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CHARACTERISTIC PARAMETERS OF OXYGEN-ENHANCED COMBUSTION PROCESS

CHARAKTERISTICKÉ PARAMETRY PROCESU SPALOVÁNÍ PŘI VYUŽITÍ VZDUCHU S OBSAHEM KYSLÍKU VYŠŠÍM NEŽ 21 %

DIPLOMOVÁ PRÁCE
MASTER'S THESIS

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Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma diplomové práce:

Charakteristické parametry procesu spalování při využití vzduchu s obsahem kyslíku vyšším než 21 %

v anglickém jazyce:

Characteristic parameters of oxygen-enhanced combustion process

Stručná charakteristika problematiky úkolu:

Průmyslové aplikace jako např. zpracování kovových a nekovových materiálů, zpracování sklářských písků aj. se vyznačují vysokou spotřebou tepelné energie, které je zapotřebí k dosažení vysokých teplot uvnitř pece. Zdrojem tepelné energie je ve většině aplikací proces spalování, kde se obvykle jako oxidační činidlo používá atmosférický vzduch. Avšak za účelem snížení spotřeby paliva je výhodné zvýšit účinnost procesu použitím spalovacího vzduchu, ve kterém je koncentrace kyslíku vyšší než 21 %, tzn. snížit koncentraci dusíku ve vzduchu, který se neúčastní chemických reakcí a působí jako balast. Takový proces se v anglické terminologii nazývá jako „oxygen-enhanced combustion“ (OEC). Krajním případem OEC je úplné nahrazení atmosférického vzduchu vysoce čistým kyslíkem. Pak se hovoří o tzv. kyslíkovém spalování. Obě zmíněné technologie se vyznačují významnou úsporou paliva, nízkým objemem spalin, sníženou tvorbou oxidů dusíku a vysokými teplotami.
Úkolem studenta je v prvním kroku porovnat klady a zápory OEC s konvenčním způsobem spalování a porovnat jednotlivé metody OEC. V dalším kroku bude úkolem studenta shrnout hlavní oblasti užití OEC a hlavní zásady bezepečné manipulace s kyslíkem. V rámci přípravy na praktickou část práce bude zapotřebí uvést základní vztahy pro výpočet výkonu hořáku, teoretické a skutečné spotřeby spalovacího vzduchu atd. V posledním kroku, který představuje praktickou část práce, bude úkolem studenta provést zkoušky spalování s obohaceným vzduchem, při kterých budou měřenými veličinami průtok paliva, vzduchu a kyslíku, teplota spalin, koncentrace oxidů dusíku, popř. tepelný tok do stěn spalovací komory.

Cíle diplomové práce:

1. Základní charakteristika, pozitiva a negativa OEC.
2. Přehled oblastí procesního průmyslu, ve kterých je OEC využíváno.
3. Zásady bezpečné manipulace s kyslíkem.

4. Přehled důležitých vztahů pro výpočty spalovacích procesů.
5. Provedení zkoušek spalování.
6. Vyhodnocení zkoušek spalování.

Seznam odborné literatury:

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3. Baukal C.E., Oxygen-Enhanced Combustion, USA, CRC PRESS, 1998, ISBN 0-8493-1695-2.

Vedoucí diplomové práce: Ing. Petr Bělohradský, Ph.D.

Termín odevzdání diplomové práce je stanoven časovým plánem akademického roku 2012/2013.

V Brně, dne 31.10.2012

L.S.

prof. Ing. Petr Stehlík, CSc. Ředitel ústavu	prof. RNDr. Miroslav Doupovec, CSc., dr. h. c. Děkan fakulty

Abstract

The thesis is focused on the investigation of oxygen enhanced combustion (OEC) and its impact on the burner characteristics. The OEC technology is used in various industrial applications, in which increased productivity, higher heat efficiency, improved flame characteristics, reduced equipment cost and/or improved product quality is required. However, the application of OEC technology can also cause problems such as refractory damage, nonuniform heating, flame disturbance, increased pollutant emission and/or flashback.

The experiments were carried out at the burner testing facility that enables to test different types of burners (gaseous, liquid or combined) up to the thermal input 1 800 kW. During the tests two staged low-NO_x burner fired by natural gas was used. The work was aimed at the studying of the influence of 21–46 % oxygen concentration on the NO_x emissions, the flue gas temperature, the distribution of the heat extracted from the hot flue gas to the wall of the combustion chamber, and the flame pattern including its stability, shape and dimensions. The combustion tests of premixed air and air-oxy/fuel methods were carried out at the thermal inputs of 300 kW, 500 kW and 750 kW for two combustion modes – one staged combustion and two staged combustion.

Keywords: oxygen enhanced combustion, premixed air, air-oxy/fuel, NO_x emission, heat flux.

Abstrakt

Diplomová práce se zabývá spalováním zemního plynu při využití vzduchu s vyšším obsahem kyslíku (21–46 % kyslíku ve spalovacím vzduchu), tzv. kyslíkem obohaceným spalováním (OEC). Technologie OEC nalezla uplatnění v průmyslu, kde se jsou nároky na zvýšenou produktivitu, dosažení vyšší tepelné účinnosti, zlepšení vlastností plamene, snížení náklady, či zlepšení kvality výsledného produktu. Ačkoliv OEC přináší řadu výhod, je nutné zmínit i nevýhody jako: poškození zařízení, nestejnoměrné zahřívání, narušení plamene, zvýšené emise anebo zpětný zášleh plamene.

Zkoušky proběhly na zkušebně hořáků, která umožňuje testovat hořáky nejen na plynná a kapalná paliva, ale i hořáky navržené pro kombinované spalování při maximálním výkonu hořáku 1 800 kW. Při zkouškách byl použit plynový „low-NO_x“ hořák se stupňovitým přívodem paliva. V diplomové práci je popsán vliv obsahu kyslíku ve spalovacím vzduchu na emise oxidů dusíku (NO_x), teplotu plamene, přenos tepla ze spalin do stěn spalovací komory, a také vlastnosti plamene, zvláště pak jeho stabilitu, tvar a rozměry. Zkoušky proběhly při výkonech 300 kW, 500 kW a 750 kW, přičemž pro výkon 750 kW proběhly testy jak při jednostupňové, tak dvoustupňové konfiguraci.

Klíčová slova: kyslíkem obohacené spalování, premixed air, air-oxy/fuel, emise NO_x, tepelný tok.

Bibliographic citation

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Affirmation

I declare that this master’s thesis is the result of my own work led by Ing. Petr Bělohradský, Ph.D. and all used sources are listed in the bibliography.

Bc. Igor Hudák

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I wish to express my sincere gratitude to my supervisor Ing. Petr Bělohradský, Ph.D. for his valuable advices, great patience and helpful attitude. The opportunity to work with him was a great honour and challenge for me. I thank to all faculty members of the Institute of Process and Environmental Engineering for their help. I give great thanks to my family, especially my parents, for their support and encouragement. I also thank to my girlfriend, who was a great support to me.

Igor Hudák, Brno, 2013

Contents

List of symbols

Symbol	**Meaning**	**Unit**
A	heat transfer area	m^2
h	heat transfer coefficient	$W\cdot(m^2\cdot K)^{-1}$
k	thermal conductivity	$W\cdot(m\cdot K)^{-1}$
LHV_i	lower heating value	$kJ\cdot m_N^{-3}$
MW_{gas}	molecular weight of the natural gas	$kg\cdot kmol^{-1}$
MW_i	molecular weight of i-th component	$kg\cdot kmol^{-1}$
Nu	Nusselt number	-
Q	transferred heat	$kW\cdot m^{-2}$
q_x	heat flux	$kW\cdot m^{-2}$
Re	Reynolds number	-
T	temperature	K
T_w	temperature of a solid wall	K
X	measured concentration of emissions	ppm
x_i	mass fraction of the i-th component	kg/kg
Y	converted concentration of emissions	mg/m^3

Greek symbols

λ	excess air ratio	-
ε	body emissivity	-
σ	Stefan-Boltzmann constant	$W/(m^2\cdot K^4)$
Ω	overall oxygen concentration	%

Abbreviations

Abbreviation	**Meaning**
AO	Air-oxy/fuel
ASU	Air Separation Unit
GOX	Gaseous Oxygen
LHV	Lower Heating Value
LOX	Liquid Oxygen
OEC	Oxygen Enhanced Combustion
PM	Premixed Air
PSA	Pressure Swing Adsorbtion
VPSA	Vacuum Pressure Swing Adsorbtion
VSA	Vacuum Swing Adsorbtion

Chemical compounds

Molecular formula	**Name**
C_2H_6	Ethane
C_3H_8	Propane
C_5H_{12}	Pentane
C_6H_{14}	Hexane
CN	Cyanide
CO_2	Carbon Dioxide
H_2	Hydrogen
H_2O	Water
HCN	Hydrogen Cyanide
CH_4	Methane
$i\text{-}C_4H_{10}$	Isobutane
N_2	Nitrogen
N_2O	Nitrous Oxide
NO_2	Nitrogen Dioxide
N_2O_4	Nitrogen Tetroxide
N_2O_5	Dinitrogen Pentoxide
$n\text{-}C_4H_{10}$	n-Butane
NH_3	Ammonia
O_2	Oxygen

1 Introduction

The costs of the energy have rapidly increased recently and for this reason it is necessary to focus our effort on the improvement of the process efficiency. Energy gained from the traditional combustion systems is partly used to heat up nitrogen that enters the combustion chamber as an inert gas from the atmospheric air, which lowers the net process efficiency in consequence. One of the possibilities to reduce the costs and to save the energy is Oxygen Enhanced Combustion (OEC). OEC is described as the elevated oxygen concentration (more than 21 % of oxygen by volume) in the combustion air or in the oxidizer stream. When OEC is used the disadvantage mentioned above can be easily solved, because less nitrogen enters the combustion chamber. The benefits of OEC, compared with the conventional technologies, can be higher thermal efficiency, lower heat loss through the flue gas or higher turndown ratio [1].

Recently the efficiency and the costs are not the only aspects that are monitored and discussed, but politicians and environmentalists also speak about the pollution from the industrial combustion processes. Chatel-Pelage et al. [2] refers that current technologies (low-NO_x burners and other modifications) will not be able to fulfil future emission limits without the application of additional technologies, such as the selective catalytic reduction. Two groups of emissions that are widely discussed are carbon dioxide (CO_2), which is responsible for the global warming and nitrogen oxides that cause the acid rain. The reduction of these two main emissions can be carried out by means of OEC. So far OEC is known as a technology that could be capable of the emission reduction in combination with special burner design and replacement of a portion of nitrogen by oxygen. Although the potential of OEC can be huge, not all of the applications can have the positive impact on emissions.

OEC is usually used in the industries with high-temperature environment. When oxygen is added into the combustion system (> 21 % O_2) the temperature in the combustion chamber rises. This benefit is utilized in the industries such as metal production (aluminium melting furnaces or ladle preheating), glass industry (glass melting furnaces), waste incinerators or power production. However, the usage of the OEC in the industrial applications has many disadvantages too, e.g. the further expansion of the OEC is limited by high costs related to the oxygen production [3].

OEC can be used with various types of fuels that include all forms – gaseous, liquid and solid. As for the gaseous fuels the natural gas is the most commonly used. Light or heavy heating oil are commonly used in liquid fuel applications, and coal and solid waste are commonly used as solid fuels. Even though the usage in term of the fuel types is various, it can bring potential obstacles. Fuel can be composed of different components and due to higher temperatures in OEC undesirable compounds can be formed, e.g. soot, dioxins, furans.

Combustion processes are commonly enhanced by oxygen in four primary ways [1]: adding O_2 into the incoming airstream (referred to as premixed air or low-level oxygen combustion), injecting O_2 into an air/fuel flame (referred to as O_2 lancing), replacing the combustion air with high-purity O_2 (referred to as oxy/fuel combustion), and separately provided combustion air and O_2 to the burner (referred to as air-oxy/fuel combustion).

Low-level oxygen method can save cost for retrofits of existing burner. However, the characteristics of low-level oxygen enrichment in an air/fuel combustion system have been studied rarely thus far. 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 was studied by the group of Wu et al. [3]. According to their research, the time elapsed for heating to 1 200 °C was only 46 % (compared with the concentration 21 % O_2 in the air. As for the species concentrations the NO_x emission was increased by 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.

Research group of Qju at al. [4] investigated the oxygen enriched combustion of natural gas in porous ceramic radiant burners. For the production of the oxygen enriched air the polymer membranes were used, which means oxygen was produced passively. The oxygen concentration was varied between 21 % and 28 %. The experimental results showed that it was possible to reach savings in the natural gas up to 22 % when oxygen concentration was increased to 28 %.

Another research group [5] used down fired vertical combustor to study oxygen enhanced and O_2/CO_2 combustion. Tan et al. 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 low concentrations.

1.1 Goals of the work

The thesis is focuses on the study of OEC and its impact on the combustion characteristics and how the industrial combustion process can be enhanced by adding oxygen. The work is divided into two main sections. The first section describes the problematic of the OEC technology in the theoretical way. Basic theory covers the combustion of gaseous fuels, namely of natural gas, and its behaviour when the pure oxygen is added. Next the basic principles of the heat distribution are described, followed by the description of the OEC methods, the formation of NO_x and the methods used for the industrial oxygen production.

In the second part of the thesis the characteristics of two OEC methods are investigated and compared. Namely the premixed air (further in the text denoted as PM) and the air-oxy/fuel combustion (denoted as AO) were studied here. The work was aimed at the studying of the influence of 21–46 % oxygen concentration on the NO_x emissions, the flue gas temperature, the distribution of the heat extracted from the hot flue gas to the wall of the combustion chamber, and the flame pattern including its stability, shape and dimensions. During the tests two staged low-NO_x burner fired by natural gas was used. The combustion tests of PM and AO were carried out at the thermal inputs of 300 kW, 500 kW and 750 kW for two combustion modes – one staged combustion and two staged combustion.

2 Basics of combustion

In general the atmospheric air contains approximately 79 % of N_2 and 21 % of O_2. Both gases flow into the combustion chamber, where they react with the hydrocarbon fuel. Natural gas is mainly represented by methane (CH_4). The products of the combustion reaction are carbon dioxide (CO_2), water (H_2O) and energy in the form of heat as it is shown in the equation (1) [6]. The mass in the chemical reactions, including the combustion, is conserved [1].

$$1\, CH_4 + 9.524\, air\ (\, 0.21 O_2 + 0.79 N_2) \rightarrow 1\, CO_2 + 2\, H_2O + 7.524\, N_2 + heat \tag{1}$$

Equation (1) represents the fact that the reaction of 1 unit of the fuel requires approximately 10 units of the combustion air. To provide the complete combustion the amount of the incoming air is required to be higher than at stoichiometric conditions. The amount of the extra combustion air is called as the excess air and it is known as an excess air ratio, usually denoted as λ [7]:

$$\lambda = \frac{\%\, O_2\ in\ flue\ gas}{0.21 - \%\, O_2\ in\ flue\ gas} \tag{2}$$

The excess air is used to ensure that all fuel is combusted and no particles of carbon monoxide (CO) or unburned hydrocarbons (C_xH_y) are present in the flue gas. There is also a negative aspect; the excess air slightly decreases the process efficiency [6], because nitrogen (N_2), which enters the reaction as an inert gas, is necessary to heat up as well. If all N_2 in the air is removed, the equation describing the combustion reaction can be rewritten as follows:

$$1\, CH_4 + 2\, O_2 \ \rightarrow 1\, CO_2 + 2\, H_2O + heat \tag{3}$$

From equation (3), for every unit of hydrocarbon fuel 2 units of O_2 are required. Compared with the equation (1) two combustion conditions can be observed. Equation (1) represents the combustion with the atmospheric air while the equation (3) characterizes the combustion with the pure O_2, called as the oxy/fuel combustion.

However, the problem described above is simplified, because the combustion air is in the most of industrial applications the atmospheric air composed of many other components. The detailed composition of the atmospheric air can be found in Table 2.1 [8]:

Component	**Symbol**	**% mole**	**% mass**
Nitrogen	N_2	78.09	75.47
Oxygen	O_2	20.95	23.20
Argon	Ar	0.933	0.05
Carbon Dioxide	CO_2	0.03	~0
Neon	Ne	0.0018	1.28
Helium	He	0.0005	0.0012
Krypton	Kr	0.0001	0.00007
Hydrogen	H_2	0.00005	0.0003
Xenon	Xe	0.000009	0.00004
Total		100.00%	100.00%

Table 2.1 *– The chemical composition of atmospheric air.*

2.1 Oxygen in the combustion air

The atmospheric air is composed of several gases which are not involved in the combustion reactions and have a negative influence on the process efficiency. Scientists and engineers realized that it will be beneficial to replace some of the nitrogen in the combustion air with pure oxygen, hence the amount of the incoming inert gases will be decreased; e.g. the manufactures from the glass industry promise the savings on the energy up to 15 % [9].

Figure 2.1 shows the dependence between the flame temperature and added oxygen [10]. When the pure oxygen is added into the combustion chamber, the flame temperature can rise significantly. For example the combustion of natural gas with the atmospheric air has the flame temperature 1930 °C, but with 23 % of O_2 in the incoming air the flame temperature increases to 2000 °C [10]. Oxygen is not only added for a purpose of increasing flame temperature, but according to the burner manufacturers the added oxygen can have a positive impact on NO_x levels (depending on the operating conditions – amount of the added oxygen, method of the OEC, etc.).

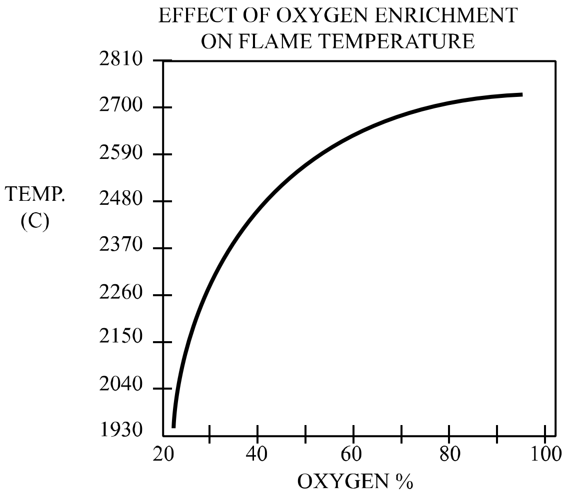


Figure 2.1 *– The effect of oxygen enrichment on the flame temperature.*

2.2 Natural gas

Natural gas is widely used gaseous fuel in the United States as well as in Europe. Natural gas has regularly non luminous flame and since it burns cleanly the production of soot particles is negligible. The composition of the natural gas has the influence on the heating value of the fuel. The natural gas that was used during the combustion tests was mostly composed of the methane followed by other higher hydrocarbons. The composition is given in Table 2.2. It can be seen that the fuel contains small amount of N_2 responsible for the formation of the fuel NO_x (nitrogen oxides emissions are discussed later in the Chapter 2.4). When the natural gas burns the colour of the flame is blue with yellow tips of the flame. If the pure oxygen is added into the combustion air the flame can turn from blue to luminous yellow depending on the oxygen concentration in the air.

