GHGT-11

Pursuing the oxy-fuel light-/heavy oil retrofit route in oil refineries - A small scale retrofit study

Morten Seljeskog, Alexis Sevault, Mario Ditaranto

SINTEF Energy Research, N-7465; Trondheim, Norway

Abstract

Two commercial, one light- and one heavy oil burner for a CEN 250 kW boiler was modified by simple means to allow for operation at controlled dry oxy-fuel conditions. The variables measured for both air- and oxy-firing were the flue gas components; CO_2, CO, O_2 and NO_x, the flue gas exit temperature and boiler water temperatures (in/out). Both burners were run on air based base cases for comparison. The light- and the heavy oil burners were fired at 90 kW and 130 kW, respectively. For the light oil burner an experimental matrix consisting of five runs on air with varying excess air, $\lambda = 1.1$-1.25, ratio was performed. For each of the air-fired runs five additional cases were run, with a mixture of O_2/CO_2 replacing the air as oxidizer, with constant X_{O2} and increasing X_{CO2}. However, for the heavy oil burner only two base cases where run at λ=1.15 and 1.25 and compared to oxy-fuel conditions with fixed X_{O2} and varying CO_2 dilution. The main reason for the low number of runs with heavy oil was the large amounts of soot formed, which made heat flux measurements rather difficult.

The results for the light oil burner show that on the average, the flue gas volume when shifting to oxy-firing is about $\times 0.7$ times the volume when firing with air. A mass based comparison show that shifting from air- to oxy-firing, on the average results in a reduction in NO formation, an increase in CO, CO_2 and O_2 in the flue gas of about 19, 2.4,4.1 and 4.3 times, respectively. For light fuel oil the flame temperature for air- vs. oxy-firing coincides at around 35-37 % O_2 through the burner. Although radiation measurements with light fuel oil was only measured in a single point, it was noticed that the measured radiation flux tends to increase linearly with increasing O_2 concentration, on the average about $\times 1.5$ higher than with air-firing.

For heavy fuel oil firing it has been shown that close to air-firing conditions can be reached at oxy-fuel operation at around 30/70. However, peaks of around $1.4 \times$ air firing were observed at certain positions. As with light fuel oil oxy-fuel experiments, heavy fuel oil seemed to be just as adaptable to oxy-firing. Also here no operational problems were observed and it is possible to achieve stable oxy-fuel conditions similar to that of air-firing.

The main conclusion so far, based on the current experience with simple oxidant switching burning light- to heavy oil on an existing burner/boiler geometry, indicates that operation similar to air-fired burner/boiler behavior is easily achievable. Besides the large amount of soot formed during heavy oil combustion no operating or technical difficulties were experienced with any of the retrofitted burners and combustion conditions comparable with air firing in terms of ignition, flame stability and flame shape was achieved in the oxy-firing mode.

1. Background

Both heavy residual fuel oil and heavy crude oil has very high viscosity and needs to be heated in special heating systems before use. Compared with lighter liquid fuels it contains rather high amounts of pollutants. Some common characteristic properties of heavy oil are; high specific gravity, low hydrogen to carbon ratios, high carbon residues, and high contents of asphaltenes, heavy metal, nitrogen and sulphur, where the latter forms sulfur dioxide in the combustion process. Also, because of its high carbon content the emissions of soot is significantly higher than for lighter liquid fuels. However, all these undesirable properties make it the cheapest liquid fuel available. The necessity for pre-heating combined with emission limitations has reduced its use mainly to power plants and larger ships. Heavy residual fuel oil is a "by-product" from refinery production while heavy crude oil is found in reservoirs around the world. Around thirty or more countries are known to have reserves. The largest heavy crude oil reserve in the world is located in Venezuela. Heavy crude oil has over the last years become an important factor in the world economy since the known reserves accounts for a significant part of the worldwide energy resources. Known resources of heavy crude oil in the world are more than twice those of conventional light crude oil.

As a first step towards a re-introduction of heavy oil in combustion processes one obvious way is to utilize the residual heavy oil available in refineries combined with the oxy-fuel CCS option. Most energy intensive companies of today have high priority on reducing their current carbon footprint and several initiatives are initiated to evaluate specific technologies for CO_2 capture and sequestration (CCS). Among the energy intensive processes are a variety of processing industry such as oil refineries which emit large amounts of CO_2 mainly through gas turbines, fluid catalytic crackers and fired heaters fossil fuel consumption, emitting 20-50 %, 20-50 % and 30-60 % of total refinery CO_2 emissions respectively [1]. Among these, the direct fired heaters are generally one of the largest emitters and are also the focus of the current work. Direct fired heaters are found in many process industries and are commonly used to heat gaseous and liquid fluids, such as distillation column feeds and reactor feeds. The heaters presents challenges of obtaining satisfactory heat transfer to the process fluid by adjusting the temperatures so that coking and metallurgical damage to the conduit is avoided. Oil and gas are the most common process heater fuels. Such fuels are often rest products from the refinery itself.

As of lately Shell is one among several larger re-finery companies which are investigating the oxy-fuel CCS option for direct fired heater implementation. Shell is investigating the effect of replacing combustion air with a mixture O_2 and CO_2, and a mixture of O_2 and typical re-circulated flue gas, on the adiabatic flame temperature, the flammability envelope and the flue gas emissivity. In addition Shell has performed simulations to compare the performance of a typical process heater on conventional air-firing to one retrofitted to oxy-firing. The economics of such a retrofit has also been evaluated [2].

One most interesting pre-combustion route for carbon capture and storage (CCS) in refineries is then the implementation of a retrofit oxy-fuel solution in the existing gas or oil fired heaters as illustrated in Fig. 1. The most intriguing concept is to keep all current heater configurations, including the burners, as is. The main reason for keeping as much as possible of the available structure is to keep the implementation cost low. The main goal of the current work is to retrofit two selected burners to oxy-fuel operation to prove the concept of switching oxidizer on existing configurations, both with light- and heavy

fuel oil. The burners were installed on a 250 kW CEN (Central European Norm) boiler. The only modification made on the burners was the confinement of the air intake allowing to supply controlled amounts of both air and mixtures of oxygen/CO_2 to allow for operation at controlled dry oxy-fuel conditions. The light fuel oil burner was fired with high quality oil containing less than 0.0005 N_2 as bound nitrogen, acquired locally as standard fuel oil N°1. The heavy oil was a commercial product know as Shell bunker oil MFO 380 [3].
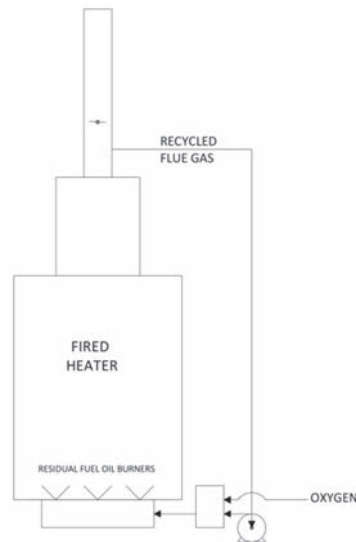

Fig. 1: Oxy-fuel fired heater retrofit approach

1.1. Main differences when switching from air to oxy-fuel combustion

Oxy-fuel combustion has several basic advantages, including high flame temperature, enhanced stability, low exhaust gas volumes and low NO_x emission. For heating and melting furnaces, productivity and energy efficiency can be greatly enhanced by using the oxy-fuel combustion because the unnecessary heating of nitrogen in air is eliminated. In the oxy-fuel combustion, the volume of exhaust gas significantly decreases and the zero NO_x emission can be achieved theoretically if no nitrogen is present through air infiltration or inherent nitrogen in fuel or oxygen.

