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Analytical and numerical investigation of the impact of various coal types on coal-fired boiler combustion parameters

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ABSTRACT

The efficiency of power plants that burn coal is inversely related to the coal's quality. Ash buildup is one of the environmental problems caused by low-quality coal's poor combustion characteristics. This article presented the results of a computational fluid dynamics (CFD) study of the combustion and flow processes in a massive furnace. We put A, B, and C—three distinct sub-bituminous coals—to the test. Keeping an eye on the furnace's temperature, species concentration, and flow rate allows us to forecast how well the coals will burn. The operator provided the precise boiler furnace geometry, which was then converted into a CFD model with minimal adjustments required for mesh optimisation. The investigation found that coal B had the maximum combustion temperature, at around 1400°C. Coal C, ironically, is anticipated to have the shortest flame duration and the largest velocity peak in some furnace zones, therefore more flow is needed to attain the same penetration as other coals. Optimal combustion is shown by the trace of the oxygen concentration within the furnace. The rear pass, fed by Coal A, has very little oxygen remaining.

Introduction

Reliable, affordable and clean energy supply is one of the basic needs of humankind. Today, our energy supply system is undergoing a long-term transition from its conventional form to a more sustainable and low carbon style, especially addressing greenhouse gas (water, carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and aerosols) emissions into the atmosphere. Strong evidence suggests that both the average global temperature and the atmospheric CO2 concentration have significantly increased since the onset of the industrial evolution, and they are well correlated. Concerns over climate change have led tomounting efforts on developing technologies to reduce carbon dioxide emissions from human activities. Technological solutions to this problem ought to include a substantial improvement in energy conversion and utilization efficiencies, carbon capture and sequestration (CCS), and expanding the use of nuclear energy and renewable sources such as biomass, hydro-, solar, wind and geothermal energy. Coal has been and will continue to be one of the major energy resources in the long term because of its abundant reserves and competitively low prices, especially for the use of base-load power generation. For instance, the share of coal in world energy consumption was 29.4% in 2009, as opposed to 34.8% for oil and 23.8% for natural gas. In terms of power generation, coal continues to be the dominant fuel, contributing about 45% of the total electricity in the US in 2009, and about 80% in China. Several technologies have been proposed for reducing CO2 emission from coal-fired power generation, namely post-combustion capture, pre- combustion capture and oxy-fuel combustion capture:

- Pre-combustion capture: Fuel is either gasified or reformed to syngas, a mixture of carbon monoxide and hydrogen, which is then shifted via steam reforming. CO2 is then separated from the syngas by shifting carbon monoxide with steam, yielding pure hydrogen (water gas shift reaction). The Integrated Gasification Combined Cycles (IGCC) for coal is an example of pre-combustion capture system.
- Post-combustion capture: CO2 is separated from the flue gases using chemical solvents, sorbents (such as calcium oxide or carbon fibres) and membranes without changing the combustion process. However, the addition of a post-combustion capture unit may change the steam cycle because large quantity of low pressure steam must be extracted from the steam cycle for the solvent regeneration process.
- Oxy-fuel combustion: Instead of using air as oxidizer, pure oxygen (O2) or a mixture of O2 and recycled flue gas is used to generate high CO2 concentration product gas; therefore, the combustion process is significantly changed. Chemical-Looping Combustion (CLC) is another combustion process that belongs to the oxy-fuel combustion category, in which pure oxygen rather than air is supplied by metal oxides for combustion, such that the mixing between CO2 and N2 is inherently avoided.

This technology is not the primary focus of this paper, and, the reader is referred to for more details on CLC.

In general, the technologies described above can be applied to generate energy from natural gas and coal with the exemption of some low rank coals due to unresolved engineering challenges, however, because of the important role of pulverized coal in base load electricity generation and its contribution to CO2 emission, this study is primarily concerned with the combustion of pulverized coal, although some mention is made of other fuels as well.

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Table1-1.Representativeperformanceandeconomics dataforthethreemaincapturetechnologies,

Performance	Supercritical PC[a]		SC[b] PC-Oxyfuel	IGCC[c]	
	w/o capture	w/ capture	w/ capture	w/o capture	w/ capture
Generating efficiency	38.5%	29.3%	30.6%	38.4%	31.2%
Efficiency penalty	CO_2 recovery (heat): -5%		Boiler/FGD: 3%	Water/Gas shift: -4.2%	
	CO_2 compression: -3.5%		ASU: -6.4%	CO_2 compression: -2.1%	
	CO_2 recovery (power): -0.7%		CO_2 compression: -3.5%	CO_2 recovery: -0.9%	
			Other: -1%		
Capital Cost ($/kWe)[e]	1330	2140 (1314)[d]	1900 (867)[d]	1430	1890
COE (c/kWh)[e]	4.78	7.69	6.98	5.13	6.52
Cost of CO_2 ($/t)[e]	40.4		30.3	24.0	