The formula used for the calculation of the average molecular weight of the gas (MW_{gas}) follows

$$MW_{gas} = \sum \frac{x_i}{100} \cdot MW_i \tag{4}$$

where x_i represents the mass fraction of the i-th component [kg/kg],
MW_i is the molecular weight of the i-th component [kg/kmol].

The lower heating value of the fuel is calculated according to the following formula:

$$LHV_{gas} = \sum \frac{x_i}{100} \cdot LHV_i \tag{5}$$

where x_i represents the mass fraction of i-th component [kg/kg],
LHV_i is the lower heating value of the i-th component [kJ/m_N^3].

COMPONENT	[% vol]	MW [kg/kmol]	LHV [kJ/m_N^3]	Contribution to overall MW [kg/kmol]	Contribution to overall LHV [kJ/m_N^3]
N_2	0.83	28.01	0	0.233	0.00
CO_2	0.07	44.01	0	0.031	0.00
C_2H_6	0.59	30.07	63687	0.177	375.75
C_3H_8	0.17	44.10	91176	0.075	155.00
n-C_4H_{10}	0.04	58.12	118584	0.023	47.43
i-C_4H_{10}	0.03	58.12	118279	0.017	35.48
CH_4	98.24	16.04	35781	15.761	35151.72
C_5H_{12}	0.02	72.15	145957	0.014	29.19
C_6H_{14}	0.01	86.18	173458	0.009	17.35
Total	100.00	-	-	16.340	35812.00

***Table 2.2** – The composition of natural gas and its lower heating value.*

2.3 Heat transfer

During the combustion reactions the heat is released. The difference between the flame temperature and the temperature of the combustion chamber is called as a temperature gradient. When the temperature gradient occurs there is always the heat that is transferred. The heat transfer itself can be described by three mechanisms.

2.3.1 Conduction

Heat transfer between molecules that are located in the close proximity is called conduction. Specific parameters of the heat transfer depend on the molecular and particular state of the material. The motion of the particle is vital for the transfer, but it can cover wide range of movements, e.g. vibrations of atoms in the crystal lattice or chaotic motion of the gas molecules. One of the equations that describe the conduction heat transfer was defined by Fourier and thus it is called Fourier's Law of Heat Conduction. According to Fourier's Law the temperature is proportional to the temperature gradient in magnitude, but the direction is exactly the opposite to the gradient [1]. The equation follows

$$q_x = -k \cdot \frac{dT}{dx} \tag{6}$$

where	q_x	is the heat flux [W/m^2],
	k	is the thermal conductivity [W/(m·K)],
	dT	is the temperature difference between two locations,
	dx	is the distance between two locations.

2.3.2 Convection

Laws of fluid mechanics could describe the whole process of the convection, because the convection is described as the mixing of molecules of gas or liquid. The convection can be defined as natural or forced. The natural convection is influenced by the gravity and the differences in the density of the substance. The forced convention is caused by the impulse from the outside such as pumps or compressors. The simplified equation for the heat convention follows [1]:

$$Q = A \cdot h \cdot (T - T_w) \tag{7}$$

where	Q	is transferred heat [W·s],
	A	is the heat transferred area [m^2],
	h	is the heat transfer coefficient [W/(m^2·K)],
	T	is the temperature of the fluid/gas [K],
	T_w	is the temperature of a solid wall [K].

Even though the equation looks simple the problem is much more complex and all the variables (e.g. Reynolds number (Re), Nusselt number (Nu), etc.) that influence the heat transfer are represented by the heat transfer coefficient.

2.3.3 Radiation

The radiation is the most important mechanism of the heat transfer in the combustion process. The radiation can be spread through every environment even through vacuum, where no particles are present [11]. In case of the radiation the heat flux is proportional to the fourth power of the black body's thermodynamic temperature and it is known as Stefan-Boltzmann's law:

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \tag{8}$$

where	Q	is the transferred heat [W·s],
	A	is the surface area [m^2],
	ε	is the body emissivity [-],
	σ	is Stefan-Boltzmann constant ($\sigma = 5.6704 * 10^{-8}$ [W/(m^2·K^4)]),
	T	is the temperature [K].

The radiation uses the photon theory, atoms and molecules can gain excess energy; at this point they become excited and unstable. The particles tend to go back to the state where they were before, thus they discharge a photon to lower the state of energy. The photon travel through the space until it reaches another particle. This process can continue until the energy is transferred.

2.4 Nitrogen oxides

When fossil fuels are combusted the main products are carbon dioxide and water vapour. Moreover, other elements and/or compounds that are contained either in the fuel or in the combustion air can interact and form new compounds such as nitrogen oxides (NO_x), sulphur oxides (SO_x), ash or solid particles – all together called emissions. NO_x levels are strictly monitored because the formation of NO_x can be rapid even compared to the formation of $SO_{x.}$

The term nitrogen oxides covers wide group of nitrogen compounds, e.g. NO, NO_2, N_2O, N_2O_4 or N_2O_5, but the symbol NO_x represents only two groups of nitrogen oxides that occur the most in the flue gas, namely the nitric oxide NO and the nitrogen dioxide NO_2. NO is known as colourless gas, which tends to react with O_2 in the atmosphere to form NO_2. Baukal [7] refers that the nitric oxide is very dangerous to human beings, because it irritates eyes, throat and also it can cause diseases such as nausea or headache.

Nitrogen dioxide is the second most represented NO_x in the flue gas. NO_2 is formed out of NO and free oxygen radicals that were formed by the fission of O_2 or peroxide radical (HO_2). The previous research [12] proved that approximately 90 % of all NO_x formed during the combustion process is NO and the rest is NO_2. Further oxidation to NO_2 takes place in the stack or in the atmosphere by the reaction with ozone. NO_2 is reddish-brown and it is a strong oxidizing agent. NO_2 is also highly toxic and hazardous, because it has the ability to cause chemical pneumonitis or pulmonary edema. It is also referred as a strong greenhouse gas that contributes to the ozone destruction in the stratosphere [13].

2.5 NO_x formation

The formation of this particular substance can be described by three mechanisms: thermal, prompt and fuel. Even though, there are three main mechanisms that describe NO_x formation, the whole problematic is more complex and many other variables can affect their formation.

2.5.1 Thermal NO_x

Thermal nitric oxides are formed at higher temperatures (above 1100 °C) in areas where is not the sufficient amount of the fuel. Thermal NO_x is formed by the reaction of oxygen and nitrogen from the combustion air and the rate of formation is accelerated with the temperature increase [7]. The process of formation of thermal NO_x was firstly described by Zeldovich [14]:

$$N_2 + O_2 \leftrightarrow NO, NO_2 \tag{9}$$

This mechanism can be usually found in the high temperature applications. Normally, when the preheated air or OEC is used, this mechanism describes the formation of the most of NO_x. According to the references [1], [15] the OEC can have a positive impact on NO_x levels in the flue gas.

The Zeldovich's mechanism can be extended for the second equation which involves the influence of the hydroxyl radials in the mixtures rich for the fuel:

$$N + OH \leftrightarrow H + NO \tag{10}$$

Equation (10) can be also called as the extended Zeldovich's mechanism. Many techniques supressing the formation of thermal NO_x exists, the purpose of all them is to limit local oxygen and nitrogen concentrations in the vicinity of the peak flame temperatures, to reduce the residence time at the peak flame temperatures, and/or to reduce the peak flame temperatures [7].

2.5.2 Prompt NO_x

Prompt NO_x is formed by the fast reaction of nitrogen from the combustion air with oxygen and radicals from the fuel [16]. All this is possible due to cyano intermediates (HCN) that are present in the combustion chamber after the reaction of N_2 with smaller cells of carbohydrates. First who observed and formed the idea of prompt NO_x, was Feminore [17], when he was dealing with the combustion of gaseous pyridine and ammonia. Feminore observed that in the areas with fuel excess, NO_x levels were raising. He was unable to explain this fact by any other yet known knowledge. Equation that describes the formation of the prompt NO_x follows [1]:

$$CH_x + N_2 \rightarrow HCN + CN \dots \tag{11}$$

2.5.3 Fuel NO_x

Fuel NO_x can be formed out of nitrogen that is chemically bounded to the fuel cell. This mechanism is dominant in the combustion of solid fuels containing high concentration of nitrogen, e.g. coal, waste [7]. Formation of the fuel NO_x is not direct, but it has to go through few reactions to create NO_x. Intermediates that are responsible for the reaction are hydrogen cyanide (HCN) and ammonia (NH_3). However, when the propane or the natural gas is burned, the formation of the fuel NO_x depends on the composition of the fuel [1]. According to the fuel composition shown in Table 2 it can be assumed that this mechanism would take part in the NO_x formation during the tests, however, in very low rate due to very low nitrogen concentration in the fuel.

$$C_nH_yN \rightarrow HCN + CN + \cdots \tag{12}$$

Equation (12) describes the formation of intermediate radicals that are subsequently oxidized with the oxygen and form NO:

$$HCN + CN + \cdots + O_2 \rightarrow NO, NO_2 \dots \tag{13}$$

2.5.4 Conversion between ppm and mg/m_N^3

The concentration of NO and NO_2 can be expressed either in ppm (which is measured) or in mg/m_N^3 which is calculated from the measured values. The equation for the conversion between ppm and mg/m_N^3 follows [18]:

$$Y = X \cdot \frac{\sum x_i \cdot MW_i}{22.414} \tag{14}$$

where	Y	is the concerted concentration of NO or NO_2 [mg/m_N^3],
	X	is the measured concentration of NO or NO_2 [ppm],
	x_i	is the mass fraction of the *i*-th component [kg/kg],
	MW_i	is the molecular weight of the *i-th* component [kg/kmol].

For example the conversion of 1 ppm of NO and 1 ppm of NO_2 to [mg/m_N^3] can be written like this, respectively:

$$1\ \text{ppm NO} = \frac{14.01+16}{22.414} = 1.34\ \text{mg/m}_N^3 \tag{15}$$

$$1\ \text{ppm NO}_2 = \frac{14.01+2*16}{22.414} = 2.05\ \text{mg/m}_N^3 \tag{16}$$

NO_x represents the sum of NO and NO_2 in mg/m_N^3, when NO has to be converted to the equivalent value of NO_2 based on the following formula [18]:

$$[NO_2]\frac{mg}{m^3} = [NO]\ \frac{mg}{m^3} \cdot \frac{m_{NO_2}}{m_{NO}} = \ [NO]\ \frac{mg}{m^3} \cdot\ 1.533 \tag{17}$$

3 Oxygen enhanced combustion

3.1 Oxygen

At the standard conditions (T = 273.15 K, p = 101.325 kPa) oxygen is a colourless, odourless and tasteless gas. The most common form of the oxygen is diatomic form – O_2. Oxygen itself is highly reactive non-metallic element and strong oxidizing agent with high electronegativity. Relative molecular weight is 32.00. Comparing the mass, the oxygen is one of the most plentiful elements in the universe and also in the Earth's crust. Oxygen stays in the liquid state (at the atmospheric pressure) below minus 183 °C [20] and is usually denoted as LOX; oxygen in the gaseous state is known as GOX. LOX has light blue colour, it is transparent and remains odourless with weight slightly higher than water. The human population needs oxygen for its life, however, the oxygen of high purity can bring health issues like the chest pain or it can cause coughing. The name oxygen means "acid-former" because of its ability to combine with other elements to form acids. In the chemical industry, oxygen is used in both heating applications and in chemical synthesis [1].

In some branches of the industry the pure oxygen is added into the combustion air. This is commonly used in high temperature applications like: metal heating, melting and glass melting. The applications in which it is efficient to use the OEC technology are usually characterized by following properties [19]:

- high flue gas temperatures, exceeding 1400 K,
- low thermal efficiencies, due to heat transfer limits,
- limited throughput, where additional heat could be an advantage,
- polluted flue gases, with high NO or flue gas volume limits.

3.2 Methods of OEC

Generally, the oxygen can be injected in the combustion air and/or flame in four ways: (1) adding O_2 into the incoming airstream, (2) injecting O_2 into an air/fuel flame, (3) replacing the combustion air with high-purity O_2 and (4) separately provided combustion air and O_2 to the burner.

3.2.1 Premixed air

Pure oxygen is injected in the incoming combustion air, when the equal distribution is achieved with a diffuser. Sometimes this method is referred as low-level O_2 enrichment or premix enrichment. This method of enrichment can be adjusted to the most of the conventional air/fuel burners. Hence, the conventional burners can easily become the OEC burners and have the benefits of the combustion with higher O_2 concentrations. The effect of additional O_2 can be observed on the flame pattern which becomes shorter and more intensive. This is not suitable for all combustion chambers, because the short flame can cause the damage of the facility [1]. Not only the added oxygen, but also a lower flow velocity of the combustion air will affect the temperatures in the combustion chamber. Higher temperatures may damage the burner or the burner block. The scheme of the burner with the premixed air is shown in Figure 3.1 [10].

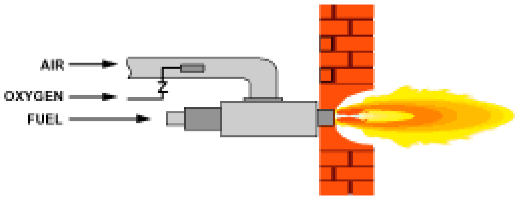


***Figure 3.1** – The burner with premixed air.*

3.2.2 O_2 lancing

O_2 lancing represents another possibility of adding O_2 into the combustion system. The advantage of this method is that there is no need to modify the existing burner for the application of this treatment. Oxygen is injected directly into the flame zone (see Figure 3.2 [10]) which results in lower NO_x emissions (compared with the premixed air method) [1]. Depending on the location of O_2 injection, the flame length can be changed (the flame can become longer or shorter) by staging the combustion reaction. O_2 lancing has better distribution of the heat than the premixed air which results in less overheating of the burner and the burner block. There is also a possibility to inject the oxygen not directly into the flame zone, but somewhere into the combustion chamber. In order to use this solution it is necessary to make another hole in the shell of the combustion chamber for the lance which results in additional installation costs and also lower productivity. However, the hole is usually very small. Although O_2 mixing with the combustion air is not as good as at the premixed air method, this disadvantage can be outweighed by better and much more efficient placement of the heat.

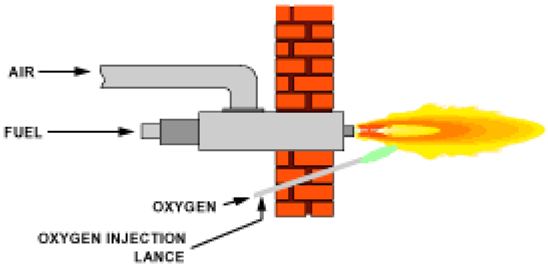


***Figure 3.2** – The burner with O_2 lancing.*

3.2.3 Oxy/fuel

In the oxy/fuel method the oxygen and the fuel remains separated inside the burner and do not mix until reaching the outlet of the burner. This method is commonly called as the nozzle-mix burner, where a diffusion flame is produced. For safety reasons the gases are not premixed, due to high reactivity of the pure O_2. For this application the purity of the oxygen is required to be higher than 90 %. This method has a big potential for being improved. For example Baukal stated [1]: "Oxy/fuel combustion has the greatest potential for improving a process, but it also may have the highest operating cost." Special type of the oxy/fuel combustion is the dilute oxygen combustion, where the oxygen and the fuel are injected individually into the combustion chamber. The temperature in the chamber must be kept above the auto-ignition temperature of the fuel. Sometimes the geometry of the burner allows the flame to be invisible. This method is sometimes referred as flameless oxidation [21]. This treatment leads to very low NO_x. Disadvantage of this process might be lower heat transfer due to reduced temperature and emissivity. The scheme of the oxy/fuel burner is shown in Figure 3.3 [10].

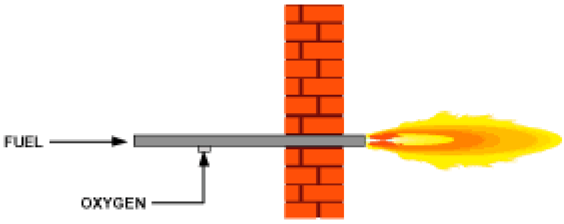


***Figure 3.3** – The burner with oxy/fuel.*

3.2.4 Air-oxy/fuel

In the last method the air and the oxygen are injected separately through the burner (as shown in Figure 3.4). It is referred as an air-oxy/fuel burner. Some of the conventional air/fuel burners are possible to retrofit to the air-oxy/fuel ones just by inserting an oxy/fuel burner through it. The retrofit of the current burner does not work every the time, therefore the special burner has to be designed and manufactured. The advantages of this method can be summarized as:

- higher levels of O_2 enrichment compared with the air enrichment or O_2 lancing,
- lower operating cost than the oxy/fuel burners (air-oxy/fuel burner uses less O_2),
- the shape of the flame and the amount of released heat can be changed by controlling the amount of O_2 in the combustion chamber.

The control of the input air/oxygen rate differs from the other methods, according to Baukal [1]: "Instead of giving the overall O_2 concentration in the oxidizer, the oxidizer may be given as the fraction of the total oxidizer that is air and the fraction of the total oxidizer that is pure O_2." The oxidizer composition is calculated as follows [1]:

$$\Omega = \frac{20.9}{0.209\ vol\%O_2 + vol\%\ air} \qquad (18)$$

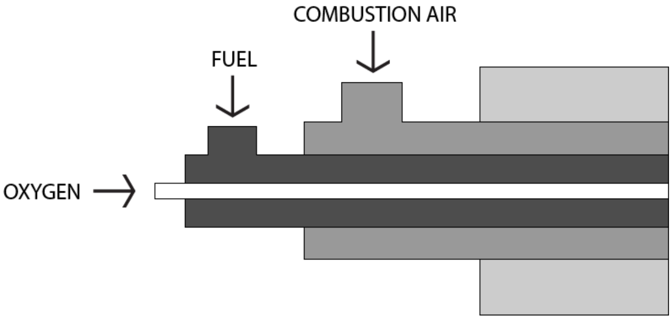


Figure 3.4 *– The burner for air-oxy/fuel method.*

3.3 Comparison of OEC with conventional technologies

Advantages:

- Lower emissions – enhanced oxygen combustion can have a positive impact on NO_x levels in the flue gas [1], [15].
- Higher efficiency – less heat is wasted on heating up of N_2 [1].
- Improved flame stability – higher O_2 concentration increases flame speeds. Thus much higher exit velocities can be used without blowing off the flame [19].
- Increased productivity – throughput can be increased due to higher flame temperature or heat transfer rate to the load [19].

