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Experimental Study of Oxygen-enhanced Combustion on NO_x Emission, In-Flame Temperatures and Heat Flux Distribution

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The aim of the present study was to experimentally investigate the performance of two oxygen-enhanced combustion (OEC) methods, namely the premix enrichment and air-oxy/fuel combustion. The OEC combustion tests were performed with the conventional experimental low-NO_x type burner, namely the two-gas-staged burner. The overall oxygen concentration was varied from 21 % to 38 %. The combustion tests were carried out at the burner thermal input of 750 kW for two combustion regimes – one-staged and two-staged combustion. The oxygen concentration in the flue gas was maintained in the neighbourhood of 3 % vol. on dry basis.
The aim of the tests was to assess the impact of the oxidant composition, OEC methods and gas-staging on the characteristic combustion parameters in detail. The parameters included the concentration of nitrogen oxides in the flue gas, flue gas temperature, heat flux to the combustion chamber wall and in-flame temperatures distribution in the horizontal symmetry plane of the combustion chamber.

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 (Baukal, 2004). The majority of industrial combustion processes use the atmospheric 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 of the combustion process. Many of high-temperature processes use an oxidant containing higher proportion of oxygen than in the atmospheric air. This type of combustion is referred to as oxygen-enhanced combustion (OEC) and has many benefits including increased processing rates, higher heat transfer efficiency, improved flame characteristics, reduced equipment cost and last but not least improved product quality (Baukal, 1998). 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.
Combustion processes are commonly enhanced by oxygen in four primary ways (Baukal, 1998): (1) adding O_2 into the incoming airstream (referred to as premix enrichment), (2) injecting O_2 into an air/fuel flame (referred to as O_2 lancing), (3) separately provided combustion air and O_2 to the burner (referred to as air-oxy/fuel combustion), (4) replacing the combustion air with high-purity O_2 (referred to as oxy/fuel combustion).
Economically, the method of low-level oxygen enrichment (21 - 30 % O_2) can save the cost for retrofits of existing burners since only minor burner modifications need to be made to permit operation at slightly higher O_2 concentrations. However, the characteristics of low-level oxygen enrichment in an air/fuel combustion system have been studied rarely thus far. The group of 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 4.4 times and CO_2 increased

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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. Merlo et al. (2013) studied the oxygen enrichment effects on the stability of a methane-air non-premixed swirling flame, and on the pollutant emissions. 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 experimental results showed that the saving in natural gas was about 22 % when oxygen concentration was increased to 28 %. Daood et al. (2012) studied the influence of OEC 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.

Few works investigated the effect of oxygen enrichment in the field of flameless combustion, e.g. Sánchez et al. (2013). 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 %.

This work investigated and compared the characteristics of two OEC methods, namely of premix enrichment (further in the text denoted as PE) and air-oxy/fuel combustion (denoted as AO). It is a direct follow-up to the experimental study of Belohradsky and Skryja (2013). The objective of the current investigation was to characterize the effects of oxygen enrichment (21-38 %) on the combustion parameters like the NO_x emissions, flue gas temperature, local wall heat fluxes and in-flame temperatures. The combustion tests of PE and AO were carried out at the burner thermal input of 750 kW and the target oxygen concentration in the dry flue gas of 3 % vol. The burner was operated at two combustion regimes – one-staged combustion and two-staged combustion.

2. Experimental setup

2.1 Testing facility

The combustion tests were carried out at the burners testing facility (Figure 1 (a)). The detailed description of the testing facility can be found in Kermes and Bělohradský (2013). 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 assess the heat extracted from the hot flue gas to the combustion chamber wall lengthwise the flame. The combustion chamber is equipped with eight inspection windows along the cylindrical part allowing the optical access to the chamber and the installation of the additional instrumentation; in this study the water-cooled thermocouples.

Flue gas is exhausted from the combustion chamber through the flue gas stack where three measurement and 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 analyser. The measuring ranges of the gas analyser are 0-25 % for O_2, 0-10,000 ppm for CO, 0-3,000 ppm for NO, and 0-500 ppm for NO_2.

