Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Capture and Separation of Carbon Dioxide from Combustion Sources

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Chapter 28

ZERO OR LOW RECYCLE IN-DUCT BURNER OXYFUEL BOILER FEASIBILITY STUDY

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ABSTRACT

The CO_2 Capture Project (CCP) has been established by eight leading energy companies to develop novel technologies that significantly reduce the cost of capturing CO_2 for long-term storage. One area considered by the CCP is the use of oxygen in combustion systems (oxyfuel combustion). This is attractive to the CCP as it produces a flue gas essentially containing only CO_2 and water, from which CO_2 can be easily captured.

This study evaluates the potential benefits of a novel oxyfuel boiler design that splits the fuel gas between a number of in-line burners. The adiabatic flame temperature is limited to a maximum of 850 °C by cooling the flue gas between each successive burner and thereby permitting conventional stainless steel construction. Steam is raised in these inter-stage coolers and superheated in the exhaust stream exiting the boiler. The design intent is to use this inter-stage cooling to control the combustion temperature rather than the more conventional alternative of recycling flue gas. Therefore, the objective is to eliminate, or at least minimise, flue gas recycle.

The study concludes that a zero recycle case is technically feasible. However, in order to deliver the required amount of steam to the specified superheated conditions, either a large number of burner stages are required (>14), or the oxygen stream needs to be over-supplied to help suppress the flame temperature. Both of these factors will add to the cost and complexity of the system considerably and the zero recycle case is not pursued further in this study on the grounds that it is not considered to be the most economic configuration.

A second case incorporating flue gas recycle is then considered. In order to limit the number of burner stages required, a substantial flue gas recycle is required. This study shows that by recycling 75% of the flue gas, a 3-stage burner design will deliver the required steam production to the required superheated conditions. Even though this case has a large recycle, it is considered to offer the lowest cost option of incorporating the in-duct oxyfuel boiler concept for the steam generation design basis.

The installed cost of the in-duct oxyfuel boiler design with flue gas recycle, including the associated air separation and CO_2 capture/compression units, is estimated to be £30 million ($52.5million), equating to a CO_2 capture cost of £90.80($158.90) per tonne of CO_2 captured per year. The installed capital expense is roughly 10% cheaper than an alternative oxyfuel boiler design based on conventional boiler technology and incorporating flue gas recycle. The footprint required by the in-duct oxyfuel boiler is also assessed and is estimated to be about twice the size of a conventional oxygen-fired boiler.

Based on the cost and footprint evaluation, it is considered that there is insufficient justification to develop the in-duct oxyfuel boiler concept within the CCP framework. Although the installed cost is slightly lower than a more conventional boiler design, it still represents a high cost of CO_2 capture and does not offer a sufficiently large enough prize to warrant further development.

Abbreviations: ASU, Air separation unit; CCP, CO_2 Capture Project; FGR, Flue gas recycle; MWt, Thermal mega watt.

INTRODUCTION

The CO_2 Capture Project (CCP) is a joint project being undertaken by eight major energy companies to develop new and novel technologies that significantly reduce the cost of capturing and storing CO_2. The project is split into three distinct elements:

pre-combustion de-carbonisation,
the use of oxygen-rich combustion systems (termed oxyfuel systems), and
post-combustion CO_2 capture.

For each element, technology development is in the context of four scenarios:

large gas-fired turbine combined cycle power generation,
small or medium sized simple cycle gas turbines,
petroleum coke gasification, and
refinery and petrochemical complex heaters and boilers.

This report details a preliminary evaluation of a novel boiler design for use in near-pure oxygen combustion systems, and relates to the “refinery and petrochemical complex heaters and boilers” scenario.

Oxyfuel combustion is attractive to the CCP as it produces a flue gas consisting largely of carbon dioxide and water, from which CO_2 can be easily separated. A key design issue with combustion of fuel in near-pure oxygen environments is that significantly higher combustion temperatures are reached, which are in excess of those experienced with conventional air-fired systems. A novel oxyfuel boiler design is considered in this study that limits the temperatures within the boiler to a maximum of 750–850 °C to allow the use of stainless steel construction and avoid more exotic and more expensive materials. This is achieved by splitting the fuel gas between a number of burners located in series, and by cooling the flue gas between each successive burner to raise steam.