Disadvantages:

- Refractory damage – higher flame temperatures, compared with air/fuel burners, can lead to overheating of some parts of the chamber and/or burner. Another potential threat is the corrosion due to higher concentrations of volatile species [1].
- Nonuniform heating – OEC can increase radiant output on single spots, which can lead to overheating and damage of the product. Also the reduced gas flow rate can result in lower heat convective transfer [1].
- Flame disturbance – the flames are usually low-momentum, which means it could be more easily disturbed than high-momentum flames [1].
- Increased pollutant emissions – however, OEC is called as the low-NO_x method, NO_x concentration can be increased rapidly when some of the OEC methods is used, especially the premixed air method [1].
- Flashback – the velocity of the gas or the combustion air can get lower than the flame speed. This causes that the flame can start to burn inside the burner or even can move into the combustion air pipeline. It happens most often when the fuel and air are premixed [1].

4 OEC in industry

In some branches of the industry the OEC is still rather a new technology, but in some of them the usage of the OEC technology is the everyday routine. Here are discussed some of them.

4.1 Glass industry

The OEC is widely used in the glass production facilities. The main reasons are the regulation of the emission limits, high demand on the yield of glass, the fuel saving and the operational flexibility. The usage of the OEC lowers the amount of nitrogen entering the combustion chamber, therefore the fuel efficiency rises accompanied with the faster speed of glass production. Moreover the implementation of the OEC technology can be cheaper than investments into the completely new facilities. According to the Air Products [10], savings can be up to 4 million dollars when large furnaces are used. Furthermore the quality of the final product can be much better when the OEC is used compared with the conventional technologies [1].

For example the technology developed by AGC Glass Europe [9] in cooperation with Air Liquid is able to save 15 % of energy in the flat glass production. Further savings can be achieved when the OEC is combined with the energy recuperation from hot flue gas. AGC Glass Europe also states that for this application the emissions to the atmosphere are lower, namely CO_2 by 12 %, sulphur oxides by 35 % and nitrogen oxides up to 80 % [9].

4.2 Metal production

Another industry area where the OEC is commonly used is the metal industry. It can be applied in both ferrous and non-ferrous metals production. The application of the OEC has the positive impact on process efficiency, fuel savings, and quality of the final product and also in some applications on emissions [6].

Oxy/fuel burners give the most significant benefits during the cold scrap heating and meltdown. The efficiency of the conventional burner decreases during the process from the range (60 to 80 %) to less than 20 %. OEC can solve the problems with the use of burners with low efficiency, which can be the yield loss or the furnace damage.

4.3 Petroleum and gas production

The companies think how to lower the operating costs of the production units and to lower the emissions, especially NO_x emissions. In order to achieve these goals, they have come up with the utilization of oxygen enhanced combustion. The OEC is applied to process heaters like the steam reformers or the petroleum liquid heaters. According to Praxair [22]: “Integration of OEC with the air/fuel heating process can favourably impact the heat release patterns to yield more uniform temperature distribution, longer run lengths, and more vendible product.“ If there are limitations in the flue gas flow rate or in the burner/fuel capacity, the OEC can be applied for this problem solving.

4.4 Power generation

Coal fired steam boilers are used for generating power. The problem in such a technology is that fossil fuels also contain the elements, which are responsible for higher emissions, eg. sulphur, nitrogen, etc.

According to Marin Ovidou et al. [23] the pure oxygen injected into the combustion air (in the steam boilers) can give numerous advantages, e.g. reduced NO emissions, increased combustion efficiency, increased production rate or increased process flexibility. Depending on the air enrichment the reduction of NO in the flue gas can reach up to 21 % [23].

The usage of clean oxygen also brings several issues [15], e.g. combustion temperature has to be lowered to prevent the utility, the boiler can lack an air in the preheater and the boiler has to be perfectly sealed to avoid suction of the false air. Therefore the conventional boiler design needs to be updated for the oxy/fuel combustion.

4.5 Welding and cutting

Oxy/fuel welding also known as oxyacetylene welding uses the oxygen enrichment for welding materials. Comparing with the common propane/air flame (flame temperature 2 000 °C) and with propane/oxygen flame (flame temperature 2 500 °C), the oxyacetylene flame is characterized by the highest flame temperature reaching 3 500 °C and therefore it is commonly used for welding pipes and tubes. Oxy/fuel welding also brings other benefits over the electric arc welding such as slower weld cooling as a result of less concentrated flame. This can have effect on weld distortion and it can lead to lower residual stresses for the oxy/fuel welding. Similar approach is used for cutting metals [24].

5 Industrial production of oxygen

Oxygen is a very strong oxidizing agent; hence every manipulation with the oxygen has to be according to the safety precautions. It is important to prevent the contact of oxygen with all organic substances, such as oils and greases. Every piece of the equipment which will come to the close contact with the oxygen has to be properly degreased. Even the maintenance of oxygen units has to be accomplished in clean and degreased clothes; otherwise the clothes and even the hair can easily initiate the fire and cause serious burns. When LOX goes through the evaporation stage all parts of the equipment are covered with ice/snow, therefore all the manipulation with the valves or the hoses must be done with gloves to prevent burns [25].

It is recommended to use the materials that are suitable for oxygen and high pressures. Not all types of the common gaskets are suitable for oxygen. The same problem is with the metal components, when not all of the alloys or metals are suitable for the contact with oxygen. Suitable materials should be also used for the other equipment like hoses, pressure regulators or flowmeters.

Two main methods are usually used for the production of oxygen utilized in the industrial application, namely the distillation and the adsorption. The main difference between them is the volume and the quality of the final product. As shown in Figure 5.1 [1] the adsorption has the limitation for the amount of 10 – 100 tonnes of oxygen per day and using this technology it is possible to get the oxygen with ca. 94 % purity. On the other hand, the distillation uses the cryogenic process and it is able to produce up to 1000 tonnes of oxygen per day with purity up to 99.5 %, however, the costs are higher than for the adsorption.

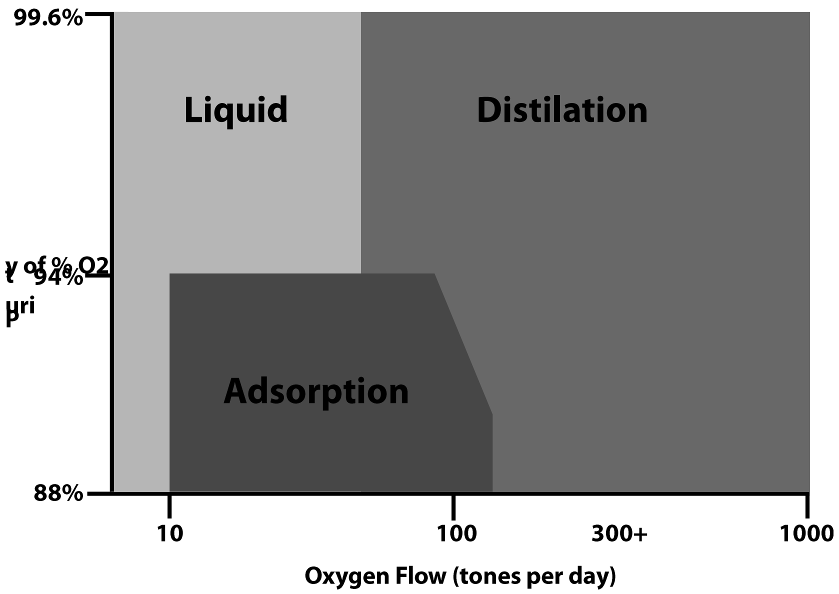


Figure 5.1 – Methods of oxygen production vs. Purity vs. Amount.

5.1 Cryogenic oxygen production

The output of cryogenic oxygen production is 99.5 % pure oxygen, which can be easily stored or mixed with other gases. The output product from cryogenic oxygen production is usually the liquid oxygen (LOX). The cryogenic unit has three main parts – Warm End (W/E) process, Coldbox and Storage facility [17]. The scheme describing the cryogenic oxygen production is shown in Figure 5.2 [26].

5.1.1 Warm end process

The atmospheric air has to be cleaned from the dust and other particles before entering the process. The amount of sucked air depends on the amount of the pure oxygen that is required as a product. Next step is vital for the process. It is important to remove all the condensate and water particles, because water residues could plug the whole cryogenic unit. Then the air passes through the molecular sieves that are designed to remove gaseous hydrocarbons. Those molecular sieves must go through the regeneration after certain time. For this reason high number of sieves has to be installed, when a part of them are in the operation and a part of them are regenerated at the same time. Subsequently the air is cooled down and enters the coldbox.

5.1.2 Coldbox

In the coldbox the air stream is cooled down to the temperature minus 112 °C and the gas is partially liquefied. Sometimes this unit is called as the Air Separation Unit (ASU). To achieve such low temperatures the process uses Joule–Thomson effect. The cooled LOX is taken to the boiler, where it is evaporated and the liquefaction is completed. The whole unit uses the network of heat exchangers where the excess heat is used to cool down/heat up other streams. Last unit in the ASU is the turbine that is responsible for the refrigeration process. High pressure gas is cooled down and expanded to low pressure. The cold air flows back to the heat exchanger to initiate the refrigeration.

5.1.3 Storage facility

The storage facility is composed of liquid oxygen tank, vaporiser and filling station. Final LOX product is compressed using of the cryogenic liquid pump to the high pressure (up to 20 MPa).

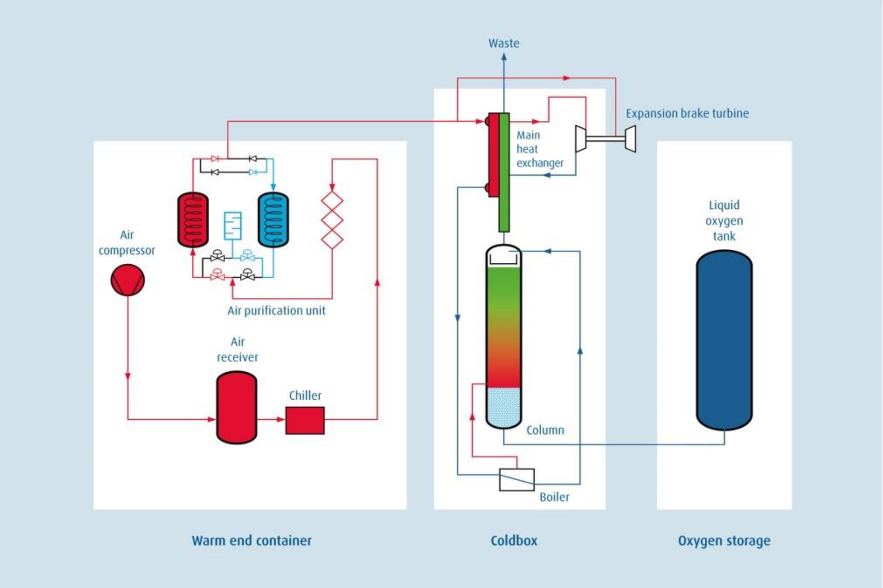


***Figure 5.2** – The scheme of the cryogenic unit for the oxygen production.*

5.2 Adsorption

In the adsorption systems the solid substances called as sorbents are used for the oxygen separation from the air. The integration between gas and adsorbent molecules is provided by the physical forces. Many materials have these characteristics, but the most common used material is the silica gel, because it has a significant capacity for holding the water. These desiccants adsorb large amount of the molecules into the pores on their surface. Area of the surface can reach up to 500 m^2/g [27]. The whole process can be speeded up/slowed down by the pressure and the temperature. Produced oxygen can be either stored in the cryogenic tanks or it can goes directly to the location where it is required.

Generally there are three main principles of adsorption that are highly developed and commonly used in the industry:

1) Pressure swing adsorption (PSA).
2) Vacuum swing adsorption (VSA).
3) Vacuum pressure swing adsorption (VPSA).

5.2.1 Pressure swing adsorption

PSA technology uses two separate units and therefore it is called swing. The high pressure of the gas is important for the accumulation of the molecules. The higher pressure is used the more molecules of gas are accumulated. When the concentration of the molecules does not rise anymore, the feed stream is switched to the second unit, meanwhile the pressure in the first unit is decreased and the unit goes through the regeneration. It means that the accumulated gas is released and stored in the storage tank. PSA method is often chosen because of the reasonable ratio purity/costs. Typical materials used in PSA are activated carbon, silica gel, alumina or zeolite. Various sizes of surfaces of different adsorbents provide the ability to capture different molecules. The scheme of PSA is shown in Figure 5.3 [29].

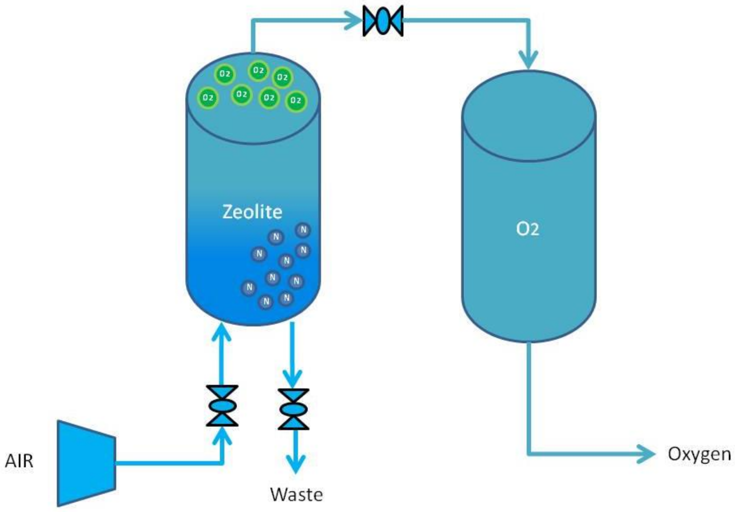


Figure 5.3 *– The scheme of the pressure swing adsorption.*

5.2.2 Vacuum swing adsorption

The main principle of the VSA is same as for the PSA. Two separate units work alternately; one captures gas molecules while the second one is regenerating. The main difference between PSA and VSA is that the VSA draws the gas through the separation process in vacuum. The VSA also operates near the ambient temperature and pressure. In the applications where nitrogen and/or oxygen are segregated thre vacuum is generated by a blower. Comparing with the PSA the VSA has higher efficiency, because it works on the steepest part of the isotherm curves and thus has the potential to extract more oxygen molecules. The absence of the air compressor (it works at the ambient pressure) results in lower operational costs. Moreover the unit requires lower demand on the maintenance due to the lower pressure magnitudes. This also helps to eliminate the condensation of water in the sieves and therefore the VSA can be used in the wet environments when no special treatment like water removal from the feed air is necessary.

5.2.3 Vacuum pressure swing adsorption

The VPSA combines the positive effects of PSA and VSA. The system can work either with one or two beds. In the single bed system the air is compressed by the blower and then it flows to the adsorbent vessel. When the system comes to the regeneration, the production of oxygen is stopped, the pressure is lowered and the oxygen is transported to the storage tank and the waste gas is blown away into the atmosphere. On the other hand, when two beds are used for the VPSA, the beds are cycled sequentially from the adsorption to the desorption. The pressure in the units varies from the overpressure to the vacuum. The scheme of VPSA is shown in Figure 5.4 [29].

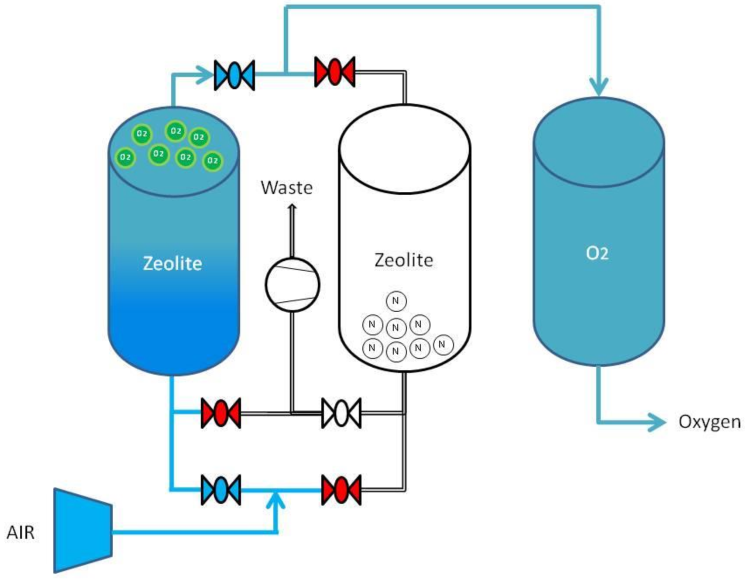


Figure 5.4 *– The scheme of the vacuum pressure swing adsorption.*

6 Experimental investigation of OEC

6.1 Goals

During the tests the influence of 21–46 % oxygen concentration on the NO_x emissions, the flue gas temperature, the distribution of heat extracted from hot flue gas to the wall of the combustion chamber, and the flame pattern including stability, shape and dimensions was studied. The combustion tests of PM and AO were carried out at the thermal inputs of 300 kW, 500 kW and 750 kW for two combustion modes – one staged combustion and two staged combustion.

6.2 Testing facility

The combustion tests were carried out at the burners testing facility. The schematic layout of the facility is shown in Figure 6.1.

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. It is possible to test burners with the total heat output of 1800 kW [30]. The forepart and the rear of the chamber are insulated with the high temperature fibrous lining with the thickness of 100 mm, the inner shell is cooled with water. Circulating cooling water is pumped from the water reservoir through the combustion chamber into the cooling tower, where it is cooled down and flows back into the water reservoir. The cooling shell of the chamber is divided into the seven individual sections with independent supply of the cooling water. The length of the first six sections in the cooling shell is 0.5 m, the last section has a length 0.9 m. The interior of the cooling shell has a specific design and water is forced to flow several times around the chamber. The forced water flow is achieved by the helix that is inserted in the cooling shell. If the spiral part would have been missing, some of the places have been exposed to the enormous heat that could lead to the failure of the unit. The spiral is welded only to the inner part of the cooling shell due to the manufacturing constrains. The result is 5 mm thick gap that causes the generation of the so called short-circuit streams. The scheme of one section is shown in Figure 6.2.

