



RETROFITTING A STANDARD OIL-FIRED BOILER TO OXY-FUEL MODE: STUDY ON RADIATIVE AND SOOT FORMATION PROPERTIES

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ABSTRACT

Oxy-fuel combustion is a recognized technology for capturing carbon dioxide (CO₂) from the power and industrial processes. Its retrofitting potential is an important characteristic for both the re-vamping of existing conventional boilers and the design of capture-ready plants. In this study a light oil fired Central European Norm boiler has been retrofitted to oxy-fuel mode by simply replacing the burner blower by a premixing chamber for O₂ and CO₂ for simulating dry flue gas recirculation. Although the transition from air to oxy-fuel did not show major issues, the heat transfer and thermal efficiency of the boiler were affected. The thermal efficiency was found to monotonically increase with increasing O₂ concentration in the oxidizer, and was equal to that of air at 32-35% O₂ depending on operating equivalence ratio. Higher heat fluxes in the radiant section of the burner were also measured for all oxy-fuel cases investigated as compared to that of air. To further investigate the differences in radiative heat transfer mechanisms implicated in the boiler, the study was pursued at laboratory scale and laminar conditions to analyse the influence of O₂ and CO₂ on both the radiative properties and soot formation. The measurements have highlighted the global effects of the oxidizer composition, where the flame lengths were shorter, the radiant fraction and peak radiative heat flux increase as the O₂ concentration increased. The radiant fraction for a 35% O₂ mixture in CO₂ combustion was found to be equal to that of an air flame despite a difference in adiabatic flame temperature. Both the O₂ concentration and the replacement of N₂ by CO₂ were shown to have an influence on soot formation. The peak soot volume fraction increased with O₂ concentration until 70% O₂ in O₂ - CO₂ oxidizers, but was found to be lower than in oxygen enriched air flames at similar Reynolds number conditions reported in the literature, supporting the idea that the increase in radiative heat flux in O₂ - CO₂ systems is more dominated by temperature than soot formation.

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1 INTRODUCTION

In the IEA 2°C scenario, carbon capture and sequestration (CCS) could account for up to 20% of cumulative carbon dioxide (CO₂) reductions by 2050 [1]. Worldwide greenhouse gas emissions from industrial activities account for 20% of the total emissions and CCS is the only technology on the horizon today that would allow industrial sectors, such as iron and steel, cement and natural gas processing, to meet deep emissions reduction goals. One of the alternatives for capturing CO₂ from combustion based sources is called oxy-fuel combustion, where a mixture of oxygen and recycled flue gas is used as a substitute for air. The prime advantage of the method is that the capture of CO₂ from the flue gases is simple and cost effective because it is only composed of CO₂ and steam, assuming complete combustion of a pure hydrocarbon fuel. There is however an efficiency penalty due to the need of an energy demanding air separation unit (ASU) to produce the oxygen. The technology described in detail in Zheng [2] can in principle be applied to any power cycle and any fossil fuel from natural gas [3-6] to coal [7-8]. Oxy-fuel combustion using pure oxygen has long been applied in the glass and melting industry [9] and has been studied at laboratory scale [10]. Nevertheless, several challenges arise when the oxidizer contains a high concentration of oxygen such as high temperatures beyond material integrity, unusual combustion properties (flame speed, flammability limits, stabilisation), economical need for operation at stoichiometric condition, ease of triggering of thermo-acoustic instabilities, CO burn out, and heat transfer [7, 9-12]. To solve the high temperature problem, dilution is necessary and CO₂ is the obvious choice since it is already present in the flue gas and can thus be recycled. The oxy-fuel technology is per today well deployed at pilot stage for gas [13] and coal-fired power plants [14-15], but still requires further development for more complex pressurized combustion systems as in gas turbines [16].

To achieve the necessary goals in CO₂ emission reductions CCS will have to be deployed intensively in the years to come. Retrofitting existing plants is a means for accelerating the deployment and a first mover low risk strategy. In this study the effect of retrofitting a light oil fired boiler to oxy-fuel mode is investigated by applying minor modifications to the burner. Differences evidenced in the heat transfer pattern of the boiler led the study to further focus on the radiative properties of diffusion flames in O₂ - CO₂ atmospheres. Because a large part of the radiation source in flames can be attributed to black body radiation from in-flame soot, a study on the influence of O₂ and CO₂ on soot formation is also presented. Radiative heat transfer is an important flame property for the design of combustion systems. The radiative flux from gaseous fuel flames arises from hot soot particles acting as black body radiators and the radiating species CO₂, H₂O, and CO. In conventional air supported combustion N₂ and O₂ are abundantly present, but have no significant absorbing or emitting properties in the infrared range, whereas in oxy-combustion of pure hydrocarbon fuels the product gases are only composed of radiating species.