PC: pulverized coal; b SC: supercritical; c IGCC: Integrated gasification combined cycle; d Figures in parenthesis are the expected capital cost for retrofits; e Based on design studies done between 2000 & 2004, a period of cost stability, updated to 2005$ using CPI inflation rate. These three major carbon capture technologies for coal- fired power plants have been studied in terms of power generation efficiency, capital costs and costs of electricity (COE). Representative energy efficiency and economic performance of these technology options are compared in Table 1-1. All of these estimates are based on 90% CO2 capture in rebuilt and retrofitted scenarios. The cost of CO2 indicates the cost that is incurred to capture 1 metric ton carbon dioxide without transportation and storage. Although the absolute numbers vary by few percentage points in these studies, all reports show the same trends. In general, all three capture technologies result in an efficiency penalty, while oxy-fuel capture and pre- capture or IGCC show advantages over post-combustion capture in terms of COE and cost of CO2. The IGCC technology yields a higher generation efficiency and a slightly lower cost than oxy-fuel combustion technology. However, all these technologies are in their early stages of development and still have great potential for improvement. In particular, these studies have a common conclusion that oxy-fuel combustion is the most competitive technology option for retrofitting existing coal-fired power plants, which at the moment have the largest potential for CCS. Although the number of newly-built coal power generation units declined since 1990s', there is a resurgence of new coal power plants in recent years. Moreover, about 98.7 GW or 29% of all the existing coal-fired power capacity were built after 1980. This situation is even more prominent in developing countries such as China and India, where the coal power generation capacity has been booming in the last two decades. It can safely be assumed that a sizable reduction of CO2 emission from existing plants would come from retrofits. Oxy-fuel combustion systems have a natural advantage in retrofitting existing PC power plants because they can reuse most of the existing plant equipment. The advantages of oxy-fuel combustion as a retrofit technology are also indicated in Table 1-1. The capital cost for supercritical PC retrofits with oxy-fuel is $867/kWe, which is significantly lower than the capital cost of post-combustion retrofit ($1314/kWe) and of newly-built IGCC plants ($1890/kWe). Considering the advantages of a relatively moderate efficiency penalty and the lowest retrofit capital expenditure, atmospheric oxy-fuel combustion systems have been widely accepted as a competitive carbon capture technology. More recently, it has been adopted to substitute the original IGCC plan in the U.S. DOE FutureGen 2.0 program. Previous studies have reviewed its fundamentals and characteristics, as well as recent developments in pilot-scale and commercial-scale demonstration plants. While successful, the technology still faces many challenges, such as air leakage into the flue gas system, the relatively low energy efficiency, the need for efficient air separation and better plant integration and flue gas clean-up, among others. In particular, significant challenges are expected in the combustion process itself, including stability and emissions, burner design and scaling, as well as determining of optimal operating conditions. Oxy-Fuel Combustion for CCS Development of the Oxy-Fuel Technology for CCS The idea of applying oxy-fuel processes with flue gas recycle in coal-fired plants to control the CO2 emission and/or produce high concentration CO2 for enhanced oil recovery (EOR) was first proposed in 1982. Following these proposals, Argonne National Laboratory (ANL) pioneered the investigation of this process in the mid and late 1980s, focusing on the system and its combustion characteristics. Soon after, more and more researchers agreed that this system complements the two other major approaches for carbon dioxide capture, which led to a renewed interest in thistechnologyinthe1990s.ResearchconductedbytheInternationalFlameResearchFoundation(IFRF),CANMET

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, IHI, as well as other institutes and industrialpartieshasmadeconsiderablecontributionsinunderstandingofthisprocess.

Along with the research and development on theair-likeoxy-coaltechnology,pilotandlargescaledemonstration plants are being built around the world.Wall et al. surveyed research on oxy-fuel technology,from pilot-scale tests, to industry-scale tests and full-scaledemonstrations,andcompiledthehistoricaldevelopmentofthistechnology worldwide.Theyear2008marksanimportantmilestonewiththecommissioningoftheworld'sfirst30MWthdemonstration plantinGermany.Morelarge-scaledemonstrations in industry-scale coal-fired boilers havebeenplannedorarealreadyunderway,asshowninTable 1-2 based on the work of Wall et al. and Herzog.Success in these demonstrations is expected to lead towider commercial deployment. Recent research has alsofocusedonextendingtherangeofoperatingconditionsof oxy-coal combustion to improve energy efficiency,environmentalperformanceandeconomicsofthis technology. For instance, pressurized systems have beenproposed for both oxy-coal combustion with recycledflue gases and oxy-syngas combustion in combinationwithsolidfuelgasificationtechnology.Theseapproachesaredescribedingreaterdetailinthefollowingsections.

Atmospheric Oxy-Coal Combustion Systems with FlueGasRecycle

Theatmosphericoxy-coalcombustionsystemshown in Figure 1-1 was first introduced as a short-termsolutiontoretrofitexistingcoal-firedpowerplanttoincludetheoptionofCCS.Inmostoxy-coalsystemstudies, recycled flue gases at various recycle ratios areused to control the flame temperature in the combustorand as a result, the flue gas consists primarily of steamwhichislaterremovedthroughcondensation,andcarbon dioxide which is purified before being sent forcompressionandsequestration.Theadditionalequipment required,whencomparedwithair-firedsystems,isdescribed below:

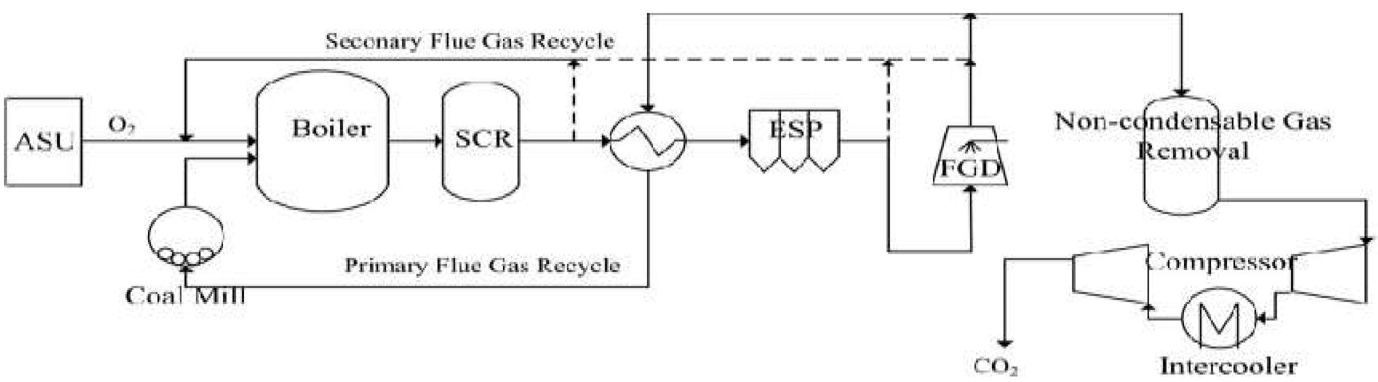

Figure 1-1. Atmospheric oxy-coal combustion system with flue gas recycle proposed for carbon capture in coalpower plants.

***Air Separation Unit (ASU)*:** When retrofitting existingPCpowerplants,thesystemprimarilyusesexistingequipmentwiththeexceptionofanASUusedtoproduceanoxygenrichstreamfor combustion.Currently, the only ASU technology that can meet thevolume and purity demand of a large scale coal-firedutility boiler is based on cryogenic distillation. Air iscompressed,cooledandcleanedpriortobeingintroduced into the distillation columnto separate airinto an oxygen-rich stream and a nitrogen-rich stream.Cryogenic air separation is energy intensive, consumingabout0.24kWh/kgO2with95%oxygenpurity.Although theoxygenpurity requirement for oxy-coalcombustion (85~98%) is lower than that needed in theprocessindustry(99.5~99.6%)[39],thesecryogenicseparation processes can consume more than 15% of thegrosspoweroutput.

***Carbon Dioxide Purification Unit (CPU)*:** CPU consistsof gas clean-up units to remove water, particulate matterand other pollutant gases from the flue gas before beingcompressed for sequestration. Because oxy-combustionis compatible with retrofits, selective catalytic reduction(SCR),electrostaticprecipitator(ESP)andfluegasdesulphurization (FGD) are typically retained as meansof NOx, particulate matter and SOx removal from thefluegases.Thismethodisalsosuitableforuseinconjunctionwithamine-typeabsorbentsforpost-combustioncapture plants.

It has been widely accepted that the non-condensableimpurities,suchasO2,maycausecorrosioninthepipeline during transportation, and this has raised doubtsabout the safety of the storage sites. Therefore, after theremovalofacidgasessuchasSOxandNOx,non-condensable N2, O2, and Ar should also be purged usinganon-condensablegaspurificationunit.Thisunitismade of multi-stage compression units with inter-stagecooling in order to separate out the inert gases. Up to thetimeofthisreview,therearestillnoagreeduponstandardsregardingtherequiredpurityofCO2forstorage and sequestration. However, it should be notedthat the acceptable degree of purity of the storage-readyCO2 results from a trade-off between efficiency lossesand operational costs during purification and the safetydemandsoftransportation andstorage.

Flue Gas Recycle (FGR) System:Recycled flue gas isrequiredtomoderatethecombustiontemperature.Considering system efficiency and operation practices,fluegasescanberecycledatdifferentlocationsdownstream of the economizer in the form of wet or dryrecycles. In the early stages of oxy-coal system studies,the requirement on CO2 purity was not stringent and thedesulfurization and de-NOx equipment were regarded asunnecessary. Therefore, all the flue gas was proposed tobe extracted from a single location downstream of theESP in wet or dry forms. Later on, Dillon et al. proposedflue gas recycling at different locations for the primary(usedfortransportingcoal)andsecondarystreamsforthe sake of energy efficiency: while the primary recyclehas to be dried and reheated to 250-300 ^{o}C to take upmoisture from the coal feed, the secondary stream can berecycledathighertemperatureswithoutdryingto