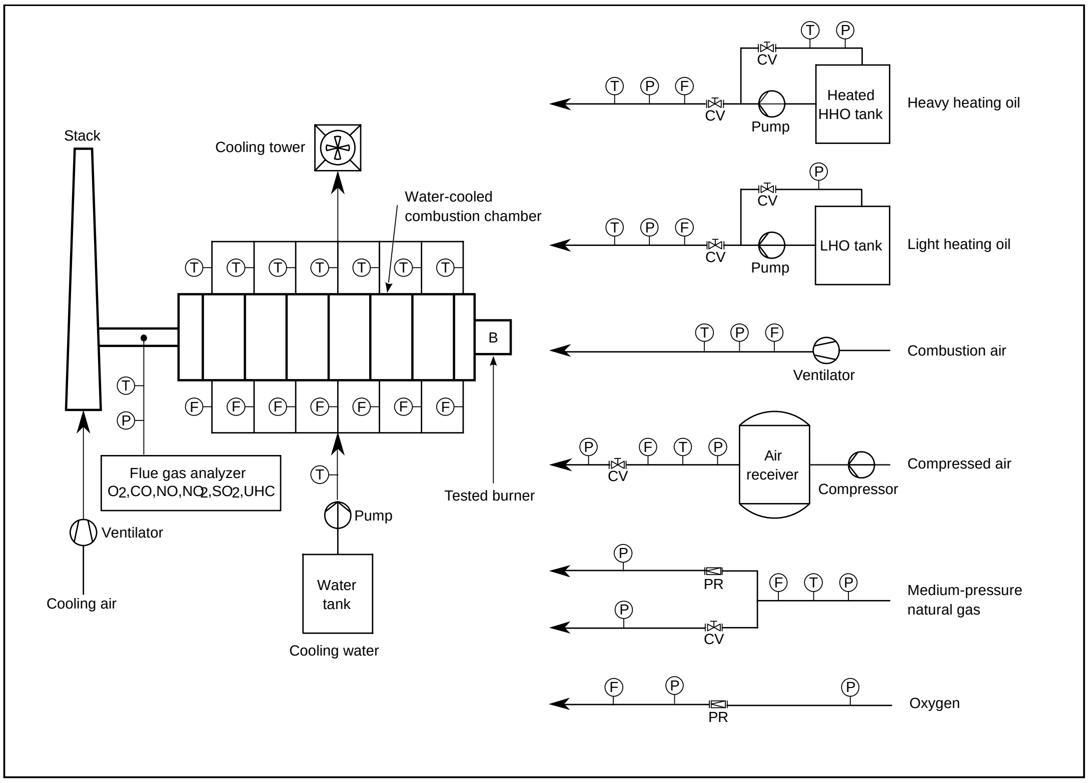


Figure 6.1 *– The schematic layout of the burner testing facility.*

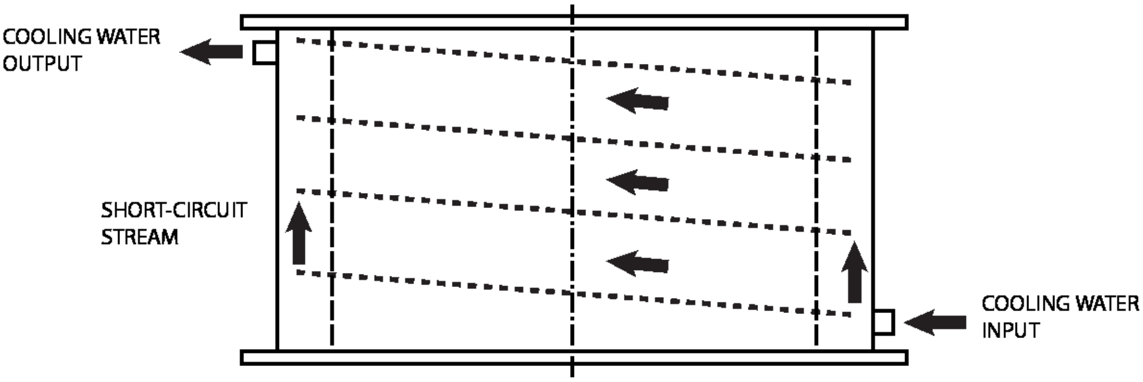


Figure 6.2 *– The scheme of cooling water flow inside the shell.*

Each section is equipped with sensors for measurement of the 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. Also one of the benefits of splitting the chamber into the section is a prevention of hidden ebullience. Every section has one inspection window on each side of the chamber (totally 16 windows), through which the flame can be observed and/or the additional measuring equipment (e.g. radiation probe, thermocouples, etc.) can be inserted. Other two inspection windows are located on the rear side of the chamber.

The combustion chamber can be operated either in negative or positive pressure. The negative pressure in the chamber is generated with the ejector located at the bottom of the stack. The atmospheric air is used as a propellant to the flue gas and it is supplied by the high-pressure fan equipped with the frequency convertor. It is possible to reach the under pressure up to minus 600 Pa. The injected air also helps to cool down the flue gas coming out of the combustion chamber. The overpressure is generated by means of the throttle that is located in the flue gas duct.

The combustion air is supplied by the pipeline of the square cross-section. The air fan can provide the maximum flow rate of 5500 m_N^3/h at the maximum over pressure 5 kPa. The pipeline is equipped with the sensors for the measurement of the temperature, the pressure and the flow rate of the combustion air.

Natural gas is supplied by the pipeline with the overpressure of ca. 100 kPa and the capacity of 250 m_N^3/h. The regulation valve provides full control of the intake of natural gas. The testing facility can also handle tests with liquid fuels e.g. light and heavy heating oil.

The testing facility is equipped with the sophisticated system for data collection and safety system. The system enables to collect data automatically every second and/or every 2 minutes. Or the data can be recorded manually by the operator. The system collects the data from all sensors including the flow rates and temperatures of the fuel, the combustion air and the cooling water, the pressures in the pipeline system and the composition of the flue gas at the exit of the combustion chamber. All the measured values can be displayed at the system panel.

The safety system ensures save and reliable operation of the facility. It helps to prevent the water overheating and in case of the emergency the system can stop the operation of the facility.

***Figure 6.3** – Testing facility.*

Flue gas is exhausted from the combustion chamber through the flue gas duct where three measurement and sampling spots are located for measuring of the pressure in the combustion chamber, flue gas temperature and flue gas composition (O_2, CO, NO, NO_2), which is measured by the Testo 350-XL analyser. The concentrations of species are expressed on a dry volume basis. The table including detailed information about the analyser (measuring ranges and sensor accuracies) is in Appendix – A I.

6.3 Burner

The burner used in the experimental study was the two-staged burner fired by natural gas. The 3D model of the burner is shown in Figure 6.4. The inner diameter of the burner quarl is 300 mm and the outer diameter is 600 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 flow rate 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 construction allows to change the position of the 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). Technical drawings of the orifice, the flame holder, the burner head and the secondary nozzles are in the Appendix – A II–A V.

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-draft ignition burner with the thermal input of 18 kW.

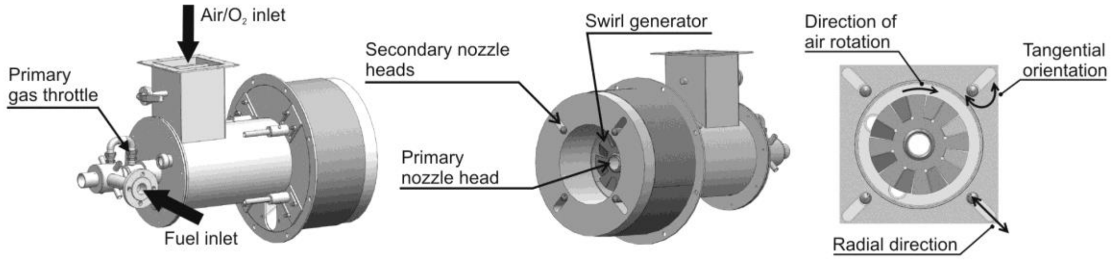


Figure 6.4 *– The model of the two staged burner.*

6.4 Oxygen

Oxygen was stored in the cryogenic vessel at the pressure of 20 MPa. During the experiment the vessel was located outside the testing facility to ensure proper diffusion of the oxygen in case of leakage or other problems. Before oxygen entered the combustion chamber it went through the evaporator (Figure 6.5a), where the state was changed from liquid to gaseous then it flew into the measuring panel (Figure 6.5b). During the tests two different measuring panels were used. The first panel was equipped with two flowmeters with the measuring ranges 1–10 m_N^3/h and 5–50 m_N^3/h. The second panel was equipped with one flowmeter with ranges between 40–400 m_N^3/h.

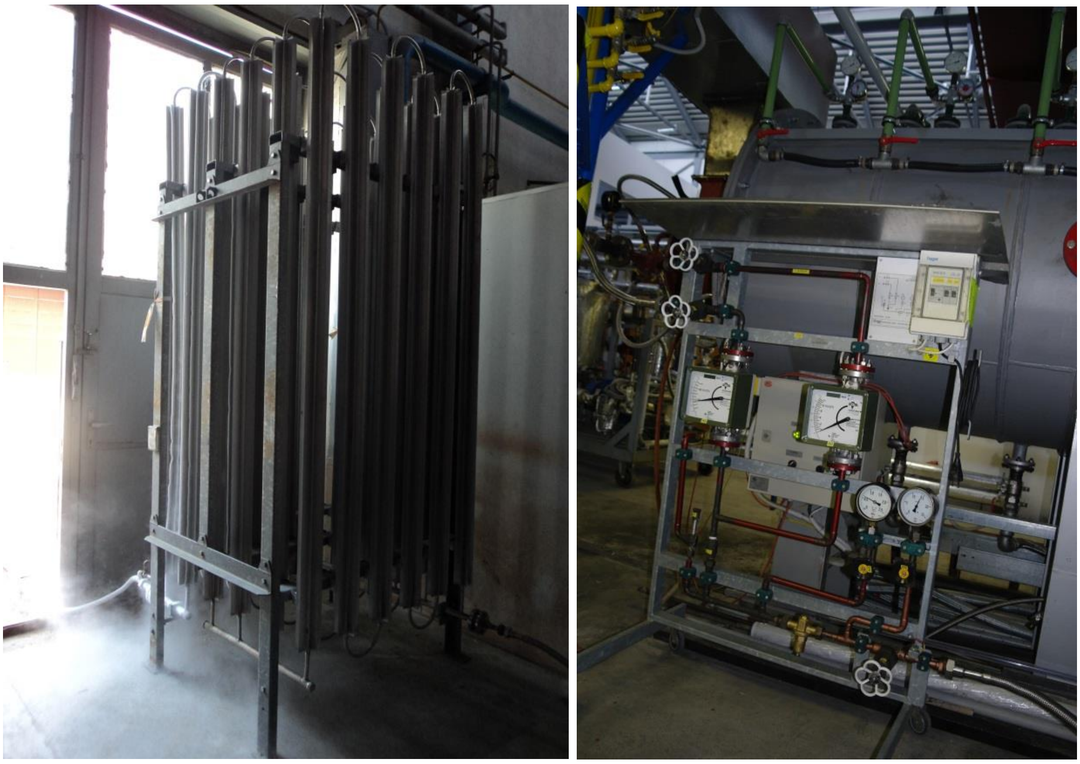


***Figure 6.5** – (a) The evaporator and (b) the measuring panel.*

6.5 Plan of tests

The experimental matrix is presented in Table 6.1 and in Table 6.2 is shown the overview of the contribution of pure O_2 to the overall oxygen level. Two tests were of interest here. In the first of the tests (denoted as TEST A), the quality and the flame characteristics were explored. The data was recorded automatically and manually in the datasheet (recorded data are enclosed on the DVD). The template of the datasheet is shown in Appendix – A VI. 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. Unlike the TEST A this test was carried out for selected oxygen flow rates (0, 40, 80, and 120 m_N^3/h) and selected thermal input (750 kW). The data was recorded only automatically.

The tests were carried out for two combustion modes, namely for one staged and two staged combustion. When one staged combustion mode was used the tests were carried out at the thermal inputs of 300 kW, 500 kW and 750 kW. In order to compare the combustion characteristics the tests were also carried out with two staged combustion, however, only at one thermal input – 750 kW. The target oxygen concentration in the dry flue gas was 3 % for all tests.

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

Table 6.1 *– Experimental matrix (● indicates that the test was carried out for the relevant oxygen flow rate).*

	Flow rate of high-purity O_2 [m_N^3/h]/ **Contribution of high purity O_2 to overall oxygen level** [%]									
	5	10	20	30	35	40	60	80	100	120
Thermal input										
300 kW	6.97	14.05	29.3	43.9	52.1	-	-	-	-	-
500 kW	4.2	8.45	17.1	25.95	-	35.2	-	-	-	-
750 kW	2.8	5.6	11.3	17.1	-	22.8	35	47.3	60.3	72.7

Table 6.2 *– The overview of the contribution of pure O_2 to overall oxygen level.*

The investigation was aimed at studying the influence of 21–46 % oxygen concentration on the NO_x emissions, the flue gas temperature, the heat flux distribution to the wall of combustion chamber lengthwise the flame, the flame pattern, flame stability and flame length and diameter. As for the PM tests, the O_2 concentration between 21–46 % matches directly the O_2 concentration in the incoming combustion air. On the other hand in the AO tests the oxygen concentration in the incoming air was always 21 %. Therefore here the term 21–46 % oxygen concentration expresses the concentration of oxygen in the air as if all the oxygen (O_2 in the air + O_2 injected directly into the flame) was supplied via the incoming combustion air.

6.5.1 Premixed air tests (PM)

For the PM tests the high purity oxygen was injected into the incoming combustion airstream through a diffuser to ensure adequate mixing. The diffuser was inserted into 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 the diffuser with the inlet pipe and the valve is shown in Figure 6.6a. The detail of the diffuser tip is shown in Figure 6.6b. The technical drawing of the diffuser is attached in the Appendix – A VII.

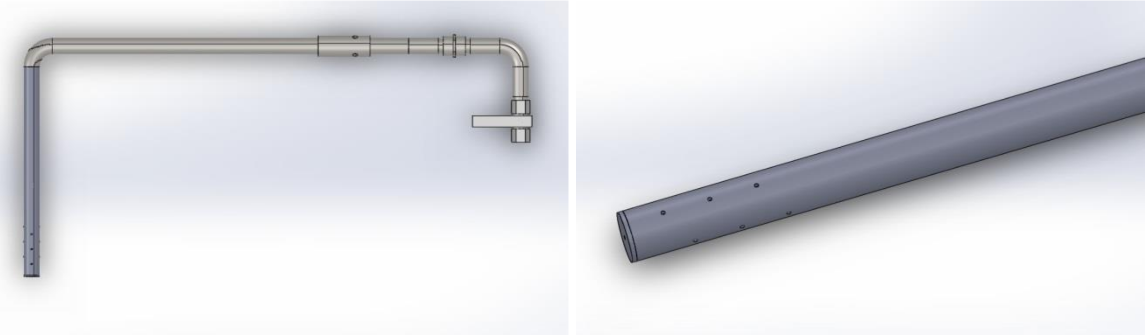


***Figure 6.6** – (a) The 3D model of the diffuser, and (b) the detail of the tip of the diffuser.*

6.5.2 Air-oxy/fuel tests (AO)

For this method the high-purity oxygen was injected directly into the flame through a nozzle head that was inserted through the centre of the burner pipe. The remaining amount of oxygen needed for complete combustion was introduced to the burner via the air. There are totally seven nozzles with the diameter of 2.7 mm drilled in the head when six of the nozzles are arranged symmetrically in a ring pattern around the tip of the head and one of the nozzles is located at the tip of the head. The nozzle head was designed for the maximal flow rate of oxygen 120 m_N^3/h. The 3D model of the oxygen lance is shown in Figure 6.7a, and the detail of the tip of the head is then illustrated in Figure 6.7b. Technical drawing of the nozzle head is attached in the Appendix – A VIII.

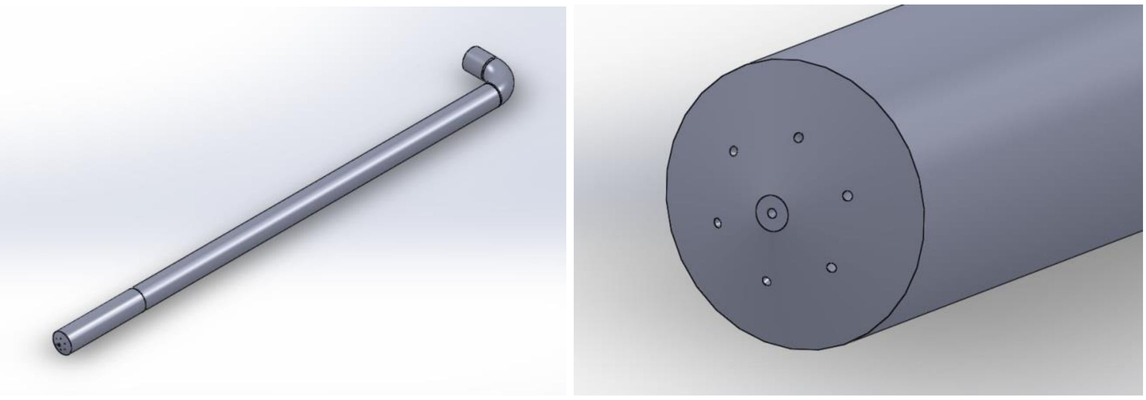


***Figure 6.7** – (a) The 3D model of the oxygen lance, and (b) the detail of the nozzle head.*

7 Results – Test A

The measured and observed results (NO_x concentration, flue gas concentration and flame pattern) are described in the following subchapters. Detailed charts with the results of both PM and AO tests are also included.

7.1 NO_x concentration

7.1.1 Premixed air

Table 7.1 summarizes the results obtained during the PM tests, including the total O_2 flow, total O_2 concentration, the values of NO, NO_x and flame characteristics.

