 1100°C) and low oxygen concentration (below 21 % of O_2 as for conventional combustion - from 21 % by volume to 10 %), were performed using an experimental single fuel jet furnace, Figure 3.

Conventional burner with natural gas supply was used to create high temperature environment with various oxygen content in exhaust gases. The concentration of oxygen was set-up 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 the test combustion chamber, Figure 4. 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.

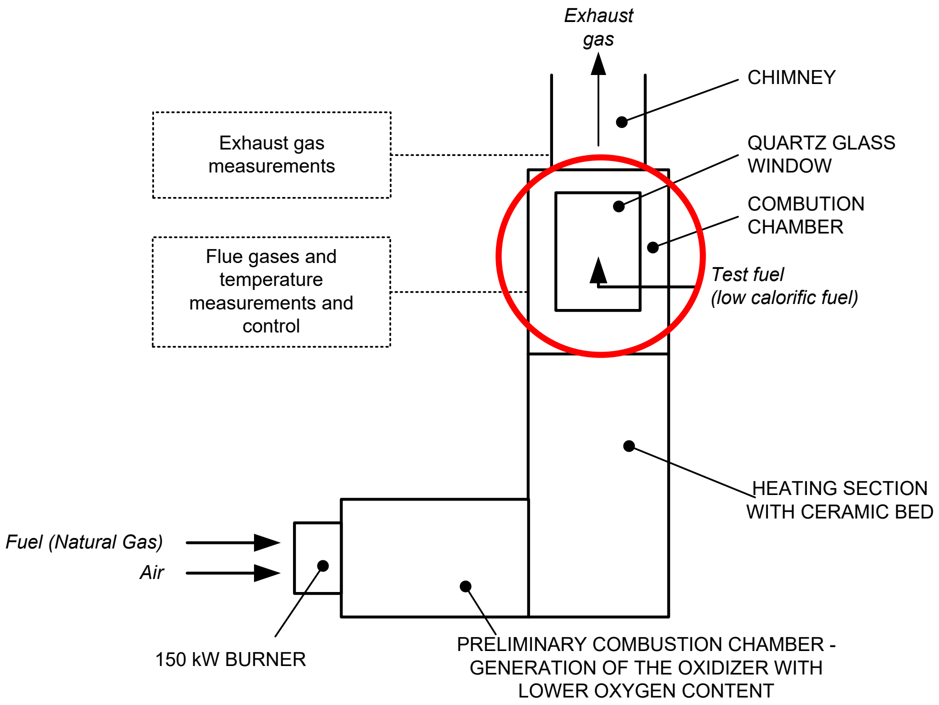

Fig. 3. The scheme of the experimental facility [36].

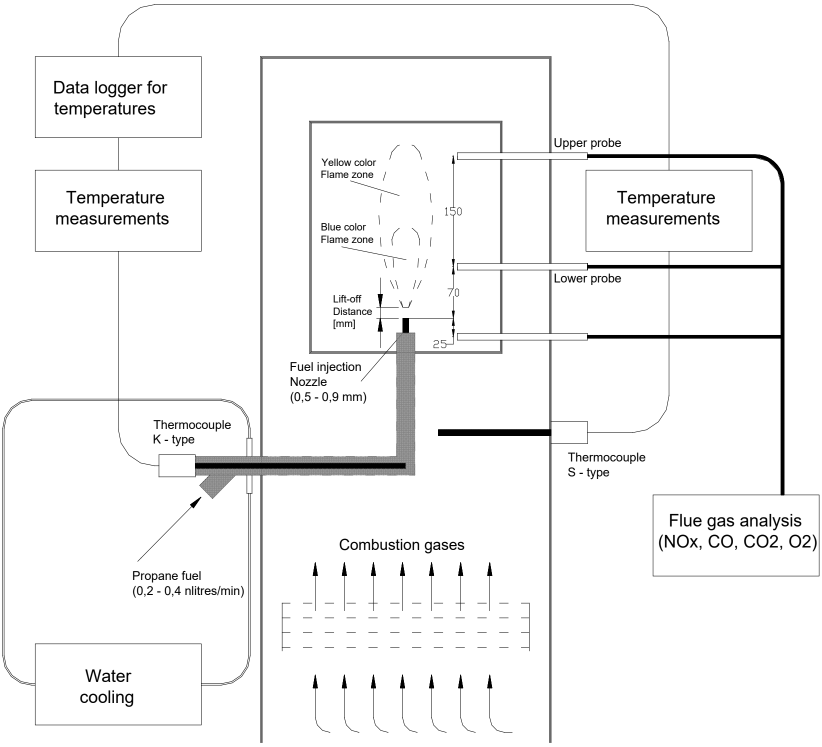

Fig. 4. The view of the test combustion chamber and fuel nozzle [36].

