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Experimental Study on the Influence of Oxygen Fraction in the Combustion Air on the Combustion Characteristics

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The presented paper was focused on the experimental investigation of a promising combustion technology, namely the oxygen-enhanced combustion (OEC). This technology is used in those industrial heating applications that require increased productivity, higher heat transfer efficiency, improved flame characteristics, reduced equipment cost and last but not least improved product quality. However, there are potential problems associated with the use of OEC if the system is not properly designed, e.g. refractory or burner damage, non-uniform heating and/or increased pollutant emissions.
The experimental study of OEC was carried out at the large-scale burner testing facility that enables to test the gaseous fuel burners, the liquid fuel burners and the combined burners up to the thermal input of 1800 kW. The combustion tests were performed with the experimental low-NO_x type burner, namely the two-gas-staged burner. The oxygen content in the combustion air was increased by means of the oxygen injection directly into the incoming airstream before entering the burner.
The aim of the tests was to assess the impact of oxidizer composition (the volume fraction of oxygen in the combustion air), burner thermal input and gas-staging on the characteristic combustion parameters including the concentration of nitrogen oxides in flue gas, the flue gas temperature, the heat flux to the combustion chamber wall, and lastly the flame stability and its dimensions.

1. Introduction

Most industrial heating processes require substantial amounts of energy, which is commonly generated by combusting hydrocarbon fuels such as natural gas or heating oil. The majority of industrial combustion processes use air as the oxidant, which consists of approximately 21 % O_2 and 79 % N_2 by volume. However, only oxygen is needed in the combustion reaction and nitrogen in air acts as a ballast that has to be heated up and carries the energy of the combustion process out with the hot flue gas, which decreases the thermal efficiency. Many of high-temperature processes use an oxidant containing higher proportion of oxygen than in air. This type of combustion is referred to as oxygen-enhanced combustion (OEC) and has many benefits including increased productivity and heat transfer efficiency, improved flame characteristics etc. (Baukal, 1998).
When the low-level oxygen enrichment (21 - 30 % O_2) is applied to the existing combustion equipment minor burner modifications need to be made to permit operation at slightly higher O_2 concentrations. It is especially used in cases when the production rate in the heating process can be significantly increased even with only relatively small amounts of oxygen enrichment. In case the combustion system is operated in intermediate (30 - 90 % O_2) or high-level (> 90 % O_2) oxygen enrichment regime the existing air/fuel burners have to be replaced by burners specifically designed to use the higher levels of O_2.
Economically, the method of low-oxygen enrichment can save the cost for retrofits of existing burners. However, the characteristics of low-level oxygen enrichment in an air/fuel combustion system have been studied rarely thus far. Some of the research works are mentioned here.
Wu et al. (2010) studied the influence of 21 - 30 % oxygen concentration on the heating rate, emissions, temperature distributions and fuel consumption in the heating and furnace-temperature fixing tests. They found in the heating tests that compared to the air with 21 % O_2, the time elapsed for heating to 1,200 °C was only 46 % for air with 30 % O_2. As for the species concentrations the NO_x emission was increased by

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4.4 times and CO_2 increased almost linearly when the oxygen concentration was increased from 21 % to 30 %. The furnace-temperature fixing tests showed that the fuel consumption at 30 % O_2 was reduced by 26 %, compared with that at 21 % O_2

Qju and Hayden (2009) investigated oxygen-enriched combustion of natural gas in porous ceramic radiant burners. The oxygen-enriched air was produced passively, using polymer membranes. The oxygen concentration was varied between 21 % and 28 %. The experimental results showed that the saving in natural gas was about 22 % when oxygen concentration was increased to 28 %.

Tan et al. (2002) used down fired vertical combustor to study oxygen-enhanced and O_2/CO_2 combustion. They concluded that very high levels of NO_x emissions are achieved due to higher flame temperatures that are related to higher oxygen concentration in the feed air used in the oxygen-enhanced combustion. However, in O_2/CO_2 combustion the NO_x formation is suppressed because N_2 is not present in the feed air, only air leakage at the fan contributed to the formation of NO_x in small concentrations.

