OXY-FUEL COMBUSTION: THE STATE OF THE ART

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Abstract – The paper deals with an oxy-fuel combustion (OFC) technology. The strong and weak points of this technology are discussed. Authors present both atmospheric- (AOFC) and pressurized (POFC) performance of the oxy-fuel combustion process. Moreover, the issues associated with air separation, CO_2 capture and other related processes are also analyzed in this paper. Finally, the prospects of further development of AOFC and POFC technologies are taken into consideration.

THE PRINCIPLES OF OXY-FUEL COMBUSTION TECHNOLOGY

The main idea of the oxy-fuel combustion process is presented in Fig 1. The upper part of the drawing describes a conventional combustion in the air, where CO_2 and other pollutants are diluted in a large amount of air-nitrogen, and hence the concentration of CO_2 is only about 16%. On the contrary, the bottom part describes a pure oxy-fuel combustion, which enables to obtain a highly concentrated stream of CO_2, which means at least 90% of CO_2 in a total volume of the flue gas. However, this figure shows even more than the idea of oxy-fuel combustion. It exposes three crucial issues concerning this technology.

- The first one is an air separation, which has to be performed in advance to the combustion.
- The second issue concerns the control of temperature in a furnace, which relates directly to the combustion conditions.
- The last issue is a post-combustion flue gas treatment, which enables CO_2 to be captured and stored.

Fortunately, nowadays one is able to manage with all these challenges, by merging the combustion unit with:

- Air Separation Unit (ASU),
- Flue Gas Recirculation (FGR),
- And CO_2 Processing unit (CPU),

which all together create the integrated whole of the oxy-fuel power plant (Fig. 2).

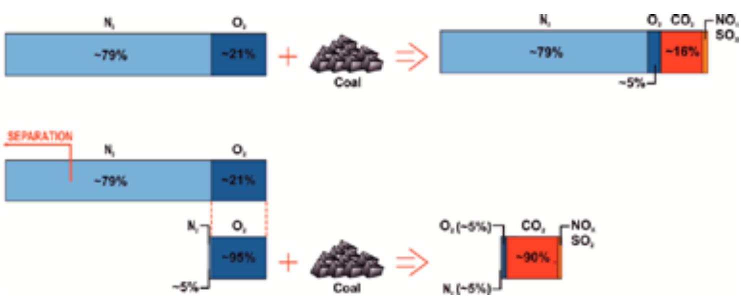

Fig. 1. The idea of oxy-fuel combustion.

Fig. 2. The diagram of oxy-fuel power plant.

AIR SEPARATION

There are commonly known several different methods of air separation, including membranes, chemical and magnetic techniques. However, nowadays, only one technology is available for ASU in large quantities, which is the cryogenic separation. Nevertheless, in case of small power units (<25MW$_e$) the adsorption methods can be also considered. Presently, the world's largest air separation unit (1 single train) offers about 4000 tons of oxygen per day. One can easily estimate that the demand_for oxygen for 500 MW$_e$ oxy-fuel power plant is about 10000 T_{O2}PD, which may mean 3 single trains of 3500 T_{O2}PD each. Although it is still a huge amount, but the largest air separation station (8 single trains), which is located in Ras Laffan in Katar, manages with 30000 T_{O2}PD, which is still 3 times more. This proves the technical readiness of the technology, however, the main point concerning an air separation is the energy penalty. The power consumption of ASU keeps the level of 200kWh/T_{O2} (Fig. 3, based on Chorowski et al., 2012) in case of high purity oxygen (>99.5%).

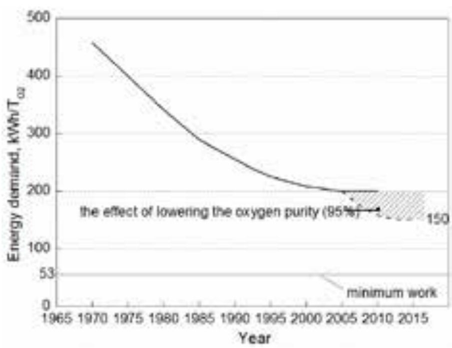

Fig. 3. Power consumption of ASU.