4 Methodology of experiments

The investigations were performed at temperatures between 700ºC and 1000ºC. The concentration of oxygen in the supplied oxidizer was 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 gaseous fuels were examined. Firstly, low calorific fuel, composition of which was 13 % H_2, 4 % CH_4, 30 % CO, 13 % CO_2, 40% N_2 and is very similar to composition of fuel obtained from wood pellets gasification [2], although higher hydrocarbons were neglected. The lower heating value of the test fuel was equal 5.8 MJ/kg. The combustion of low calorific fuel was compared with combustion of second fuel - propane with calorific value equal 46.3 MJ/kg. The velocity of the test fuel was changed up to 110 m/s by changing the amount of test fuel. It was the highest velocity possible to achieve for this fuel and determined by used flow meters.

5 Numerical simulations

The numerical modelling was performed using ANSYS CFD software [41]. The three-dimensional mesh of the combustion chamber was created in ANSYS GAMBIT 2.4.6, Fig. 5, while the all numerical simulations were conducted using Fluent 19.2 software.

The numerical domain contains 2 119 30 unstructured Tet/Hybrid elements. In order to obtain accurate results, the cells of this grid were heavily compacted in an area with high gradients of flow parameters.

The three-dimensional equations were employed to model the flow with full reaction mechanisms in the combustion chamber, Table 1.

In order to simulate the interaction between chemistry and strong turbulent flows, the Renormalization Group turbulence model k-ε (RNG k-ε) and the Finite Rate/Eddy Dissipation Model (EDM) were used. The Finite Rate/Eddy Dissipation Model is based on the Arrhenius finite rate chemistry and the eddy-dissipation concept of Magnussen and Hjertager, where the kinetic rates are deliberately set very high and thus turbulent mixing is guaranteed to be the controlling rate.

The simulations of the combustion process were performed for different concentrations of oxygen in the oxidant respectively 8, 12, 15 i 18 % with temperatures of 900ºC, 850ºC, 800ºC and 750ºC.

In addition, thermal radiation was taken into account, the magnitude of which was calculated using the Discrete Transfer Method (DTM) model, [42]. The radiation properties of the exhaust gas were assumed to be those of a perfectly grey body, depending on the temperature or concentration of the components. In order to determine the absorption coefficients, a radiation model called Weighted-Sum-of-Grey-Gases (WSGG) was used in the calculations.

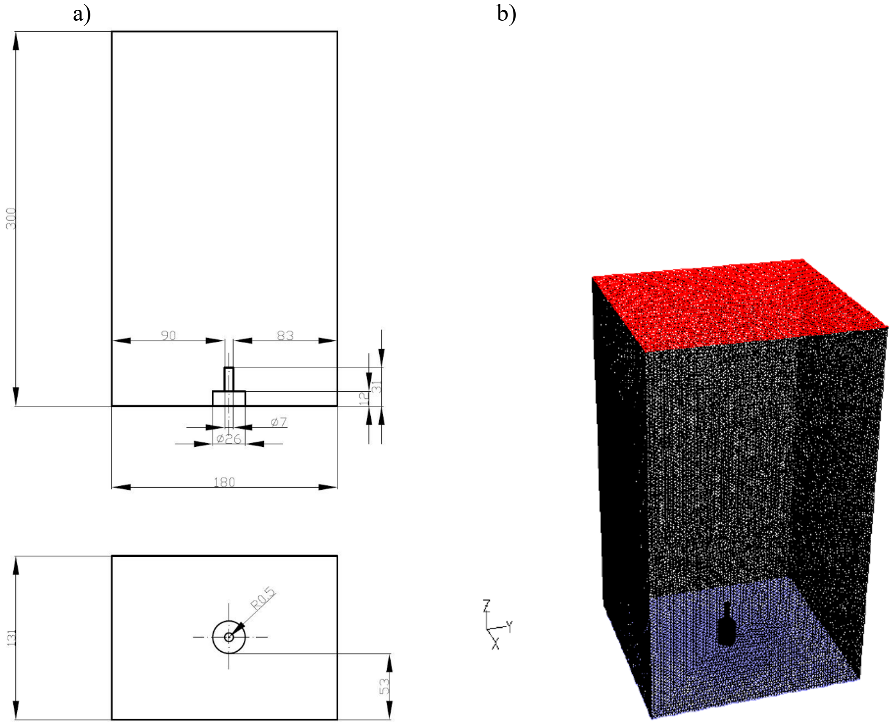

Fig. 5. The view of combustion chamber: a) main dimensions, b) 3D mesh.