The most widespread use of oxy-fuel combustion for power processes is for pulverized coal in an atmosphere of nearly pure oxygen which is mixed with recycled flue gas. Almost pure oxygen for combustion is produced in cryogenic air separation units and is mixed with recycled flue gas. The main similarities and differences between oxy- and air firing have already been established and are mostly related to coal combustion [4]. It has been shown that a recirculation rate between 65-75% can maintain combustion conditions similar to air-fired operation. To achieve a similar adiabatic flame temperature the O_2 concentration must be higher, typically 30%, higher than that for air of 21 %, and require about 60 % flue gas recycling. Increased concentrations of CO_2 and H_2O in the flue gas result in higher gas emissivities. However, comparable radiative heat transfer for oxy-fuel retrofit can be obtained when the O_2 concentration of the gases passing through the burner is less than 30 %. Typically, when air firing oil or coal about 20% excess air is used. Oxy-firing requires excess O_2 for complete burnout in the same order as with air-firing, between 3-5 %. Switching to oxy-fuel results in increased flue gas density and heat capacity but also reduce the flue gas volume significantly. Overall, this results in increased heat

transfer in the radiative section and lower heat transfer in the convective downstream boiler section.

Mixing the recycled flue gas with the oxygen is necessary because materials of construction currently available cannot withstand the high temperature resulting from combustion in pure oxygen. Tests have shown that in order to obtain similar heat transfer characteristics for an oxygen/recirculated flue gas flame as for an air fired system, an oxygen level of between 30-35 vol% is required [5]. Pilot scale studies in 2000 on a 3 MW_t coal combustion pilot by Energy & Environmental Research Center (EERC) for Argonne National Laboratory (ANL) showed that for wet and dry recycle; an oxygen concentration of respectively 23.8 % and 27 % through the burners is required to match the heat transfer performance of air-fired combustion. The same experiments also showed that for a wet recycle ratio of 0.76 and for a dry recycle 0.73 the overall heat transfer performance compared with air was matched [6].

Ditaranto and Oppelt [7], found in laboratory scale flames of low Reynolds number that similar heat flux distributions and radiant fraction values were found for air combustion and 35% O_2 in CO_2, despite a difference in flame temperature.

Concerning retrofitting existing installations, the O_2-concentration parameter can be tuned to increase radiative heat transfer at the expense of convective heat transfer zones further from the flame [8]. This is in contrast to air-fired systems, where approximately half of the heat transfer occurs in the boiler and the balance of the heat transfer is convective in the downstream passes. In both retrofit and new systems, the changes inherent in oxy-combustion affect many parameters; including flame behavior, heat and mass transfer, combustion gas chemistry and behavior, char burnout, and slag development, chemistry, and deposition.

In Table 1 two calculated factors based on the amount of radiating gases for air- and oxy-firing is shown [4]. Two methods are used to calculate the temperature profile in radiant boilers in open cycle MHD system. The first method, essentially a one dimensional technique, assumes that the gas radiates to the immediate surrounding wall with the exception of the entrance and exit end walls. The emissivity and absorptivity of the gas is taken from the Hottel chart, which is based upon an assumed mean beam length, local temperature, and molecular local concentrations of CO_2/H_2O. A second method, the zone method, is used to perform the corresponding calculations, and the results of the two methods are compared.

Table 1. Comparison of amount of radiating gases [4]

Factor	Air	Oxy-firing	Implications
$CO_2 + H_2O$	0.3	0.9	Higher emissivity
H_2O/CO_2	1	0.1 (wet)	
		0.2 (dry)	

Some preliminary results shown in Fig. 2, also from coal combustion, illustrate the difference in heat flux to the boiler walls for air- and oxy-firing [9]. The tests were performed in Doosan Babcock's oxy-fuel retrofit full-scale burner test facility at Renfrew in Scotland. Results show a lower heat flux to the walls. Also here the results for coal can to a certain extent be used as an indication of what to expect when oxy-firing oil/heavy oil.

Work done by RWE on radiative and convective heat transfer in oxy-coal combustion concludes that for dry recycling [9] the air operation radiative heat flux is equivalent to 72-75 % recycle ratio due to different radiative properties of carbon dioxide compared to nitrogen and that the radiative heat flux peak shifts downstream as recycle rate increases. It was found that convective heat transfer was equivalent to air at 74 % recycle ratio and that there is a recycle ratio for which both radiative and convective transfer can be reasonable matched between air and oxy-fuel operation and that it therefore will be possible to

design a boiler for efficient operation in both oxy-fuel and air conditions. In addition it was found that the flame stability decreases with increasing recycle ratio.

The authors observed from the measurements on oxy-fuel coal firing, that dry recycling tends to increase radiation [9]. Depending on the recycling ratio however, it was also possible to achieve the opposite. Whether the recycling is wet- or dry also affects radiation. Oxy-fuel operation, compared to air-firing, tends to smoothen the heat transfer through the boiler i.e. the high amounts of CO_2 and H_2O in the gas volume passing through the boiler absorbs radiation from the flame zone which then is transferred further down in the boiler by convection (see Fig. 2).
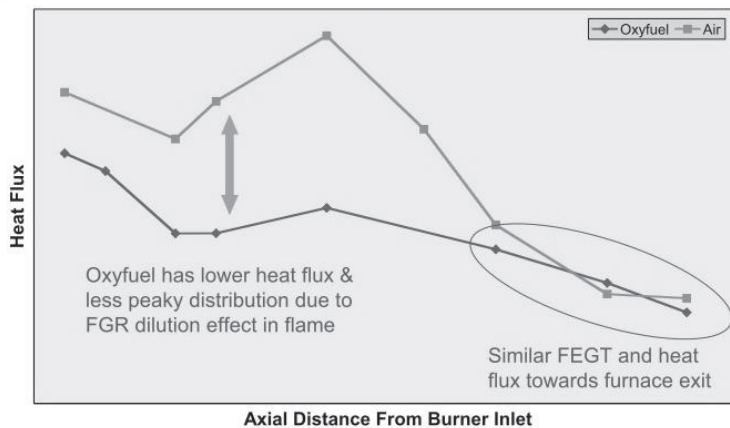

Fig. 2. Preliminary results, wall heat flux [9]

Results from retrofitting a 30 MW_{el} coal fired boiler for oxy-firing, have provided indicative oxy-firing parameters necessary to achieve similar boiler heat transfer as with an air-fired case. Results for coal can to a certain extent be used as an indication of what to expect when oxy-firing oil/heavy oil.

Table 2. Results from oxy-fuel with coal, retrofit demonstration scale (30 MW_e) [6],[10]

Cases	Air	Oxy-firing dry	Oxy-firing wet
% XS Air/O_2	20	3.5	4.6
O_2 vol% burner inlet	0.21	0.38	0.25
O_2 vol% flue gas	0.033	0.033	0.0033
$T_{Adiabatic}$ (K)	2200	2359	2040.7
T_{Gas}(K)	1432	1364	1348
Recycle ratio	-	1.36	2.55
Emissivity (Gas)	0.36	0.47	0.58
Emissivity (combined)	0.50	0.65	0.70
Associated heat	235.3	198.3	240.7
$Q_{Absorbed\ heat}$ (kW/m^2)	94.93	95.7	95.6

1.2. NO_x controlling with oxy-fuel

Because the progress of the oxygen separation technologies leads to continuously cut down the cost of oxygen, the oxy-fuel combustion might gradually gain popularity for the application of the high-temperature industrial combustion systems. Since it is difficult to perfectly eliminate nitrogen in oxy-fuel combustion, the NO_x emission control remains an issue. Both inherent nitrogen in oxygen or fuel and the air infiltration through furnace leakages are mainly responsible for the NO_x formation in the real oxy-fuel combustion systems. Therefore, in the design and application aspects of oxy-fuel combustors, furnaces or boilers, the NO_x emission should be minimized. In the case of air-fuel combustion, various methods, such as flue gas recirculation (FGR), premixing and staged combustion, have been developed and applied to reduce NO_x emissions. Much useful experimental data for various air-fuel combustion conditions is also available. On the other hand, experimental data for oxy-fuel combustion are quite limited. Ditaranto et al. [11][12][13] showed that the oxy-fuel combustion considerably increases thermal efficiency and has a pronounced potential to reduce NO_x emission. The authors observed that the NO_x emission is highly sensitively to air leaks into the combustion chamber.