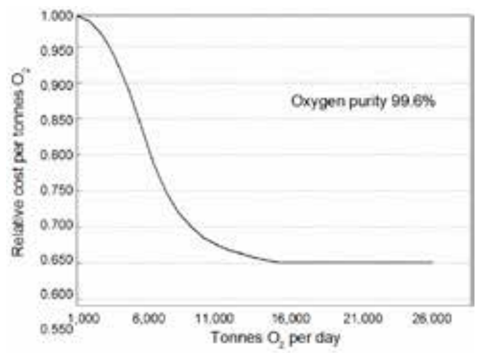

Fig. 4. Relative cost of oxygen production.

However, the recommended purity of oxygen for the purpose of oxy-fuel combustion (including the impact on CPU) is about 95%, which enables to reduce the energy consumption by 25%. The other advances applied to ASU can result in further reduction in energy consumption. They include the thermal integration between ASU and steam cycle or the utilization of by-products coming from air separation (mainly nitrogen). The waste heat from ASU can be used for instance to preheat water in steam cycle or to heat up a waste nitrogen, which can be further employed to the fuel drying. Another issue is the capital cast of cryogenic air separation unit, which is calculated in a range of 24-40 kEuro/T_{O2}PD depending on the size of the installation. Fortunately, the effect of scale is significant (see: Fig. 4, based on Air Products and Chemicals, 2010), especially in a range of 1000-10000 T_{O2}PD, where the investment expenditure are reduced roughly by 35%.

FLUE GAS RECIRCULATION

The fuel combustion in pure oxygen or even highly concentrated inlet gas seems to be rather unfeasible due to both technical and safety reasons. Therefore, a flue gas recirculation is applied in oxy-fuel combustion systems to drop the adiabatic temperature (see: Fig. 5, based on Saastamoinen, 2006), which is necessary in order to maintain efficient combustion performance and to avoid agglomeration of solid particles. Concurrently, the larger gas flow is necessary to force the solids movement, which is especially important in a fluidized-bed boiler technology.

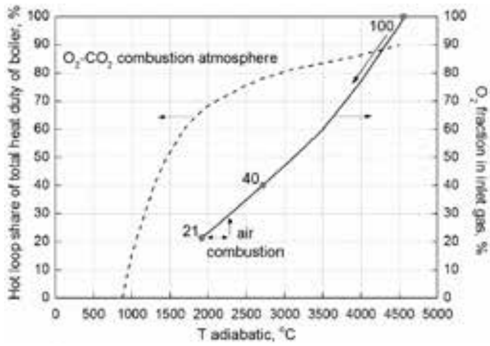

Fig. 5. The oxygen fraction in inlet gas vs. the adiabatic combustion temperature.

However, the oxygen fraction in O_2-CO_2 mixture needs to be slightly higher compared to that in the air, mainly due to the differences in a specific heat capacity of core gases (N_2 and CO_2) in both cases (see: Table 1).

Table.1: The properties of N_2 and CO_2.

	N_2		CO_2	
	800°C	900°C	800°C	900°C
Specific heat, kJ/(kmol K)	33.1	33.6	55.0	56.0

It has been proved by many researchers in their experimental and numerical works as well as during real pilot-scale investigations that O_2 fraction under oxy-fuel conditions should be in a range of 27-30%-vol. in order to keep the temperature level associated with air combustion. These values correspond however to the flue gas recirculation ratio of 68-74%, which is defined as $RR=m_{Rec.FG}/(m_{Rec.FG}+m_{FGtoCPU})$. The key issue seems to be also the performance of flue gas recirculation, which means wet-, dry- or partially dried recirculation. The FGR ratio and thereby O_2 enrichment will depend mainly on fuel properties (moisture content, calorific value, ash behavior) and boiler construction including the size and locations of available heat exchange surfaces. Moreover, it can be seen in Fig. 5 that the share of the hot loop (incl. furnace and in-furnace walls, separator, return leg and Intrex) in the total heat duty of the boiler (incl. backpass heat exchangers) increases with the increase of adiabatic temperature that associates with the increase of oxygen fraction in an inlet gas. One should remember that the heat transfer under oxy-fuel conditions is also affected by higher radiation intensity of both: CO_2 – which replaces air-nitrogen in combustion atmosphere and H_2O – as a result of higher boiler load.