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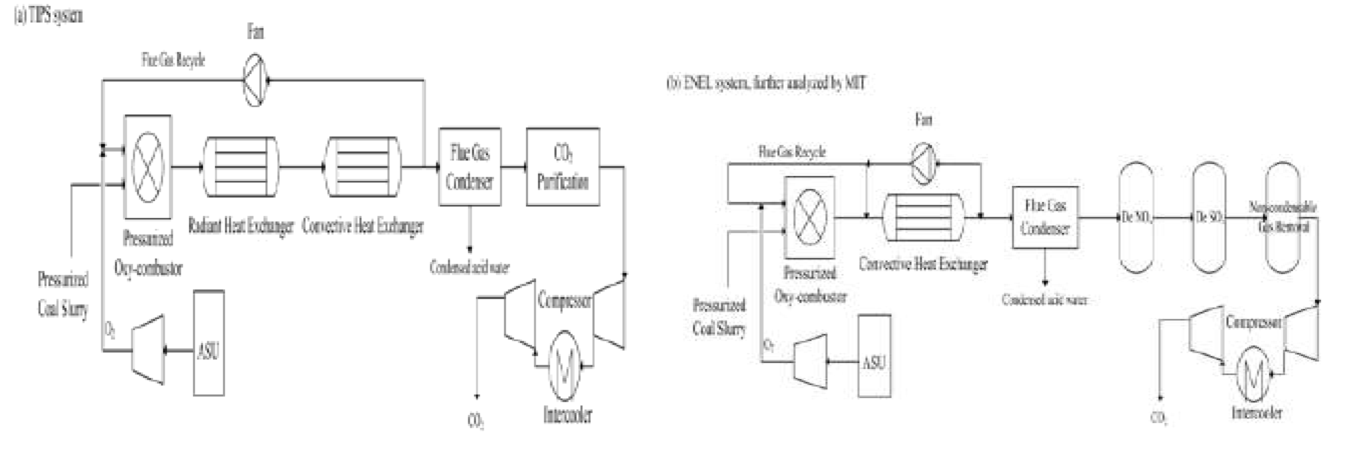
eliminate thermodynamic losses caused by cooling andre-heating.

Today, with a stricter requirement on CO_2 purity forpipelinetransportationandstorage,pollutioncontrolequipmenthavebeenagaintakenintoaccountinthefluegasrecycleconfigurations.Moreover,sinceSO_2concentration in the flue gas may accumulate due to fluegasrecycle,resultingin2or3timeshigherconcentration thaninconventionalair-firingsystems,theprimaryrecyclehastobeatleastpartiallydesulphurized for medium and high sulphur coal, to avidcorrosioninthe coalmilland fluegaspipes.



Pressurizedoxy-coalcombustionsystemsproposedforcarboncaptureincoalpowerplants,

a)SchematicoftheThermoEnergyIntegratedPowerSystem(TIPS),(b)SystemproposedbyENELbasedona combustionprocesspatentedbyITEA,

Pressurized Oxy-Coal Combustion Systems Pressurizedoxy-fuelcombustionsystemshavebeenproposedrecently,withtheobjectiveofimprovingtheenergyefficiencybyrecoveringthelatentheatofsteaminthefluegas.Thefluegasvolumeisreducedunderelevatedpressure,whichresultsinsmallercomponentsandpossiblereductionsincapitalcostforthesame poweroutput.Severalstudieshavereportedonthetechnicalandeconomicfeasibilityofthisprocess,allconcludingthattheoverallprocessefficiencyimproveswithincreasingoperatingpressure.Thisismainlybecauselatentheatrecoveryfromthefluegasesbecomes possible at higher temperatures. Other potentialadvantagesofpressurizedoxy-fuelsystemsarethereductionoftheauxiliarypowerconsumptionsuchastherecyclefanwork,andtheeliminationofairingressintothesystem.However,therearechallengesassociated with combustion and heat transfercharacteristicsatelevatedpressures,andhencetheburners, steam/gas FURNACEs and condensingFURNACEsmustbe redesigned.

Figureillustratestwodifferentpressurizedoxy-coalcombustionsystemsproposedintheliterature.Oneofthe first designs is the Thermo Energy Integrated PowerSystem (TIPS) proposed and studied by CANMET andBabcockpower.Thissystem(Figure1-2a)usesapressurized combustion unit and FURNACEs, as well asa flue gas condenser (FGC). Downstream of the radiatedboilerandconvectiveFURNACEs,steam inthefluegases is condensed in the FGC, where most of the latentheat in the flue gas is recovered by the feed water in thesteam cycle. The rest of the flue gas, which is essentiallyCO_2, is purified and compressed to the sequestrationspecifications. In contrast, the hot flue gases from thepressurized combustor is quenched to about 800 ºC bythe recycled cold flue gas, eliminating the need for aradiant FURNACE and thus incurring a lower capitalcost. It should be noted that in these pressurized oxy-coal systems coal is fed in the form of coal- water slurry(CWS). Since the pressurized system takes advantage ofthelatentheatrecoveryfromthesteaminthefluegas,

using a coal-water slurry does not significantly decreasetheoverallenergyefficiency. Forthepressurizedoxy-fuelpowerplantswithCO_2enrichedfluegasstreams,desulphurizationandNO_xremoval solutions have been proposed with potentiallylowercostandhigherenergyefficiency,usingleadchamber chemistry and nitric acid chemistry at elevatedpressures. For instance, Air Products utilizing two highpressurecountercurrentreactiveabsorptioncolumns(see Figure 1-2 (b)) combines them into a single highpressure column to remove SO_x as H_2SO_4 and NO_x asHNO_3.BothsolutionsclaimtohavesignificantlyreducedthecostofCO_2purificationwiththelatterhavinganadvantageintermsofreducedpowerconsumptionand capitalcost.