The boiler design comprises a horizontal flue gas path, containing a number of in-duct burners, and vertical heating tubes, within which the steam is raised, and is not dissimilar in layout to a Gas Turbine Heat Recovery Steam Generator. The intent is that this approach will significantly reduce or eliminate any recycle of flue gas that would otherwise be required to help control the combustion temperature.

The aim of this study is to assess the feasibility of the in-duct burner boiler design and evaluate the potential for eliminating flue gas recycle. Furthermore, the study compares the installation costs of an in-duct oxyfuel boiler with a more conventional oxyfuel boiler incorporating flue gas recycle. Finally, the study draws conclusions as to the justification of developing this concept within the CCP framework.

The study work was commissioned by the CCP and co-ordinated by BP. Technical evaluation and costing was undertaken by Mitsui Babcock.

EXPERIMENTAL/STUDY METHODOLOGY

The study is undertaken in two parts. Firstly, the feasibility of the in-duct boiler is considered and a design proposed. Secondly, the installation costs of the proposed design are estimated and compared to a more conventional oxyfuel boiler with flue gas recycle.

Conclusions are then drawn as to the justification of developing the in-duct boiler within the CCP programme.

Basis of Design
The basis of design for both the novel in-duct oxyfuel boiler design and the more conventional oxyfuel boiler with flue gas recycle relates to typical refinery conditions and is as follows:

Deliver 500,000 lb/h of steam at a pressure of 127.6 barg and super-heated temperature of 518.3 °C. Boiler feed water is available at a pressure of 138.9 barg and temperature of 148.9 °C.

Boiler to be fired with fuel gas of the following composition:

Methane	13 v/v %
Ethane	20.3 v/v %
Propane	27.8 v/v %
Butane	7 v/v %
Pentane	3 v/v %
Nitrogen	1 v/v %
Carbon dioxide	0 v/v %
Hydrogen	27 v/v %
Hydrogen sulphide	1 v/v %

A conventional air separation unit (ASU) is to be assumed producing oxygen with a purity of 95 v/v % and containing impurities of nitrogen (2 v/v %) and argon (3 v/v %).

Adiabatic flame and flue gas temperature within the boiler to be restricted to a maximum of 850 °C to permit the use of stainless steel construction.

The scope of each oxyfuel system, for the purposes of costing, is to include:

Boiler plus flue gas recycle (where applicable),
Air separation unit,
CO_2 separation and compression.

RESULTS AND DISCUSSION

The following section reviews the in-duct burner concept and proposes a preferred case. A comparison of this case against a more conventional oxyfuel steam generation process is also presented which includes an assessment of the likely installed cost and footprint.

In-Duct Oxyfuel Boiler Concept
The in-duct oxyfuel boiler concept aims to limit the temperature within the boiler to a maximum of 850 °C by splitting the fuel gas between a number of burners, located in series formation, and then cooling the resultant flue gas between each successive burner. The limitation in temperature permits the use of conventional stainless steel construction, thereby avoiding the need for more exotic and therefore expensive materials. Cooling between each burner stage and of the flue gas exiting the final burner stage raises superheated steam to meet the specification defined in the basis of design (refer to previous section). Conceptually, a 3-stage burner design would, for example, have the following layout:

- 1st stage in-duct burner: oxygen plus one-third of the fuel gas;
- staggered rows of evaporator tubes to cool flue gas and raise steam;
- 2nd stage in-duct burner: oxygen plus one-third of the fuel gas;
- staggered rows of evaporator tubes to cool flue gas and raise steam;
- 3rd stage in-duct burner: oxygen plus one-third of the fuel gas;
- staggered rows of evaporator tubes to cool flue gas and raise steam;
- further rows of superheater tubes to deliver steam to the required temperature/pressure;
- final rows of boiler feed water pre-heat tubes.

Note that the number of burner stages is not fixed at three, but is merely used above as an example. Furthermore, some optimisation of the fuel gas split will be required by any final design, rather than splitting equally as indicated above.

The design of the boiler is similar to that used for raising steam from the exhaust streams of Gas Turbines. The burners are located in a horizontal flow path with evaporator, superheater and boiler feed water pre-heat tubes located vertically.