CO_2 CAPTURE

The flue gas that leaves an oxy-fuel boiler contains mainly nitrogen, oxygen and water vapor in addition to CO_2. The composition of flue gas, which finally gets to CPU, depends mainly on:

- oxygen purity, by means of ASU efficiency, which is responsible for N_2 (+Ar) impurity in an amount of 1-6%,
- combustion conditions, by means of excess oxygen and fuel properties, which are responsible for O_2 impunity in an amount of 3-5% and for H_2O impurity in an amount of 10-40%, respectively,
- operating conditions, by means of air leakage and manner of FGR, which are responsible for O_2 and H_2O impurities, respectively.

Currently, there are no legal requirements regarding the quality of recovered-CO_2 getting ready for transport and storage. However, the recommended purity of CO_2 for transport and storage in geological reservoirs is at least 95%, with water content close to zero.

Therefore, the best available technology for CPU is presently cryogenic separation (similar to ASU), in terms of flue gas quantities and costs of operation. It is estimated that total power consumption of CPU with standard performance can reach 120-130 kWh/T_{CO2}, which enables to achieve the CO_2-recovery level of

90%. However, for the oxy-fuel power plant with near-zero CO_2 emission the advanced CPU is required (see: Fig. 6, based on Stromberg, 2011), which is provided with an additional module for ultimate CO_2 capture from vent-gas. For this purpose the adsorption methods or membranes are the most commonly considered, which enable to achieve the total CO_2 capture up to 99% and up to 97%, respectively. In case of VPSA (Vacuum Pressure Swing Adsorption) module for instance, the total cost calculated together for CPU and ASU increase by 5% only.

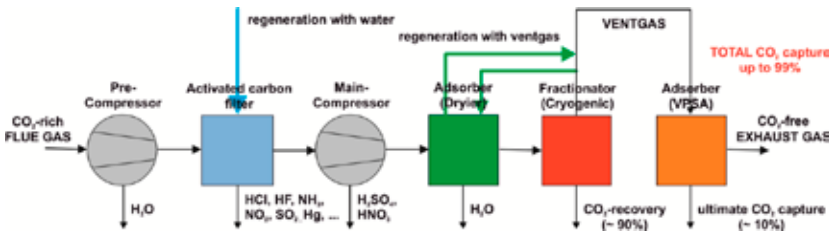

Fig. 6. The diagram of CO_2 Processing Unit.

ENERGY/ EFFICIENCY PENALTY

The performance of OFC technology has a significant influence on the net efficiency of an oxy-fuel power plant, which is even much stronger than the influence on the combustion process itself or on the heat transfer. These penalties result mostly from the specific power consumption of ASU and CPU, which include air and CO_2 compression as well as flue gas recirculation. The amount of energy that is required for air separation is roughly two times higher than that consuming during CO_2 treatment. Nowadays, the efficiency penalties of oxy-fuel power plant are assessed at roughly 7-9 percentage points, however the lower value correspond to the highly integrated and optimized OFC system. The shares of ASU, CPU and other equipment in the total auxiliary onsite power are presented in Fig. 7 (based on Lockwood, 2014). The latest target of Air Liquide assumes the possibility of reducing the efficiency penalty to around 5 percentage points by 2020 (Paufique et al., 2013). It is believed that this aim might be achieved mainly by advances in ASU and CPU and thermal integration of the units as well as by oxygen preheating and optimization of FGR. The potential energy savings in future oxy-fuel power plant are illustrated in Fig. 8 (based on Paufique et al., 2013). Moreover, it is expected that improvements in FGD by means of fully dry abatement technology might lead to further reduction in energy losses.

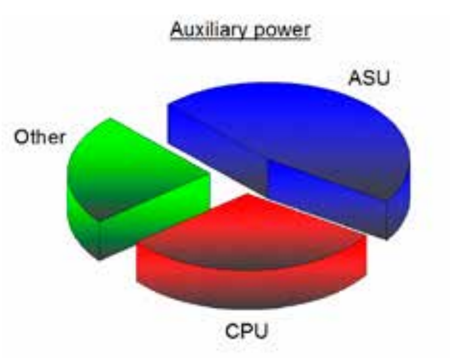

Fig. 7. Contribution of ASU, CPU and others in auxiliary power.