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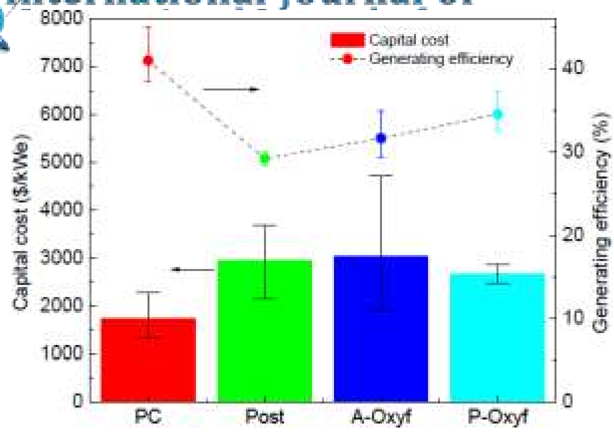

EnergyEfficiencyPerformanceoftheOxy-CoalCombustionSystems

An important question to address at this juncture is thecomparativeperformanceoftheatmosphericandpressurizedoxy-fuelcombustionsystemsdescribedabove. Figure 1-3 shows the capital expenditure ($/kWe)and efficiency (HHV%) of these systems for newly-builtpowerplants,comparedtotheperformanceofsupercriticalpulverizedcoalsystemswithoutcaptureand with post-combustioncapture.. Forinstance, fueltype,sizeandconfigurationofthepowerplants,percentageofCO2captured,andparametersofthesteam turbine, etc. Allowing for differences in modellingassumptions, the results from these studies are averagedin Figure 1-3, with the minimum and maximum valuesshown as error bars; and they should only be comparedqualitatively.

System efficiency estimates showed a loss of about 10-15% percentage points when post-combustion capture isadded to the base case PC power plant. On the otherhand,theatmosphericoxy-fuel combustionshowsanadvantage of 1-5 percentage points when compared withpost-combustion capture; while the pressurized systemgains a further 3 percentage points efficiency. The mainadvantage of pressurized oxy-fuel system is the highersaturationtemperatureofwater at elevatedpressures,which enables more thermal energy recovery and therecuperationoflatententhalpy,asstatedpreviously.AlthoughthepowerconsumptionoftheASUishigherin the pressurized combustion system, the power savingsin the CO2 compression unit and in the recycled flue gascompressorisevenhigher,culminatinginabetteroverallefficiency.

CFD Modeling of Pulverized Coal CombustionandtheChallengesunderOxy-FuelConditions

Overview

CFD techniques have become the third dimension in fluid dynamics and combustion studies alongside analytical modeling and experimental diagnostics. CFD provides a relatively inexpensive (when sub models are used in connection with Reynolds-averaged Navier- Stokes (RANS) or when using coarse grain large-eddy simulation (LES) models) and indispensable tool to perform comprehensive studies on the fluid flow, heat transfer and chemical reactions in combustion.

Currently, CFD modeling of oxy-coal combustion utilize approaches and sub-models that are similar to those developed under air-fired conditions. With the accumulated knowledge on the fundamental differences between air-fuel and oxy-fuel combustion, some effort has gone into developing and validating sub-models for the new combustion environment. A selection of the CFD simulation studies on oxy- fuel combustion is summarized in Table 2-1, which includes the sub-models used for turbulence, radiation heat transfer, char combustion and homogenousreactions. Since the existing sub-models were developedfor conventional air-coal combustion, their assumptionsand approximations may not be valid in the CO2-richenvironment. In the following sections, the developmentof CFD sub-model for an accurate prediction in oxy-coalcombustion is reviewed, and the findings of these recentnumericalstudiesaresummarized.

Table2-1.SummaryofCFDsimulationsandtheirsub-modelsforoxy-fuelcombustion.