The design aims to maximise heat recovery from the flue gas by using the exhaust gas from the final evaporative tube bank to both superheat the steam and to provide pre-heat to the boiler feed water.

Given the basis of design outlined previously, the total thermal capacity of the boiler is 174 MWt. This is split between heat required to vaporise the boiler feed water (evaporative heat) and that required to superheat the steam (superheat). To achieve the steam conditions given in the basis of design, this split is roughly 70% evaporative heat and 30% superheat. Any proposed design must meet this split in order to deliver the required superheated steam. Assuming a typical boiler thermal efficiency and the fuel gas composition given in the basis of design, the fuel gas demand is approximately 3.84 kg/s.

Two boiler designs are considered:

- a zero recycle case—in which there is no flue gas recycle. The temperature within the boiler is controlled merely by inter-burner cooling;
- a flue gas recycle case—in which some of the flue gas is recycled to the front-end of the boiler to help in controlling the combustion temperature.

Zero Recycle Case

To establish a boiler design for this case, the first issue is to evaluate the number of burner stages that will be required. The limitation to combustion in each stage is that the adiabatic flame temperature must be controlled below 850 °C to allow the use of stainless steel. Figure 1 was developed to indicate the number of burner stages that are required for varying gas throughputs. This chart is specific to the requested basis of design and illustrates the impact of over-supplying oxygen to help control the combustion temperature (the reason for this is elaborated later on).

For a relatively low oxygen stream mass flow of 17.6 kg/s, Figure 1 indicates that 18 burner stages are required. The number of burner stages can be reduced to 14 by optimising the fuel gas distribution, rather than splitting the fuel flow equally between all burners. Note that the oxygen feed rate is slightly more than the minimum amount of oxygen required for satisfactory combustion, but is representative of a boiler design with minimal gas throughput.

Whilst this 14-stage burner design does meet the design demands of limiting the maximum combustion temperature to 850 °C and raising 500,000 lb/h of steam, it is unable to deliver steam to the required superheated conditions. The total thermal duty of the inter-burner evaporator banks is approximately 160 MWt, which is well above the required evaporator thermal duty of about 120 MWt (70% of 174 MWt). Furthermore, there is insufficient sensible heat in the flue gas exiting the final bank of evaporator tubes to meet the superheat thermal duty (roughly 14 MWt c.f. the required superheat duty of around 52 MWt). The zero recycle case, therefore, fails to meet the required thermal performance. Two options are considered in order to redress this shortfall:

- Replace a number of evaporator tube banks at the back-end of the boiler with superheater tubes, thus switching some of the evaporative duty in the original design to superheat duty;
- Over-supply oxygen to each of the burners to act as a diluent and suppress the adiabatic flame temperature, thus reducing the number of burner stages required. This reduces the evaporative thermal duty of the boiler and also increases the amount of sensible heat remaining in the flue gas exiting the last bank of evaporative tubes. Both factors lead to an increase in superheat duty.