Table 1. The oxidation of low calorific fuel combustion data used during numerical simulations.

Fuel	**Low calorific fuel (syngas)**	
Chemical formula	13 % H_2, 4 % CH_4, 30 % CO, 13 % CO_2, 40 % N_2	
Chemical reaction I	Chemical reaction	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$
	Pre-exponential factor	1e+15
	Activation energy	1e+08
Chemical reaction II	Chemical reaction	$CH_4 + 1\frac{1}{2}O_2 \rightarrow CO + 2H_2O$
	Pre-exponential factor	1e+15
	Activation energy	1e+08
Chemical reaction III	Chemical reaction	$CO + \frac{1}{2}O_2 \rightarrow CO_2$
	Pre-exponential factor	1e+15
	Activation energy	1e+08

6 Results

This part is divided into two subparts. First of it shows experimental research results of low calorific fuel combustion process under HiTAC conditions, while second one presents numerical simulations'.

6.1 Experiments

Figure 6 shows results of direct photo of low calorific fuel combustion process at constant temperature of oxidizer and fuel volumetric flow rate with various concentration of oxygen.

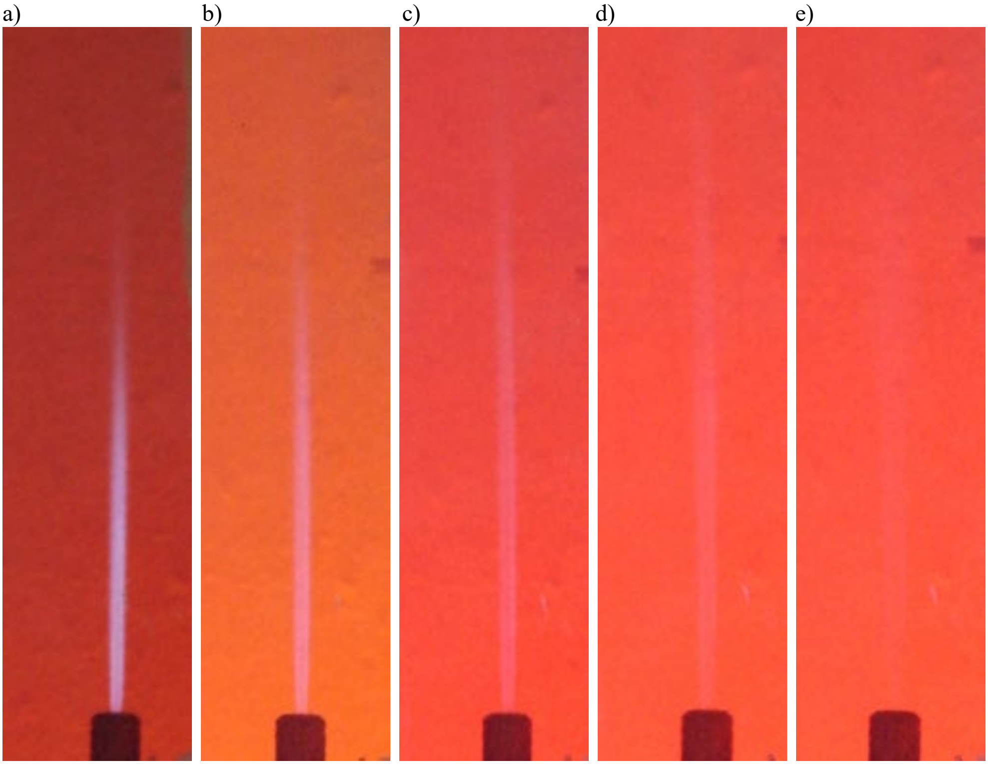

Fig. 6. The direct photo of low calorific fuel combustion process in 800°C and fuel consumption of 1.22 l/min (0.14 kW) with different oxygen concentration: a) 21 %, b) 18 %, c) 15 %, d) 12 % and e) 8 %.

