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LES and RANS of air and oxy-coal combustion in a pilot-scale facility: Predictions of radiative heat transfer

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HIGHLIGHTS

- LES and RANS predictions are made of a pilot-scale combustion test facility.
- Heat flux measurements from air and oxyfuel experiments are compared with CFD predictions.
- FSCK and WSGG models are examined in RANS and LES calculations.
- LES considerably improves the prediction of radiative heat flux.
- LES with FSCK shows the best overall agreement with the measurements.

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ABSTRACT

This study evaluates the use of large eddy simulation (LES) and Reynolds-averaged Navier Stokes (RANS) models for the prediction of turbulent coal combustion under air and oxyfuel environments in a pilot-scale 250 kW_{th} furnace. The furnace is part of the UKCCSRC Pilot-scale Advanced Capture Technology (PACT) facilities and was designed for detailed analysis of the combustion process. The prediction of thermal radiation is validated against experimental measurements under both air- and oxy-firing regimes. Two radiation models were evaluated during the RANS calculations, the widely used weighted sum of grey gases (WSGG) and the full-spectrum correlated k (FSCK) model, while the LES case was calculated using the FSCK radiation model. The results show that the choice in gas radiation model demonstrates only a small change in the temperature and heat flux predictions in the RANS calculations, while the LES solutions are able to achieve better agreement with measured values than the RANS predictions for both air-fired and oxyfuel coal combustion.

1. Introduction

The international community is committed to preventing the rise of temperature attributable to anthropogenic climate forcing through the reduction of greenhouse gas (GHG) emissions. Nations have implemented targets to reduce their GHG emissions compared to baseline levels recorded in 1990, with the UK has committing to a 34% reduction in GHG emissions by 2020, which rises to an 80% reduction by 2050. The energy sector will be required to greatly curb its GHG emissions to realise these targets, however with the rising global population, and the industrialisation of developing countries, fossil fuels are still expected to be utilised.

Coal in particular is expected to remain an important global energy resource due to its widespread availability and operating flexibility, however coal-fired combustion is one of the largest global sources of (CO_2) emissions [1]. It is necessary to develop carbon capture and storage (CCS) technology so that the benefits of coal-fired energy generation can be realised without violating efforts to reduce CO_2 emissions.

This study focusses on oxyfuel technology for carbon capture. The oxyfuel process for a thermal power station involves firing combustible fuel with a high-purity oxygen stream, which is often diluted with recycled flue gas to control flame temperature and heat transfer. The resulting flue gas from the oxyfuel process contains a high concentration of CO_2 that can be economically purified to a level suitable for transport and storage [2]. Oxyfuel combustion has been demonstrated at small and medium scales [3–5],

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and is being developed for large scale projects, such as the White Rose CCS[1] and FutureGen 2.0[2] projects.

Oxyfuel technology can be retrofitted to existing combustion facilities, however, with such significant changes to the combustion environment, it is important to develop an understanding of the influence that switching to oxyfuel will have over heat transfer, chemical reactions and flame stability. Furthermore, the control over the oxygen concentration in the recycled flue gas will provide an additional parameter with regards to combustion efficiency and material corrosion control to optimise against the cost of the oxygen supply, as well as offering further benefits with regards to fuel flexibility [6].

It will be beneficial in the design and optimisation of oxyfuel combustion to be able to predict the influence of operating parameters on the combustion performance. Under oxyfuel, the increase in the concentration of radiatively participating species, namely CO_2 and H_2O, significantly modifies the transfer of thermal radiation [7]. Modelling techniques, such as Computational fluid dynamics (CFD), have been used to predict air-fired combustion facilities, however the novelty of the oxyfuel combustion environment poses challenges to models that are often empirically defined for air-firing. Pilot-scale facilities are important to validate (CFD) models before they can be applied to larger cases as they provide well controlled environments where detailed experimental measurements can be performed.

This study presents both experimental measurements and numerical solutions for a 250 kW down-fired combustion test facility, which is part of the UKCCSRC Pilot-scale Advanced Capture Technology (PACT) facilities, operating with both air-fired and oxyfuel coal combustion. The facility was constructed to offer detailed analysis of the combustion process under a range of environments. The measurements of the two combustion modes are used to validate CFD predictions using advanced turbulence and spectral radiation treatment.