Earlier studies on oxy-fuel combustion are reported already from the 1990's [17-18], with focus on coal as fuel. Unlike in air supported combustion, the oxygen is supplied pure from



the ASU and must be mixed with recycled flue gas when introduced into the boiler. A common strategy, especially in retrofit cases, is to target a O_2 - CO_2 composition for which the flame behaves as in air. Several compositions have been found to fulfil that requirement. For Andersson et al. [19] 27% O_2 in a propane-fired oxy-fuel boiler was satisfactory, although the radiative heat flux was up to 30% higher. In another example (Tan et al. [5]) 28% O_2 for a natural gas flame is reported to match similar heat distribution as in air. This oxygen concentration in the oxidizer ought to be dependent on the fuel propensity to generate soot. Indeed, oxy-fuel operation at 27% O_2 increases in-flame soot volume fraction in several studies [19-22]. However, when using coal as fuel, other strong emitters are present such as coal and more generally solid particles [22]. Therefore, an increment of gas radiation due to higher CO_2 concentration is not evidently demonstrated. Wang et al. [23] were able to split the relative contribution of soot and gas radiation to the radiative heat flux of turbulent oxygen enriched natural gas and propane flames, and showed that soot radiation has a contribution lower than 15% for propane and even less for natural gas. Ditaranto and Oppelt [24] made a study, partly reported in this work, on radiative heat flux in oxygen enriched combustion with CO_2 as diluent and showed that the peak heat flux was monotonically increasing up to the maximum O_2 concentration investigated (70%). This local value was more than twice than that in the air case.

The scope of the present work is to highlight the role of radiation and soot formation in oxy-fuel atmospheres to understand the differences in performance obtained when retrofitting a conventional boiler to oxy-fuel mode. First a semi-industrial scale fuel oil fired boiler is operated in air then switched to oxy-fuel mode. Differences in heat transfer behaviour are highlighted and further studied in two laboratory scale set-ups. The complex interaction of processes like turbulent flows, chemistry, and spray found in the industrial scale flame burning liquid fuel is restrained by using gaseous fuel and laminar to transient diffusion flames, where targeted measurements of radiative heat flux and soot volume fraction are performed.

2 EXPERIMENTAL

The present paper compiles results obtained from three different set ups. First, a standard Central European Norm (CEN) boiler of 250 kW class represents the case study for retrofit from air to oxy-fuel operation. The CEN boiler sketched in Figure 1 has a 397 mm inner diameter and 1 meter long radiant section which ends by a water-cooled back-plate which can be positioned so as to control the amount of flue gas flowing straight to the chimney and that being forced back towards the burner plane, from which it goes through the fire tubes. In the present case the back plate was totally closed to operate the boiler most efficiently in full fire tube mode. The boiler is first operated in air mode for approximately 60 minutes in order to reach steady-state conditions monitored by a steady output temperature of 70 °C for the process water. The experimental test matrix points could then be started by adjusting the mass flow with glass tube rotameters and eventually by switching to oxy-fuel mode. The burner was fired with commercial high quality light oil



No. 1 with elemental composition 86.25% C, 13.6% H, 0.15% S and less than 5.10-4% vol. N₂.

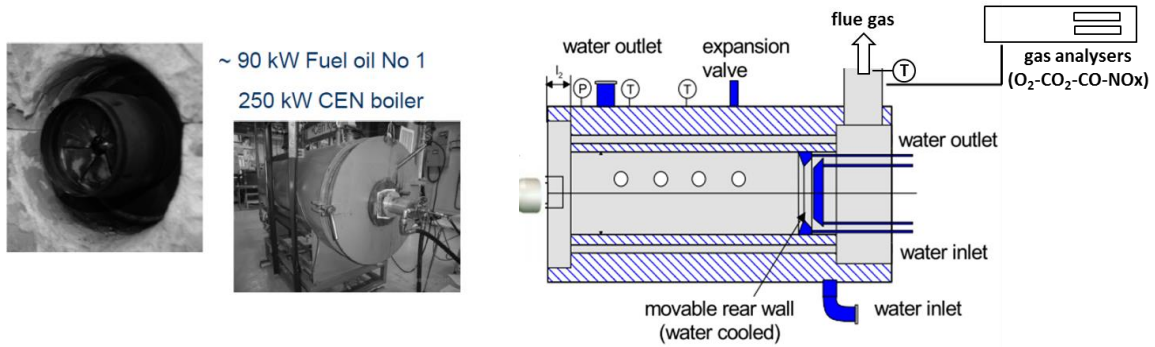


Figure 1: Experimental set-up used in the semi-industrial boiler. Left: picture of the fuel oil burner head, middle: picture of the CEN boiler, right: sketch of the CEN boiler and instrumentation.

The boiler is operated at a power load of approximately 90 – 95 kW because of limitation in the CO₂ supply capacity which restricts the experiment duration. The burner, shown in Figure 1, is a conventional pressure spray nozzle mounted in a swirling flow of air or oxy-fuel oxidizer. In oxy-fuel mode, O₂ and CO₂ are initially mixed in a plenum chamber with perforated plates prior to injection in the air duct of the burner. No modification of the air duct implies that flow velocities are lower in the oxy-fuel mode. The boiler is monitored with a type K thermocouple placed in the exit flue gas path and a gas sampling probe for concentration measurement. After passing through a gas cooler to condense out the water vapour, the gas sample is analysed with a conventional gas analyser HORIBA PG250 for NO_x, O₂, and low concentrations of CO and CO₂, and an Edinburgh Sensor Analyser when CO and CO₂ concentrations are high in the range 0 – 10% and 0 – 100% respectively. The analyser uses non-dispersive IR detection for CO, SO₂, and CO₂; chemiluminescence for NO_x and a galvanic cell sensor for O₂. An in-boiler mounted MEDTHERM Schmidt-Boelter Thermopile heat flux probe viewing most of the flame was inserted through one viewing port. The boiler thermal efficiency is calculated as follows:

$$Efficiency_{boiler} = 1 - \frac{H_{flue\ gas} - H_{reactants}}{LHV}$$

Where the enthalpies H_i are the enthalpies per kg fuel calculated from the inlet mass flow rates of fuel and reactants, mass balance, and the species specific heat capacities taken at an average inlet and flue gas temperature. The lower heating value (LHV) of the fuel is 43 MJ/kg. Losses are assumed independent of operation mode and neglected in the calculation.