Daood et al. (2012) studied the influence of different oxygen concentrations and staging levels on NO reduction and carbon burnouts during the coal air-staged combustion. The experiments revealed that oxygen-enriched air-staged combustion at the 31 % level of staging resulted in approximately 7 % and 35 % NO reduction for 28 % and 35 % overall oxygen concentration, respectively. Moreover the oxygen enrichment improved the carbon burnouts.

Some of the studies of oxygen-enhanced combustion have been carried out in the field of flameless combustion, e.g. by Sánchez et al. (2013) who investigated the effect of oxygen enrichment from 21 % to 35 % vol. on the performance of flameless combustion furnace equipped with a regenerative burner. The results showed that for all oxygen enrichment rates it was possible to obtain no luminous effect, wide reaction zone and uniform temperature profile, which are typical features of flameless combustion phenomena. NO_x emissions were below 5 ppm and the global efficiency increased almost 5 % for an oxygen enriched level of 30 %.

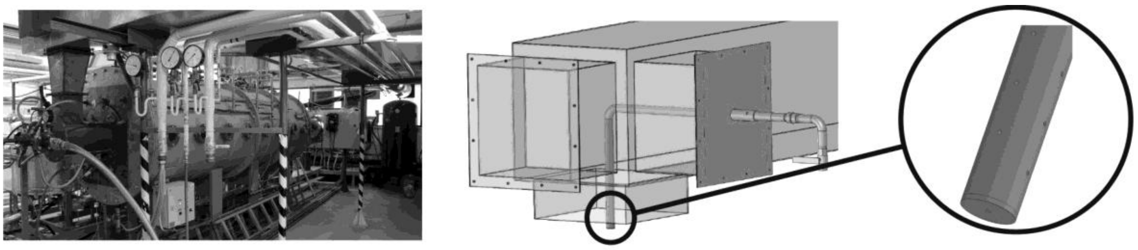
1.1 Specific objectives

This work was aimed at studying the influence of 21 - 46 % oxygen concentration in the air on the NO_x emissions, the flue gas temperature, the distribution of heat extracted from hot flue gas to the wall of combustion chamber, and the flame pattern (stability, shape and dimensions). The experimental tests were carried out for two combustion modes – one-staged and two-staged combustion.

2. Experimental setup

2.1 Testing facility

The combustion tests were carried out at the burners testing facility see Figure 1a. The key apparatus of the facility is the two-shell horizontal water-cooled combustion chamber with the inner diameter of 1 m and the length of 4 m. The cooling shell of chamber is divided into seven individual sections with independent supply of cooling water. Each section is equipped with sensors for measurement of cooling water flow rate, inlet and outlet temperature. This unique construction enables to partially simulate conditions similar to the ones in fired process heaters and to assess the heat extracted from the hot flue gas to the combustion chamber wall lengthwise the flame. Flue gas is exhausted from the combustion chamber through the flue gas stack where three measurement and sampling spots are located for measuring of pressure in the combustion chamber, flue gas temperature and flue gas compositions (O_2, CO, NO, NO_2), which is measured using the Testo 350-XL analyzer. The measuring ranges of the gas analyzer were 0 - 25 % for O_2, 0 -10,000 ppm for CO, 0 - 3,000 ppm for NO, and 0 - 500 ppm for NO_2.



(a) (b)

Figure 1: (a) Water-cooled combustion chamber in the burners testing facility, and (b) the 3D drawing of the diffuser inserted in the air duct.

The high-purity oxygen was injected into the incoming combustion airstream (referred to as the premix enrichment) through a diffuser to ensure adequate mixing. The diffuser was inserted in the air supply duct before entering the burner. It was designed for the maximal oxygen flow rate of 160 m_N^3/h. Totally 13 holes with the diameter of 2.1 mm are drilled in the body of the diffuser when 12 holes are aligned in six rows, each row with two holes (even rows are positioned at angle 90° towards odd rows) and one hole is located in the closed end of the diffuser. The 3D model of diffuser with a part of air duct is shown in Figure 1b.