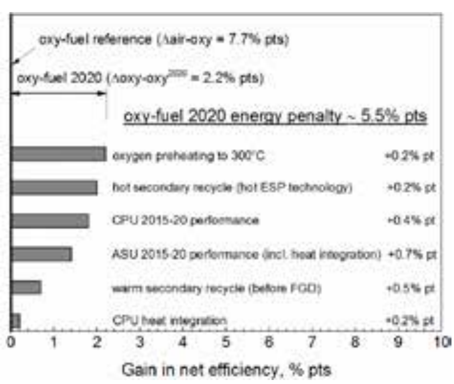

Fig. 8. Potential energy savings in future oxy-fuel power plant.

POLISH NATIONAL STRATEGIC PROGRAM ON OXY-FUEL COMBUSTION

Rapid development and great achievements all around the world in the field of oxy-fuel combustion encouraged polish government to begin in 2010 the national strategic program "Advanced Technologies for Energy Generation", which includes the project "Oxy-combustion technology for PC and FBC boilers with CO_2 capture" dealing with this promising technology. The project has been carried out by thee universities: Czestochowa University of Technology (CzUT), Silesian University of Technology and Wroclaw University of Technology; two R&D centers: Institute for Chemical Processing of Coal (IChPW) and Institute of Power Engineering (IEn); and four industrial partners: Tauron Wytwarzanie SA Lagisza Power Plant, PGE GiEK SA Turow Power Plant, Foster Wheeler Energia Polska and Eurol ITS. The core investigations have been conducted at three small pilot-scale combustion facilities: 0.1 MW_{th} CFB (CzUT), 0.2 MW_{th} PCFB (IChPW) and 0.5 MW_{th} PC (IEn). Moreover, two mobile units for air separation and CO_2 capture were constructed and tested in real environment. The achievements of this project are reported elsewhere (Czakiert, 2015).

Figure 9b. 0.2 MW_{th} PCFB facility.

Figure 9c. 0.5 MW_{th} PC facility.

Figure 9a. 0.1 MW_{th} CFB facility.

Figure 9d. Mobile VPSA-O_2 unit.

Figure 9e. Mobile VPSA-CO_2 unit.

THE INTRODUCTION TO PRESSURIZED OXY-FUEL COMBUSTION

Development a high-efficiency oxy-combustion design for pulverized combustion (PC), fluidized bed combustion at atmospheric (AFBC) and pressurized (PFBC) regime needs to consider the advantages and limitation of the mentioned technologies. In this section the benefits and limitations of pressurized boilers are considered and analysed. The first part is related to the comparison of the power generation efficiency, including air- and oxy-fuel technology. The other advantages and limitations are also discussed based on operational (real scale commercial units) and computational analysis.

ADVANTAGES AND LIMITATIONS OF PRESSURIZED COMBUSTION (AIR- AND OXY- REGIME)

Table 2 presents the comparison of main advantages and limitations of PFBC. Pressurized combustion, especially pressurized fluidized bed combustion, PFBC, has many advantages. One of the most important advantage is the possibility to obtain higher power generation efficiency than that of pulverized coal firing, given the same steam conditions (Shimizu, 2013). From the thermodynamic point of view, the main benefit obtained from pressurized fluidized bed is the possibility of increasing plant efficiency by coupling a Rankine cycle with a gas turbine (Franco and Diaz, 2009). PFBC technology is able to receive very low emission of gaseous pollutants and particulates. It is known that higher pressure in the combustion chamber creates a preferential conditions to inhibit NO_x creation during combustion process (Lasek et al., 2013). Moreover, when additional methods of pollutants removal are applied (e.g. selective catalytic reduction (SCR) of NO_x) then ultra-low emission can be achieved. For example, it was reported from the running experience of 250 MW_e PFBC boiler (The Osaki PFBC plant, The Chugoku Electric Power Co., Inc.) that emission of SO_2 and NO_x was only 7.1 ppm and 14.4 ppm respectively (Komatsu et al., 2001). However, PFBC technology has limitations that are mainly related to high investment and operating costs. It was estimated by Research Institute of Innovative Technology for the Earth (RITE) (Wang et al., 2009) and reported by Shimizu (2013) that in Japan the cost per unit of PFBC power generation achieved the range of ¥320000/kW. For the comparison, the cost of pulverized coal firing boiler with ultra-supercritical steam with the net HHV efficiency of 40.9% was only ¥230000/kW.

Table.2: The comparison of main advantages and limitations of PFBC.