2.2 Burner

The burner used in the experimental study was the two-gas-staged power burner fired by natural gas. 3D model of the burner is shown in Figure 1b. The inner diameter of the burner quarl block 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 regime was used, the ratio primary/total fuel was set to 0.28.

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 in tangential and radial direction (see Figure 1b). In the reference tangential position the nozzles are oriented directly towards the burner axis. In the reference radial distance the distance of nozzle heads from the burner axis is 180 mm and can be extended by 50 mm.

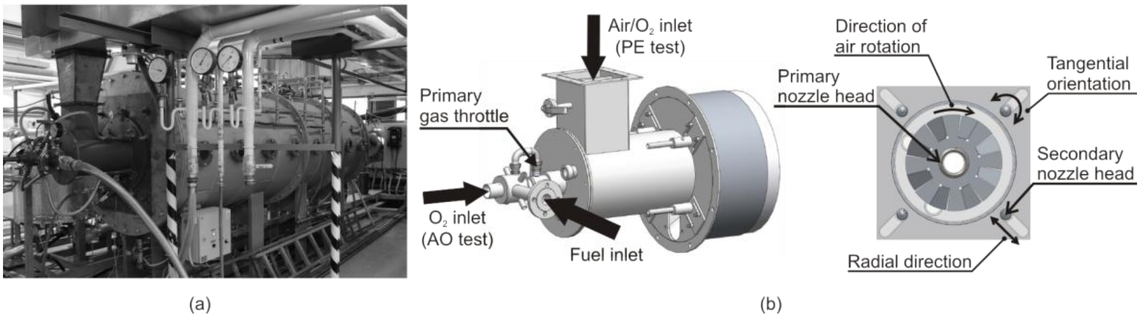

Figure 1: (a) The testing facility, and (b) the 3D model of experimental two-gas-staged burner

During the tests, when staged combustion regime was used, the secondary nozzle heads were turned by 20° in the direction of air (flame) swirl motion and their radial distance was set to the maximum (i.e. 230 mm from the burner axis). The burner is equipped with the so-called flame holder that has the form of swirl generator consisting of eight pitched blades. Flame ignition is performed with a gaseous premixed natural-draught ignition burner with the thermal input of 18 kW.

2.3 Oxygen supply

When the PE tests were carried out, the high-purity oxygen was injected into the incoming combustion air stream through the diffuser to ensure adequate mixing. The diffuser was inserted in the air supply duct before entering the burner and was designed for the maximal oxygen flow rate of 160 m_N^3/h (where “N” indicates that the volume is expressed at normal conditions 0 °C, 101.325 kPa).
When the AO tests were carried out, the high-purity oxygen was injected directly into the flame through the nozzle head that was inserted through the centre burner pipe. The balance of the oxygen needed for complete combustion was introduced to the burner via the combustion air. The nozzle head was designed for the maximal flow rate of oxygen 120 m_N^3/h.

2.4 Plan of combustion tests

The experimental matrix is presented in Table 1. As for the PE tests, the O_2 concentration between 21-38 % matches directly the O_2 concentration in the incoming combustion air. On the other hand, in the AO tests the oxygen was not mixed with the combustion air and hence the oxygen concentration in the incoming air was always 21 %. Thus the term 21-38 % oxygen concentration here expresses the overall oxygen concentration as if both air stream and oxygen stream (injected directly in the flame) are mixed.
Three tests were of interest here. In the first test, denoted as TEST A, the NO_x emissions and flue gas temperature 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. In the last test, denoted as TEST C, the in-flame temperatures in the middle plane of the combustion chamber were measured. Unlike the TEST A, the TEST B and TEST C were carried out only for selected oxygen flow rates (0, 20, 40, and 80 m_N^3/h).