Table 1. Flames properties and inlet conditions range

<i>Fuel</i>	<i>Flame configuration</i>	<i>Conditions</i>	<i>Measured quantities</i>
Light oil nr.1	Industrial burner in CEN boiler		<i>T, heat flux</i>
CH ₄	Jet in coflow	Re = 468 – 2340	<i>heat flux, T_{wall}, species</i>
C ₂ H ₄	Jet in coflow	Re = 120	<i>Soot vol. frac.</i>

The results on radiative heat transfer from oxy-fuel flames were obtained in another set up with a laminar non-premixed flame configuration used elsewhere [24] and briefly described here (cf. Figure 2). It consists of a 5 mm diameter nozzle surrounded by a 100 mm diameter co-flow of oxidizer gas at a velocity of 0.25 m/s. The oxygen supply from the co-flow was always higher than the stoichiometric amount. The flames were confined by a 350 mm diameter cylindrical chamber coated with black body paint and instrumented with thermocouples. The thermocouples were welded inside non-through holes drilled from the outside of the chamber. The wall thickness at the measurement location was less than 1 mm and the temperature measurements were assumed to represent the inside wall temperature. They were used to correct the total radiation measurements from background emission. Radiative heat flux was measured through a moveable slot at the wall with a heat flux micro-sensor (HFM, Vatell Corp.) mounted in a water cooled holder equipped with an electronic shutter to correct each measurement from the background signal. The holder serves the purposes of limiting the solid angle of collection, avoiding the contribution of convective heat flux to the measurement, and isolating thermally the sensor from its surrounding. To correct the sensor signal from background radiation, measured wall and gas layer (flame – wall path profiles) temperatures, and species concentrations in the radiation path to the sensor were used as inputs in the program RADCAL [25], a one dimensional narrow-band model which predicts the radiant intensity leaving a non-isothermal volume of non-homogeneous gas concentration. Necessary view factors to apply the correction were calculated by Monte Carlo ray tracing method adapted to the geometrical configuration. The fuel gas used in the measurements of heat flux was methane.



The soot volume fraction measurements were performed on a diffusion flame configuration similar to the previous. Measurements of soot were made by Laser Induced Incandescence (LII) which is a method based on heating the soot particles in the flame to the point of vaporization by a laser pulse. The LII and flame set up is described in detail in Ditaranto et al [26]. The black body emission signal from the heated particles present in the measurement volume is known to be proportional to the soot volume fraction [27]. The method allows instantaneous measurement at several locations in the flame, but is not self-calibrated in this set-up. The calibration was done by Laser Beam Extinction along one radial profile at a given height. The fuel gas chosen for this study was ethylene, which ensured high levels of soot volume fraction, therefore allowing a better accuracy in the measurements than with methane. All the flame characteristics are summarized in Table 1.

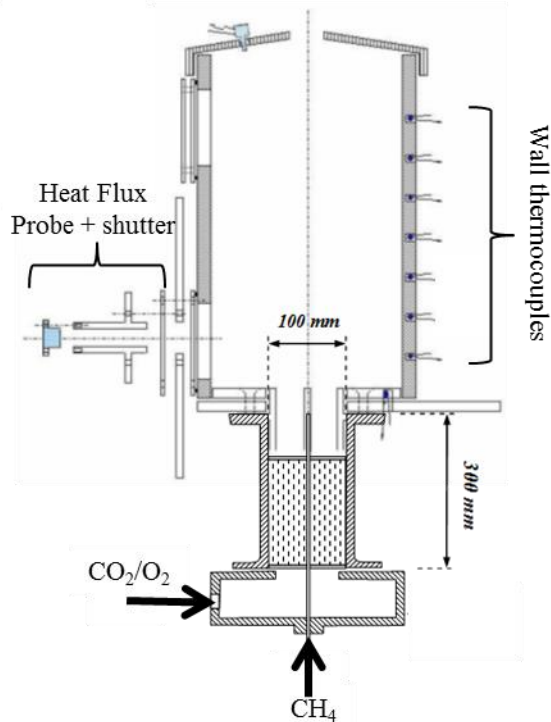


Figure 2: Experimental set-up used in the non-premixed jet in co-flow flame for heat flux measurements.

3 RESULTS AND DISCUSSION

3.1 Retrofit of a CEN boiler to oxy-fuel mode

To assess the effect of directly retrofitting a boiler to oxy-fuel operation, the burner head was used unchanged, but the blower house was replaced with a mixing chamber where O_2 and CO_2 were injected. No modifications were made to the boiler itself. The boiler was first tested in air mode and the measurements of heat flux, flue gas temperature and species concentrations recorded as a reference case. Typical turbulent luminous flames in air and oxy-fuel operation are shown in Figure 3. When the boiler is operated in oxy-fuel mode, the flame visible emission is very dependent on the O_2 concentration in the oxidizer. At high O_2 concentration flames are shorter and the luminosity is very intense and appears white to the eye.