Advantages	Limitations
The possibility to obtain higher power generation efficiency (Shimizu, 2013) Lower NOx (Lasek et al., 2013; Komatsu et al., 2001) and N_2O (Shimizu, 2013) emission Reduction in pollutant emissions and an enhancement in the intensity of reaction (Wall et al., 2002) Limitation of the yield of tar during devolatilization stage (Shimizu, 2013) The smaller size of a boiler at the same capacity as an atmospheric unit (Murakami et al., 2009; Murakami et al., 2010)	Higher investment costs (Shimizu, 2013) The weight of the pressure vessel (Shimizu, 2013) Longer conservation time after the shutdown of a boiler. Shorter operational time due to erosion-related problems (Shimizu, 2013) Limitation in fuel flexibility comparing to atmospheric units (Shimizu, 2013) Increase of risk of hot-spot formation under higher pressure (Shimizu, 2013) Agglomeration and slagging of the bed when the local temperature increases more than 1100°C (Ishom et al., 2002)

Pressurized oxy-fuel combustion (POFC) is also suggested as a one technology within clean coal technologies (CCT). Due to potentially higher power generation efficiency, it was suggested that pressurized oxy-fuel combustion systems had the potential of better performance over conventional atmospheric oxy-fuel combustion power cycles (Hong et al., 2009). It is known that oxy fuel systems have a lower efficiency comparing to air-fired units due to the energy penalty of the additional and necessary systems like air separation unit, CO_2 purification and compression, feed water pump and fun compression work. Most of the parasitic power demand comes from the air separation unit which consumes nearly 20% of gross power output (Hong et al., 2009). Fig. 10 shows the comparison of net power and parasitic power demand for the atmospheric oxy-fuel power cycle and the pressurized oxy-fuel power cycle, reported by Hong et al. (2010). Even the pressurized units needs more power for air separation unit, the overall net power output is higher due to "power saving" for CO_2 purification and compression. It was reported by Hagi et al. (2014) that energy penalty for conventional, atmospheric oxy-fuel units reaches 10% of efficiency comparing to conventional air-fired unit. For staged-pressurized oxy-combustion (SPOC) concept the penalty can reach as low as 3.8 %-pts only. Table 3 shows the comparison of the main parameter of pressurized air- and oxy-combustion units. It can be seen that the pressurized unit can reach (theoretically) the net efficiency as high as 43.6%. However, it should be explained that such achievement is a challenge for material science to provide efficient and not so expensive material that can be able to meet the requirements of the pressurized combustion and steam under ultra-supercritical conditions.

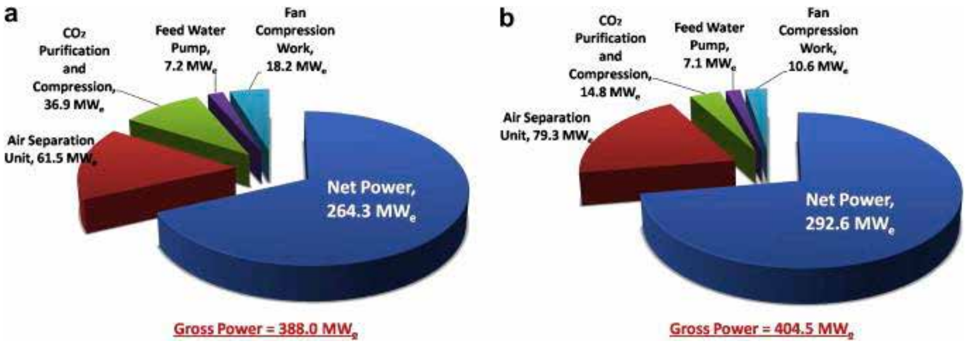

Fig. 10. The comparison of net power and parasitic power demand for the atmospheric oxy-fuel power cycle (a) and the pressurized oxy-fuel power cycle (b), reported by Hong et al. (2009).

Table.3: The simplified comparison of the main parameter of pressurized air- and oxy-combustion units.