3. Results and discussion

3.1 NO_x emissions

Figure 2a shows the measured concentrations of NO_x [mg/m_N^3] as a function of oxygen concentration. The major proportion of NO_x produced during the combustion was thermal NO_x, which was directly associated with higher flame temperature peaks due to higher O_2 concentration (Baukal (2004)).
As for the PE tests, it can be seen that NO_x showed approximately exponential dependence on the in-flame temperature both for one-staged and two-staged regime. Due to this, even a minor variation in temperature accelerated NO_x formation. When the PE one-staged combustion regime was used, the NO_x emission increased sharply from 160 mg/m_N^3 to 7,100 mg/m_N^3 as the O_2 concentration in the combustion air increased from 21 % to 33 %. Further O_2 enrichment was not possible for two reasons. First, the measured values of NO_x were out of the measuring range of the flue gas analyser. Second, the swirl generator’s blades and burner quarl began to glow due to very high temperatures at the burner tile.
However, when the PE two-staged combustion regime was used as the common NO_x reducing technique, the increase in NO_x formation was not as steep as during PE one-staged regime since the reaction of fuel with oxygen was staged.

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

Trial – combustion regime	Flow rate of high-purity O_2 [m_N^3/h]/ O_2 concentration in the air [%]								
	0/21	5/21.5	10/22	20/23.1	30/24.3	40/25.6	60/29	80/33	100/38
TEST A									
Premix enrichment									
PE one-staged	●	●	●	●	●	●	●	●	-
PE two-staged	●	●	●	●	●	●	●	●	●
Air-oxy/fuel									
AO one-staged	●	●	●	●	●	●	●	●	-
AO two-staged	●	●	●	●	●	●	●	●	●
TEST B									
Premix enrichment									
PE one-staged	●	-	-	●	-	●	-	●	-
PE two-staged	●	-	-	●	-	●	-	●	-
Air-oxy/fuel									
AO one-staged	●	-	-	●	-	●	-	●	-
AO two-staged	●	-	-	●	-	●	-	●	-
TEST C									
Premix enrichment									
PE one-staged	●	-	-	●	-	●	-	●	-
PE two-staged	●	-	-	●	-	●	-	●	-
Air-oxy/fuel									
AO one-staged	●	-	-	●	-	●	-	●	-
AO two-staged	●	-	-	●	-	●	-	●	-

The NO_x rose gradually from 85 mg/m_N^3 to 2,900 mg/m_N^3 as O_2 concentration increased from 21 % to 38 %. 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 thermal input in the range between 0.3-50 MW in the Czech Republic, as long as O_2 concentration was less than 25 %. Additionally the NO_x reached the value only 1,700 mg/m_N^3 at 33 % O_2, which is by four times less than obtained in the PE one-staged tests at the same O_2 enrichment.

As for the AO tests, the NO_x emissions did not increase so dramatically compared to the PE tests. When the AO one-staged combustion tests were carried out, the NO_x emissions increased gradually to 1,500 mg/m_N^3 as the flow rate of injected oxygen increased from 0 m_N^3/h to 80 m_N^3/h (corresponding to the overall O_2 concentration 21 - 33 %). It was observed that further increase of O_2 flow rate slightly reduces NO_x. The reason is that the major portion of the fuel is combusted in the flame core into which the high-purity oxygen is injected. Hence, the flame core is very rich in the oxygen and very poor in the nitrogen. This in turn results in very low NO_x, although the flame temperature peaks are very high. The balance of the fuel is combusted with the combustion air downstream of the main combustion zone at lower temperatures that are not favourable for thermal NO formation. It can be assumed that further increasing of O_2 concentration will lower NO_x because less N_2 is available to form NO_x.

The excellent results were obtained when the fuel-staging was utilized together with the AO combustion method. The values of NO_x were fluctuating around the value of 90 mg/m_N^3 and the maximum value reached only 120 mg/m_N^3 at the oxygen flow rate of 80 m_N^3/h. The reason was that the portion of the fuel was directed into the primary combustion zone while the balance of the fuel was directed into the secondary zone. This made the primary zone fuel lean, which is less conducive to NO_x formation compared to one-staged combustion (Baukal, 2004). The flame temperature peaks were much lower in the fuel-staging regime because the combustion is staged over some distance. Consequently, the lower temperatures contributed to reduce the NO_x emissions.