2.2 Burner

The burner used in the experimental study was the two-gas-staged burner fired by natural gas. The 3D model of burner is shown in Figure 2. The inner diameter of the burner quarl is 300 mm. The gas inlet consists of twelve primary nozzles and eight secondary nozzles. The primary nozzles are drilled in the primary nozzle head and are aligned in two circular sets. There are four nozzles with the diameter of 3.0 mm in the first set and eight nozzles with the diameter of 2.6 mm in the second set. The maximum thermal input of the primary stage can be regulated by the exchangeable primary gas throttle of different diameters placed before the inlet to the primary stage of the burner. During the tests, when staged combustion was used, the ratio primary/total fuel was set to 0.28.

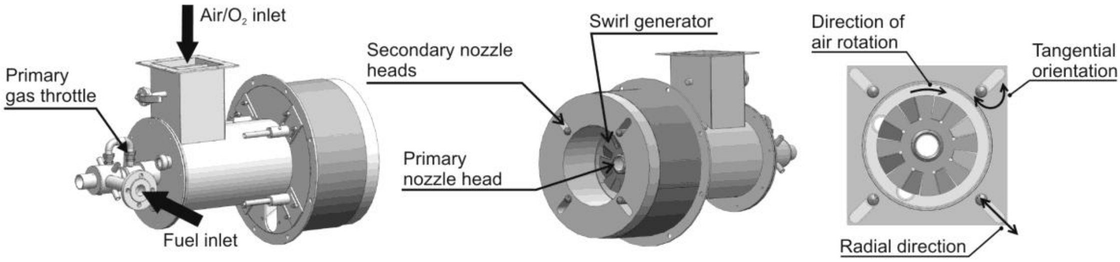


Figure 2: The 3D model of experimental two-gas-staged burner.

The secondary gas inlet is provided by four nozzle heads with the pitch angle of head of 30°. Each head has two nozzles with the diameter of 3.3 mm. The burner is constructed so that it is possible to change the position of secondary nozzle heads towards the burner tile, namely in tangential and radial direction. In the reference tangential position the nozzle heads are oriented directly towards the burner axis. The orientation can be changed both clockwise (in the direction of flame's swirl motion – positive angle) and counter clockwise (negative angle). In the reference radial distance the distance of nozzle heads from the burner axis is 180 mm and can be increased by 50 mm. During the tests, when staged combustion was used, the secondary nozzle heads were turned by +20° and their radial distance was set to the maximum (230 mm). The burner is equipped with the so-called flame holder that has the form of swirl generator. The swirl generator consists of eight pitched blades and is mounted to the central burner pipe. Flame ignition was performed with a gaseous premixed natural-draught ignition burner with the thermal input of 18 kW.

2.3 Plan of combustion tests

The investigation was aimed at studying the influence of 21 - 46 % oxygen concentration in the air on the NO_x emissions, the flue gas temperature, the heat flux distribution to the wall of combustion chamber lengthwise the flame, and the flame pattern. The experimental matrix is presented in Table 1. The tests were carried out at three levels of thermal input – 300 kW, 500 kW, and 750 kW – when only primary stage was used for the combustion of fuel, and compared with the tests at the thermal input of 750 kW when two-staged combustion was utilized. The target oxygen concentration in the flue gas was 3 % for all tests.
Two tests were of interest here. In the first of the tests (denoted as TEST A in Table 1), the quality and the flame characteristics were investigated. The second test (denoted as TEST B) was focused on the evaluation and comparison of local wall heat fluxes into the sections of the combustion chamber. This test was carried out at the maximal thermal input at different oxygen concentrations for both one-staged and two-staged mode.

3. Results and discussion

3.1 NO_x emissions

Figure 3 (a) shows the measured concentrations of NO_x [mg/m_N^3] as a function of oxygen concentration in the combustion air. The concentrations are expressed on a dry volume basis.