Unit	Plant output (net)	Operating pressure in a chamber, bar	Steam conditions	Plant gross thermal efficiency, %	Fuel	Ref
Air-fired units (results from real-condition run of a boiler)						
Chugoku Electric Power Co. Osaki Power Station PFBC	2x250 MW	9.59	16.6 MPa 566/593°C	41.5	Coal	(Shimizu, 2013; Tomo, 2003)
Kyushu Electric Power Co. Karita Power Station PFBC	360 MW	13	24.1 MPa 566/593°C	42.5	Coal	(Shimizu, 2013; Tomo, 2003)
Hokkaido Electric Power Co. Tomato - Atsuma Power Station PFBC	85 MW	9.5	16.6 MPa 566/538°C	40.1	Coal	(Shimizu, 2013; Tomo, 2003)
Oxy-fuel units (modeling)						
				Net efficiency		
(wet recycling), coal water slurry added to combustor (flue gas temp. 1550°C)	239 MW (60% Thermal load flexibility)	7.41		31.61	Coal, LHV=29.88 MJ/kg	(Zebian and Mitsos, 2014)
	109 MW 30% Thermal load	7.41		24.48	Coal, LHV=29.88 MJ/kg	(Zebian and Mitsos, 2014)

	flexibility					
	358 MW 90% Thermal load flexibility	7.41		34.55	Coal, LHV=29.88 MJ/kg	(Zebian and Mitsos, 2014)
wet-recycling pressurized oxy-coal combustion process with carbon capture and sequestration	409 MW	7.41		34.34	LHV=29.88 MJ/kg	(Zebian and Mitsos, 2013)
	401 MW	8.92		33.23	LHV=25.23 MJ/kg	(Zebian and Mitsos, 2013)
300 MWe wet-recycling pressurized oxy-coal combustion process with carbon capture and sequestration		5.75	25 MPa 600 /610°C	34.48	LHV=29.88 MJ/kg	(Zebian et al., 2012)
A 300 MWe coal-fired power plant (efficiency in function of pressure, 10 bar opt)	300	10	25 MPa 600 /610°C	35		(Hong et al., 2010)
Coal water slurry, (flue gas temp. 1550°C)	292.6	10	25 MPa 600 /620°C	34.9	Coal, LHV=27.971 MJ/kg	(Hong et al., 2009)
Staged, Pressurized Oxy-Combustion (SPOC) 550 MWe plant	302-513	16	n/a	n/a	Pulverized coal, HHV= 20.47 MJ/kg	(Xia et al., 2016)
573 MW pressurized oxy-coal combustion with supercritical steam cycle. (flue gas temp. 1550 °C)	573 MW	10	25 MPa 600 /620°C	43.62	Pulverized coal slurry (bituminous) HHV= 32.51 MJ/kg	(Aneke and Wang, 2015)
Staged, Pressurized Oxy-Combustion (SPOC) 550 MWe plant	555	16	24.2 MPa	36.7	HHV=20.47 MJ/kg HHV=27.11 MJ/kg	(Gopan et al., 2014)
Staged, Pressurized Oxy-Combustion (SPOC)	894 MW	16	30 MPa 600 /620°C	42.3	LHV=26.7 MJ/kg	(Hagi et al., 2014)
Pulverized boiler, flue gas temp. (flue gas temp. 1550°C)	578	10	28 MPa 600 /610°C	34.5	LHV=25.17 MJ/kg	(Soundararajan and Gundersen, 2013)
300 MWe wet-recycling pressurized oxy-coal combustion process with carbon capture and sequestration.		5.75	25 MPa 600 /610°C	34.48	Coal water slurry LHV=29.88 MJ/kg	(Lasek et al., 2015)

THE SCALING UP OF PRESSURIZED COMBUSTION IN OXY-FUEL REGIME

Despite of the many advantages of pressurized oxy-fuel combustion, it should be explained that this technology is still waiting for the full development and scaling up to commercial level. At the present, the scale of POFC reaches the scale of technical scale (process development unit, PDU). Fig. 11 presents the scaling up of POFC realized in Institute for Chemical Processing of Coal, IChPW. The first step was to investigate kinetic of combustion at oxy-fuel regime under higher pressure. It was observed that increase of pressure caused the decrease of combustion activation energy. The increase of total pressure caused the increase of partial O_2 pressure and, as a consequence, overall chemical reaction rate was increased. During experiment of oxy-fuel combustion using pressurized BFB it was observed that the change of combustion regime from air- to oxy- fuel mode caused significant reduction of NO_x emission (more than 75%). Increase of pressure caused further enhancement of NO reduction achieving the level of 200 mg/m_n^3 at 6% O_2. The application of low O_2 concentration in the oxidant (~15 v.%) at higher pressure (6 bar) caused ultra-low NO emission less than 20 mg/m_n^3). The transition period between air- and oxy-fuel regime for BFB (smaller scale) and CFB (bigger scale) was 20 minutes and 50 minutes respectively. The scaling up of the POFC boilers are promising due to potentially high energy conversion efficiency (see Table 3). However, modelling of the system should be confirmed by the experimental investigations at real, demo-scale. Fig. 12 (Lasek et al., 2015) shows the comparison of dynamic characteristic obtained from flexible transition from air- into oxy-fuel regime using the experimental rig at different scale. The transition time is very important to flexible regulation of energy delivery from power plant when change of combustion regime is necessary.