Author	Simulated object		Modeling approaches					
	Facility	Fuel	Code	Turbulence	Radiation	Char Combustion	Homogeneous Reaction Mechanism	Chemistry-Turbulence
Wang et al. [28]	BCL Subscale combustor	Wage coal	1-DICOG (1-D)	N/A	Zone Method [128], transparent gas	$C+O_2$ $C+CO_2$ $C+H_2O$	Vilatiles combustion	Chemical Equilibrium
Khare et al. [129]	IHI 1.2 MWth vertical pilot scale test facility	Coal A	Fluent	$k-\varepsilon$	P-1 WSGG	$C+O_2$	Volatiles combustion	Chemical Equilibrium
Nozaki et al. [77]	IHI 1.2 MWth horizontal combustion test facility	Coal A/B	VEGA-3	$k-\varepsilon$	Multi-flux Radiation model [130] Three-gray-gas model	$C+O_2$ $C+CO_2$ $C+H_2O$ [131]	Volatiles combustion	EBU
Chui et al. [132]	CANMET 0.3 MWth VCRF	Western Canadian sub-bituminous coal	CFX-TASCflow	Standard $k-\varepsilon$	N/A	$C+O_2$	Volatiles combustion	EBU
Rehfeldt et al. [78]	E.ON 1 MWth horizontal firing facility and IVD 500 kWth down firing facility	Tselentis coal and Lausitz lignite coal	Fluent	Standard $k-\varepsilon$	DO	$C+O_2$ $C+CO_2$	N/A	N/A
Toporov et al. [133]	RWTH Aachen U test facility	Rhenish lignite	Fluent	$k-\varepsilon$	DO WSGG	$C+O_2$ $C+CO_2$ $C+H_2O$	Volatile breakup CO and H_2 burning [134]	Finite Rate/Eddy Dissipation
Chen et al. [62]	ISOTHERM PWR® 5 MWth pressurized test facility	Bituminous coal	Fluent	Realizable $k-\varepsilon$ $k-\omega$	DO WSGG	$C+O_2$ $C+CO_2$ $C+H_2O$	Modified JL	Finite Rate/Eddy Dissipation
Andersen et al. [135]	100 kW down-fired furnace [68]	Propane	Fluent	Realizable $k-\varepsilon$	P-1	N/A	WD [136] and Modified WD [135], JL [137] and Modified JL [135]	EDC
Vascellari et al. [138]	IFRF 2.4 MW furnace	Gottelborn hvBp coal	Fluent	Standard $k-\varepsilon$	P-1	$C+O_2$ $C+CO_2$ $C+H_2O$	Volatile decomposition, tar partially oxidation, Modified JL [139]	EDC
Muller et al. [140]	IFK 0.5 MWth test facility	Lausitz lignite	AIOLOS	Standard $k-\varepsilon$	DO Leckner's model [141]	$C+O_2$ $C+CO_2$ $C+H_2O$	JL [137]	EDC
Nikolopoulos et al. [142]	330 MWe PC boiler in Meliti power plant, Greece	Lignite from Achlada mine	Fluent	Standard $k-\varepsilon$	DO EWBM	$C+O_2$ $C+CO_2$	Volatile combustion and CO burning	Finite Rate/Eddy Dissipation
Edge et al. [143]	0.5 MWth Air- and oxy-fired combustion test facility with Doosan Babcock triple-staged low-NOx burner and IFRF Aerodynamically air-staged burner	Coal A and B	Fluent	RNG $k-\varepsilon$ and LES	DO WSGG/FSK	NA	Volatile combustion and CO burning	EDM

Eaton et al. (1999) present a revision of combustionmodels.Themodelsaregenerallybasedonthefundamentalconservationequations ofmass,energy, chemical species and momentum, while theclosureproblemissolvedbyturbulencemodelssuchasthe$k$−ε(LaunderandSharma,1974),combustionmodelslikeArrhenius(Kuo,1996;Turns, 2000), Magnussen – EBU – "Eddy Breakup"(Magnussen and Hjertager, 1976); radiative transfermodels based on the Radiative Transfer Equation – RTE(Carvalhoetal.,1991)andmodelsto devolatilization and combustion of solid and liquidfuels.

Abbas et al. (1993) describe an experimental andpredictedassessmentoftheinfluenceofcoalparticle size on the formation of NOx of a swirl-stabilized burner in a large-scale laboratory furnace.Three particle size distributions, 25, 46, and 121 μmaverage size, of high volatile coal were fired undersimilaroperationconditions.Thedatapresentedcombinedetailedin-flamemeasurementsofgastemperature,gasspeciesconcentrationsofCO,

CH4, O2, NOx, HCL,NH3, particle burnout, and"on-line" N2O, with the complementary predictedstudies. The predicted results are in good agreementwith experimental data. Although the NOx emissiontrends with particle size are similar, predicted valuesfor each fraction are higher, suggesting a limitationin the NOx reducing mechanisms used in the model.Threemechanisms–thermal,fuelandprompt–wereusedtocalculate theNOxformation.

Xuetal.(2000)employedtheCFDcodetoanalyzea coal combustion process in a front wall pulverizedcoal fired utility boiler of 350 MW with 24 swirlburnersinstalledatthefurnacefrontwall.Fivedifferent cases with 100, 95, 85, 70 and 50% boilerfullloadweresimulated.Comparisonswereaddressed, with good agreement between predictedandmeasuredresultsintheboiler for all but onecase thus validating the models and the algorithmemployedin thecomputation.

Lietal.(2003)numericallyinvestigatedthecombustion process using only a two-fluid model(instead of the Eulerian gas – Lagrangian particlemodels)forsimulatingtree-dimensionalturbulentreactive flows and coal combustion. To improve thesimulation of the flow field and NOx formation, amodified$k$−ε − k p two-phase turbulence model anda second-ordermoment (SOM) reactive rate modelwere proposed. The proposed models were used tosimulate NOx formation of methane-air combustion,and the prediction results were compared with thoseusing only the presumed-PDF (Probability DensityFunction)-finitereaction-ratemodelandexperimental data. The proposed models were alsousedtopredictthecoalcombustionandNOxformation at the exit of a double air register swirlpulverized-coal burner. The results indicate that apulverized coal concentrator installed in the primaryair tube of the burner has a strong effect on the coalcombustionand NOxformation.