Table 1: Experimental matrix (● indicates that the test was carried out for the relevant oxygen flow rate).

Thermal input	Flow rate of high-purity O_2 [m_N^3/h]/ O_2 concentration in the air [%]										
[kW]	0	5	10	20	30	40	60	70	80	100	120
TEST A											
300 one-staged	●/21	●/22.3	●/23.7	●/27.2	●/32	-	-	-	-	-	-
500 one-staged	●/21	●/21.7	●/22.5	●/24.3	●/26.4	●/28.9	-	-	-	-	-
750 one-staged	●/21	●/21.5	●/22	●/23.1	●/24.3	●/25.6	●/29	●/31	-	-	-
750 two-staged	●/21	●/21.5	●/22	●/23.1	●/24.3	●/25.6	●/29	-	●/33	●/38	●/46
TEST B											
750 one-staged	●/21	-	-	-	-	●/25.6	-	●/31	-	-	-
750 two-staged	●/21	-	-	-	-	●/25.6	-	-	●/33	-	●/46

The major proportion of NO_x produced during combustion was thermal NO_x, which was directly associated with higher flame temperature peaks and higher O_2 concentration. It can be seen that NO_x showed exponential growth with temperature. Due to this, even a minor variation in temperature caused a huge increase in NO_x emissions.

When one-staged combustion mode was used, NO_x emissions increased sharply from 160 mg/m_N^3 to 7,000 mg/m_N^3 as the O_2 concentration increased from 21 % to 32 %. Further O_2 enrichment was not possible here since the measured values of NO_x were out of the measuring range of the analyzer. However, when two-staged combustion mode was used as a NO_x reducing technique, the increase in NO_x formation was not too steep than that in one-staged combustion mode. It rose gradually from 85 mg/m_N^3 to 4,900 mg/m_N^3 as O_2 concentration increased from 21 % to 46 %. Moreover, the NO_x concentration was less than 200 mg/m_N^3 (which is the currently valid NO_x emissions limit for stationary sources with the heat output in the range of 0.3-50 MW in the Czech Republic) as long as O_2 concentration was less than 25 %. In addition, the NO_x reached only 1,700 mg/m_N^3 at 32 % O_2, which is by four times less than that in one-staged combustion at the same O_2 concentration.

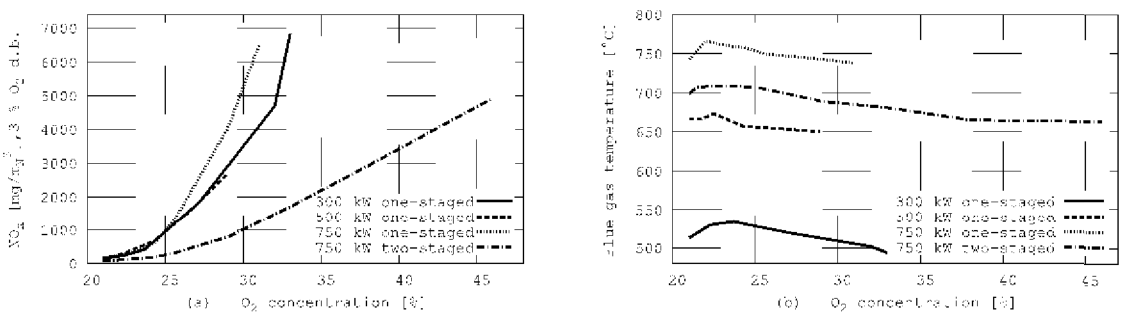


Figure 3: (a) Variations of NO_x emissions and (b) of flue gas temperature at different oxygen concentration.

The acquired results are in good agreement with the results of Daood et al. (2012), which clearly indicated that without implementing the two-air-staged combustion configuration, especially in the case of conventional type burners, NO_x emissions dramatically increase with addition of oxygen in the secondary air. Whereas, in case of air staging, NO_x emissions levels were initially found to increase and then to decrease rapidly at the fullest oxygen concentration in the secondary and over-fire air streams.