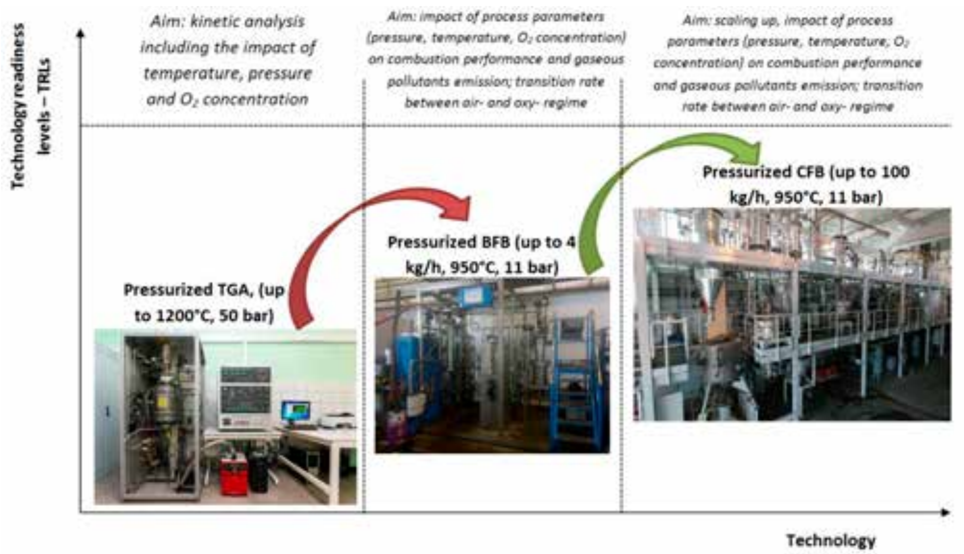

Fig. 11. The experience in scaling up of pressurized oxy-fuel technology, realized in IChPW.

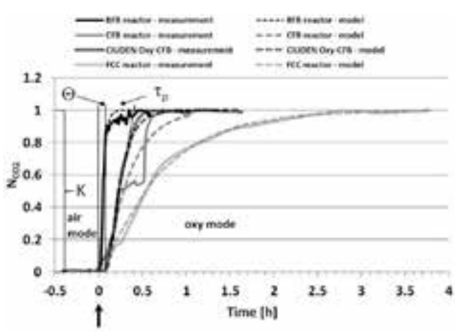

Fig. 12. Dynamic characteristic of transition process between air- into oxy-fuel mode for four facilities – normalized CO2 flow output against time.

SUMMARY

The oxy-fuel combustion is a mature technology ready to demonstration in a large scale, which can be considered for the retrofit of older boilers as well. The crucial benefit of oxy-fuel performance is a highly concentrated stream of CO_2, which leaves combustion chamber directly. The main disadvantages are the separation of air in large quantities and the treatment of contaminated flue gas prior to the transport and storage of recoverd-CO_2. The cryogenic method is recommended for both air separation and CO_2 capture. However, the key point concerning this technology is the energy penalty, which reduces the power plant net efficiency by roughly 9%, at present. Therefore, further development of oxy-fuel combustion requires advanced methods to be applied in OFC systems in order to minimize the internal power consumption. Moreover, the legal regulations together with a public awareness seem to be of great importance.

The pressurized performance of oxy-fuel combustion has already revealed significant environmental benefits. An increase of pressure helps to reduce the total NO_X emissions. In fact, increasing pressure does not significantly influence NO creation but does create preferential conditions for NO reduction on the char surface. Also, some selected experimental work concerning BFB oxy-combustion revealed also a decrease of SO_2 emission under pressurized conditions; however, the issue needs more particular studies.

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