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Numerical modelling of oxy fuel combustion, the effect of radiative and convective heat transfer and burnout

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HIGHLIGHTS

- CFD model is developed to investigate the oxy-fuel combustion in furnace.
- Radiative and convective heat flux is significantly manipulated by the RR.
- A working range for air to oxy-firing is determined showing unique balance.
- Air equivalent radiative heat flux can be obtained at a RR of ≈71%.
- Unburned carbon in ash (CIA) is improved in oxy-fuel conditions.

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ABSTRACT

In this study, a numerical investigation on the radiative and convective performance of the combustion of pulverised Russian coal having higher Calorific value in a 0.5 MWth combustion test facility (CTF) has been conducted for air and CO_2-rich oxy-fired environment considering an IFRF Aerodynamically Air Staged Burner (AASB) configured with the furnace. This study is carried out considering a finite volume method (FVM) tool using AVL Fire version 2009.2 coupled with the user defined subroutines especially for the coal devolatilisation and char combustion modelling. This code is validated comparing the experimental radiative heat flux with the numerically predicted data and results show that reasonable agreement has been found with the measured radiative heat flux on the furnace wall. Different combustion environments were investigated including an air-fired as reference case and three recycled flue gas (RFG) fired combustion environments. The different cases are composed of varying recycled ratio (RR) between 65% and 75%. It was found that the flame temperature distribution for the reference case (air fired) and RR72% case were found to be similar. The flame temperature increased with O_2 concentration and decreasing RR. With the decrease of RR, the length of the flame is also shortened. The ignition condition improved with enriched O_2 concentration in the RR65% (O_2 30.9%, CO_2 69.2% by mass) case. The results show that radiative and convective heat flux is significantly manipulated by the RR. The position of peak radiative flux moves downstream with increasing RR due to increased mass flow rate and reduced O_2 at higher RR. With the increase of normalised total flow (NTF), mean flame temperature and exit temperature decreased whereas with the increase of normalised O_2 flow (NOF), mean flame temperature and exit temperature increase. The presented working range for the Russian coal, suggests that the air equivalent radiative heat flux can be obtained at a RR of ≈71% while air equivalent flame temperature were observed at RR of 72%. Reasonable agreement has been obtained for unburned carbon in ash (CIA). An improved burnout was observed in RR conditions.

1. Introduction

Combustion of fossil fuel is a proven thermochemical conversion technology for heat and power production which is connected with formation of pollutant, also a source of deterioration of the global environment. Coal is a major source of fossil fuel, responsible for generating electrical energy in the world [1]. Also, combustion of coal results in the emission of greenhouse gases, the accumulation of which in the atmosphere since the start of the industrial revolution has been contributing to climate change [2]. In this concern, international efforts, like Kyoto protocol bound

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Nomenclature

A_c	pre-exponential factor (s^{-1})
A_v	pre-exponential factor (s^{-1})
A_p	cross sectional area of particle (m^2)
C_D	drag coefficient
C_{fu}	combustion model constant, (= 3.0)
C_{pr}	combustion model constant, (=0.5)
Dp	diameter of the particle (μm)
E_c	activation energy (kJ mol^{-1})
E_v	activation energy (kJ mol^{-1})
F_{idr}	drag force (N)
F_{ig}	gravitational force (N)
F_{react}	reaction force (N)
G	production due to the buoyancy force
K	turbulent kinetic energy (m^2/s^2)
K_v	rate constant of devolatilisation
m_{vp}	mass of particles at devolatilisation (kg)
m_{RFG}	amount of recycled flue gas
m_{PFG}	amount of product flue gas
m_p	mass of the particle (kg)
min	minimum value of the operator
P	pressure (N/m^2)
P_A	atmospheric Pressure (N/m^2)
Pr	Prandtl number
p	sum of partial pressure (N/m^2)
P_g	partial pressure of oxygen at furnace (N/m^2)
P_s	oxygen partial pressure at surface (N/m^2)
Re_p	particle Reynolds number
R_p	radius of the particle (μm)
$\bar{r}_{fu}$	fuel consumption rate (kg/m^3 s)
s	path length
S_Φ	variable source, Φ
$S_{p\Phi}$	additional source term
S	stoichiometric air/fuel ratio
T	temperature (K)
T_p	temperature of the particle (K)
T_g	gas temperature (K)
U_i	velocity in the ith direction (m/s)
V_p	velocity of the particle (m/s)
$\lvert u_{rel} \rvert$	relative velocity (m/s)
V	product of volatiles at time, t
V_f	ultimate product of volatiles
x_i	spatial distance in the ith direction
$\bar{y}_{pr}$	mass fraction of product (kg/kg)
$\bar{y}_{ox}$	mass fraction of oxidizer (kg/kg)
$\bar{y}_{fu}$	mass fraction of fuel (kg/kg)