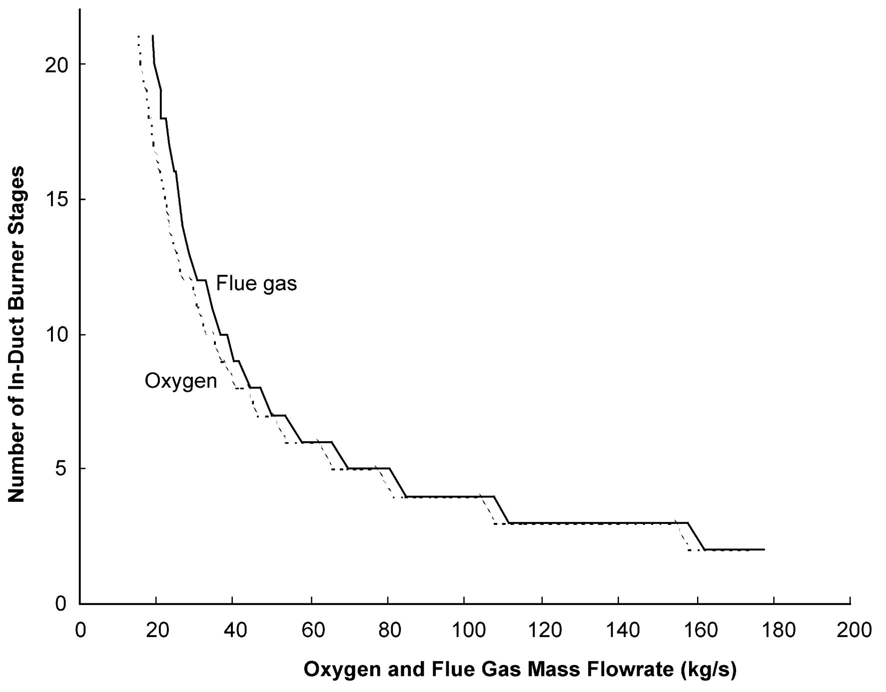

Figure 1: Oxyfuel burner stages needed for various throughput rates. This figure assumes that: (i) The maximum adiabatic flame temparature is 850°C, (ii) The fuel gas mass flow rate is 3.84 kg/s, (iii) The fuel gas is equally distributed between each burner stage, (iv) Oxygen and fuel gas composition is as outlined in the basis of design, (v) Inter-burner cooling is assumed to be from 850°C to 360°C (note that the boiling point of water in the evaporator tubes is about 334°C).

The alternative to over-supplying oxygen is to introduce flue gas recycle, an option considered in this chapter.

Impact of replacing evaporative tubes banks with superheaters
Replacing evaporative tube banks with superheaters limits the extent of flue gas cooling that can be achieved at the back-end of the boiler. Consequently, in these burner stages, less fuel gas can be burnt. Fuel gas supply to the other burners cannot be increased as the adiabatic flame temperature is set to the maximum of 850 °C in each burner stage. Additional burner stages are, therefore, required in order to burn all the fuel gas, and thereby generate the required amount of steam. Increasing the number of burner stages will increase the capital cost and this option is not pursued further on the grounds that it is considered to be uneconomic.

Impact of over-supplying oxygen
Increasing the oxygen mass flow rate from 17.6 to 84 kg/s reduces the number of burner stages from 14 to 4, whilst maintaining the adiabatic flame temperature below 850 °C. Consequently, the thermal duty of the inter-stage evaporative tubes drops to 107 MWt and the sensible heat in the flue gas exiting the final bank of evaporative tubes (approximately 67 MWt) is sufficient to deliver the required superheat duty. Therefore, the steam generation rate and conditions are met by this option.

Clearly, however, over-supplying oxygen has a significant cost penalty caused by a marked increase in the size of the ASU. In addition, oxygen content of the flue gas exiting the boiler rises to about 74wt %, thus significantly increasing the duty on the downstream unit to separate CO_2 from impurities.

Therefore, this option has also been dropped on the basis of the significant increase in the duties of both the ASU and the CO_2 separation unit.

Flue Gas Recycle Case

The previous section outlined the case for eliminating flue gas recycle. In order for that case to meet the steam generation demands, either additional burner stages are required to increase the superheat duty or the oxygen stream must be over-supplied. Neither option is considered acceptable on the grounds of cost and, therefore, the alternative considered here is to introduce some recycle of the flue gas.

In order to limit the number of burner stages to a reasonable number and thereby maximise the potential for the in-duct burner concept to prove economically viable, a gas throughput of over 80 kg/s is pursued, the majority of which is a diluent to control the adiabatic flame temperature. The use of oxygen as a diluent has been considered in the previous section and is discounted on the basis of cost. The diluent, therefore, must largely comprise of recycled flue gas. However, to maintain acceptable combustion conditions, a certain level of oxygen must be present. Therefore, a flue gas recycle of 75% is considered for this case.

Assuming this flue gas recycle rate, an evaluation of the boiler heat and material balance yields the following:

A 3-stage burner design is possible, based on a maximum adiabatic flame temperature of 850 °C.

The total thermal duty of the evaporative tube banks is 107 MWt, leaving about 67 MWt of superheat. This is roughly equal to the 70:30 split necessary to deliver the required superheated steam.

Oxygen content of the boiler flue gas is approximately 11.9wt %—considered acceptable for downstream CO_2 capture.

This option, therefore, meets the steam generation demands whilst also limiting the maximum temperature within the boiler to less than 850 °C.