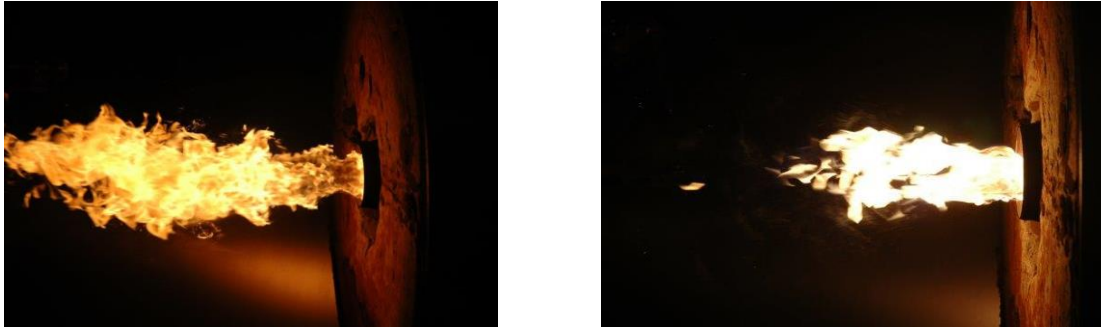


Figure 3: Direct photographs of 90 kW fired light oil flames taken outside the boiler, left: air mode, right: oxy-fuel mode (30%-70% O₂-CO₂).

The O₂ concentration in the oxidizer was varied from 30% to 48% at various excess oxygen ratio. The corresponding calculated adiabatic flame temperatures are shown in Figure 4 where the excess oxygen ratio is expressed as λ_{calc} , the inverse of the equivalence ratio calculated from the flue gas species concentration and known fuel flow rate. As O₂ increases, the adiabatic temperature increases due to the decreasing thermal ballast effect of the diluent. The data in Figure 4 shows that to achieve a similar temperature as in the air mode, the O₂ concentration should be approximately 35%. The reason for which a similar temperature as in air is achieved at a higher concentration is due to the higher heat capacity of CO₂ compared to N₂. Although the flames are not adiabatic, the calculated adiabatic temperatures are representatives of the trend of the highest temperatures to be found in the flames. Figure 5 gathers the results of flue gas temperatures for all cases studied and show a trend which is opposite to what is intuitively expected. Indeed, the highest temperature is obtained with air as oxidiser and the temperature decreases as the O₂ concentration increases. The adiabatic flame temperature is the maximum local temperature achievable in the flame and is not necessarily representative of the flue gas temperature in a heat process. The CEN boiler is a fire tube type boiler, having tubes immersed in flowing water. The heat from the flame is recovered in the water both in the radiant and convective sections, and in the flue gas. The results therefore indicate that more heat is transferred to the boiler in oxy-fuel mode. One could think that the lower flue gas temperature is due to a higher specific heat capacity in oxy-fuel mode. However the thermal efficiencies of the boiler shown in Figure 5 indicate otherwise, as heat is more effectively transferred to the boiler. The data shows that the balance in lower flue gas volume and higher specific heat capacity resulting in efficiency equals to that in the air case occurs at approximately 32% - 35% O₂ in the oxidizer. The heat transfer budget is however not straightforward as at higher O₂ concentrations, the volume flow rate of CO₂ decreases, but temperature increases, having opposite effects on the gas velocity and consequently on the convective heat transfer. Moreover, the flame zone temperature increases, affecting the radiative heat flux through soot formation and gas temperature. Indeed, the optical thickness in oxy-fuel mode is much larger than in air flames in which most of the gas is nitrogen and non-absorbing.

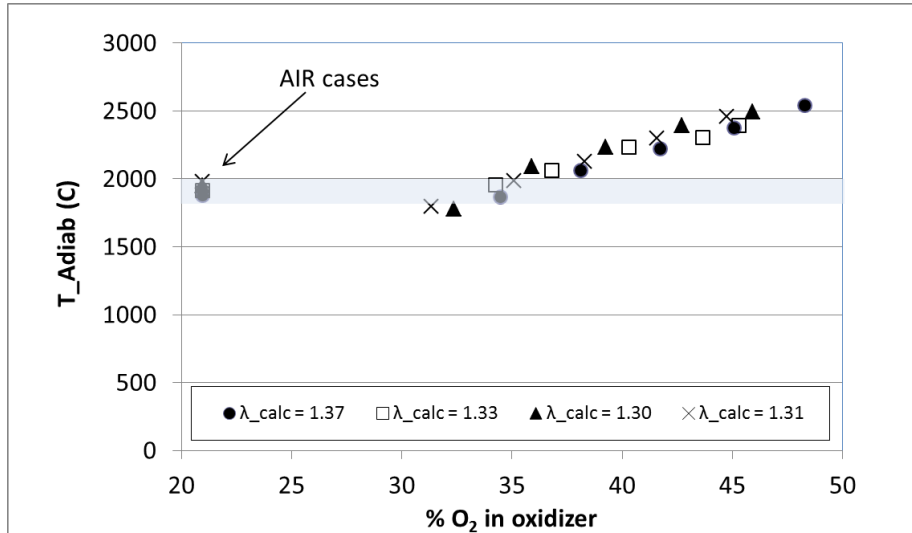


Figure 4: Calculated adiabatic temperature at various oxygen concentrations in the oxidizer and excess oxygen ratio λ_{calc} .