When shifting from air to oxy-firing ideally no nitric oxides should form in the flame zone. The fuel used in the current experiments is a high quality fuel oil and should contain no bound nitrogen.

Then there are two more possible sources of nitrogen, which should be kept in mind. The first possible source is nitrogen rests originating from the production of O_2. The quality used during the experimental campaign is so-called industry quality with a purity of > 99.5 %. In the current work, it has been assumed a rest fraction of 0.2 vol% N_2 in bottled O_2. The second source of nitrogen then possibly originates from air leakage into the boiler. Normally the Central European Norm (CEN) boiler it kept at minimum an under-pressure of about 100 mbar to avoid exhaust leakage. Air leakage into large boiler installations is a known problem when using oxy-fuel. However, normally the NO_x formed from the nitrogen bound in the fuel largely exceeds what is formed by the nitrogen from air leakage.

In the current experiments, the oxidant is a mockup from bottled gas and operates in dry mode. In normal oxy-fuel operation, the flue gas would have been recycled either wet or dry. The recycled gas contains minor components as e.g. CO, unburned HC's, particles and NO_2/NO etc. This is not the included in the current investigation.

The combustion conditions of importance to nitrogen chemistry differ between the state of air and oxy-fuel operation due to the low concentration of air-nitrogen and the recycling of flue gases. Two combustion kinetic routes mitigating the emission of NO_x from oxy-fuel combustion are reburning and high-temperature reduction. Reburning reactions rapidly reduce NO_x, which is recycled back to the flame zone. Reburning is promoted by sub-stoichiometric combustion and by controlling combustion temperatures. The high-temperature reduction is made feasible by the low concentration of nitrogen in oxy-fuel combustion, which may reverse the Zeldovich mechanism (responsible for thermal NO_x formation) to reduce the NO_x formed from fuel-bound nitrogen. To achieve this result, a combustion strategy with low air-ingress, sub-stoichiometric conditions and high inlet oxygen concentration is required. In contrast with the strategy for reburning reduction, the combustion strategy for high-temperature reduction is not conventional, but benefits from reduced flue gas flow and efficient combustion [13]. Important strategies to reduce NO_x in oxy-combustion are to use increased recycling rate to reduce the temperature in flame zone and to avoid thermal NO_x because of the very low concentration of N_2 in the oxidizer. In addition there can be effects from reduction of recycled NO_x in the volatile matter release section and reburning by interactions between recycled NO_x and fuel-N and hydrocarbons released from coal may further decrease NO_x formation i.e. rapid reduction of recycled NO_x into HCN and NH. In addition, NO-char interactions may play a role.

2. Experimental Section

Measurements on light- and heavy fuel oil on two commercial burners refers to base cases, which are air as oxidizer. The experimental base-case set-ups consisted of in-house retrofitted light- and heavy oil commercially available burners retrofitted to operate both with air and with air fully replaced by O_2/CO_2. This was achieved in both burners, by confining the air-box mixing chamber of the original burners as illustrated in Fig. 4 (a) and Fig. 5 (b). The total inside depth of the combustion chamber and its diameter is 1000 mm and 397 mm, respectively. It is closed upstream by a water-cooled back-plate forcing the flue gases to turn 180° back along the combustion chamber surface and then return 180° into the water-cooled tubing system before reaching the chimney, as illustrated by the arrow in Fig. 6(c). The oxygen used is of industrial 2.5 quality and supplied by a pair of interconnected bottles. A battery of 12 bottles in series supplied the carbon dioxide.
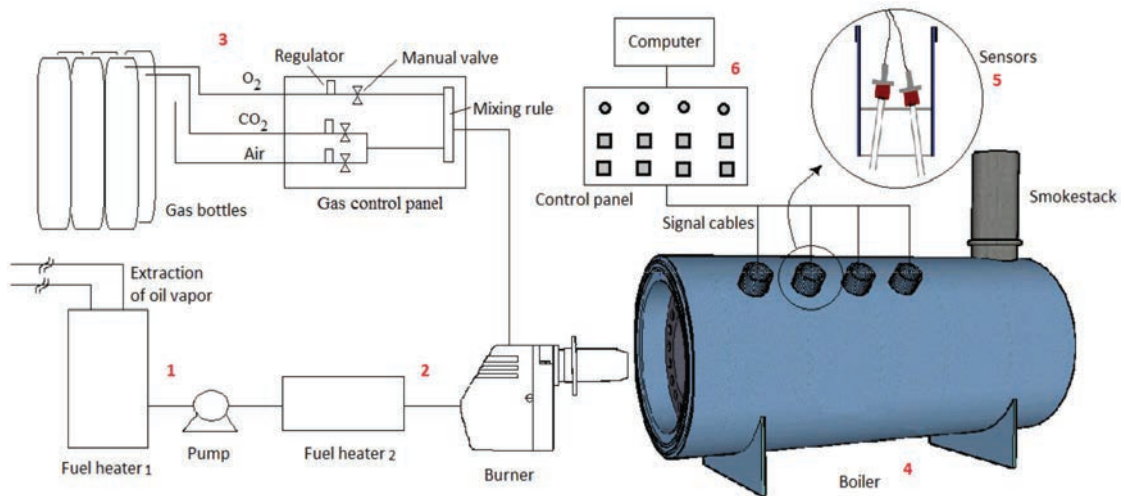

Fig. 3. Overview of the experimental setup

Light fuel oil was fired at room temperature of around 20 °C. For the heavy fuel oil, preheating was necessary. Heavy fuel oil was preheated in two steps. The first step heats the fuel up to 90°C. The second step heats the oil up to a preset temperature of 128 °C. Both steps are illustrated in Fig. 3 as fuel heater 1 and 2. Once the fuel had reached the preset temperature, the burner initiated its ignition sequence. Both for light and heavy fuel oil all experiments where initiated with air. The boiler system was then run for about 60 minutes to reach steady-state conditions, meaning a steady cooling water output temperature of 70°C. Having reached steady-state condition, a manual stepwise change was done by adjusting the mass flow controllers, to reach complete oxy-fuel operation. The boiler water cooling system automatically controlled the outlet water temperature set to 70 °C. For the light fuel oil cases, only one single 180° heat flux measurement was taken. For heavy fuel oil operation eight single point 10° confined points were taken along the combustion chamber axis. For both cases water-cooled Schmidt-Boelter sensors were used. For the light fuel oil case a single sensor was fixed in the first support tube. For the heavy fuel oil the sensors were fixed two by two in support tubes, placed into orifices in the boiler. To confine the viewing angle of the sensors and protect them from the intense convective heat flux from the flame, tubes where mounted between the sensors and the flame as shown in Fig. 6 (a) and (c).