It can be observed that when the oxygen concentration was decreased the visibility of the flame was also decreased, although the length and volume of the flame was larger, and the basic shape was the same [43]. It is long and narrow and has little fluctuation. An important difference is the colour. Due to the hydrogen content in its composition, low calorific gas burns with a blue flame. Compared to the combustion of high calorific fuel, the flame is smaller because fuel flow rate is 1.22 l/min, which, due to the low calorific content of the fuel, results in a low chemical energy flux contained in the fuel of approximately 0.14 kW - much lower than for other fuels. Even at low oxygen concentration the combustion process is stable.

In turn in Figure 7 the results of low calorific fuel combustion process at constant temperature of oxidizer and oxygen concentration with different volumetric flow rate of fuel are presented.

a) b) c) d) e)

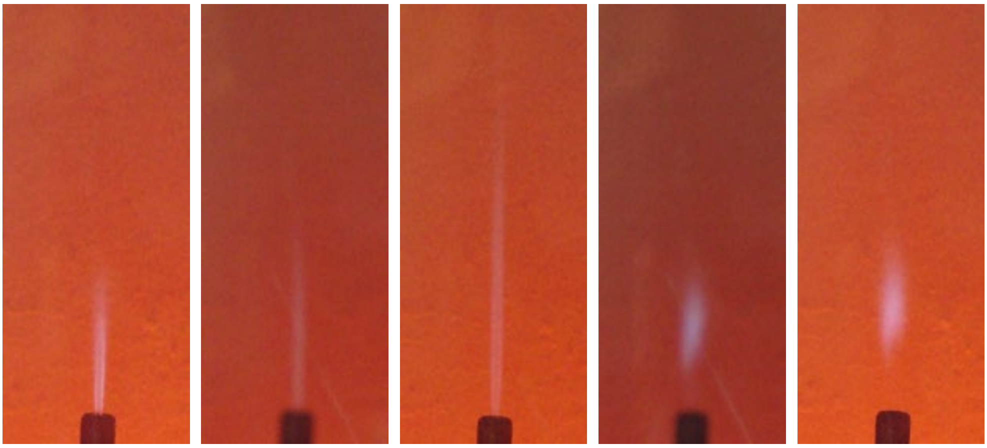

Fig. 7. The direct photo of low calorific fuel combustion process in 800°C and 18 % oxygen concentration with various velocity of fuel: a) 50 m/s (0.07 kW), b) 65 m/s (0.08 kW), c) 80 m/s (0.11 kW), d) 100 m/s (0.13 kW) and e) 110 m/s (0.14 kW).

In the above images, the appearance changing of the flame can be observed depending on the amount of fuel being burned. Up to 80 m/s the flame seemed to be laminar and the combustion process started close to the nozzle. At higher velocities of fuel supplied the flame was lifted although combustion was stable.

6.2 Numerical simulations

Figure 8 shows the changes of the maximum temperature with decreasing of oxygen concentration in the oxidiser during the combustion process of a low calorific fuel. The lift-off of the flame above the nozzle in this case is barely visible and difficult to determine.

The temperature value, as in the combustion of propane and methane, decreases as the amount of oxygen in the oxidiser decreases. The maximum temperature at a concentration of 18 % oxygen is 2306 K and at 9 % oxygen it reaches 1834 K. The temperature drop in these cases is about 470 K.

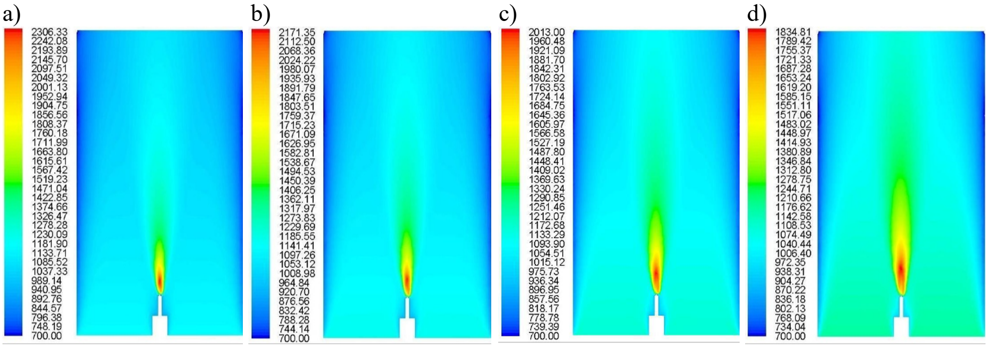

Fig. 8. The temperature field [K] during low calorific fuel combustion process at constant temperature of oxidizer 900°C and different concentration of oxygen in oxidizer: a) 18 %, b) 15 %, c) 12 % and d) 8%.