In a numerical investigation, Kurose et al. (2004)employedatree-dimensionalsimulationtothepulverizedcoalcombustionfieldinafurnaceequipped with a low-NOx burner, called CI-α, toinvestigate in details the combustion processes. Thevalidities of available NOx formation and reductionmodels were investigated too. The results show thatarecirculationflowisformedinhigh-

gastemperature region near the CI-α burner outlet,andthislengthenstheresidencetimeofcoalparticlesinthishigh-gas-temperatureregion,promotes the evolution of volatile matter and theprocess of char reaction, and produces an extremelylow-O2regionforeffectiveNO reduction.

Zhangetal.(2005)presentedanumericalinvestigation on the coal combustion process usingan algebraic unified second-order moment (AUSM)turbulence-chemistrymodeltocalculatetheeffectofparticletemperaturefluctuationoncharcombustion.TheAUSModelwasusedtosimulategas-particlesflowsincoalcombustionincluding sub-models as the $k - \varepsilon - k p$ two-phaseturbulence model, the EBU-Arrhenius volatile andCO combustion model, and the six-flux radiationmodel.ThesimulationresultsindicatethattheAUSMcharcombustionmodelpresentedgoodresult,sincethelattertotallyeliminatestheinfluence of particle temperature fluctuation on charcombustionrate.

Bosoagaetal.(2006)presentedastudydevelopingaCFDmodelforthecombustionoflow-gradelignite and to characterize the combustion process inthetestfurnace,includingtheinfluenceofthegeometryofburnerandfurnace.Anumberofcomputationswere madeinordertopredicttheeffect of coal particle size, the moisture content oflignite, and the influence of combustion temperatureand operation of the support methane flame on thefurnaceperformanceandemissions.Theinfluence of lignite predrying was also modeled to investigatethe effects of reduced fuel consumption and CO2emissions. It was found that the increase of moisturetends to reduce NOx, and the methane support flamegreatlyincreasesNOx.

In another work, Backreedy et al. (2006) presented anumerical and experimental investigation of the coalcombustionprocesstopredictthecombustionprocess of pulverized coal in a 1 MW test furnace.The furnace contains a triple-staged low-NOx swirlburner. A number of simulations were made usingseveral coal types in order to calculate NOx and theunburned carbon-in-ash, the latter being a sensitivetest for the accuracy of the char combustion model.TheNOxmodelingincorporatesfuel-NO,thermal, andpromptmechanismstopredicttheNOformationon the combustionprocesses.

Kumar and Sahur (2007) studied the effect of the tiltangle of the burners in a tangentially fired 210 MWeboiler,usingcommercialcodeFLUENT.Theyshowedtheinfluenceofthetiltangleintheresidencetimeofthecoalparticlesandconsequently in the temperature profiles along theboiler.

Asotani et al. (2008), also using the code FLUENT,studiedtheignitionbehaviorofpulverizedcoalclouds in a 40 MW commercial tangentially firedboiler.The resultsfor unburnedcarbonin ash andforoutlettemperaturewerevalidatedrespectivelybytheoperatingdataandbythedesignparameter.Aqualitativecomparisonbetweentheresultsfortemperature and ignition behavior in the vicinity ofthe burners was made, using the images of a hightemperatureresistant videocamerasystem.

At thesamelineChoi and Kim (2009),alsousingthecodeFLUENT,investigatednumericallythecharacteristicsofflow,combustionandNOxemissionsina500MWetangentiallyfiredpulverized-coalboiler.Theyshowedthatthe

Methodology

BoilerDescription

Theboilersystemunderstudyisa700MWboilerwitha tangential-firing configuration. The firing equipmentconsists of 28 coal burners. The burners system providespulverized coal to the boiler from pulverizers where ithas been crushed to consistent sizes. The primary airflow carries thefinecoal to theburners for combustiontotakeplaceintheboilerfurnace.Thefurnaceisrectangular in shape with four burners firing from eachcorner,thuscreatingafireballatthecenterofthefurnace.

Thenumericalmodellingoftheboilercombustionprocess wascarriedoutusinganANSYS-FLUENTrelation among temperature, O2 mass fraction andCO2 mass fraction has been clearly demonstratedbasedonthecalculateddistributions,andthepredictedresultshaveshownthattheNOxformationintheboilerhighlydependonthecombustion process as well as the temperature andspecies concentration. The strategic role of energyandthecurrentconcernwithgreenhouseeffectsenhance the importance of the studies of complexphysicalandchemicalprocessesoccurringinside boilersofthermalpowerplants.Combustioncomprises phenomena such as turbulence, radiativeand convective heat transfer, particle transport andchemicalreactions.Thestudyofthesecoupledphenomenaisachallengingissue.Thestateoftheartincomputationalfluiddynamicsandtheavailability of commercial codes encourage numericstudies of the combustion processes. In the presentwork,acommercialCFDcode,CFX©AnsysEurope Ltd., was used to study the pulverized-coalcombustion process in a 160 MWe thermal powerplanterectedinthecoreoftheBraziliancoalreserves

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region, with the objective of simulating theoperationconditionsandidentifyinginefficiencyfactors.