2.1. Experimental setup light fuel oil

The burner was operated at nominal effect of 90 kW in the 250 kW rated CEN boiler. The mixing of the oxidant stream (O_2/CO_2) was achieved by counter flow mixing with an additional perforated pressure drop mixing plate. The original oil lance was kept as well as the end swirl plate and the flame tube as shown in Fig. 4(a). The burner nozzle and the swirl plate configuration is shown in Fig. 5(b) as well as the burner mounted on the boiler in Fig. 5(c). The original Weishaupt system controlled the burner and took care of oil-flow and ignition as well as flame monitoring.
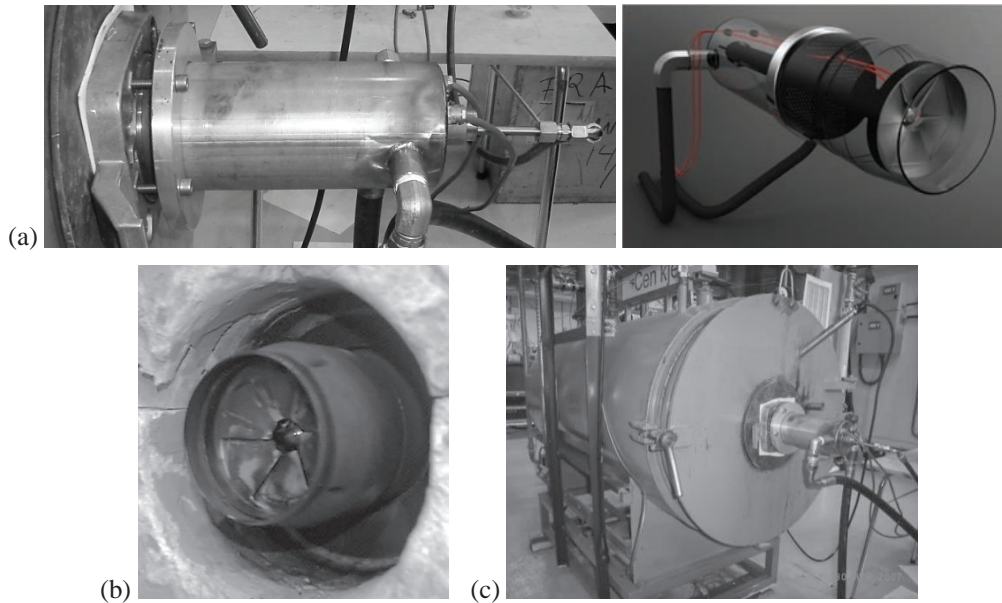
Fig. 4.   (a) Redesigned mixing chamber for the light fuel oil burner (b) swirl plate in flame tube and (c) burner mounted in boiler

2.2. Experimental setup heavy fuel oil

For the implementation of the oxy-firing with heavy fuel oil a commercial burner was procured, an Italian build named Riello RN28 [14] with a throughput between 10-20 kg/h oil as illustrated in Figure 5. The burner is a two-step burner operated only at the first step close to 130 kW during the experimental runs. The burner was delivered with an external in-house designed electrical preheating system able to pre-heat the fuel to about 90 °C. The second preheater accompanying the burner then took the fuel up to the final inlet temperature set at 128 °C. VV Parts AS in Oslo [15], Norway, supplied both the burner and the preheating system. The preheating system is illustrated in Fig. 3. The Riello RN28 burner with its accompanying preheat system is illustrated in Fig. 5(a). Fig. 5(b) illustrates the simplicity of adapting the burner to oxy-fuel operation, simply by confining the air intake.

The heat flux sensor system is illustrated in Fig. 6(a)-(c). The sensors are aligned two by two along the center axis of the combustion chamber and all our confined by a tube giving each sensor at 10° viewing angle. The main reason for confining the sensors is to be able to perform point wise measures along the flame. Fig. 6(c) shows the distance from the swirl plate flame holder to the midpoint viewed by each of the sensors with each sensor notation.
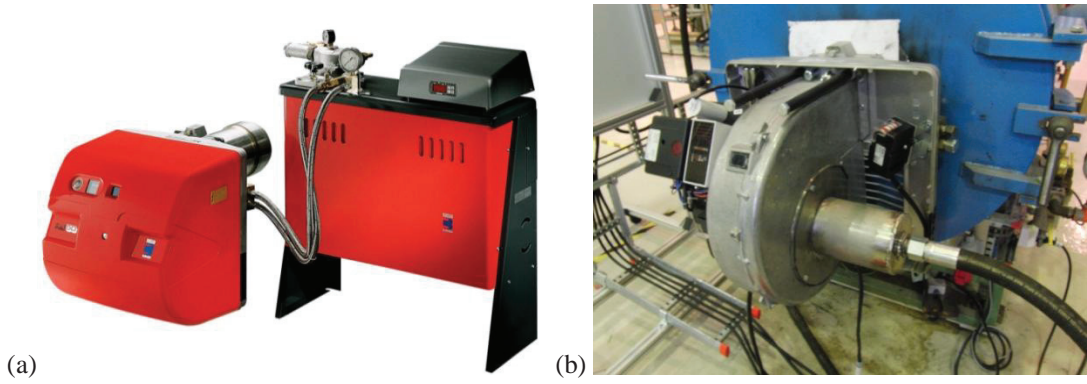
(a)　　　　　(b)

Fig. 5. (a) The Riello RN28 burner system [14] (b) retrofitted air-box
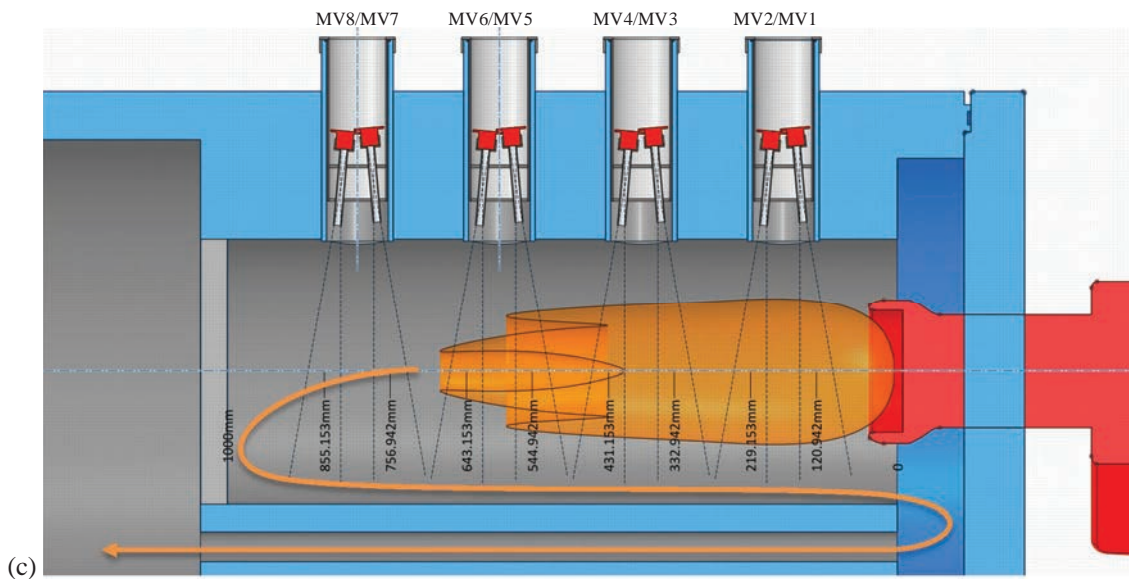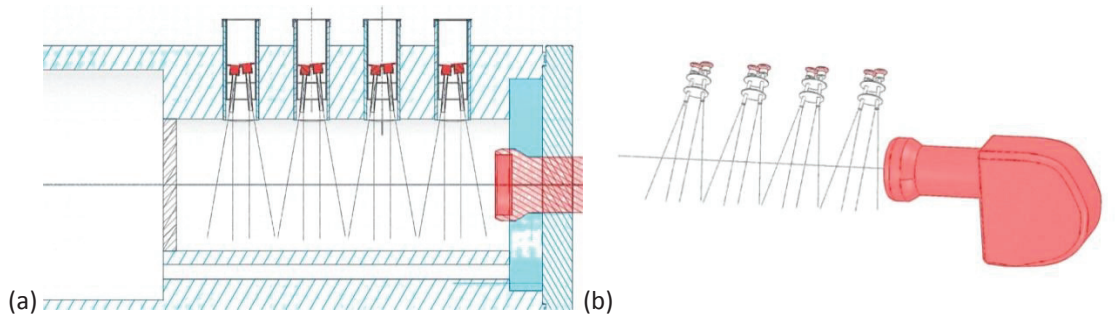

(a)　　　　　(b)

Fig. 6. (a) (b) sensor placement (c) heat-flux sensor placement and flue-gas flow pattern

2.3. Instrumentation

The flow of air and O_2/ CO_2 is controlled by mass flow controllers procured from Alicat Scientific, Inc.; a) MCR-500SLPM-D/5M, 5IN, Gas: O_2, b) MCR-2000SLPM-D-PAR-1.25/5M, 5IN, Gas: Air, Range: 2500slpm, c) MCR-2000SLPM-D-PAR/5M, 5IN, Gas: CO_2. The controllers are operated manually through a display panel on each of the controllers.