Figure 9 presents the mass contribution of oxygen O_2 during the combustion of a low calorific fuel. The size of the dark blue area increases as the oxygen concentration in the oxidant decreases. This is due to the reaction of oxygen with the combustible compounds contained in this fuel.

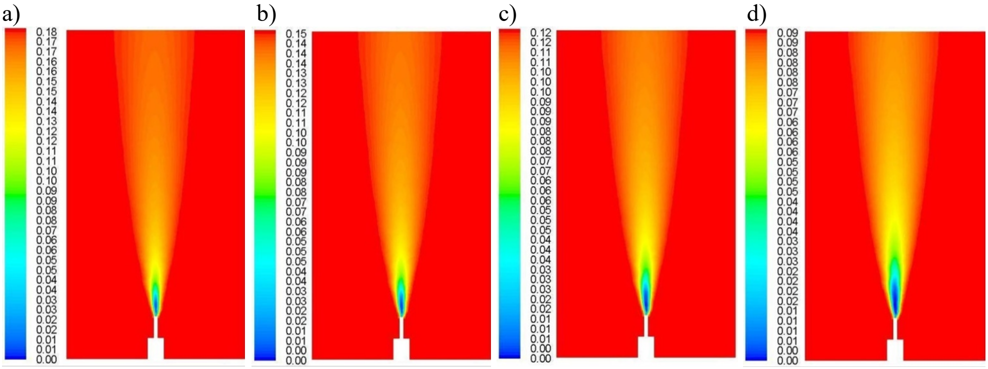

Fig. 9. The mass fraction of oxygen [%] during low calorific fuel combustion process at constant temperature of oxidizer 900°C and various concentration of oxygen in oxidizer: a) 18 %, b) 15 %, c) 12 %, d) 8%.

In turn Figure 10 presents comparison of experimental research and numerical simulations of low calorific fuel combustion process at constant temperature level of oxidizer – 900°C and oxygen concentration – 18 %.

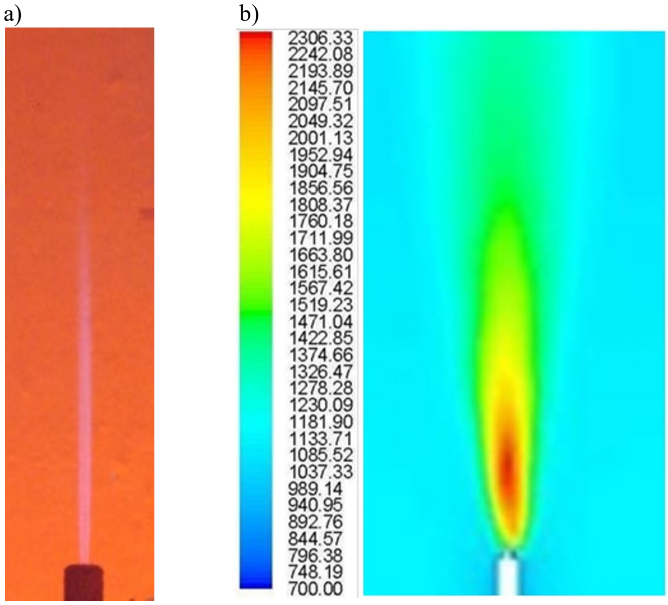

Fig. 10. The comparison of results obtained during low calorific fuel combustion process at temperature of oxidizer 900°C and 18 % oxygen concentration in oxidizer: a) experiment, b) numerical simulation.

The results obtained for the combustion of low calorific gas show:

- the flame in the experiment carried out is slender, long with little fluctuation, flame lift difficult to observe;
- the flame in the numerical simulation is slender, elongated with low fluctuation, flame lift difficult to observe.

The appearance of the flame in both cases is similar. Its shape is slender and elongated and has low fluctuation. They are similar in length and shape. Flame lift for case a as well as b was difficult to notice.

7 Conclusions

The High Temperature Air Combustion seems to be very useful combustion technology to burn low calorific fuels, which comes e.g. biomass gasification processes. It is very difficult to achieve stable combustion process of such fuel at low temperature level as it occurs during conventional combustion. Blow out occurs even at low velocity flow of fuel (for which combustion of propane is stable). Increasing temperature of oxidizer above 700ºC influences on the flame stability at wide range of fuel velocity and oxygen concentration in oxidizer. Under the conditions of high temperature the lower oxygen concentration of main combustion flow leads to a more uniform temperature field.

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