3.2 Flue gas temperature

Figure 3 b shows the variations of the flue gas temperature at different oxygen concentrations. It is evident from the figure that the flue gas temperature slightly increased as O_2 concentration increased to 23 % compared to air/fuel combustion. However, further increasing of O_2 concentration caused moderate decrease in the flue gas temperature. The possible reason was that the temperature was affected by increasing radiant heat flux from the hot flue gas to the combustion chamber's wall (see Figure 4).

3.3 Flame pattern

The produced oxygen-enhanced flames were stable during all combustion tests. It was observed that the air/fuel flames are characterized with blue core and yellow-red envelope. On the other hand, the core of OEC flames become yellower as the O_2 concentration increased and hence the flame luminosity is higher compared with air/fuel flames. Moreover, the flame emissivity is higher, too. This is due to higher

concentrations of CO_2 and H_2O, which are the gases that radiate in a flame (there is no radiation from the N_2 in the flame).
The dimensions of the visible part of flame including length and diameter were determined based on a subjective observation of an operator and hence the observations have to be considered only as orientational. The flame length was measured from the front of combustion chamber where the burner is mounted. The flame diameter was estimated based on the visual comparison of flame diameter towards the outer diameter of burner quarl (600 mm) and the inner diameter of combustion chamber (1 m). It was observed that the enrichment of oxygen into the combustion airstream lengthened the flame by 20 % as O_2 concentration was increased up to 35 %. However, this is in contradiction with Baukal (1998) who states that premix enrichment of oxygen into the combustion airstream shortens the flame length. The plausible explanation for this is that the required amount of combustion air and the exit velocity of enriched-air decrease while O_2 concentration increases, which results in lower mixing intensity of fuel with air. Consequently, the fuel needs for the burnout longer time which results in flame extension. As for the diameter, it was observed 0.4-0.6 m and 0.9-1 m when one-staged and two-staged combustion mode was used, respectively.

3.4 Heat flux distribution

The measured heat flux profiles for the TEST B are presented and compared in Figure 4. Before start of the TEST B the combustion chamber was set into the thermodynamic state. This state was considered if both the flue gas temperature (maximal allowed change within 30 min is 10 °C) and the values of local wall heat fluxes (continuously evaluated) are steady. The heat flux profiles were measured at the thermal input of 750 kW for both one-staged and two-staged combustion mode.
As it is evident from Figure 4, the obtained trend curves of heat flux are characterized with very similar shape for all investigated O_2 concentrations both when one-staged (a) and two-staged (b) combustion mode was utilized. The curves are simply shifted upwards and reach its maximum in the third section for all trials. It can be seen that with increasing O_2 concentration more heat is transferred from hot flue gas to the walls of chamber's sections since less energy is wasted in heating up N_2 and the radiative heat transfer is enhanced due to higher concentrations of CO_2 and H_2O. From the figure, the heating intensity was observed to be significantly higher in the first three sections during two-staged combustion tests compared with one-staged combustion tests.

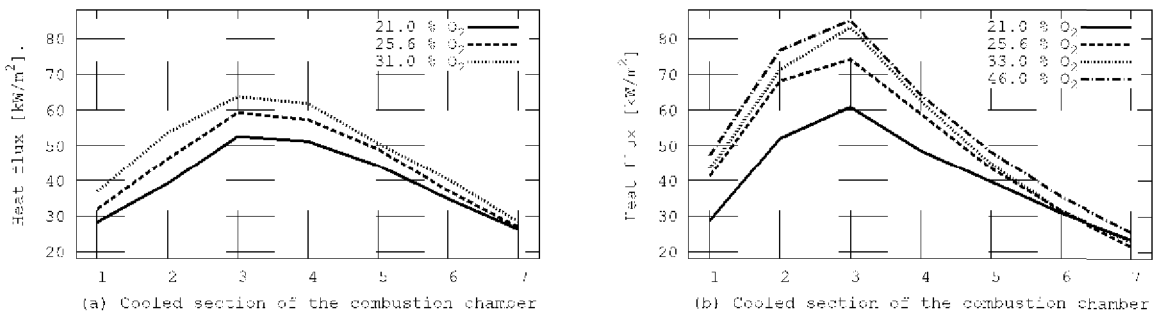


Figure 4: Heat flux distributions lengthwise the chamber at different oxygen concentration for the combustion mode (a) 750 kW one-staged, (b) 750 kW two-staged.