Selected case

Based on the details contained in the previous two sub-sections, the selected design for an in-duct oxyfuel boiler incorporates recycling 75% of the flue gas.

The zero flue gas option will deliver the required steam rate and conditions, but only if additional burner stages are included or if the oxygen is over-supplied to act as a temperature suppressant. Although technically feasible, these options are considered to be more expensive than recycling 75% of the flue gas and are not selected for further consideration on this basis.

The boiler design is based on counter-current heat transfer and consists of a series of evaporator, superheater and economiser (used to pre-heat the boiler feed water) sections positioned in the flue gas stream and between successive burners. To maximise heat recovery and thermal efficiency, due consideration is given to the back-pressure, pinch point, superheater and economiser approach temperatures, steam temperature and pressures, and the flue gas outlet temperature.

Each of these parameters has been evaluated based on the experience of Mitsui Babcock and on economic considerations.

The back-pressure is dictated, to a large extent, by the steam generator cross-sectional flow area. A high back-pressure will reduce the cost of the steam generator (smaller diameter equipment), but will adversely affect the cost of supplying oxygen and of recycling the flue gas.

The pinch point temperature and the approach temperatures have a major impact on the overall unit size. Figure 2 indicates the temperature profile over the boiler.

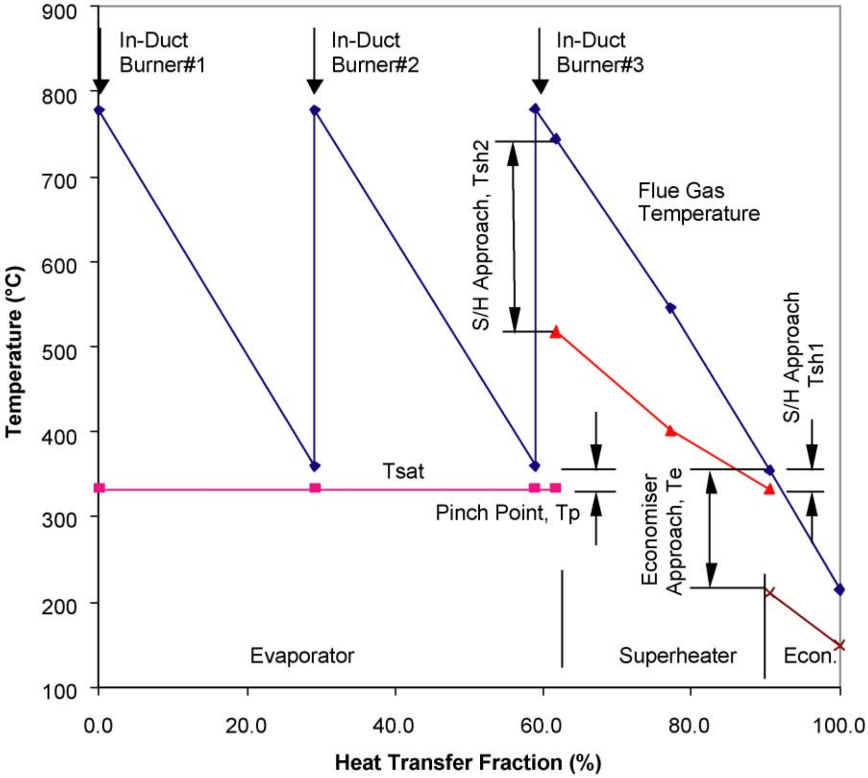

Figure 2: Temperature profile for oxyfuel boiler with 75% flue gas recycle.

The following conditions have been adopted to generate a technically acceptable and economic design:

pinch point, T_p, of 27 °C,
minimum superheater approach, T_{sh1}, of 22 °C,
maximum superheater approach, T_{sh2}, of 226 °C,
maximum economiser approach, T_e, of 144 °C

Smaller pinch point and approach temperatures are possible and will improve the thermal efficiency, but will also lead to larger heat transfer areas and higher capital costs. The economiser approach temperature is set to avoid steaming at the design point.

Review of 75% flue gas recycle case
The selected in-duct boiler design is reviewed in this section by comparison with a conventional boiler designed for oxygen-firing and incorporating flue gas recycle. This comparison considers the installed capital cost of each option and the installed footprint and thus allows conclusions to be drawn as to the justification of pursuing the in-duct oxyfuel boiler design further.