Thermal input		Total O_2 concentration [%]	Flow of O_2 [m_N^3/h]	NO [ppm]	NO_X [mg/m_N^3]	Length of the flame [m]	Flame diameter [m]	Flue gas temperature [°C]
300 kW	one staged	20.75	0	75	161	1.25	0.4	513
300 kW	one staged	21.58	3.5	110	232	1.2	0.4	529
300 kW	one staged	23.35	10	200	423	1.25	0.4	534
300 kW	one staged	26.91	20	864	1856	1.75	0.4	519
300 kW	one staged	31.88	30	2240	4693	2.2	0.4	502
300 kW	one staged	35.36	35	3298	6841	2.2	0.4	494
500 kW	one staged	20.75	0	75	163	1.8	0.5	663
500 kW	one staged	21.30	4	95	204	1.8	0.5	667
500 kW	one staged	21.92	8	122	258	1.75	0.45	674
500 kW	one staged	22.55	12	164	357	1.7	0.45	663
500 kW	one staged	23.36	16.5	227	482	1.9	0.45	662
500 kW	one staged	23.97	20	309	670	1.9	0.6	660
500 kW	one staged	25.00	25	481	1031	1.9	0.6	656
500 kW	one staged	26.13	30	702	1501	2	0.5	653
500 kW	one staged	27.39	35	1054	2237	2	0.5	655
500 kW	one staged	28.35	39	1280	2668	2	0.5	650
750 kW	one staged	20.75	0	82	172	2.25	0.6	743
750 kW	one staged	21.71	10	114	243	2.4	0.6	766
750 kW	one staged	22.80	20	178	381	2.5	0.6	761
750 kW	one staged	23.99	30	281	605	2.75	0.6	758
750 kW	one staged	25.36	40	524	1107	2.75	0.6	750
750 kW	one staged	25.38	40	622	1315	2.8	0.6	745
750 kW	one staged	28.70	60	1695	4036	3.1	0.6	743
750 kW	one staged	33.2	80	3436	7123	3.1	0.6	748
750 kW	two staged	20.75	0	37	85	2.3	1	699
750 kW	two staged	21.22	5	41	94	2.5	1	707
750 kW	two staged	21.71	10	47	107	2.5	1	708
750 kW	two staged	22.79	20	65	143	2.25	1	709
750 kW	two staged	24.00	30	98	191	2.25	1	708
750 kW	two staged	25.35	40	148	317	2.5	1	705
750 kW	two staged	28.73	60	380	796	2.75	1	689
750 kW	two staged	33.19	80	828	1716	3	1	681
750 kW	two staged	39.72	100	1454	2934	3	1	665
750 kW	two staged	48.93	119	2334	4924	2.7	1	673

***Table 7.1** – The summary of results of Test A – Premixed air.*

Figure 7.1 shows the measured concentration of NO_x in the flue gas [mg/m_N^3] as a function of the oxygen concentration. The major contribution to the overall NO_x concentration had the thermal NO_x, which was directly associated with higher flame temperature peaks and higher O_2 concentration.

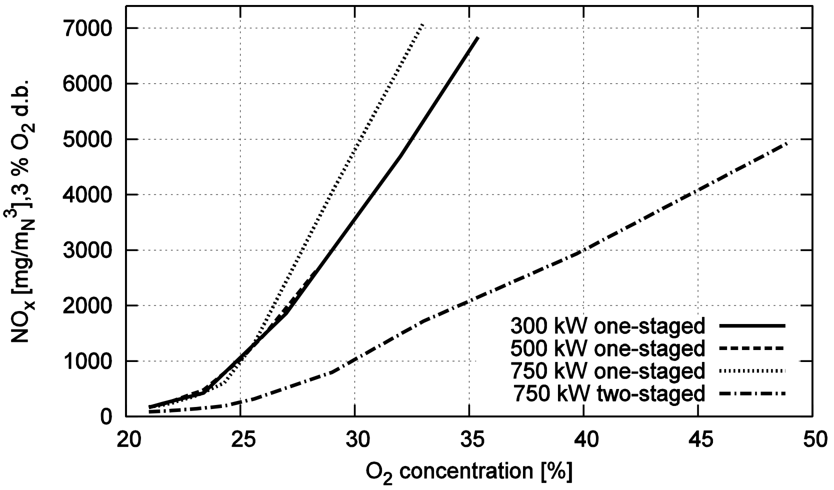


***Figure 7.1** – The effect of O_2 concentration on NO_x concentration in PM tests.*

As for the PM tests it is obvious that the NO_x levels rises exponentially with the temperature. Higher the temperature peaks are in the combustion chamber more NO_x is formed. The NO_x concentration for the thermal input 300 kW was 160 mg/m_N^3 at 21 % of O_2. When more high purity oxygen was added into the combustion air the value raised up to 7 000 mg/m_N^3 at 35.4 % of O_2 in the air. The maximum concentration of NO_x was reached at 35.4 % of O_2 in the combustion air (it equals to the flow rate of 35 m_N^3/h of pure oxygen into the combustion air). Here it was not possible to increase the oxygen concentration further more due to two limitations. The first one, the blades of the swirl generator and the burner quarl started to glow due to very high flame temperature at the burner tile and due to the lower flow rate of the combustion air that has also the role of the cooler of the burner body. The second limitation was that the measured values of NO and NO_2 were out of the measuring range of the sensors.

For the thermal input of 500 kW the NO_x value was approximately 160 mg/m_N^3 at 21 % of O_2. When the pure oxygen was mixed into the combustion air stream the amount of the NO_x in the flue gas raised up to the 2 700 mg/m_N^3, when the O_2 concentration was 28.4 %. In total, the concentration of O_2 in the combustion air reached 28.4 %, that corresponds to 40 m_N^3/h of pure oxygen supplied into the system.

The NO_x emission had the most dramatic growth at the thermal input of 750 kW when one staged combustion mode was used. During the tests the measuring range for NO_x was exceeded at O_2 concentration higher than 30 %, therefore further testing had to be stopped. The NO_x emission was approximately 170 mg/m_N^3 by the combustion of natural gas with atmospheric air (21 % of O_2). When the oxygen was added to the air, the NO_x raised up to 4 000 mg/m_N^3 at the oxygen concentration of 28.7 %.

The tests with the two staged combustion mode at the thermal input of 750 kW achieved much better results than for the three previous ones. The formation of NO_x was lower due to staged reactions between the fuel and the oxygen, which lowers temperature of flame core (compared to 750 kW one staged). NO_x level was 85 mg/m_N^3 for the test with the atmospheric air, but it rose up to 5 000 mg/m_N^3 at the O_2 concentration 48.93 %.

Almost for the whole testing session the concentrations of NO_x in the flue gas exceeded the limits that are set by the legislation (current NO_x emission limit in the Czech Republic is 200 mg/m_N^3 [31]). To meet the emission limit, the O_2 concentration would have to be lower than 24 % (for two staged 750 kW).

7.1.2 Air-oxy/fuel

Figure 7.2 illustrates the dependence between the concentrations of oxygen entering the combustion chamber and the measured concentration of NO_x in the flue gas [mg/m_N^3] for the air-oxy/fuel method. All the measured results for the AO tests are shown in Table 7.2.

Thermal input		**Total O_2 concentration** [%]	**Flow of O_2** [m_N^3/h]	**NO** [ppm]	**NO_x** [mg/m_N^3]	**Length of the flame** [m]	**Flame diameter** [m]	**Flue gas temperature** [°C]
300 kW	one staged	21.96	5	99	208	1.25	0.4	596
300 kW	one staged	23.34	10	155	324	1.25	0.35	586
300 kW	one staged	27.01	20	156	330	1.25	0.35	568
300 kW	one staged	31.80	30	100	222	2	0.3	610
500 kW	one staged	21.46	5	90	189	2	0.6	704
500 kW	one staged	22.23	10	96	200	1.9	0.6	690
500 kW	one staged	24.00	20	199	408	2	0.5	699
500 kW	one staged	26.11	30	295	566	2.2	0.5	682
500 kW	one staged	28.79	40	273	560	2.25	0.4	682
750 kW	one staged	21.22	5	80	170	2.25	0.6	747
750 kW	one staged	21.71	10	86	181	2.25	0.6	758
750 kW	one staged	22.80	20	100	210	2.25	0.6	771
750 kW	one staged	24.00	30	114	290	2.5	0.6	781
750 kW	one staged	25.38	40	210	426	2.75	0.6	777
750 kW	one staged	28.73	60	560	1130	3	0.5	749
750 kW	one staged	33.29	80	744	1509	3	0.4	736
750 kW	one staged	39.83	100	700	1435	3	0.35	707
750 kW	two staged	21.21	5	47	98	2.1	0.9	703
750 kW	two staged	21.71	10	44	92	2	0.9	704
750 kW	two staged	22.78	20	38	82	2.25	1	727
750 kW	two staged	24.00	30	40	85	2.5	1	708
750 kW	two staged	25.33	40	38	82	2.5	1	710
750 kW	two staged	28.73	60	50	105	2.4	0.9	676
750 kW	two staged	33.14	80	53	117	2.2	0.85	669
750 kW	two staged	39.64	100	40	89	2.2	0.85	651

Table 7.2 *– The summary of results of Test A – Air-oxy/fuel.*

During the tests carried out at the thermal input of 300 kW the maximum reached O_2 concentration was 31.8 %. Lower and therefore insufficient, flow rate of the combustion air resulted in the overheating of the swirl generator. For this reason further air enrichment was unfeasible. The NO_x concentration was increasing from 160 mg/m_N^3 (at 21 % of O_2) to 330 mg/m_N^3 (at 27 % of O_2). However, with higher concentration of O_2 the change in the NO_x trend is observed and then the NO_x concentration dropped to 222 mg/m_N^3 (at the concentration 31.8 % of O_2). The decrease of the NOx concentration is the result of the injection of O_2 directly into the flame. Fuel reacted with O_2 in the flame core while N_2 from the atmospheric air was kept outside at lower temperature zone and therefore less thermal NO_x is produced.

As for the thermal input of 500 kW the NO_x concentration increased (compared to 300 kW) from 189 mg/m_N^3 (at 21% of O_2) to 566 mg/m_N^3 (at 26.1 % of O_2). When the O_2

concentration was further increased it had the positive effect on the NO_x formation, NO_x dropped to 560 mg/m_N^3 (at 28.8 % of O_2). However, the flow rate of combustion air through the burner was too low which resulted in the overheated swirl generator and the burner quarl. Moreover, the so-called flashback was observed, because the combustion rate was higher than the rate of the combustion air.

The formation of NO_x (for one staged 750 kW) was lower compared to NO_x at thermal inputs of 300 kW and 500 kW, until the O_2 concentration reached 25.4 %. Then the NO_x started to rose drastically as shown in Figure 7.2. The maximum was reached slightly above 1 500 mg/m_N^3 (at the concentration 33.3 % of O_2). When O_2 concentration was further increase the descending trend was observed and NO_x dropped to 1 435 mg/m_N^3 (at 39.8 % of O_2).

The tests at thermal input of 750 kW (two staged) had the best results from the entire testing session. The staged combustion of fuel and oxygen had positive impact on the NO_x level which was the lowest from all tests. NO_x was fluctuating around the value of 90 mg/m_N^3 (from the concentration 21 % to 25.3 % of O_2). For higher O_2 concentration up to 33.1 % NO_x raised up to 120 mg/m_N^3, however after that NO_x dropped again to 90 mg/m_N^3. At the maximum concentration the contribution of the pure oxygen flow to the overall oxygen level was 60.3 %.

Although the concentrations of NO_x for air-oxy/fuel method dropped significantly (compared to PM), the only mode, that was able to comply with the current emission limit (200 mg/m_N^3 for the Czech Republic [31]) the whole time, was two staged 750 kW.

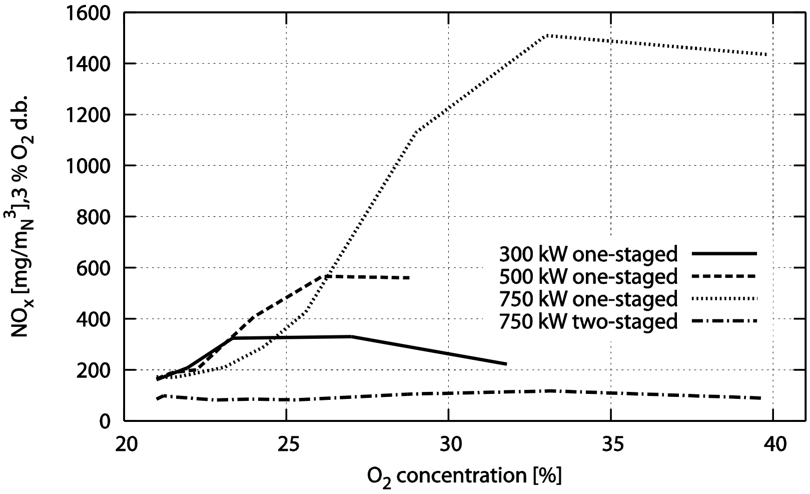


***Figure 7.2** – The effect of O_2 concentration on NO_x concentration AO tests.*

7.1.3 Comparison of PM and AO methods

As it was discussed above, the best results of all tests were achieved at two staged 750 kW with the AO combustion. Both tests of the PM were unacceptable in the terms of emission limits. The formation of NO_x was more rapid for the PM than for the AO which was mostly caused by the thermal NO_x. As for the PM NO_x levels increased steeply compared to AO, where NO_x levels increased moderately and at higher O_2 concentrations decreased. To compare differences between NO_x values at the thermal input 750 kW see Table 7.3 and Table 7.4, in which the differences between NO_x levels at O_2 concentration of 28.7 % and at reached maximum O_2 concentrations, respectively. It can be seen that the AO gives much better results in the matter of NO_x emissions. The results are graphically illustrated in Figure 7.**3**.

Method	**NO_X** [mg/m_N^3]
Premix enrichment	
750 kW one-staged	4036
750 kW two-staged	796
Air-oxy/fuel	
750 kW one-staged	1130
750 kW two-staged	105

Table 7.3 *– Concentration of NO_x for concentration of 28.7 % of O_2.*

Method	**Concentration of O_2** [%vol]	**NO_X** [mg/m_N^3]
Premix enrichment		
750 kW one staged	28.7	4036
750 kW two staged	48.3	4923
Air-oxy/fuel		
750 kW one staged	39.6	1435
750 kW two staged	39.6	89

Table 7.4 *– NO_x levels at the maximum concentrations of oxygen.*

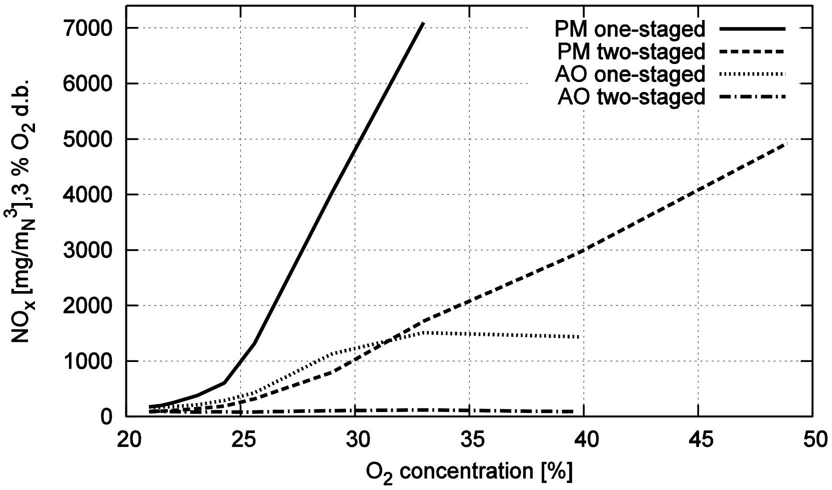


Figure 7.3 *– The comparison of NO_x trend curves between the PM and AO tests.*

7.1.4 The effect of orifice diameter

To study the impact of different fuel distribution the tests were carried out with the orifice of bigger diameter. All previous two staged tests were carried out with the orifice with the diameter of 5.5 mm, where the ratio primary/total fuel flow rate was set to 0.28. Another four tests were carried out with the orifice with the diameter of 7 mm where the ratio primary/total fuel flow rate was 0.51. The use of the orifice with the diameter of 7 mm resulted in the growth of the NO_x in the flue gas, but the NO_x emissions limits for the Czech Republic were not exceeded [31]. The maximum value for the test was 152 mg/m_N^3 (at 33.3 % O_2) as shown in Figure 7.4.

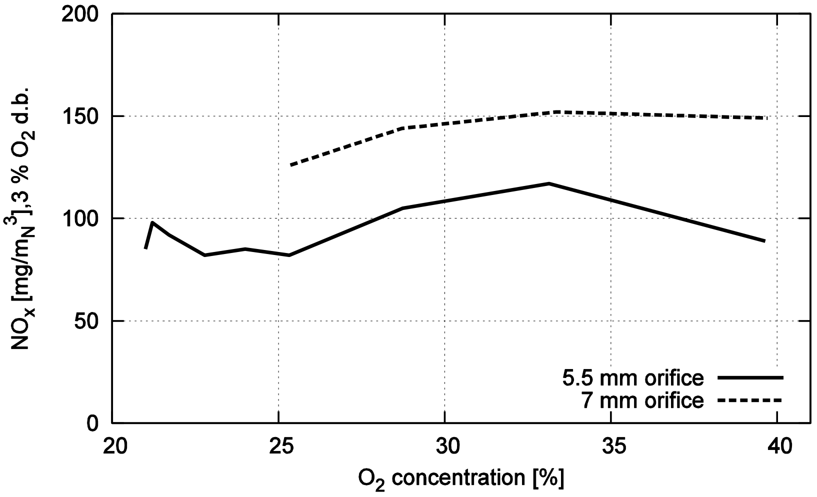


Figure 7.4 *– The effect of orifice diameter on NO$_x$ emission.*

7.2 Flue gas temperature

7.2.1 Premixed air

Figure 7.5 shoes the effect of oxygen concentration on the flue gas temperature. With increased O_2 concentration the flue gas temperature grows until it reaches the tipping point. Then the temperature decreases moderately, which was most probably caused by the higher heat flux into the walls of the combustion chamber (discussed in Chapter 8). The highest temperature was measured at the thermal input of 750 kW one staged, namely 766 °C at 21.7 % O_2, then it dropped to 743 °C. From figure the dependence of flue gas temperature on the thermal input is clearly seen. The lowest temperatures of flue gas mas measured at thermal input of 300 kW (494 °C at 35.36 % O_2).

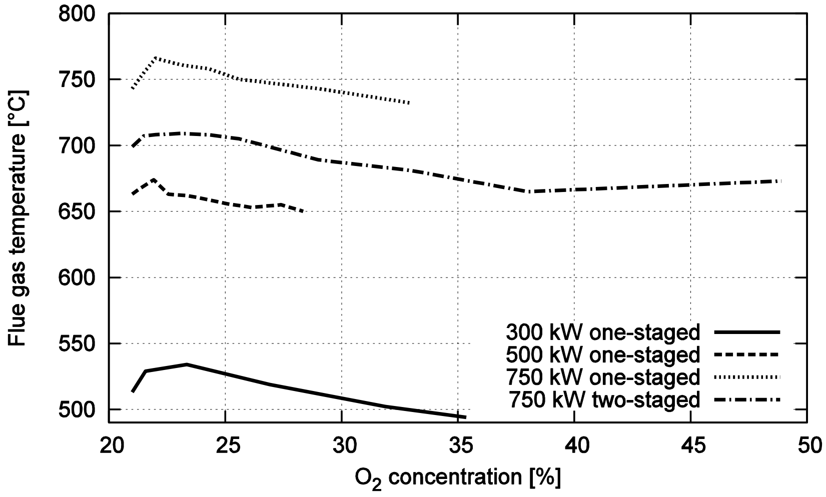


Figure 7.5 *– The effect of O$_2$ concentration on the flue gas temperature in PM tests.*

7.2.2 Air-oxy/fuel

Figure 7.6 illustrates the effect of the pure O_2 on the flue gas temperature for the AO method. The results of all tests except of the test at thermal input of 300 kW can be described similarly. The temperature was increasing for lower O_2 concentrations (< 23 %) up to the tipping point where the temperature started to drop. The maximum temperature was measured for 750 kW one staged (781 °C at 24 % O_2). The maximum temperatures in other tests were following: 727 °C at 22.8 % O_2 (750 kW two staged), 699 °C at 24 % O_2 (500 kW). Further increase of O_2 concentration resulted in the decrease of the temperature which can be explained by higher heat flux into the walls of the combustion chamber.