The analyzer, PG-250 Horiba, is specially adapted for measuring high CO/ CO_2 concentrations. It is a portable stack gas analyzer that can simultaneously measure up to five separate gas components using the same measurement methods used in Horiba's line of permanent Continuous Emissions Monitoring Systems (CEMS). The PG-250 is ideal for CEMS certification testing or for use when stack gas emissions must be monitored periodically at one or multiple stacks. The PG-250 uses non-dispersive IR detection for CO, SO_2, and CO_2; chemiluminescence (cross-flow modulation) for NO_x and a galvanic cell sensor for O_2 measurements. The CO/ CO_2 IR analyzer is also specially designed to measure very high concentrations of CO/CO_2.

In addition to the two above-mentioned analyzers, a portable gas-conditioning unit was acquired. The M&C portable gas-conditioning unit PSS-5 is designed to carry out precise gas analyses at different locations. The PSS 5 gas-conditioning unit was equipped with an ECP gas cooler with patented Jet Stream heat exchanger, which cools the sample gas to constant +5 °C independent of the ambient temperature. As soon as the operating temperature of +8 °C is reached after start up, the gas pump is switched on automatically via the status contact of the gas cooler. The SR 25.1 peristaltic pump ensures a constant condensate removal, which makes a long-term measurement possible without problems. The corresponding particle filtration is carried out by a filter type FP 2T.

Schmidt-Boelter heat flux gauges were used to measure the heat flux in W/m². Fig. 7 shows the general view of a sensor and its main components. These sensors are water-cooled, and can be used at temperatures between 800-1000 °C. When not water-cooled, the maximum body temperature is limited to about 200 °C. The body is made of copper generally. These sensors are made by winding a spiral of constantan wire around an electrically insulating wafer. The wafer is a high thermally conductive material usually made of anodized aluminum. This process creates a row of thermocouple junctions at the points on both sides of the wafer where the plating ends. This makes a thermopile with the wafer, which measures a temperature difference across the thermal resistance layer or wafer to determine the incident heat flux. The thermopile generates an output signal voltage, which is proportional to the heat flux, for a small temperature difference.

Fig. 7. General view of a Schmidt-Boelter sensor

The thermocouples on one side of the wafer produce a first signal when a wave of heat energy reaches them, and the thermocouples on the other side of the wafer produce a second signal when the wave of heat energy reaches them. The two signals combine to produce a second-order response. With conventional construction the only way to achieve fast response times is to use an extremely thin wafer. The accuracy supplied by the manufacturer is typically ± 3 %.

3. Results and discussion

3.1. Results and discussion - light fuel oil

The variables measured for both air- and oxy-firing were the flue gas components; CO_2, CO, O_2 and NO_x, the flue gas exit temperature and boiler water temperatures (in/out). In addition, a flux sensor was installed in one of the angled see-holes, measuring the radiated flux from the main flame zone. The measured volume based flue gas species concentrations were converted to mass base for a more correct comparison since both the oxidant and the flue gas volume streams changes significantly when switching from air to oxy-firing.

Table 3: Experimental matrix light fuel oil

Exp. no	Lambda	O_2	CO_2	Total flow of oxidant
		l/min	l/min	[l/min]
Air 1-1	1.25	375		1788
1-1	1.25	378	403	781
1-2	1.25	378	459	837
1-3	1.25	378	526	904
1-4	1.25	378	612	990
1-5	1.25	378	717	1095
Air 3-1	1.2	357		1705
3-1	1.2	357	493	850
3-2	1.2	357	526	883
3-3	1.2	357	605	962
3-4	1.2	357	701	1058
3-5	1.2	357	784	1141
Air 4-1	1.15	343		1636
4-1	1.15	343	403	746
4-2	1.15	343	459	802
4-3	1.15	343	531	874
4-4	1.15	343	612	955
4-5	1.15	343	717	1060
Air 5-1	1.1	328		1568
5-1	1.1	328	403	731
5-2	1.1	328	459	787
5-3	1.1	328	531	858
5-4	1.1	328	612	939
5-5	1.1	328	717	1044

The measurement strategy was to heat the boiler with air until steady-state conditions was reached. The planned matrix consisted of five runs with air with varying excess air ratio. The second matrix was run at wrong conditions and these results were disregarded. For each of the air-fired runs five additional cases were run, with O_2/ CO_2 replacing the air as oxidizer, and by keeping the amount of oxygen equal to each of the air-fired cases. In the subsequent runs the amount of CO_2 was increased stepwise, to dilute the

oxygen content down to a level were the flame potentially would become unstable/ extinguished. Performing the experiments with only one pair of oxygen bottles limited the experiments from being run until steady state. Each case was therefore run until acceptable stabilization of the measured flue gas composition was reached, for about 10 minutes, followed by subsequent registration of all measured variables. The results from the current experiments are based on the assumption of having 0.2 vol% N_2 in the O_2. Measurement accuracy was obtained from instrument documentation. Table 4 and Table 5 show the accuracy and the percent error for measured variables, respectively.

Table 4. Measurement accuracy

CO_2 +/- 2 %	0.98
CO +/- 2 %	0.98
O_2 +/- 1 %	0.99
NO_x (testo) +/- 5 %	0.95
NO_x Horiba +/- 1 %	0.99
Calibration gas: +/- 2 %	0.98
Rotameters +/- 1.6 %	0.98

Table 5. Measurement errors

Err NO	4.53
Err CO	5.50
Err O_2	4.53
Err CO_2	5.50
$T_{adiabaticcalc}$	9.23

The changes in oxidant- and flue gas volumes passing through the boiler are important when comparing air- to oxy-firing because it affects the heat transfer pattern, that is both the radiation and the convection pattern. Fig. 8 show the change in volumes related to the experimental matrix for the flue gas stream when switching from air to oxy-firing in the current burner/boiler configuration in kg/h and in m^3/h, respectively. We observe that on the average, the flue gas volume when shifting to oxy-firing is about x 0.7 times the volume when firing with air, assuming a flue gas temperature in the combustion chamber is proportional to the calculated adiabatic flame temperature.
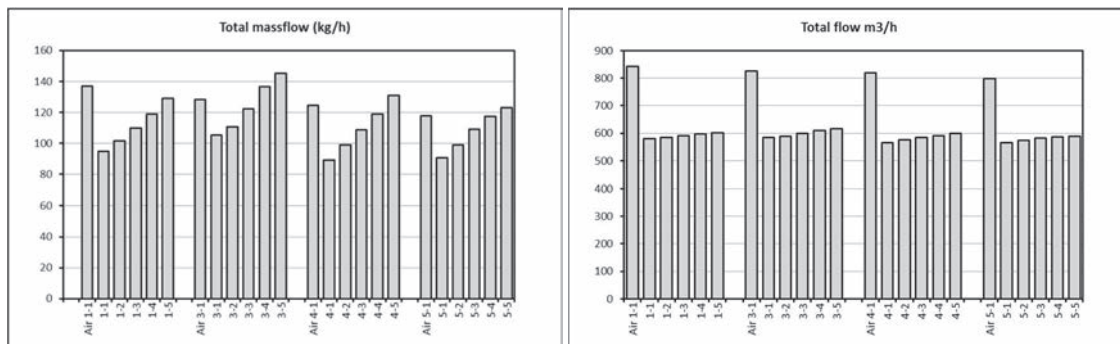