A better insight into the radiative characteristics of the flames in the boiler can be obtained in Figure 6. An increase in heat flux to the wall of the boiler as the O_2 concentration increases is evidenced, with nearly 50% increase over a 15% O_2 concentration difference. It is indeed expected that a higher temperature flame enhances the heat flux. However temperature is not the only contributor to heat flux as soot, a black body, is also strongly participating to the heat radiated by flames. Besides, in oxy-fuel mode the coupled effects of temperature and higher availability of O_2 on soot formation are not straightforward to assess. To further complicate the overall situation, the evaporation of the liquid droplets in varying atmospheres and temperature also affects the soot formation.

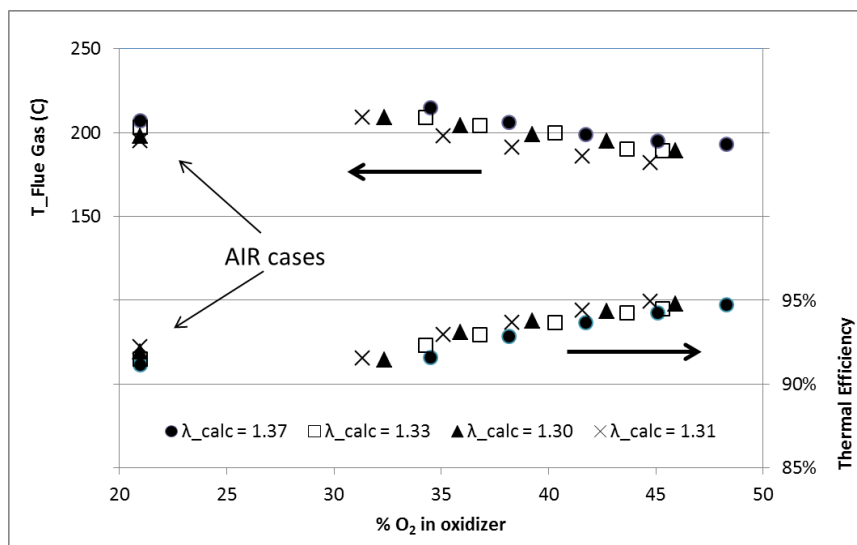


Figure 5: Flue gas temperature and boiler thermal efficiency measured in air and oxy-fuel modes at various oxygen concentrations in the oxidizer and excess oxygen ratio λ_{calc} .



Retrofitting a standard CEN boiler to oxy-fuel mode is therefore shown to be feasible, but indicated changes in the boiler characteristics that affect the boiler thermal efficiency. A full understanding of the underlying reasons is difficult to apprehend due to the many thermal and chemical processes involved in an industrial boiler configuration. In order to decouple the different processes from each other, two further studies are presented in the following sections: one focussing on the radiative characteristics of oxy-fuel flames in simple laboratory flame configurations, another one isolating the soot formation dependency to O_2 concentration.

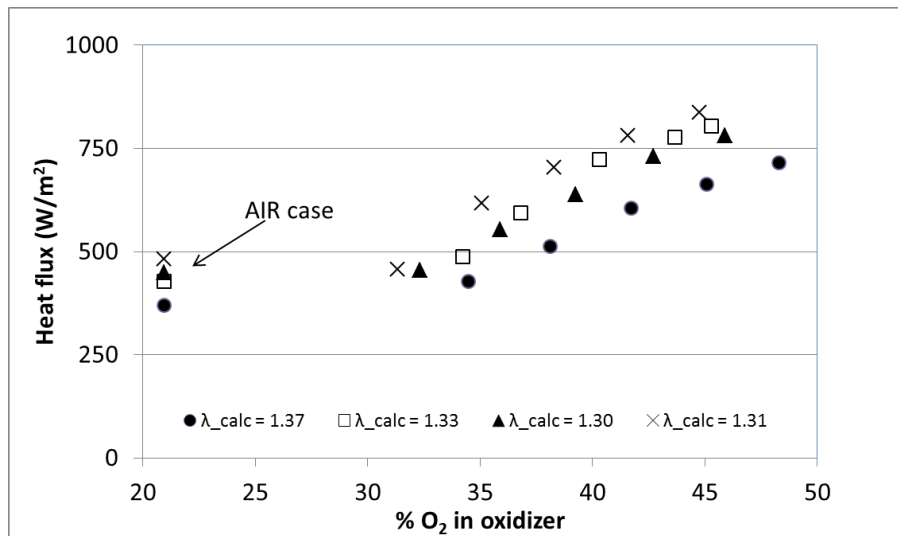


Figure 6: In boiler heat flux measurements in air and oxy-fuel modes at various O_2 concentrations in the oxidizer and excess oxygen ratio λ_{calc} .

3.2 Radiative heat flux

The parameters investigated in this part of the study include the oxidizer composition and the Reynolds number varying in the range 468 to 2340. Methane was used as fuel to avoid the complexity of higher hydrocarbon chemistry and the presence of droplets in the spray. The structure of the non-premixed diffusion flames evolves very rapidly in the laminar regime and the observed visible flame length increases nearly linearly with the Reynolds number. An increase in O_2 concentration in the oxidizer shortens the flame as a result of an increase in the stoichiometric mixture fraction. Indeed, the flame front is displaced closer to the centreline, because a lower degree of mixing between the fuel and oxidiser needs be achieved to sustain combustion.