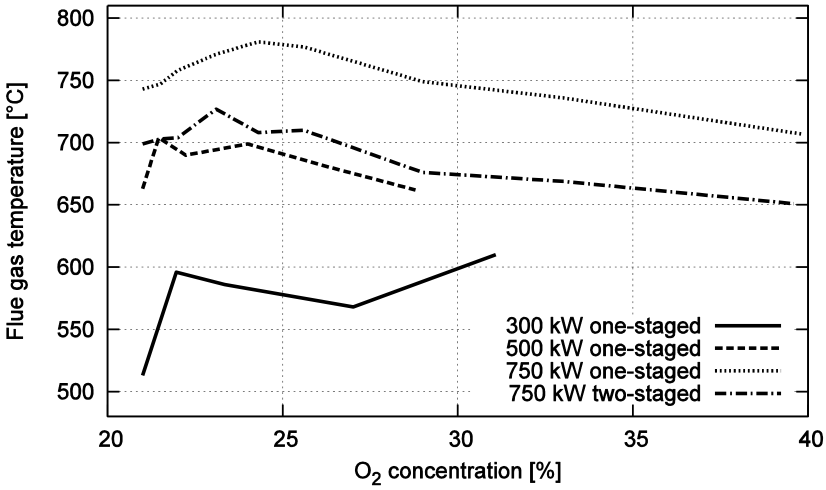


Figure 7.6 *– The effect of O_2 concentration on the flue gas temperature in AO tests.*

7.2.3 Comparison of PM and AO methods

Figure 7.7 illustrates the differences between individual OEC methods at 750 kW on the flue gas temperature. The flue gas temperature increases moderately as the O_2 concentration increases to the 23–24 %. However, further increase of the O_2 concentration resulted in the decrease of flue gas temperature. As far as one particular combustion mode (one staged or two staged) is concerned the temperatures are nearly same for both OEC methods and the temperature differences are in the range of 10 °C.

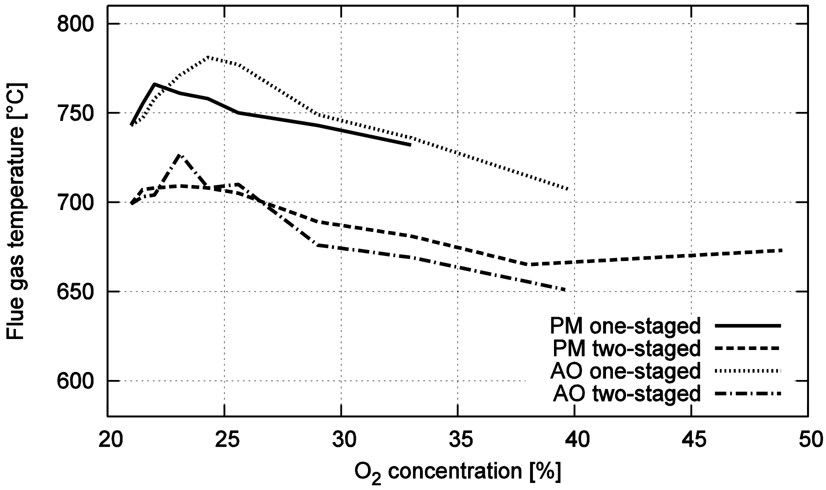


Figure 7.7 *– The comparison of flue gas temperature trend curves between PM and AO.*

7.2.4 The effect of orifice diameter

The use of the orifice with the diameter 7 mm resulted in higher flue gas temperature compared to the orifice with the smaller diameter, shown in Figure 7.8. This is caused by that more fuel is injected through the primary stage and less heat is released to the wall of the combustion chamber.

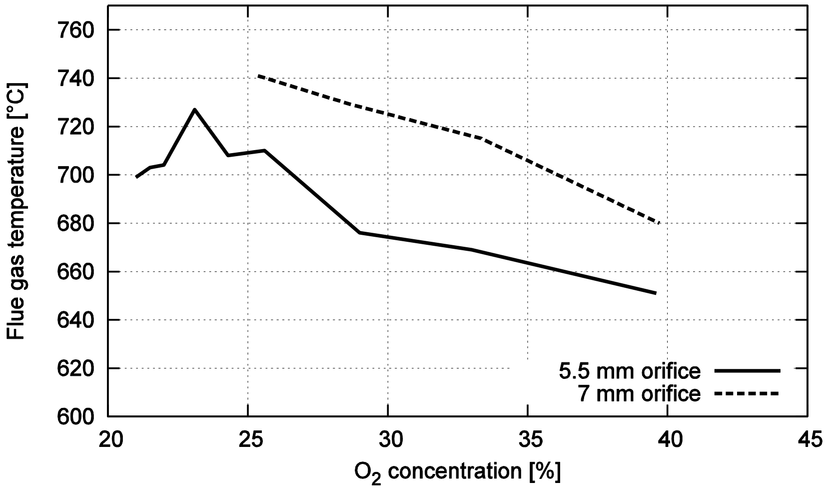


Figure 7.8 *– The effect of orifice diameter on the flue gas temperature.*

7.3 Flame pattern

The produced oxygen-enhanced flames were stable and sharp during all combustion tests. The air-fuel flames, as it was observed, were characterized with the blue flame core and the yellow-red envelope. On the other hand, the core of OEC flames became yellower as the O_2 concentration increased. Generally the produced OEC flames were more luminous compared with air-fuel flame. Moreover, the flame emissivity was higher, too. This is due to higher concentrations of CO_2 and H_2O, which are the gases that radiate in the flame (there is no radiation from the N_2 in the flame).

The dimensions of the visible part of the 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 the burner quarl (600 mm) and the inner diameter of the combustion chamber (1 m).

7.3.1 Premixed air

Flame of natural gas combusted with the atmospheric air (21 % O_2) is recognizable by the blue core and the yellow tails.

As for the thermal input of 300 kW the flame was lengthen by 45 % (from 1.25 m to 2.2 m) and it remained “soft” during the entire test period. However, this is in contradiction with Baukal [1] who states that the premixed air method shortens the flame length. The plausible explanation for this is that the required amount of the 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 requires for the burnout longer time which results in the flame extension. With added oxygen red/yellow colour appeared in the flame core. At the concentration 23.4 % of O_2 the flame was observed to be bent up markedly. Above the O_2 concentration of 26.9 % the blue colour in the core disappeared and the core was composed of yellow and red. The flame diameter remained unchanged during the entire test period, namely 0.4 m.

As for higher thermal inputs the flame characteristics were similar. The length of the flame was extended from 1.8 m to 2 m (by 10 %) at 500 kW. With very slight increase of O_2 concentration the core remained blue, but the flame envelope got more red/yellow. Above the concentration of 23.4 % the ratio between blue/yellow in the core changed, blue colour was replaced by yellow/red. With further enhancement the flame started to bend up and the flame became “softer”. The bend of the flame was caused by the influence of lift force. Above the concentration of 26.1 % the core was formed by 80 % red and yellow, while the rest of the flame volume remained blue. Further increase of O_2 concentration resulted in the complete elimination of the blue colour from the flame core. The flame remained stable during the entire testing session. The flame diameter was changing for different O_2 concentrations from 0.45 to 0.6 m.

During the tests at 750 kW it was observed that the air enrichment lengthened the flame by 25 % (from 2.25 m to 3.0 m) as O_2 concentration was increased up to 35 %. The diameter was observed in the range of 0.5–0.6 m and of 0.9–1 m when the one staged tests and the two staged tests were performed, respectively.

As for the color of flame, the flame core was blue and the flame envelope was red/yellow up to the oxygen concentration of 24 %. With increasing oxygen concentration the flame core was changing gradually from blue to yellow. The whole flame became yellow when O_2 concentration was higher than 29 %.

7.3.2 Air-oxy/fuel

The characteristics of flame observed during air-oxy/fuel tests were rather different. As for the flame characteristics at 300 kW tests, the flame had conical shape and was extended by ca. 17 % from 1.25 m to 1.5 m (which is actually 0.5 m shorter than at PM) and the flame diameter was reduced from 0.4 m to 0.3 m, while increasing oxygen concentration. At low levels of oxygen enhancement (< 27 %) the flame was predominantly yellow/red with traces of blue. Further increase of oxygen concentration resulted in the rapid change of color when the flame turned to blue and no traces of yellow were observed.

As for 500 kW tests, the flame length varied from 1.9 m to 2.25 m (flame was extended by ca. 16 %). The flame was 2 m long at 21.5 % of O_2 and 1.9 m at 22.3 % of O_2. However, then it was observed that the flame started to extend with further increasing of oxygen concentration. The diameter of flame decreased 0.6 m to 0.4 m with increasing amount of injected oxygen. For lower oxygen enhancement the flame was characterized by blue core and yellow envelope.

With increasing oxygen concentration the blue was suppressed and more yellow color appeared up to the O_2 concentration of 26.1 %. At this oxygen concentration yellow color disappeared and the flame became blue with the conical shape. Yellow started to appear again at the concentration of 28.8 % O_2. Low flow rate of the combustion air resulted in the overheating of the swirl generator blades and flashback directed in the combustion air pipe line. Further increase of oxygen concentration would cause the damage of swirl generator and/or the burner itself and for these reasons the tests had to be stopped.

As for 750 kW one staged tests, the flame length increased by 16 % (from 2.3 m to 2.75 m) as the O_2 concentration increased. On the other hand, the flame length observed at 750 kW two staged tests was lengthened from 2.1 m to 2.5 m as the O_2 concentration increased from 21 % to 35 %. Further increase of O_2 concentration caused that the flame was shortened by ca. 0.3 m. The flame diameter was observed in the range of 0.4–0.6 m and of 0.8–0.9 m when one staged and two staged combustion was performed, respectively.

During the 750 kW one staged tests the flame was irregularly pulsating. At low-level oxygen enhancement the flame core was blue and the flame envelope was red/yellow. While increasing the oxygen concentration up to 33 %, the blue color was gradually suppressed by yellow. The flame was characterized by the conical shape.

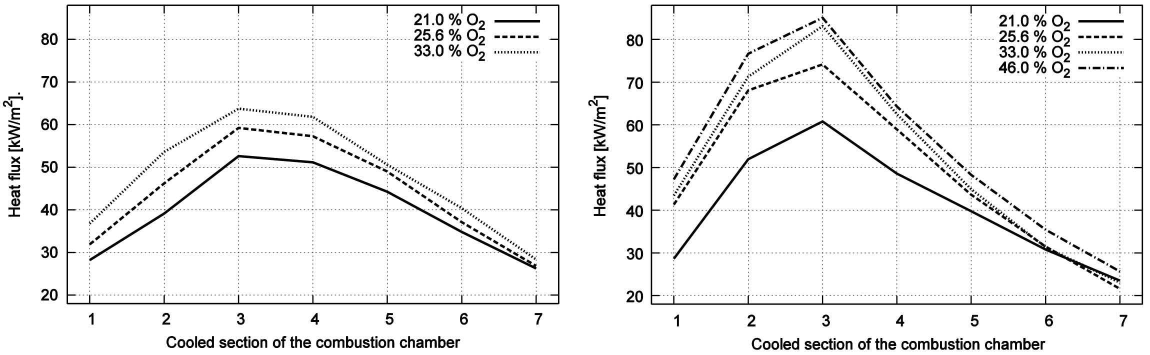
As for 750 kW two staged tests, the flame was touching the walls of the combustion chamber. At the oxygen concentration higher than 23 % the flame core was shifted from the burner tile for ca. 20 cm, however the flame was permanently stable. This was possibly caused by improper mixing of fuel with oxygen as the fuel was distributed through two stages. When the orifice with bigger diameter, namely 7 mm, was used, the shift of the flame from the burner tile was a trifle smaller, however, the NO_x emission increased at the same time.

8 Results – Test B

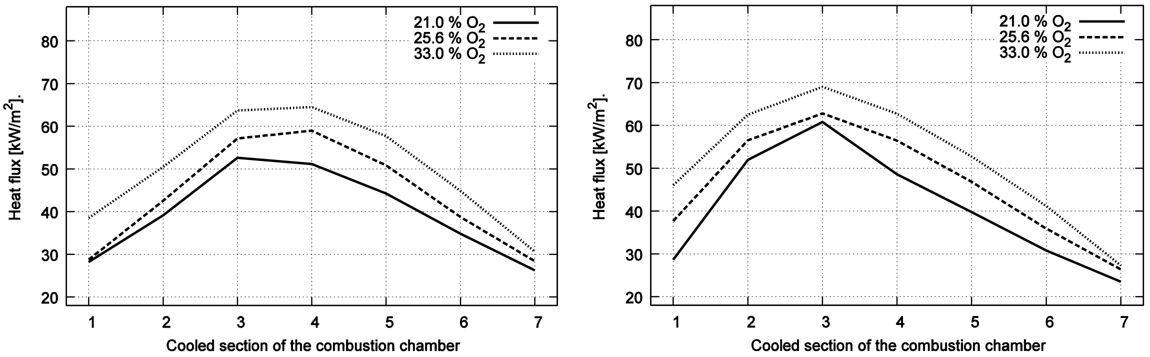
Before the start of the TEST B, the evaporated water from the cooling section of the chamber was removed and the whole combustion chamber was set into the thermodynamic state. This state was considered if both the flue gas temperature (maximal allowed change within 30 min is 10 °C) and the values of local wall heat fluxes (continuously evaluated) are steady.

8.1 Heat flux

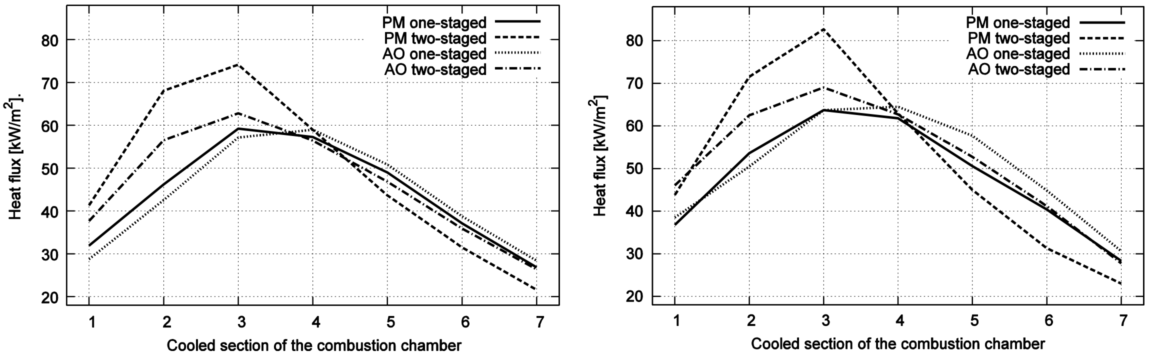
As it is evident from Figure 8.1 the obtained trend curves of heat flux are characterized by very similar shape for all investigated O_2 concentrations/flow rates as far as for both tested OEC methods and combustion modes. The curves are simply shifted upwards and reach its maximum in the third section for all trials. It can be seen that with increasing O_2 concentration more heat is released from the hot flue gas to the walls of chamber's sections because less energy is wasted in heating up of N_2 and the radiative heat transfer is enhanced due to higher concentrations of CO_2 and H_2O. The values that were achieved by the test are given in Table 8.**1**.



(a) PM – one staged (b) PM – two staged



(c) AO – one staged (d) AO – two staged



(e) PM and AO – 25.35 % of O_2 (f) PM and AO – 33.20 % of O_2

Figure 8.1 *– Heat flux profiles lengthwise the chamber at different O_2 concentrations.*

Mode		O_2 conc. [%]	O_2 flow [m_N^3/h]	Section 1 [kW/m^2]	Section 2 [kW/m^2]	Section 3 [kW/m^2]	Section 4 [kW/m^2]	Section 5 [kW/m^2]	Section 6 [kW/m^2]	Section 7 [kW/m^2]	Efficiency [%]
one staged	PM	20.75	0	28.20	39.13	52.58	51.17	44.26	34.79	26.24	61.09
one staged	PM	25.36	40	31.88	46.21	59.23	57.27	48.99	37.11	26.82	67.69
one staged	PM	30.80	70	36.76	53.59	63.74	61.81	50.59	40.38	28.34	73.41
two staged	PM	20.75	0	28.64	51.96	60.80	48.57	39.73	30.77	23.50	62.20
two staged	PM	25.35	40	41.30	68.08	74.15	58.94	43.62	31.48	21.54	72.89
two staged	PM	33.20	80	43.78	71.54	82.68	62.94	44.96	31.29	22.99	77.59
two staged	PM	48.74	119	47.18	76.68	85.07	64.31	48.27	35.44	25.61	82.36
one staged	AO	25.37	40	28.73	42.53	57.16	58.96	50.82	38.75	28.37	67.41
one staged	AO	33.29	80	38.51	50.45	63.72	64.50	57.68	44.84	30.60	76.84
two staged	AO	25.36	40	37.66	56.51	62.79	56.46	46.81	35.88	26.35	70.30
two staged	AO	33.14	80	46.03	62.49	69.02	62.74	52.73	41.16	27.25	78.12

Table 8.1 *– The summary of results of Test B.*

8.2 Thermal efficiency

Figure 8.2 illustrates the variations of the thermal efficiencies at different oxygen concentrations for the TEST B. The trend of the curve is increasing with the oxygen concentration. The thermal efficiency of the combustion process was increased from 60 % at 21 % O_2 to 78 % at 49 % O_2, i.e. more heat is available for the overall process. Additionally, 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.