Fig. 8. (Left) Total flue gas mass flow for series 1, 3,4 and 5 vs. air (right) Total flue gas volume flow for series 1, 3,4 and 5 vs. air

The change in species concentration in the exhaust when changing from air- to oxy-firing occurs as expected, i.e. the main shift in species concentration on mass basis is from N_2 to CO_2. For minor species, the most striking shift is the drop in NO and the slight increase in CO. SO_2 from the fuel remains unchanged. Shifting to dry oxy-fired operation also shifts the composition of CO_2 and H_2O in the exhaust. Two commonly used factors used to illustrate the change in radiating gases when shifting to oxy-firing are (see Table 1), given by $(H_2O + CO_2)/V_{tot}$ (nl/nl) and H_2O / CO_2 (nl/nl) illustrates this shift. The ratios calculated from the current experiments correspond very well to the values referred to in Table 1 as showed in Fig. 9. Also note that the current experiments relate to dry oxy-firing imitating that water is condensed out before recycling the exhaust back to through the burner.
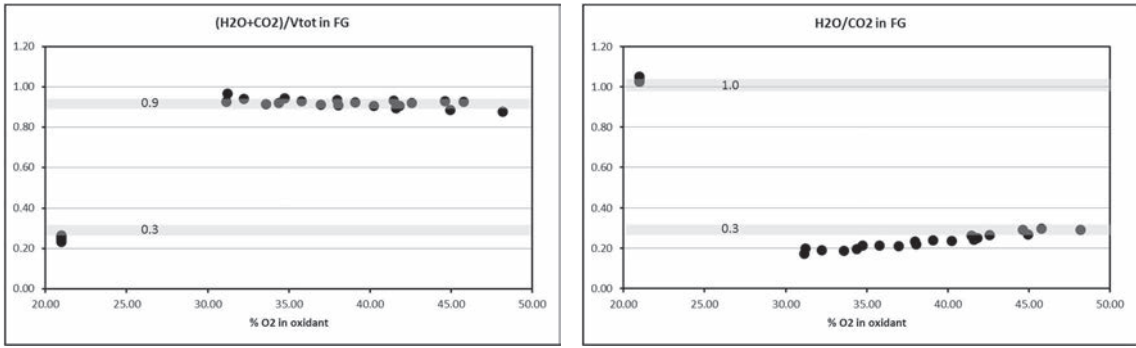
Fig. 9. (Left) Factor comparing the amount of radiating gases for air- vs. oxy-fired operation: H_2O / CO_2 (right) Factor comparing the amount of radiating gases for air- vs. oxy-fired operation: $(H_2O + CO_2)/V_{tot}$

As seen in Fig. 10 and Fig. 11, a mass based comparison shows that shifting from air- to oxy-firing, on the average results in a reduction in NO formation and an increase in CO of about 19 and 2.4 times, respectively. The CO_2 will increase about 4.1 times. The current experimental matrix also resulted in an overall increase in the O_2 concentration in the exhaust of about 4.3 times compared to air-firing.
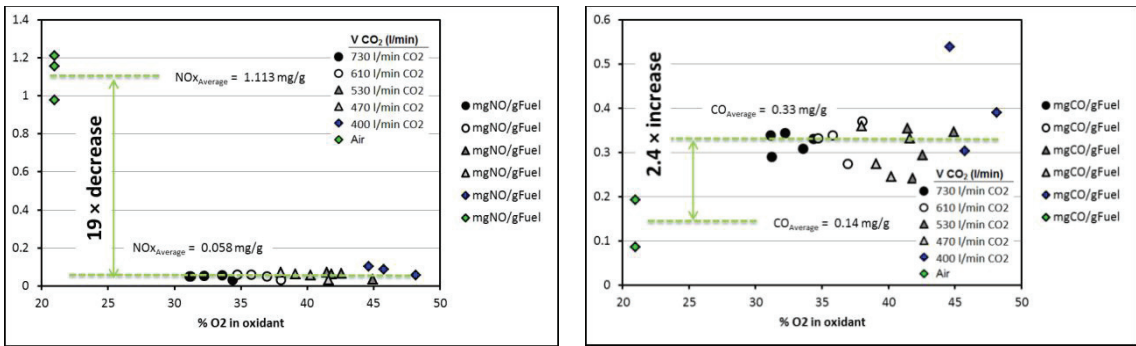
Fig. 10. (Right) Comparison with air - measured NO mg/g fuel vs. % O_2 in oxidant (left) Comparison with air - CO in mg/g fuel vs. % O_2 in oxidant
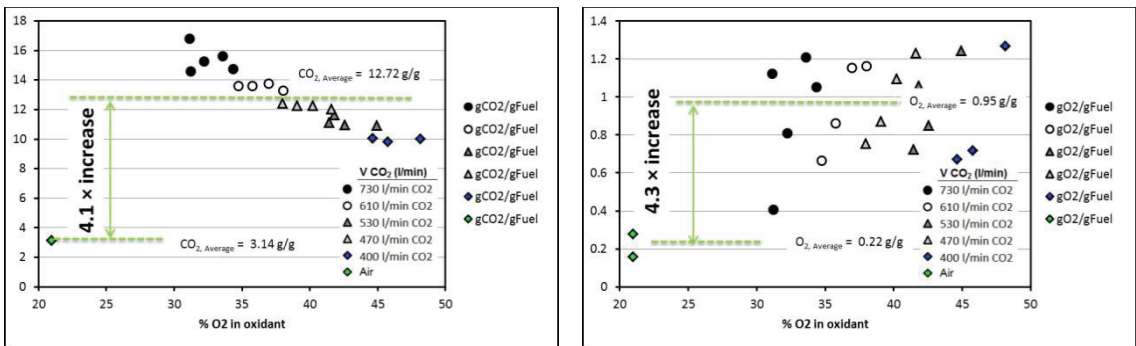
Fig. 11. (Right) Comparison with air - measured CO_2 in g/g fuel vs. % O_2 in oxidant (left) Comparison with air - measured O_2 in g/g fuel vs. % O_2 in oxidant

A further optimization seems necessary to lower the amount of unused oxygen down to a lower level without compromising flame stability.

The experiments showed that the flame temperature for air- vs. oxy-firing coincide at around 35-37% O_2 through the burner as seen in Fig. 12.
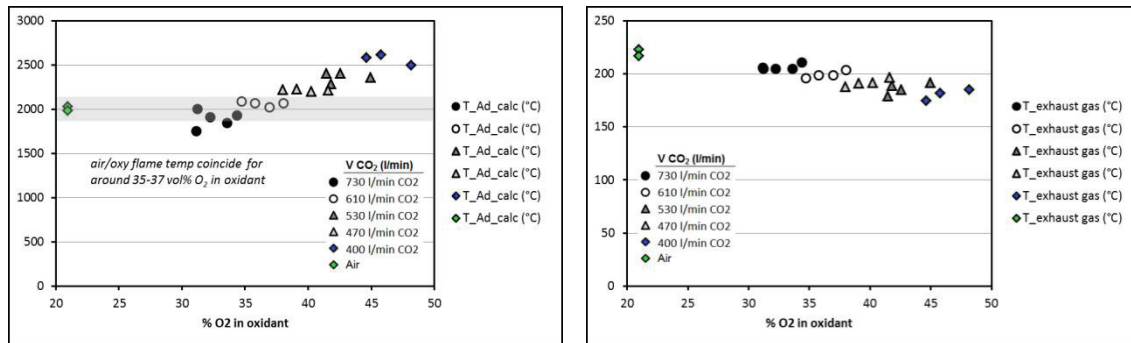

Fig. 12. (Right) Calculated adiabatic temperature, T_{Ad} ºC (left) Measured exhaust temperature $T_{exhaust}$ ºC