3.2 Flue gas temperature

Figure 2b presents the variation of flue gas temperature at different oxygen concentrations. The graph shows that the flue gas temperature was decreasing as O_2 concentration was increasing. The temperature decrease was affected by decreasing concentration of N_2 in the oxidant, which absorbs heat and carries energy out with the flue gas. This effect is then associated with increasing radiant heat flux from the hot flue gas to the combustion chamber's wall (see Figure 3).

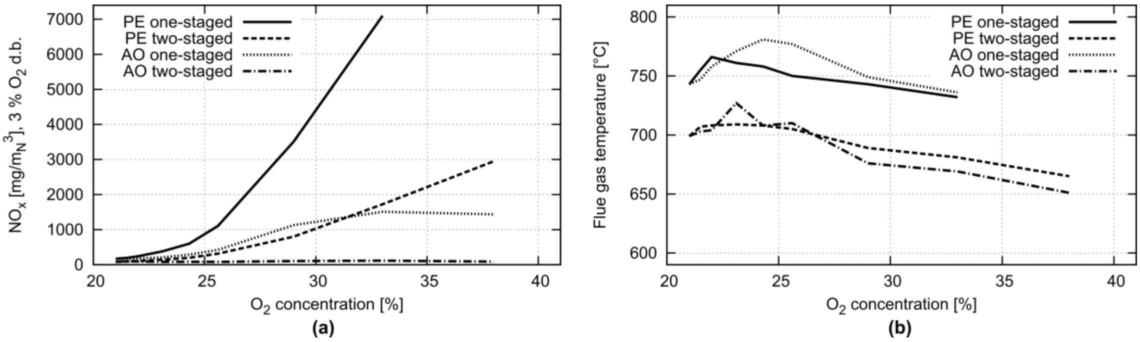

Figure 2: Effects of oxygen concentration on (a) NO_x emissions and (b) flue gas temperature

3.3 Heat flux distribution

The facility utilizes the measurement based on heat absorbed by the cooling water in each chamber's section. The measured heat flux profiles for the TEST B are presented and compared in Figure 3. As it is evident, the obtained trend curves are characterized with very similar shape for all investigated O_2 concentrations and for all tested regimes. The individual curves are shifted upwards and reach their maximum in the third section for all trials. It can be seen that with increasing O_2 concentration more heat is released from the hot flue gas to the walls of chamber's sections because 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 and due to increased residence time of the hot flue gases in the chamber. The thermal efficiency of the combustion process was increased, on average from 60 % at 21 % O_2 to 77 % at 33 % O_2.

3.4 In-flame temperatures

The in-flame temperatures in the horizontal symmetry plane of the combustion chamber were measured using the water-cooled platinum/platinum-rhodium thermocouples of type R installed through the inspection windows. Due to the limited number of pages of the paper, only two 2-D temperature contour plots for the PE one-gas-staged combustion regime are displayed in Figure 4. This regime is characterized with the significant increase of NO_x as O_2 concentration increases. From the figure, the temperature rose near the burner region as the O_2 concentration increased. For example, the temperature was about 1,320 °C for 21 % O_2 (Figure 4a), whereas for 33 % O_2, it rose to about 1,520 °C (Figure 4b).