2. Combustion test facility

The combustion test facility that is the subject of this study is a vertical down-fired cylindrical furnace, fitted with a scaled 250 kW_{th} burner provided by Doosan Babcock. The burner introduces combustion gases into the furnace through three registers, referred to as the primary, secondary and tertiary, which is illustrated in Fig. 2. A central annulus exists for preheating the furnace with a natural gas flame, however this annulus was not used during the measurements. The coal is transported into the furnace through the primary annulus, with the majority of the combustion oxidant supplied through the secondary and tertiary annuli. The three inlets are swirled with blades fitted into the burner to stabilise the flame and increase the turbulent mixing of the oxidant and fuel.

The cylindrical furnace has an inner diameter of 0.9 m and is 4 m high and is illustrated in Fig. 1. The facility is comprised of eight sections that are lined with a 0.1 m thick refractory. The facility was designed to allow for detailed measurements and characterisation of the combustion process under a wide range of operating conditions, and has numerous measurement ports located down the length of the furnace. Each section is 0.5 m high, with the first six sections being water cooled. The top two sections of the furnace contain a number of ports for intrusive and non-intrusive flame measurements. The furnace is maintained at sub-atmospheric pressure by an exhaust fan to ensure safe operation. The same batch of El-Cerrejon coal was fired during the air and

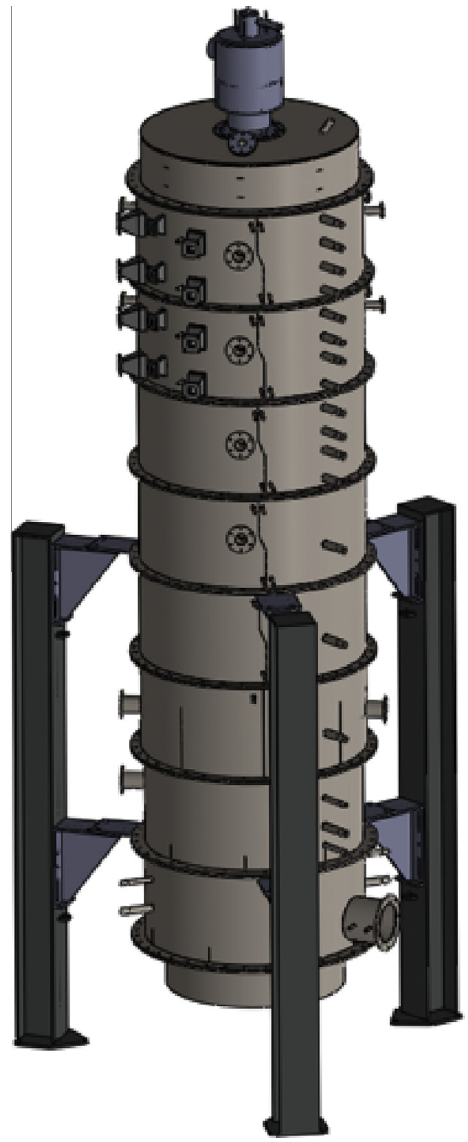

Fig. 1. CAD image of the combustion test facility.

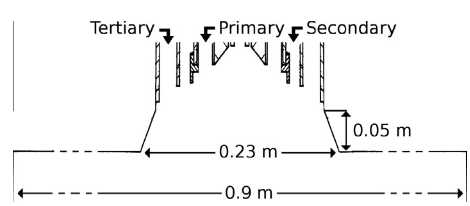

Fig. 2. Sketch of the near burner region of the combustion rig.

oxyfuel combustion measurements in this study. The calorific, proximate and ultimate analyses of the coal are shown in Table 1.

The operating conditions for the air and oxyfuel cases are detailed in Table 2. Both cases were run with the same 200 kW thermal load with the same exit O_2 concentration, measured at 3.3% (dry vol.). The oxyfuel case was fired using an overall 27% (vol.) O_2 concentration, with a balance of CO_2. The O_2 and CO_2 in the oxyfuel case were supplied from liquid storage tanks. The secondary and tertiary gases are preheated using electrical heaters to achieve temperatures that are comparable to values used for utility boilers. The oxygen concentration of the primary gas, which transports the coal, was reduced in the oxyfuel test case to ensure safe

[1] http://www.whiteroseccs.co.uk/.
[2] http://futuregenalliance.org/futuregen-2-0-project/.