Oxy-firing tends to lower the temperature of the exhaust gas. When it comes to radiation, shifting to from air oxy-firing the measured radiation flux tends to increase as shown in Fig. 13 (left). At oxy-fuel conditions it increases with increasing oxygen content in the oxidizer. At the lowest experimental flow rate and lowest oxygen content, radiation levels with the air-fired case. However, one series shows reduced radiation compared with air and a further reduction as the oxygen content increases. From literature, it has been reported that when oxy-firing coal, both higher- and lower radiation has been measured. Experiments show that this depends mainly on the recycling rate and whether the recycling is wet or dry.
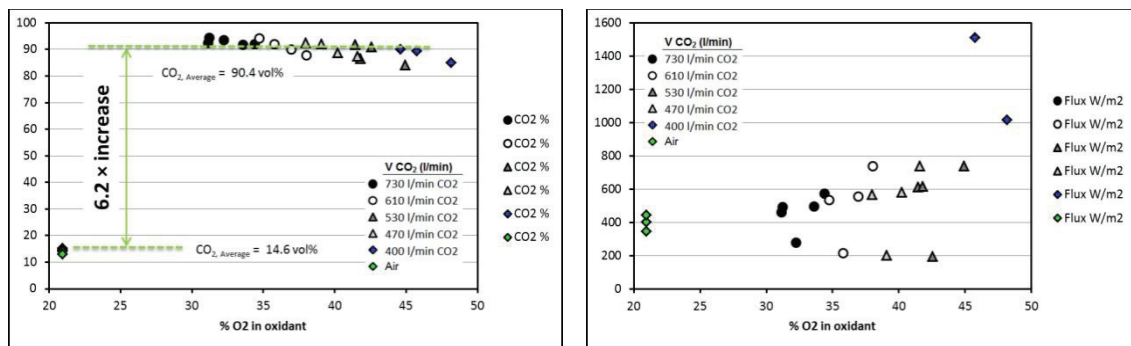

Fig. 13. (Right) Measured CO_2 concentration in the flue (left) Measured single point heat flux in W/m^2

3.2. Results and discussion - heavy fuel oil

For the heavy oil burner only two cases were run, that is at λ= 1.15 and 1.25. The main reason for the low number of runs with heavy oil was the large amounts of soot formed making heat flux measurements rather difficult. To avoid deposition of soot on the heat flux sensors the boiler was run at a higher under pressure to allow surrounding air to penetrate through the heat flux sensor confinement seats. This

penetration of surrounding air into the combustion chamber did not affect the combustion conditions but resulted in an unknown dilution of the flue gas, making the flue gas measurements unreliable. Fig. 14 pictures the measured heat flux with heavy fuel oil at $\lambda = 1.25$. This figure clearly illustrates the heating period, the transition period by manually reducing air while increasing O_2/CO_2 volumes to establish fully 50/50 O_2/CO_2 oxy-fuel conditions. The highest heat flux peak is observed at MV4 heat flux sensor position, both for air and act 50/50 oxy-fuel conditions. NO_x levels up to 200 ppm were measured as well as CO levels up to several vol%. Oxygen levels up to 6 vol% were measured, keeping in mind the dilution caused by the increased boiler under pressure to avoid soot deposition. It was also observed that significant soot deposition resulted in increased flue gas temperatures up until 450 °C as compared to normal operation of around 250 °C. A shift from air to oxy-fuel at 50/50 resulted in a radiation increase of around 1.7 times at the MV4 position, with an average radiation increase of about 1.4 for all sensors.
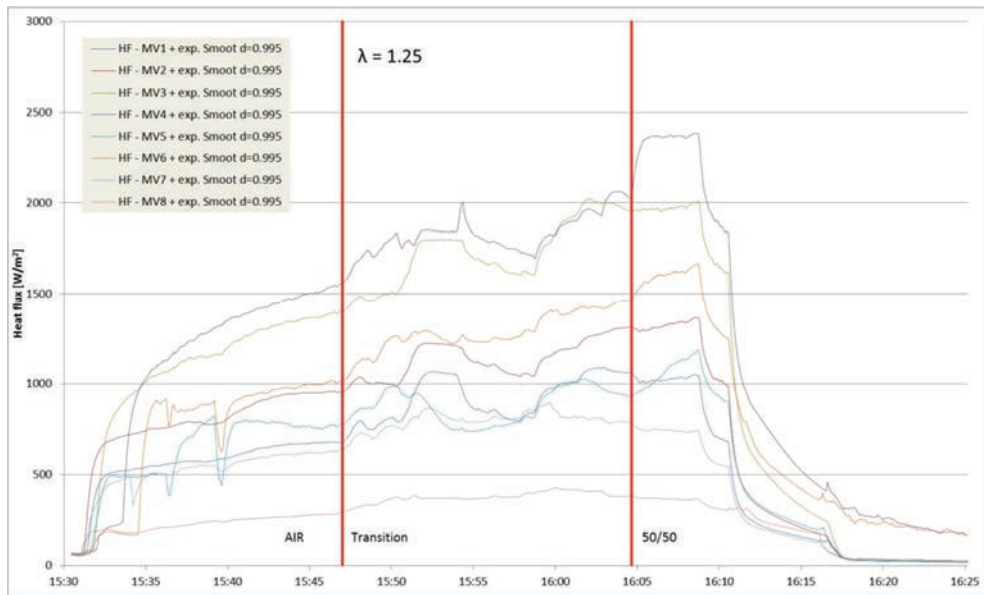

Fig. 14. Measured heat flux for heavy fuel oil experiment with $\lambda = 1.25$, illustrating stabilization with air, the transition from air to oxy-fuel, and fully oxy-fuel O_2/CO_2 equal 50/50. The MV_X notation relates to heat sensor MV1-8.
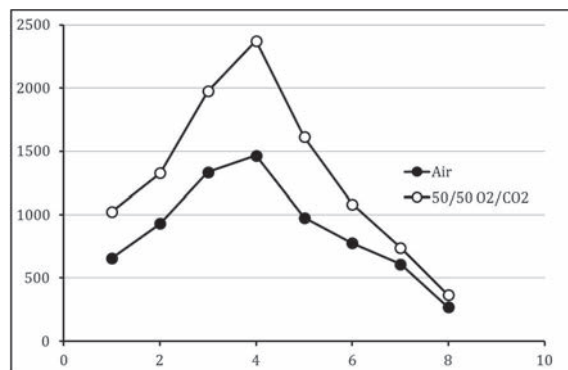

Fig. 15. Measured heat flux for heavy fuel oil experiment with $\lambda = 1.25$, averaged heat flux profile along combustion chamber axis.

Fig. 15 shows the averaged heat flux profile along the combustion chamber axis, illustrating the increased heat flux caused by oxy-fuel operation. No shift caused by oxy-fuel operation in the length direction was observed.

Fig. 16 illustrates the measured heat flux for heavy fuel oil experiment at $\lambda = 1.15$. This figure clearly shows the importance of comparing heat fluxes measured at boiler equilibrium. If rapid changes are done to the boiler system before thermal equilibrium has been reached, unexpected results might be measured. This is clearly seen in Fig. 16 were the measured heat flux at 30/70 clearly exceeds 50/50 operation.
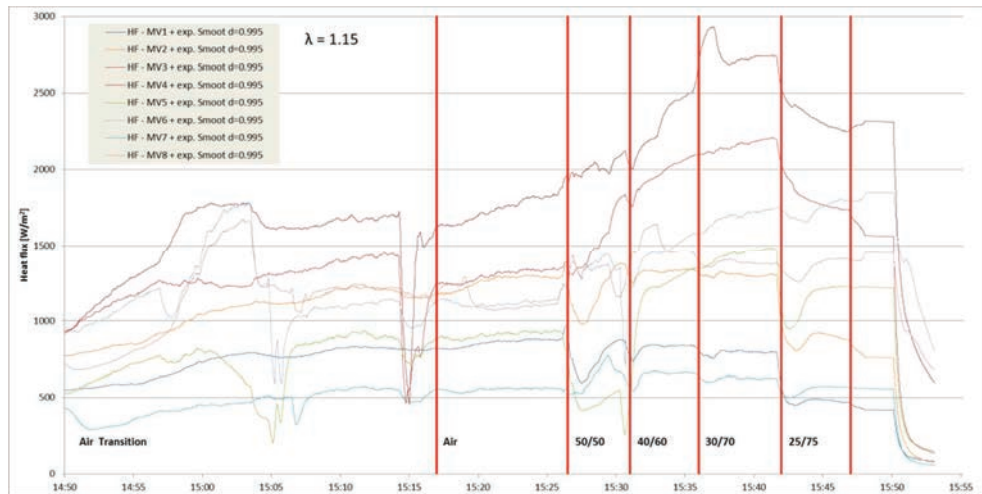

Fig. 16. Measured heat flux for heavy fuel oil experiment with $\lambda = 1.15$, illustrating stabilization with air during boiler heat up, air base case and then fully oxy-fuel O_2/CO_2 equal 50/50, 40/60, 30/70 and 25/75. The MV_X notation relates to heat sensor MV1-8.