Figure 7 shows the vertical distribution of the measured radiative heat flux corrected for background radiation as described in §2, for a Reynolds number of 2340 at varying oxidizer compositions. The effect of O_2 concentration is clearly evidenced and shows that although the radiative flame length shortens, the peak intensity increases considerably. This behaviour could be attributed to both the higher gas temperature achieved and the higher



local soot concentration. Indeed the studies of Lee et al. [20] and Beltrame et al. [21] found that the soot inception rate increases when enriching the oxidizer with oxygen. These results are in agreement with the findings of Wang et al. [23] who made similar measurements in various flames, although in fully turbulent conditions and by oxygen enriching the air (i.e. no CO₂ in the oxidiser). Unlike our results obtained with methane as fuel, they observed that the increase in radiative heat flux in a propane flame peaked at an O₂ concentration of 55%, which was then followed by a decrease in heat flux. We were not able to observe such a phenomenon up to 70% O₂, the higher limit of our measurements. Finally, it is observed that the axial location of the peak heat flux value is shifted upstream in the flame, closer to the nozzle as a result of the changes in flame structure and length.

In Figure 8 the peak heat flux value for varying amounts of O₂ in the CO₂ containing oxidizer is seen to increase linearly to reach 71 kW/m² at 70% O₂ when Re = 2340. The large increase in peak heat flux (a doubling in the range investigated) for the same thermal power input has important practical consequences for the hardware components around the flame and their cooling management. The peak radiative heat flux of the flame in the air case (32 kW/m²) is close to that obtained at the lowest O₂ concentration in CO₂ investigated (i.e. 35%), albeit a higher adiabatic temperature calculated to be approximately + 80 °C. The combined chemical effect of CO₂ on soot formation [22;28] and the absorption of radiation through the gas layer surrounding the flame can be responsible for the difference. Tan et al. [5] reported heat flux profiles that were 5% lower in a 28% O₂ in CO₂ oxidizer than in air. Andersson and Johnsson [30] found in a propane-fired 80 kW furnace higher radiation intensity than in air already at 27% O₂ in CO₂. In the same way Payne et al. [17] obtained a heat radiation distribution along the flame similar to the air case in a 50 MWe lignite boiler at an O₂ concentration somewhat lower than 31% in CO₂. Part of the explanation of these discrepancies could reside in the higher gas temperature of the surrounding gas in their boiler and in a different sensitivity to O₂ enrichment (equivalently flame temperature) of the fuel propensity to sooting. In addition, the studies referenced here concern large scale burner and boiler configurations with highly turbulent flow pattern, which is known to decrease the flame radiant fraction [31].

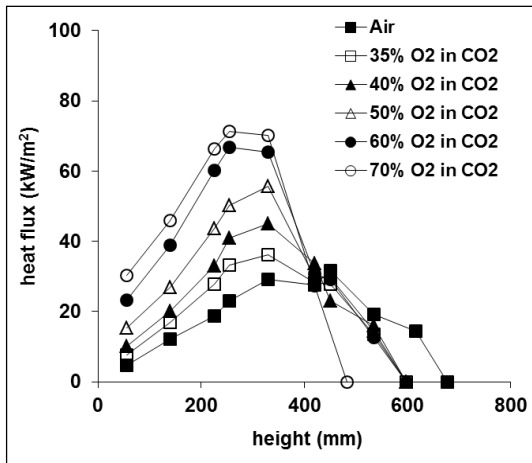


Figure 7: Effect of oxidizer composition on radiative heat flux distribution at $Re = 2340$ [24]

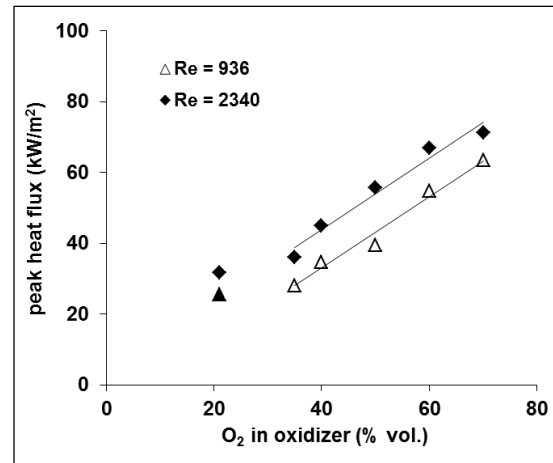


Figure 8. Peak heat flux values vs O_2 in CO_2 oxidizer except at 21% being air for two Reynolds numbers [24]

The monotonic increase in peak heat flux with O_2 concentration observed in Figure 8 is in contrast with results obtained in the O_2 enriched air flames of both Fuentes et al. [32] and Wang et al. [23]. Wang et al. [23] in a propane turbulent flame measured a maximum peak at 55% O_2 followed by a decrease. Fuentes et al. [32] in ethylene laminar flames observed a slowing of the increase in peak heat flux for O_2 concentration greater than 25%, which they attributed to a flattening in peak soot concentration.

3.3 Radiant fraction

The radiant fraction, representing the fraction of the fuel input power radiated from the flame, has been extensively studied as a function of the fuel characteristic and was observed to be strongly correlated with the soot propensity of the fuel [33-35]. The radiant fraction has been calculated by integrating the axial heat flux profiles and assuming the flame as a cylinder which length is defined at the point where the heat flux vanishes. The results seen in Figure 9 show a linear dependency to O_2 concentration in the oxidizer up to 60% O_2 at all Reynolds number considered. The radiant fraction also depends on the inlet flow conditions of the flame at least in the laminar regime where one notes approximately 5%-point increase from a laminar $Re = 468$ to a low turbulent $Re = 2340$ flame. Scaling analyses in turbulent flames show that the radiant fraction tends to decrease with increasing Reynolds number through increased mixing rate and diminution of soot formation [36]. However, in the laminar regime, flame length is linearly dependent on jet exit velocity which influence on radiant fraction overweighs the effect of increasing velocity on turbulence, truly due to increased residence time and slower oxidation rate of soot.