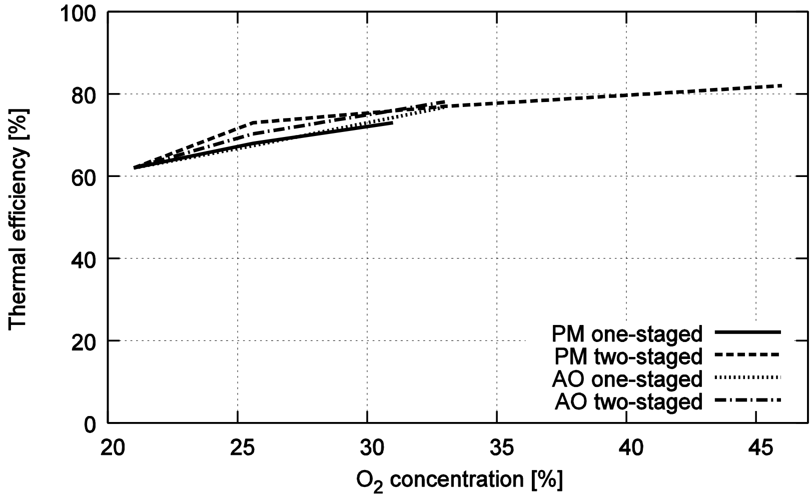


***Figure 8.2** – Thermal efficiencies at different oxygen concentrations.*

9 Conclusions

The thesis was focused on the study of OEC technology and its impact on combustion characteristics. The goals of the thesis were:

- To study of basic principles of combustion and OEC (Chapter 2 and Chapter 3)
- To make an overview of the applications of OEC (Chapter 4)
- To make an overview of technologies for the oxygen production and of safety rules for the manipulation with oxygen (Chapter 5)
- To carry out the combustion tests using two OEC methods (Chapter 6)
- To make an analysis of results (Chapter 7 and Chapter 8)

The results obtained during the tests proved that the OEC can be applied to different industrial areas. Further detailed investigation of different combustion settings can bring positive results in terms of emissions and funds savings. It was revealed that NO_x emission increases steeply especially when the premixed air method is used. While the oxygen concentration increased from 21 % up to 33 %, NO_x concentration was increased 40 times for one staged mode and 20 times for the two staged combustion mode. However, NO_x emission can be also kept at low concentrations when the air-oxy/fuel method is applied.

Tests were also focused on the evaluation of heat flux distribution lengthwise the combustion chamber. The tests proved rate of transferred heat is significantly higher when the combustion is performed with the oxygen enhancement than with the atmospheric air. The thermal efficiency was increased by 20 % when the combustion was performed with the oxygen concentration of 38 % compared to the combustion with the atmospheric air.

Although the single tests shown positive results in terms of lower emissions and higher heat transfer rate, more data is required to decide which OEC method could be beneficial for the existing facility. The process of the selection would be affected by the required rate of return, emission limits and/or by the total need of the transferred heat.

9.1 Future work

Even though some work has already been done in the field of oxygen enhanced combustion, there are still areas which need to be explored more in detail. Other tests will be carried out during this year and will be focused on the characteristics of another OEC method, namely – O_2 staging which is referred to as O_2 lancing. The oxygen will be injected into the combustion chamber through the secondary nozzles of the burner. Furthermore, the so-called furnace-temperature fixing test, the heating test and the measurement of temperature distribution in the furnace will be carried out for different oxygen concentrations and OEC methods (premixed air, air-oxy/fuel, O_2 lancing).

Some of the research groups have already done the series of tests that cover the premixed air, air-oxy/fuel or O_2 lancing. They have described the impact of the oxygen on the temperature and emissions, but the throughput financial analysis has not been compiled yet. This matter will be also included in the future work.

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DVD Contents

The attached DVD contains:

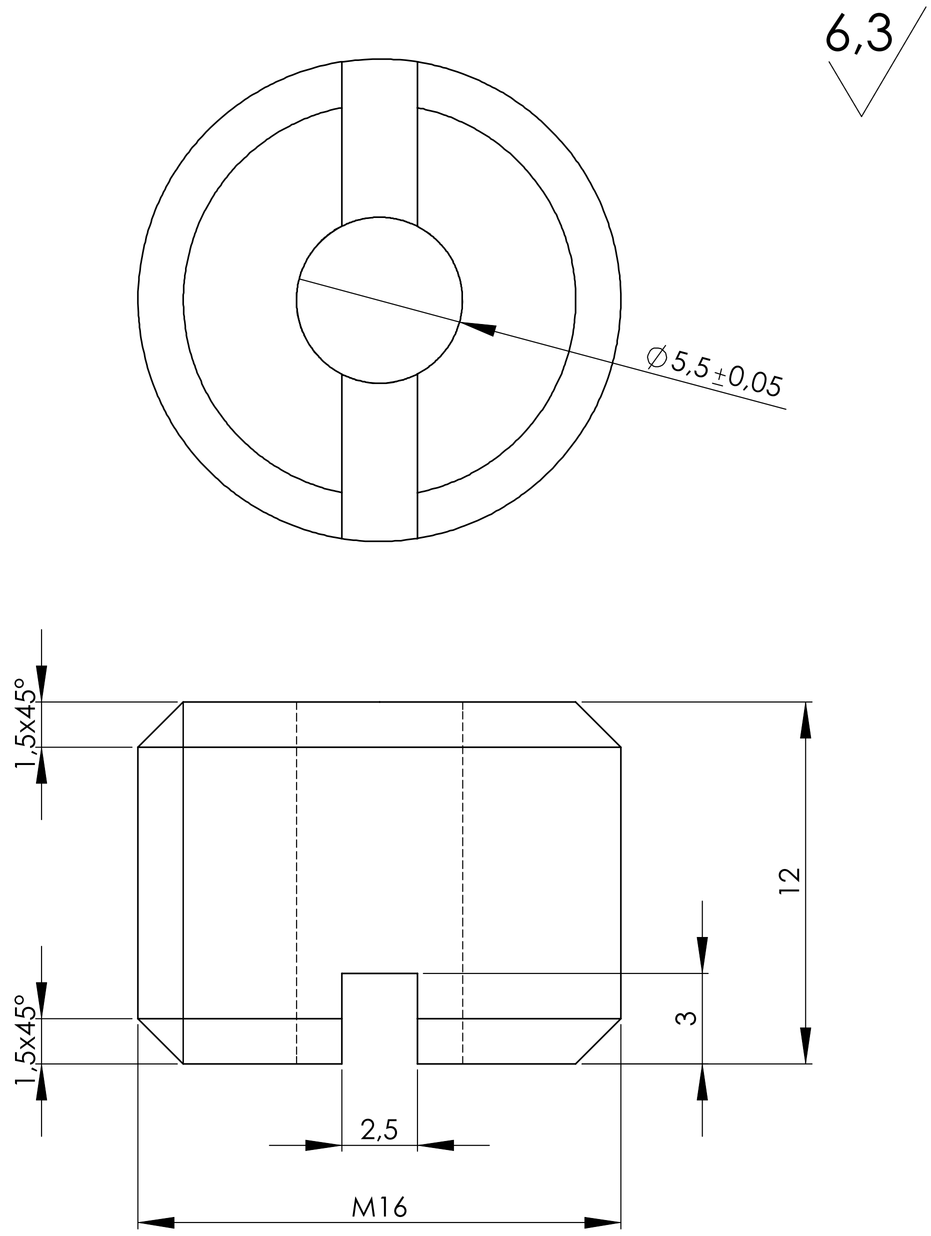
- thesis document in the PDF format
  - ..\Thesis.pdf
- datasheets with the recorded data
  - ..\Datasheet.xlsx
- calculations and graphs of the heat flux
  - ..\Heat flux.xlsx
- raw data from the data collection system
  - ..\Data\

Appendix

A I – Ranges and accuracies of sensors in TESTO 350 – XL
A II – The technical drawing of the orifice
A III – The technical drawing of the flame holder
A IV – The technical drawing of the burner head
A V – The technical drawing of the secondary nozzle
A VI – The data sheet for the manual record of the measuring data
A VII – The technical drawing of the diffusor
A VIII – The technical drawing of the oxygen nozzle

Probe type	**Temperature**	**O_2**	**CO (H_2 compensated)**	**COlow**	**CO_2**	**NO**	**NOlow**
Measuring range	-40... +2192 °F	0... +25 Vol.% O_2	0... +10000 ppm CO	0... +500 ppm CO	0... CO_2max Vol% CO2	0... +3000 ppm NO	0... +300 ppm NO
Accuracy ±1 digit	<33 °F (-40... +212 °F) <0.5% m.v. (+212...+2192 °F)	±0.8% of f.v. (0...+25 Vol.% O_2)	±5% of mv (+100...+2000 ppm CO) ±10% of mv (+2001...+10000 ppm CO) ±10 ppm CO (0...+99 ppm CO)	±5% of mv (+40...+500 ppm CO) ±2 ppm CO (0...+39.9 ppm CO)	Calculated from O2	±5% of mv (+100...+1999.9 ppm NO) ±10% of mv (+2000... +3000 ppm NO) ±5 ppm NO (0...+99 ppm NO)	±5% of mv (+40... +300 ppm NO) ±2 ppm NO (0...+39.9 ppm NO)
Resolution		0.01 Vol.% (0... +25 Vol. O_2)	1 ppm CO (0...+10000 ppm CO)	0.1 ppm CO (0...+500 ppm CO)	0.01 Vol. % CO2	1 ppm NO (0...+3000 ppm NO)	0.1 ppm NO (0...+300 ppm NO)
Reaction time		20 s	40 s	40 s	20 s	30 s	30 s
Reaction type		t95	t90	t90	t95	t90	t90
Probe type	**NO_2 measuring module**	**SO_2**	**Efficiency**	**Flue gas loss**	**Differential pressure 1**	**Differential pressure 2**	**Flow Velocity**
Measuring range	0... +500 ppm NO_2	0... +5000 ppm SO_2	0... +120 %	-20... +99.9 % qA	± 80″ H_2O	± 16″ H_2O	0... 7900 ft/min
Accuracy ±1 digit	±5% of mv (+100... +500 ppm NO_2) ±5 ppm NO2 (0...+99.9 ppm NO_2)	±5% of mv (+100...+2000 ppm SO_2) ±10% of mv (+2001...+5000 ppm SO_2) ±5 ppm SO_2 (0...+99 ppm SO_2)			<1% of m.v. (-20″...-80″ H_2O) <1% of m.v. (+20″...+80″ H_2O) <0.5% (-19″...+19″ H_2O)	<1% of m.v. (-16″...1.2″ H_2O) <1% of m.v. (+16″...+1.2″ H_2O) <0.5% (-1.2″...+1.2″ H_2O)	
Resolution	0.1 ppm NO_2 (0... +500 ppm NO_2)	1 ppm SO_2 (0...+5000 ppm SO_2)	0.1 % (0... +120 %)	0.1 % qA (-20...+99.9 % qA)	0.01″ H_2O	0.01″ H_2O	10 ft/min
Reaction time	40 s	30 s					
Reaction type	t90	t90					

A I – Ranges and accuracies of sensors in TESTO 350 – XL.



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NOVÝ VÝKR.: New.Drwg.:
NÁZEV: Name:

Orifice

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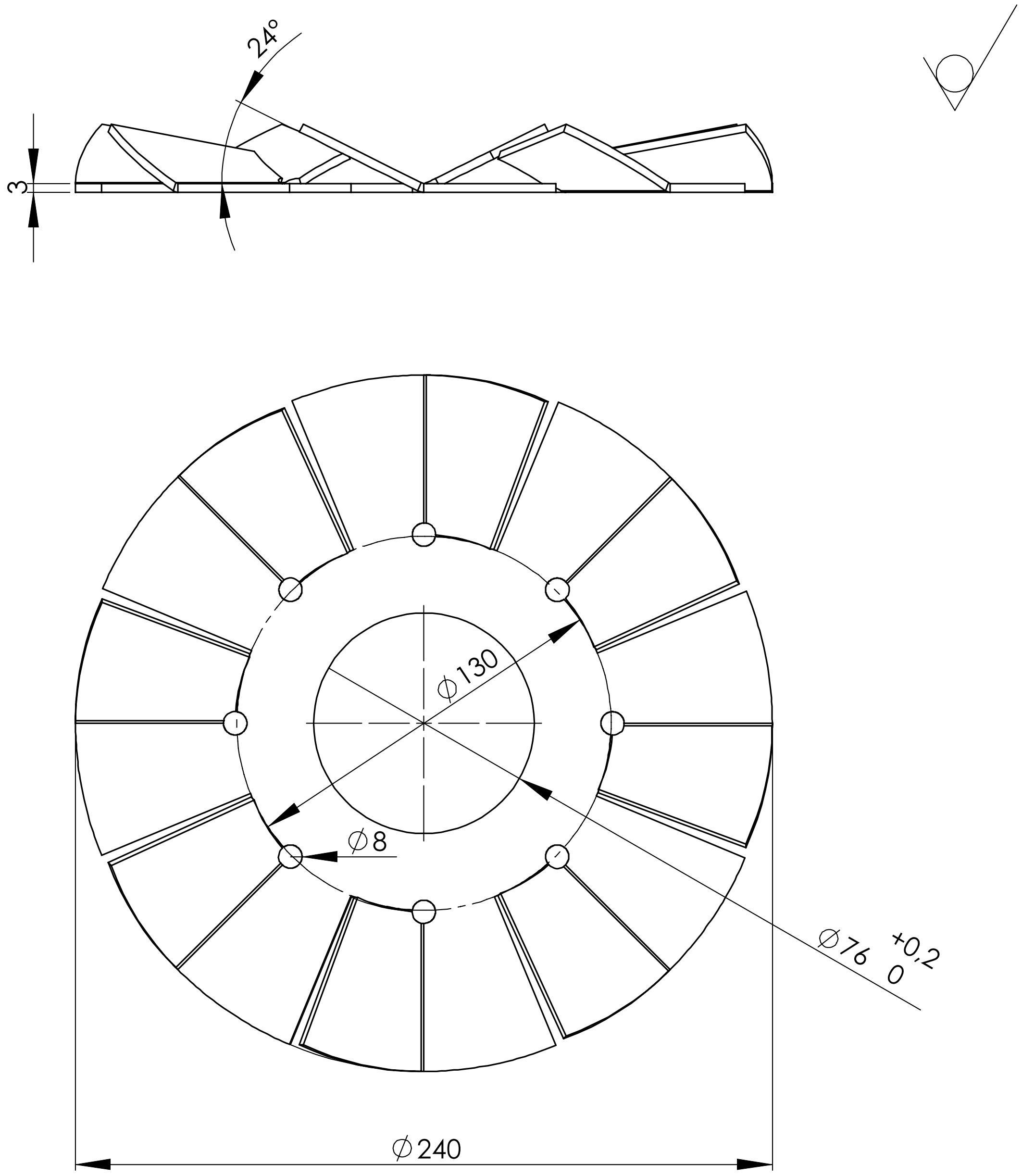
A II – The technical drawing of the orifice.



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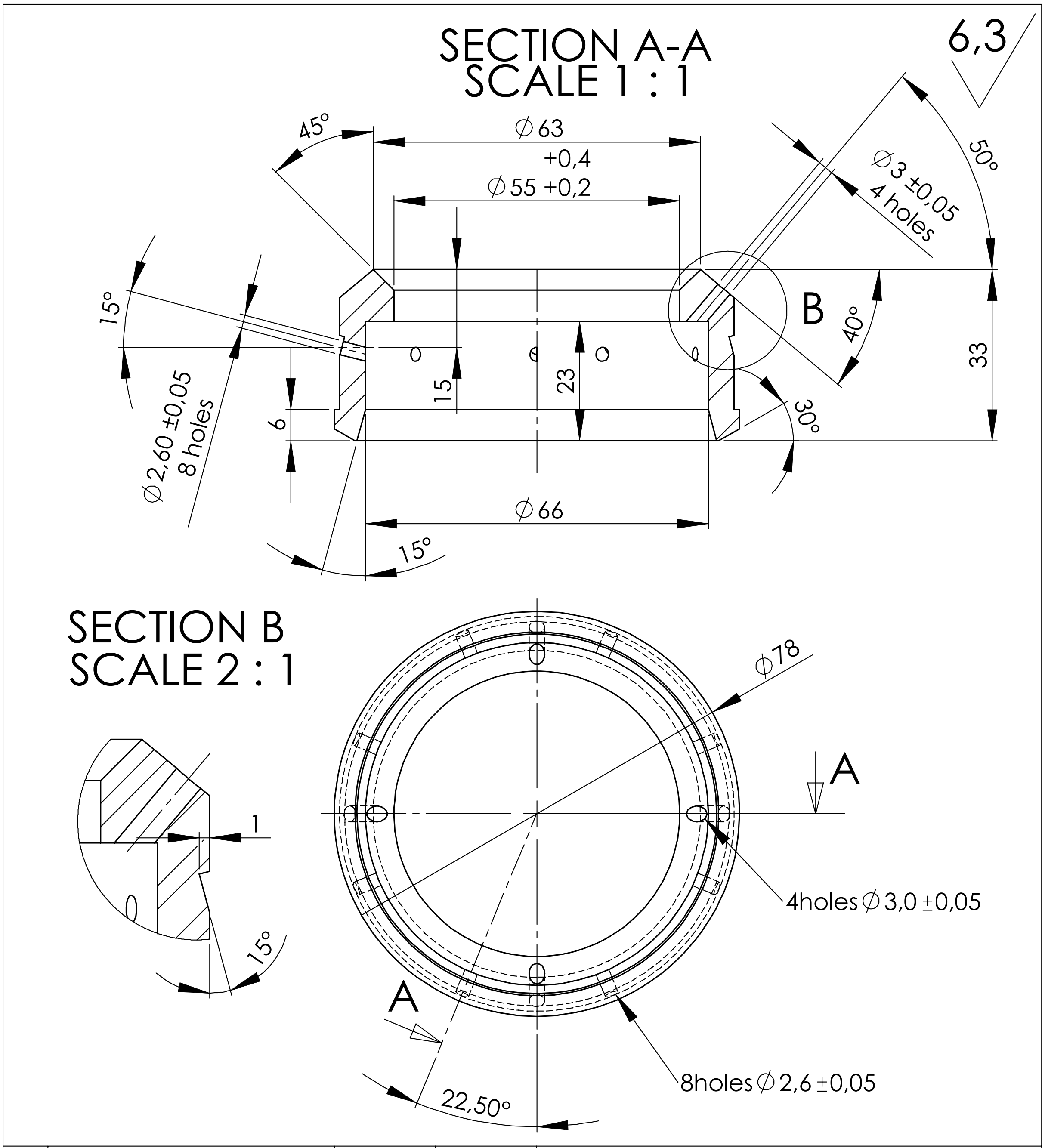
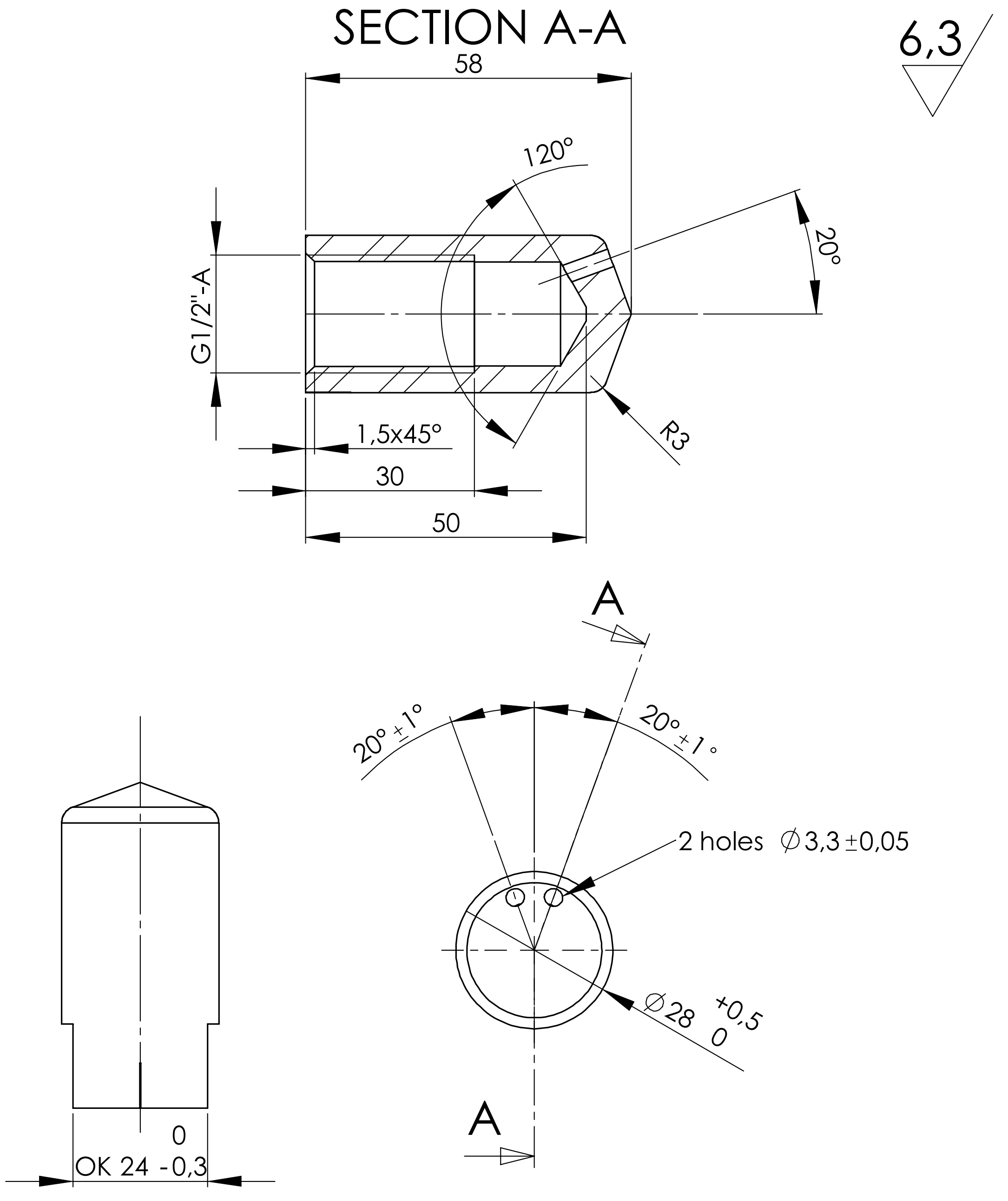
A III – The technical drawing of the flame holder.