Installed capital cost. The installed capital cost for both the selected in-duct oxyfuel boiler and the conventional oxygen-fired boiler are given in Table 1. The scope for each option includes a conventional ASU and downstream CO_2 capture and compression unit.

These costs (Table 1) include design, manufacture, supply, construction and commissioning, but exclude costs for civil work, foundations, spares, permits/licenses and owners costs. It should also be noted that the costs for the additional major items (i.e. ASU, CO_2 separation/compression unit and the flue gas recycle) have been taken from previous studies conducted by Mitsui Babcock for the CCP.

TABLE 1
COMPARISON OF INSTALLED CAPITAL COST FOR IN-DUCT 75% FLUE GAS RECYCLE OXYFUEL BOILER AND CONVENTIONAL OXYGEN-FIRED BOILER WITH FLUE GAS RECYCLE

Unit	**In-duct oxyfuel boiler with 75% FGR**	**Conventional oxygen fired boiler with FGR**
CAPEX (million US$)		
Boiler installed cost	14.875	21
Air separation unit price	19.425	19.425
CO_2 separation and compression unit price	9.8	9.8
ASU and CO_2 separation/compression installation and pre-commissioning	7	7
FGR system installed cost	1.4	1.4
Total	52.5	58.625
Cost per tonne of CO_2 captured per year ($/te/yr)	158.9	177.45

Notes: Costs outlined in the above table relate to the year 2000. CO_2 captured assumed to be 38.1 tonnes/h.

The key conclusion to draw from the above table is that the in-duct oxyfuel boiler offers the potential to cut the cost of an oxyfuel steam generation system by about 10% (from $58.625 million to $52.5 million). Whilst the reduction in capex for the boiler itself is quite significant, once other associated items of equipment have been included, the benefits of the in-duct concept become less attractive.

Footprint. Table 2 outlines the physical dimensions of the two oxyfuel boilers.
As indicated above, the selected in-duct oxyfuel boiler concept has a footprint that is roughly twice the size of a conventional boiler of equal thermal capacity.

TABLE 2
OXYFUEL BOILER PLANT FOOTPRINT COMPARISON

	In-duct oxyfuel boiler with 75% FGR	**Conventional oxygen fired boiler with FGR**
Height—ground level to steam drum (m)	14.6	33
Width—boiler sidewall tubes/duct (m)	7.1	6.7
Depth/length—between boiler heating surfaces (m)	21.9	10.8
Approx. footprint (m^2)	155	73

CONCLUSIONS

The conclusions drawn from this study are as follows:

The in-duct oxyfuel boiler concept with zero recycle is technically feasible, but is not considered to be economically attractive. The required steam superheat conditions cannot be met without either

Replacing some of the evaporator tube banks with superheaters, or by
Increasing the oxygen mass flow rate through the boiler.

Both options are considered too costly. The former leads to an increase in the number of burner stages beyond 14 in order to raise the required amount of steam and the latter to a significant increase in the ASU duty and to the scope of the CO_2 capture unit.

Recycling 75% of the flue gas from the in-duct oxyfuel boiler leads to the requirement for a 3-stage burner design. Although this option does have a high flue gas recycle, it is considered to represent the most economic way of utilising the in-duct oxyfuel boiler concept whilst still delivering steam to the required conditions and flow rate.

The installation capital cost of the in-duct oxyfuel boiler with 75% flue gas recycle is estimated at $58.625 million and is roughly 10% less than a conventional boiler design incorporating oxygen firing and flue gas recycle. This installed capital cost equates to a CO_2 capture cost of £158.90 per tonne of CO_2 captured per year.

This potential benefit over more conventional equipment is not considered sufficient justification to warrant development of the in-duct oxyfuel boiler concept. Further development with the CCP framework is, therefore, not recommended.

Although variations on the cases evaluated in this report are possible, a substantial drop in the installed capital cost is not considered to be probable. The above conclusion that there is insufficient justification to warrant further development is, therefore, considered to be robust.

With regard to a conventional boiler design, the in-duct boiler concept will lead to a reduction in height, but will require a footprint area of roughly twice the size.

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