Considering that flame length decreases with increasing O_2 concentration, the increase in total radiated heat flux at constant fuel input power is considerable (3 and 2.3 times from 35% to 70% O_2 in the oxidizer at $Re = 468$ and 2340 respectively). The same trend was observed in the natural gas flames of Wang et al. [23] in a similar burner configuration, but turbulent conditions where increasing from 30% to 70%, led to an increase in radiant



fraction of 8%-points in natural gas flames. In our data set the increase reaches approximately 10%-points and the rate of increase seems stronger. The change in oxidizer composition affects the radiative properties of the flame through the local flame temperature and the concentration of the absorbing species CO_2 . Despite the difference in temperature, flames developing in the CO_2 oxidizer with 35% O_2 ($T_{ad} = 2302 \text{ K}$) have radiative characteristics similar to that developing in air ($T_{ad} = 2226 \text{ K}$), highlighting the displacement of the trade-off between the physical and chemical processes responsible for the heat radiation budget in $\text{O}_2 - \text{CO}_2$ oxidizers.

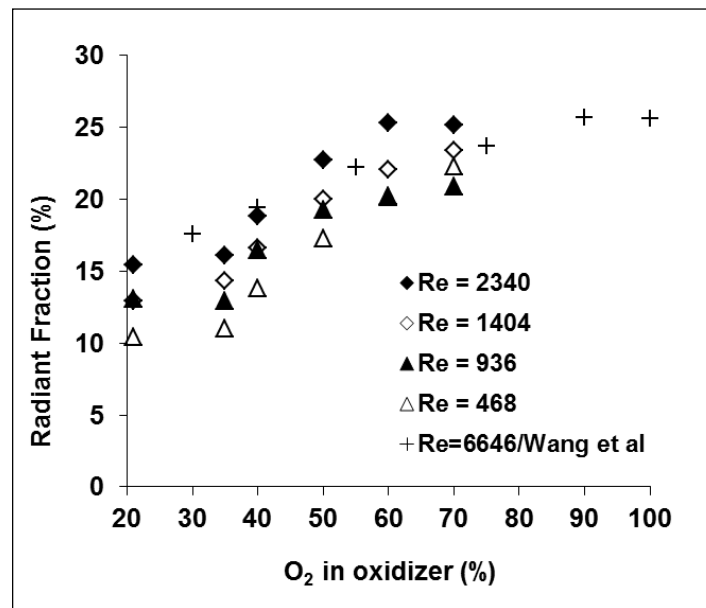


Figure 9. Radiant fraction vs. oxygen in oxidizer at different Reynolds number. Oxidizer is $\text{O}_2\text{-CO}_2$ except for the data of Wang et al. [23]: $\text{O}_2\text{-N}_2$ and natural gas as fuel.

3.4 Soot volume fraction

For the study of soot in oxy-fuel flames only one flame configuration has been studied while the oxidizer composition was varied. The flame is a laminar jet flame of ethylene so that the effect of O_2 and CO_2 concentrations in the oxidizer on the soot formation process can be isolated from any complicating turbulent effects. Such a flame configuration with ethylene as fuel has been widely studied in the field of soot kinetics and can therefore be easily compared with literature data. The flames shown in Figure 10 are maps obtained by LII where the colours from cold to warm are indicative of soot volume fraction. These soot volume fraction maps are reconstructed from individual maps of 5 mm height, explaining some lack of continuity that can be sometimes observed.

The effect of oxidizer composition on flame length is clearly observable in Figure 10. The zones of maximum soot concentration forms a near cylindrical shape that does not always close on the centreline towards the end of the flame, as it does for the products of



combustion (CO_2 , CO , H_2O). Soot forms earlier in the flame as the O_2 concentration in the oxidizer increases. For the lowest O_2 concentration investigated (25%), soot is almost undetectable in the lower part of the flame. This is not the case for the similar flame developed in air and it highlights the soot suppression effect of CO_2 through both chemical and thermal effects as previously described by Liu et al. [28].