Greek symbols

μ_t	turbulent viscosity (m^2/s)
e	particle emissivity
τ_R	turbulent time scale (s^{-1})
i_b	blackbody emissivity
Φ	variables
λ	thermal conductivity (W/m K)
i'	radiation intensity (W/m^2)
i'_{n+1}	total radiation intensity (W/m^2)
a_i	absorption coefficient
ρ	gas density (kg/m^3)
ε	turbulent dissipation rate (m^2/s^3)
ρ_g	density at gas phase (kg/m^3)
ρ_p	density at particle phase (kg/m^3)
Γ	diffusion coefficient of variable Φ
σ	Stephan–Boltzmann constant ($W/m^2 K^4$)

List of abbreviations

IFRF	International Flame Research Foundation
AASB	Aerodynamically Air Staged Burner
DTRM	discrete transfer radiation method
EBU	Eddy Breakup combustion model
RTE	radiation transfer equation
CTF	combustion test facility
FVM	finite volume method
GCV	gross calorific value
NTF	normalised total flow
NOF	normalised O_2 flow
RFG	recycled flue gas
PFG	product flue gas
GHG	greenhouse gas
VM	volatile matter
RR	recycled ratio
HC	hydro carbon
FC	fixed carbon

an obligation for the reduction of emissions specially CO_2 from industrialized countries. For the reduction of CO_2 emissions from coal fired power plants, a number of CO_2 capture technologies, can be implemented for continuing the use of fossil fuel [2–5] such as post-combustion capture, pre-combustion capture, and oxy-combustion. Apart from these processes, different separation techniques are also suggested as gas phase separation, absorption, adsorption and hybrid processes. Recent developments in the CO_2 capture technologies include some innovative concepts (i.e., calcium looping, chemical looping, and amines scrubbing systems) suggested in literature. Calcium looping (CaL), a post combustion capture technology, is suggested as a competitive concept for CO_2 reduction technique [6] for power plants. CaL is achieved by oxy-firing for the generation of CO_2 rich flue gas which is absorbed by CaO and $CaCO_3$ in carbonator. But this technique is relatively more energy consuming. The ECO-Scrub combustion concept [7], a combination of partial oxy-fuel combustion and post combustion capture, provide comparatively higher efficiency than only post combustion process. Another important concept is chemical looping combustion (CLC) [8–12]. In CLC, high purity and concentrated CO_2 stream is produced as there is no contact between the fuel and the air as metal oxide works as transportation media for O_2. Hence, lower energy is required compared to other CO_2 separation processes.

Among all the carbon capture technologies, oxy-fuel combustion is a greenhouse gases (GHG) abatement technology in which coal is burned using a mixture of O_2 and recycled flue gas (RFG), to obtain a rich stream of CO_2 ready for sequestration [4]. This carbon capture technology has been considered as one of the most effective technologies to reduce gaseous emissions. In general, the conventional boiler use air as an oxidizer in the combustion process, hence nitrogen is the main component in the flue gas as its concentration in the air is approximately 79% by volume. But, in the oxy fuel combustion, air is replaced with oxygen and recycled flue gas mixture. The flue gas produced in oxy fuel combustion has very high concentration of CO_2 comparing with the flue gas achieved in the air combustion and is ready for sequestration. The basic schematic of oxy fuel combustion with the RFG is presented in Fig. 1. Recycled ratio (RR) is the most significant parameter in an oxy-fuel system when operated with RFG. It is a function