REV.	OBSAH REV. -Modification	DATUM-Date	PODPIS-Sign.		
MAT.KONEČNÝ: Final mater.: 17 255.4			Tř.o. W.cl.	HMOTNOST kg: Net.Weight kg: 0.80	MĚŘÍTKO: Scale: 1:1, 2:1
ROZM.-POLOT.: Dim-Semi Prod.: ∅80 - 38					
				ČSN: Stand.:	
KRESLIL: Drawn by: I. Hudák	NORM.REF.: Stand.ref.:			POZNÁMKY: Notes:	Č.KUSOVNÍKU: Part List No:
PŘEZKOUŠEL: Checked by:	SCHVÁLIL: Approv.by: P. Bělohradský				
VÝR.PROJEDN.: Discussed by:	DATUM: Date:			STARÝ VÝKR.: Previous Drwg.:	NOVÝ VÝKR.: New.Drwg.:
NÁZEV: Name: Burner head				4 H-ZPH1000 040 Listů - Number of Sheets: 1 List - Sheet: 1	REV.

A IV – The technical drawing of the burner head.



REV.	OBSAH REV. -Modification	DATUM-Date	PODPIS-Sign.

MAT.KONEČNÝ: Final mater.: 17 255.4
Tř.o. W.cl.
ROZM.-POLOT.: Dim-Semi Prod.: ∅30 - 61
HMOTNOST kg: Net.Weight kg: 0,25
MĚŘÍTKO: Scale: 1:1
ČSN: Stand.:
KRESLIL: Drawn by: I. Hudák
NORM.REF.: Stand.ref.:
POZNÁMKY: Notes:
Č.KUSOVNÍKU: Part List No:
PŘEZKOUŠEL: Checked by:
SCHVÁLIL: Approv.by: P. Bělohradský
VÝR.PROJEDN.: Discussed by:
DATUM: Date:
STARÝ VÝKR.: Previous Drwg.:
NOVÝ VÝKR.: New.Drwg.:
NÁZEV: Name:

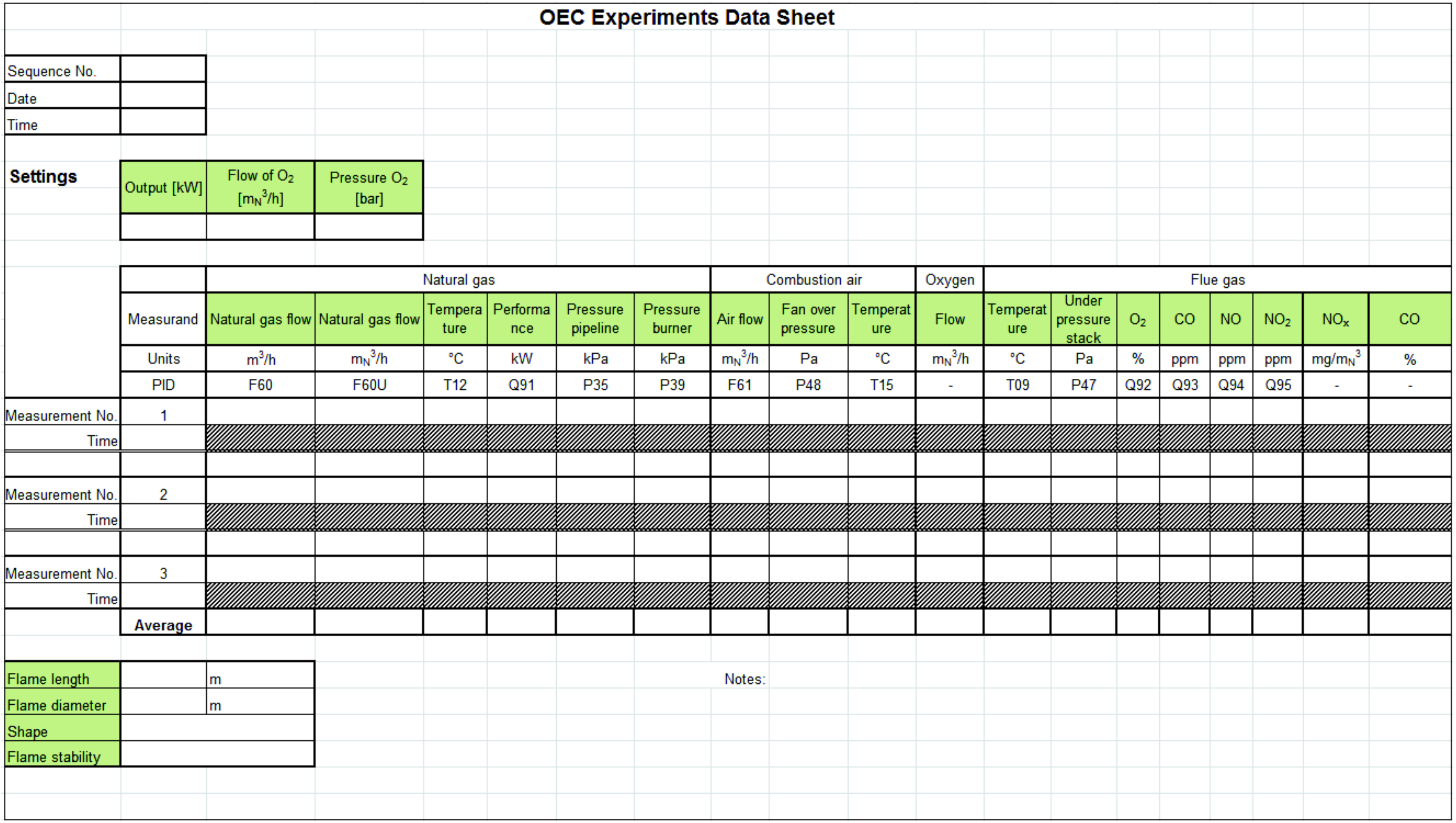
Sec.nozzle-2x3,3/20°

4 H-ZPH1000 204

REV.

Listů - Number of Sheets: 1
List - Sheet: 1

A V – The technical drawing of the secondary nozzle.



OEC Experiments Data Sheet

Sequence No.	
Date	
Time	

Settings

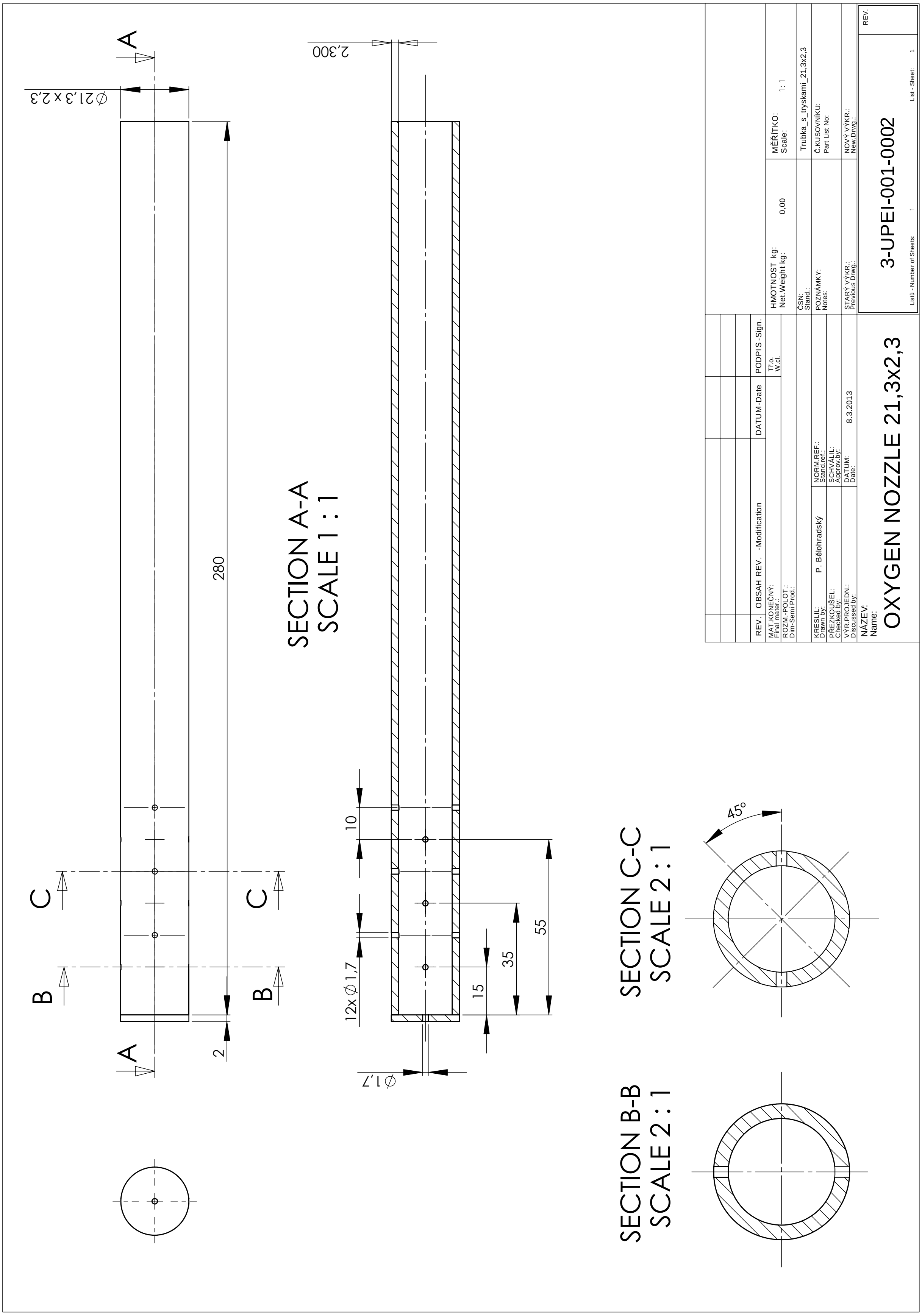
Output [kW]	Flow of O_2 [m_N^3/h]	Pressure O_2 [bar]

		Natural gas						Combustion air			Oxygen	Flue gas							
	Measurand	Natural gas flow	Natural gas flow	Temperature	Performance	Pressure pipeline	Pressure burner	Air flow	Fan over pressure	Temperature	Flow	Temperature	Under pressure stack	O_2	CO	NO	NO_2	NO_x	CO
	Units	m^3/h	m_N^3/h	°C	kW	kPa	kPa	m_N^3/h	Pa	°C	m_N^3/h	°C	Pa	%	ppm	ppm	ppm	mg/m_N^3	%
	PID	F60	F60U	T12	Q91	P35	P39	F61	P48	T15	-	T09	P47	Q92	Q93	Q94	Q95	-	-
Measurement No.	1																		
Time		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Measurement No.	2																		
Time		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Measurement No.	3																		
Time		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Average																		

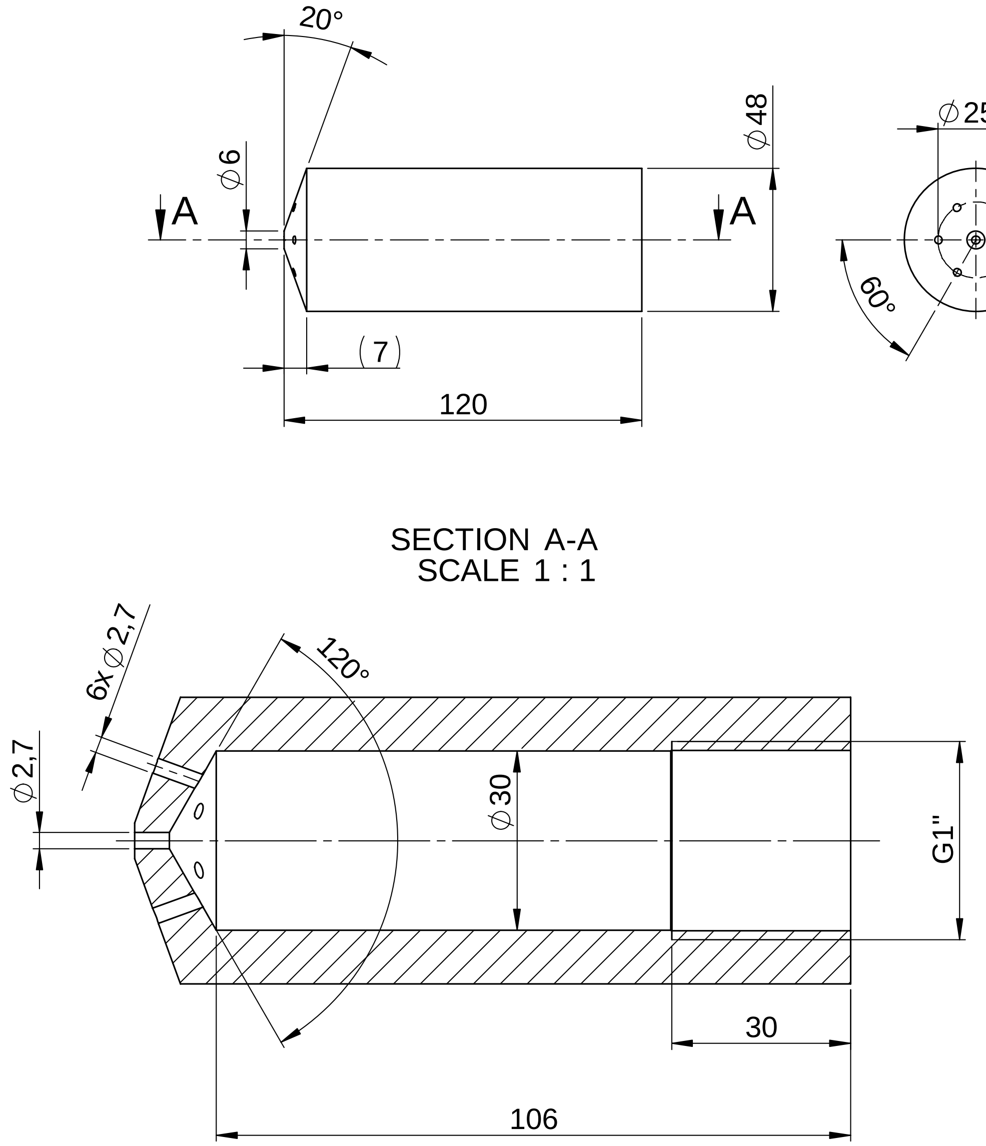
Flame length		m
Flame diameter		m
Shape		
Flame stability		

Notes:

A VI – The data sheet for the manual record of the process data.



A VII – The technical drawing of the diffusor.



REV.	OBSAH REV. -Modification	DATUM-Date	PODPIS -Sign.
MAT.KONEČNÝ: Final mater.:	Tř.o. W.cl.	HMOTNOST kg: Net.Weight kg:	MĚŘÍTKO: Scale: 1:2
ROZM.-POLOT.: Dim-Semi Prod.:		ČSN: Stand.:	FORMÁT VÝKRESU : A4
KRESLIL: Drawn by: I. Hudák	NORM.REF.: Stand.ref.:	POZNÁMKY: Notes:	Č.KUSOVNÍKU: Part List No:
PŘEZKOUŠEL: Checked by:	SCHVÁLIL: Approv.by: P. Bělohradský		
VÝR.PROJEDN.: Discussed by:	DATUM: Date:	STARÝ VÝKR.: Previous Drwg.:	NOVÝ VÝKR.: New.Drwg.:
NÁZEV: Name: Nozzle 140 mN3/h		4-UPEI-002-0004 Listů - Number of Sheets: 1 List - Sheet: 1	REV.

A VIII – The technical drawing of the oxygen nozzle.