The local concentration of soot is dependent on two opposite effects: on the one hand the formation of nuclei and growth to soot particles, on the other hand the oxidation of soot in regions where oxygen is available. Since both these kinetic processes are temperature dependent, it implies that the soot formation region is dependent on the mixture fraction and temperature structure in the flame. Although all the flames have a similar mixture fraction structure (same velocity conditions in fuel and oxidizer inlets), the location of the stoichiometric mixture fraction contour and thus the temperature field is dependent on the oxidizer composition. The result of this trade-off for each case can be seen in Figure 11 which shows the soot concentration for the various O_2 - CO_2 compositions at the same non-dimensional height above the nozzle, taken here at $\frac{1}{2}$ of the flame length. The trend is that the maximum soot concentration increases with O_2 concentration until 70% O_2 before decreasing. A comparison with air supported combustion indicates that soot concentrations for the O_2 - CO_2 flames are considerably lower than flames in air. For example Honnery and Kent [37] measured peak soot volume fraction at half flame length in air-ethylene flame of similar configuration in the 15 - 20 ppm range, whereas the peak value in our study is hardly 12 ppm, but at a much higher degree of O_2 concentration (70%). Assuming that O_2 enrichment affect soot formation and radiation similarly independently of fuel, the comparison of soot production in Figure 11 for ethylene and radiant fraction in Figure 9 for methane suggests that that both parameters are correlated. However, the peak values (cf. Figure 8) clearly show that a three-fold increase in flux between the air and the 70% O_2 cases whereas the soot concentration should be equivalent. Therefore, it appears most probable that the large difference observed in heat flux by increasing O_2 in the oxidizer is dominated by the increased temperature of the soot and gas. The parallel increase in heat flux and soot volume fraction in the CO_2 system is thus probably fortuitous. The results of Wang et al. [23], although in turbulent propane flames, strengthens this hypothesis as they do not observe a parallel correlation between radiant fraction and soot volume fraction as O_2 increases in air. In fact they evaluated that soot radiation had a contribution lower than 15% for propane and even less for natural gas.

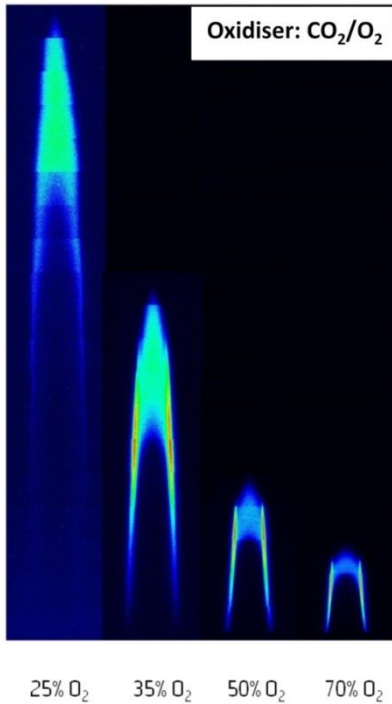


Figure 10. Soot volume fraction maps at varying O_2 concentration in the oxidizer (colour intensity scale adjusted for each flame).

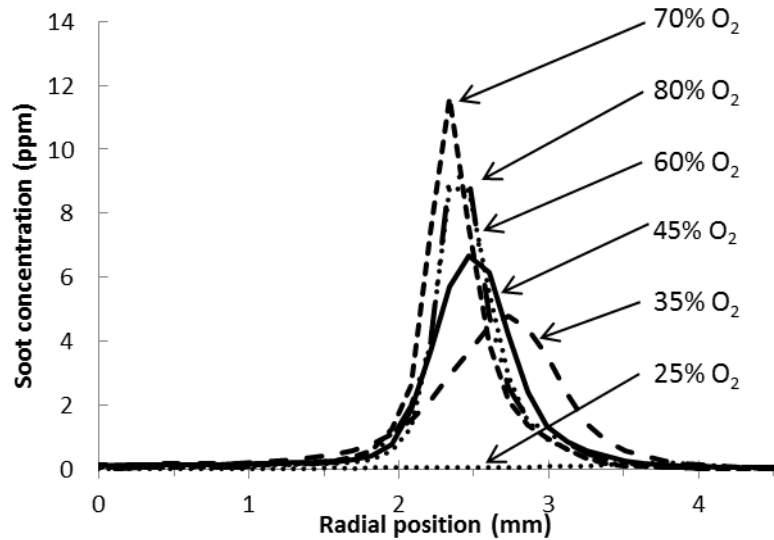


Figure 11. Soot concentration profiles at $\frac{1}{2}$ flame length at varying O_2 concentration in the oxidizer.

4 CONCLUSIONS

A light oil nr 1 fired CEN boiler has been retrofitted to oxy-fuel mode by simply replacing the burner blower by a premixing chamber for O_2 and CO_2 for simulating dry flue gas recirculation. Although the transition from air to oxy-fuel did not show major issues, the heat transfer and thermal efficiency of the boiler were affected. The thermal efficiency was found to monotonically increase with increasing O_2 concentration in the oxidizer, and was equal to that of air at 37% O_2 . Higher radiative heat fluxes in the radiant section of the burner were also measured for all oxy-fuel cases investigated as compared to that of air. The investigation was pursued at laboratory scale to analyse the influence of O_2 and CO_2 on both the radiative properties and soot formation. The measurements have highlighted the global effects which can be summarized as follows:

- As the O_2 concentration increases, the distribution of the radiative heat flux and the flame length are shorter.
- Similar heat flux distributions and radiant fraction values were found for air combustion and 35% O_2 in CO_2 , despite a difference in adiabatic flame temperature.
- The radiant fraction of flames in the oxygen enriched oxidizer increases monotonically with increasing O_2 concentration in $O_2 - CO_2$ oxidizers as in O_2 enriched air flames.



- The peak soot volume fraction in our ethylene laminar flames increases with increasing O₂ concentration until 70% O₂ in O₂ - CO₂ oxidizers, unlike O₂ enriched air flames which have been reported elsewhere to peak at 40% in turbulent propane flames.
- Both the O₂ concentration and the replacement of N₂ by CO₂ have an influence on soot formation through temperature and chemical effects.

The results obtained from targeted laboratory experiments and those reported in the literature on oxygen enriched air flames, support the idea that the increase in radiative heat flux in O₂ enriched oxidizer systems is probably more dominated by temperature than soot formation.

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