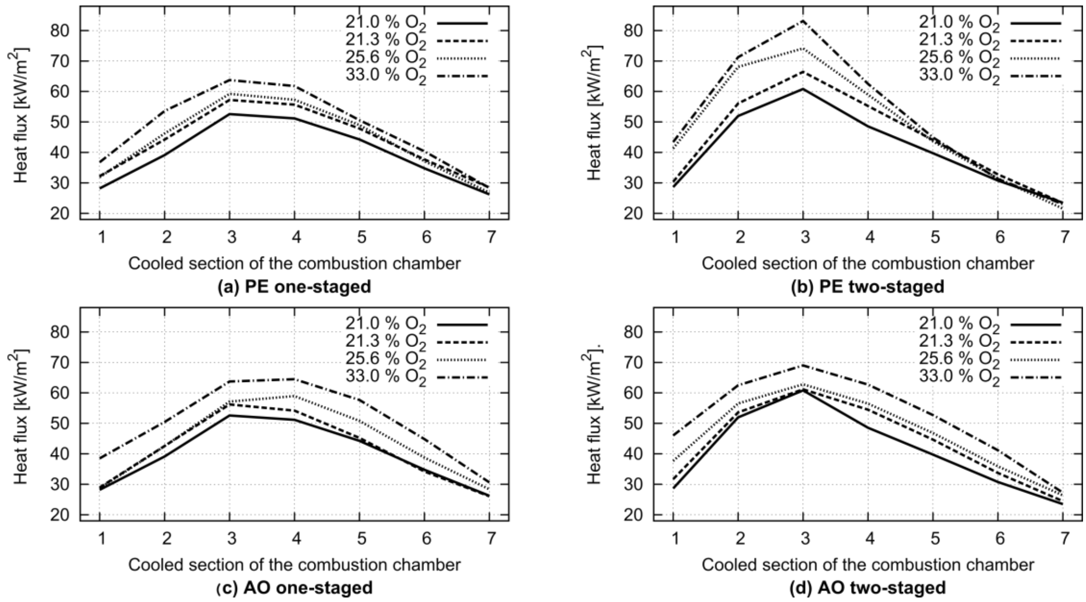

Figure 3: Heat flux profiles lengthwise the chamber at different oxygen concentrations

Generally for all tested combustion regimes, the temperature gradient near the burner region became progressively greater (higher contour density) and the uniformity of the temperature field was disturbed as the O_2 concentration increased which complies with the results obtained with Wu et al. (2010).

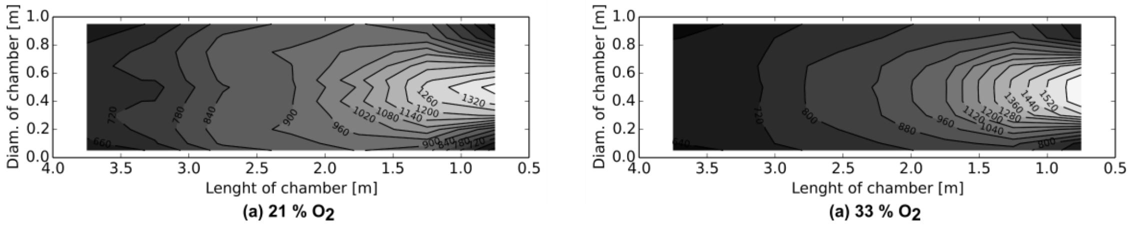

Figure 4: Temperature distribution for the PE one-staged combustion regime

4. Conclusions

In the present study, three types of combustion tests were carried out to investigate the effects of oxygen concentration in the range of 21 - 38 %. The influences of two oxygen-enhanced combustion methods and oxygen concentration on the NO_x emissions, flue gas temperature, heat flux distribution, and in-flame temperature distribution were examined. The general conclusions drawn from the results of this work are as follows:

1. The formation of NO_x emissions strongly depends on the used OEC method and combustion regime. The sharp increase of NO_x was observed during the PE tests when NO_x emissions increased more than by 40 times and by 20 times for one-staged and two-staged regime, respectively. Significantly better results were obtained during the AO tests, especially when the fuel was staged. In this case the NO_x emissions was below 120 mg/m_N^3 for all oxygen flow rates.
2. The oxygen enrichment resulted in the increase of CO_2 concentration in flue gas from 10 % to 15 % as the oxygen concentration increased from 1 % to 38 %. Higher CO_2 concentration in flue gas is then considerable favourable for using CO_2 capture technologies.
3. Flue gas temperature decreased with increasing oxygen concentration affected by decreasing N_2 concentration in the oxidant and by increasing radiant heat flux.
4. The radiative heat transfer was enhanced as oxygen concentration increased. The available heat at 33 % O_2 was higher by approximately 20 % compared with that at 21 % O_2. At the same time the combustion efficiency increased from 60 % to nearly 80 %.
5. Increasing the oxygen concentration led to higher temperature gradient and non-uniform temperature distribution in the horizontal symmetry plane of the combustion chamber.

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