A more idealized operation due to increased time for stabilization is illustrated in Fig. 17. In accordance with previous results the highest heat flux is measured at the MV4 position. Fully oxy-fuel operation at 50/50 increases the heat flux to about 1.4 above air-firing.
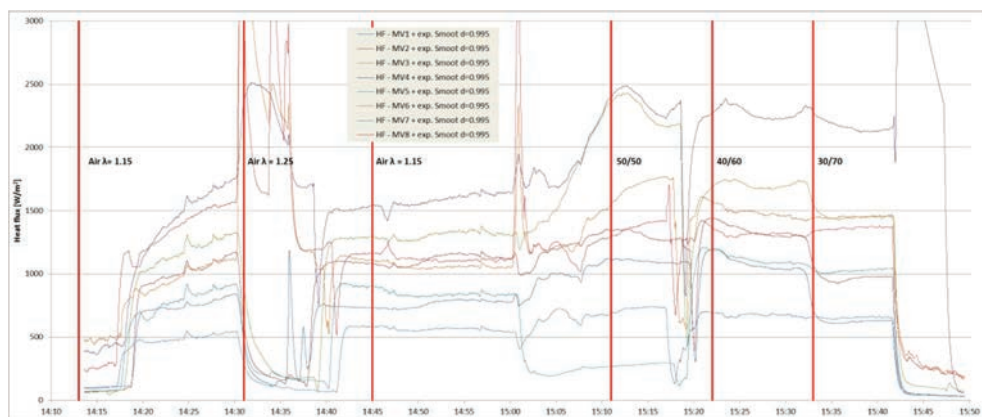

Fig. 17. Measured heat flux for heavy fuel oil experiment with $\lambda = 1.15$, illustrating stabilization with air during boiler heat up at $\lambda = 1.15$, changing to $\lambda = 1.25$, changing back to $\lambda = 1.15$ air base case and then fully oxy-fuel O_2/CO_2 equal 50/50, 40/60 and 30/70. The MV_X notation relates to heat sensor MV1-8.

Adjusting to 40/60 and 30/70 steadily decreases the heat flux. At 30/70 the measured radiation profile reaches that of air firing, except for the MV4 position which is still around 1.4 times higher than with air-firing.

4. Summary and conclusion

Two commercial, one light- and one heavy oil burner was modified to allow for operation at controlled dry oxy-fuel conditions on a 250 kW CEN boiler. The variables measured for both air- and oxy-firing were the flue gas components; CO_2, CO, O_2 and NO (as NO), the flue gas exit temperature and boiler water temperatures (in/out). The measured volume based flue gas species concentrations were converted to mass base for a more correct comparison since both the oxidant and the flue gas volume streams changes significantly when switching from air to oxy-firing. As a basis for the planned experiments on fuel oil, a base case experimental matrix consisting of five runs with air with varying excess air ratio was performed. For each of the air-fired runs five additional cases were run, with O_2/CO_2 replacing the air as oxidizer. This was the case for the light fuel oil experiments. However for the heavy fuel oil experiments, because of the large amounts of ash formed, only parts of the above matrix were run.

For light fuel oil the results show that on the average, the flue gas volume when shifting to oxy-firing is about 0.7 times the volume when firing with air. A mass based comparison show that shifting from air- to oxy-firing, on the average results in a reduction in NO formation and an increase in CO of about 19 and 2.4 times, respectively. The CO_2 will increase about 4.1 times. The current experimental matrix also resulted in an overall increase in the O_2 concentration in the exhaust of about 4.3 times compared to air-firing. The experiments indicate that the flame temperature for air- vs. oxy-firing coincide at around 35-37% O_2 through the burner. Concerning radiation, shifting to from air oxy-firing the measured radiation flux tends to increase. Regarding the running of the light fuel oil burner, no operational problems were encountered and it was possible to achieve stable oxy-fuel conditions similar to that of air-firing.

For heavy fuel oil firing it has been shown that close to air-firing conditions can be reached at oxy-fuel operation at around 30/70. However, peaks of around 1.4 × air firing were observed at certain positions. As with light fuel oil oxy-fuel experiments, heavy fuel oil seemed to be just as adaptable to oxy-firing. Also here no operational problems were observed and it is possible to achieve stable oxy-fuel conditions similar to that of air-firing.

Acknowledgements

References

[1] CO_2 abatement in oil refineries: fired heaters. Tech Rep, PH3/31, Foster Wheeler, IEA Green House Gas R&D Programme, 2000

[2] J. Jamaluddin, Oxy-Fired process heaters: A scouting study, technical session 2, Capricorn Resort, Yeppoon, Australia, 2011

[3] Shell marine products, http://www.shell.com /home /content /marine products /products /fuels /500cst/, 2011.

[4] PECS oxy fuel review, 31, 283-307, 2005.

[5] DOE, Oxy-fuel Combustion Fact Sheet, www.netl.doe.gov, August 2008

[6] T. Wall, Fundamentals of Oxy-Fuel Combustion, Oxy-fuel Combustion Research Network Vattenfall Europe, Cottbus, Germany, 29/30 November 2005

[7] M. Ditaranto, T. Oppelt, Radiative heat flux character-istics of methane flames in oxy-fuel atmospheres, Experimental Thermal and Fluid Science 35 (2011) 1343– 1350.

[8] M. Bruce G., 7 - clean coal technologies for advanced power generation, in: Clean Coal Engineering Technology, Butterworth-Heinemann, Boston, 2011, pp. 251– 300.

[9] J. Smart, P. O'Nions, G. Riley, E. Jamiesion, Radiative and convective heat transfer in oxy coal combustion, session 1a (Part 1), RWEnpower, Cottbus, Germany.

[10] G. Hesselmann, E. Cameron, D. Sturgeon, C. McGhie, F. Fitzgerald, Oxy-fuel firing and lessons learned from the demonstration of a Full-Sized utility scale 40MW OxyCoalTM combustion system, Johannesburg, South Africa.

[11] M. Ditaranto, J. C. Sautet, J. M. Samaniego, Struc¬tural aspects of coaxial oxy-fuel flames, Experiments in Fluids 30 (2001) 253–261.

[12] J. Sautet, M. Ditaranto, J. Samaniego, O. Charon, Properties of turbulence in natural gas-oxygen diffusion flames, International Communications in Heat and Mass Transfer 26 (1999) 647–656.

[13] J. Sautet, L. Salentey, M. DiTaranto, Large-scale turbulent structures in non-premixed, oxygen enriched flames, International Communications in Heat and Mass Transfer 28 (2001) 277–287.

[14] Riello, Riello burners - burners for boilers - gas burners - light oil burners - dual fuel burners, http://www.rielloburners.co.uk/index.php?section=98, 2011.

[15] http://www.vvparts.no/