Figure 5 illustrates the variations of net heat transfer rate and furnace thermal efficiency at different oxygen concentrations. The trend of both parameters was increasing with oxygen concentration. The net heat transfer rate increased from 460 kW at 21 % O_2 to 620 kW at 46 % O_2. This implied that the thermal efficiency was increased from 60 % to 80 %y (i.e. more heat is available for the overall process). In addition, increasing the oxygen concentration can in fact save energy, i.e. it can reduce fuel consumption when less fuel is required for a given unit of production because of the improvement in available heat.
In comparison to the results obtained during the tests of oxygen-enhanced flameless combustion mode performed by Sánchez et al. (2013), the increase of the furnace efficiency was rather higher. The results of Sánchez et al. (2013) showed the increase of 5 % in the furnace efficiency when the oxygen concentration in the combustion air was 30 %. On the other hand regarding pollutant emissions during the flameless combustion mode, NO_x emissions were below 5 ppm due to the low process temperature and to the high internal flue gas recirculation ratio used during the flameless combustion mode.

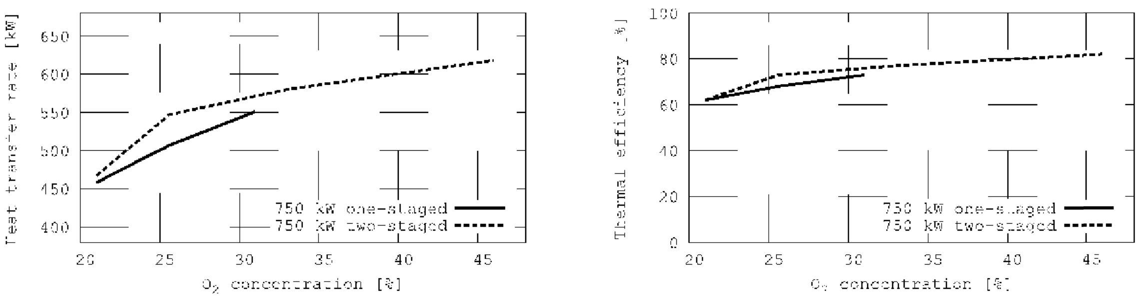


Figure 5: Net heat transfer rate and furnace thermal efficiency at different oxygen concentrations.

4. Future work

The future work of the research project will be focused on the investigation of the influence of separate injection of air and oxygen through a burner (referred to as an air-oxy/fuel combustion) on the same combustion parameters like those studied in this work. Further, the temperature distributions in the furnace for different O_2 concentrations and OEC methods (premix enrichment, air-oxy/fuel) will be measured and the heating and furnace-temperature fixing tests will be carried out.

5. Conclusions

In the present study, two types of combustion tests were carried out to investigate the effects of oxygen concentrations in the range of 21 - 46 %. The influence of oxygen concentration in the airstream on NO_x emissions, flue gas temperature, heat flux distribution, and flame characteristics was examined. The general conclusions drawn from the results of this work were as follows:

1. NO_x emissions increased sharply due to the higher furnace temperature as oxygen concentration increased. When the oxygen concentration was increased from 21 % to 32 %, the NO_x concentration increased more than by 40 times and 20 times when one-staged and two-staged combustion mode was used, respectively.
2. The radiative heat transfer was enhanced as oxygen concentration increased. The available heat at 46 % O_2 was higher by 20 % compared with that at 21 % O_2 when two-staged combustion mode was used.
3. The produced oxygen-enhanced flames were stable and more luminous than the air/fuel flames. The increase of oxygen concentration caused that the OEC flame was longer by about 20 % compared with air/fuel flame.

Acknowledgement

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