2021 R1 CFD package assuming steady, turbulent andcompressibleflow.Theresearchcommencewiththecollectionofaboilerdesigndataandconfiguration.CFDmodelswerebuiltbasedonthedesignandvalidatedusingoperational datafrom theboiler.Themodelwasthenbeusedtopredictthebehaviorofseveralcoalsoncombustioncharacteristicssuchasflame temperature, O2 & CO species composition andfurnaceexitgastemperature(FEGT)withthesameboiler setting which were mass flow of air & coal andburnertilting angle.

The properties of coals

Coal properties	Coal A	Coal B	Coal C
Calorific Value, kJ/kg	5732.57	6122.24	6495.45
Moisture, %	13.30	5.89	6.55
Volatile matter, %	43.80	41.03	40.98
Fixed carbon, %	41.25	43.69	45.32
Ash, %	1.65	9.40	7.16
C, %	61.80	70.80	73.45
H, %	5.63	5.76	5.76
O, %	31.21	21.90	18.81
N, %	1.09	1.34	1.46
S, %	0.27	0.50	0.53

GEOMETRY

ForimportingtheModelofHeatExchanger,

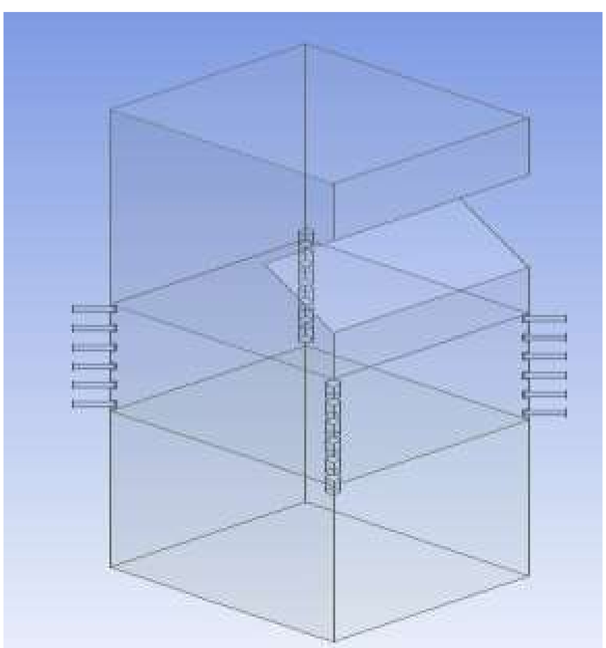
Startworkbench2021R1→selectthefluidflow(fluent)
→ Edit Geometry → import External Geometry →Choose the image file which is in IGES format
→Generateasshown inthe Fig 5.2

Geometry:

Geometrywascreatedin3Dmodellingsoftwarecreoandwasimportedin toAnsysenvironment

Geometryspecifications

length	28.6 m
Breadth	24.9 m
Height	64.5 m
BurnerDiameter	900mm
Numberofburners	24



Geometry

MeshGeneration

Thegeometryandmeshgeneratedfortheboilermodelis shown in Figure 3.1. The overall framework of themeshing scheme used in this study is quadrilateral mesh.Fine mesh was constructed in critical regions, such as intheareaclosedtoburners,primaryandsecondarynozzlesandwithinthewinebox.Themodelwasdevelopedbasedontheactualoperatingboilerinthepowerplant.Fromthedrawingobtained,fewsupplicationsweremadetoavoidextremeskewnesslevelthatmightaffectthestabilityofthecalculation.Thesimplicationsmadehowever,doesnot affect thefinal outcome as the main aim is to observe the flow andcombustiontemperatureoftheoverallfurnaceflowdomain.Thenumberofmeshconstructedisapproximately 2.3 million cells. Prior grid dependencystudyhasbeenundertakenanditisshownthatthecurrent mesh is sufficient enough to resolve the flowfield,especiallyincomplexregionswhereflowpropertiesarecritical.Comparisonofthesimulationresults with different mesh density is shown in Figure 2.Themeshquantitywasreducedby20%andincreasedby 20%. It is shown that the differences of the predictedtemperaturebetweenthesevaryingmeshwerenegligible.

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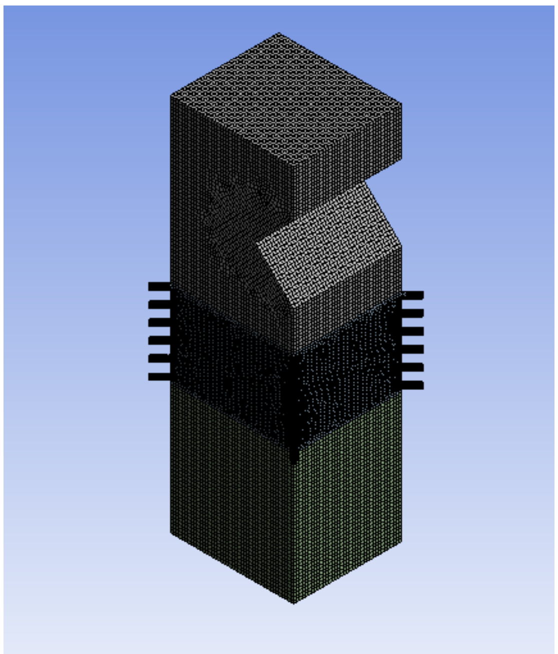


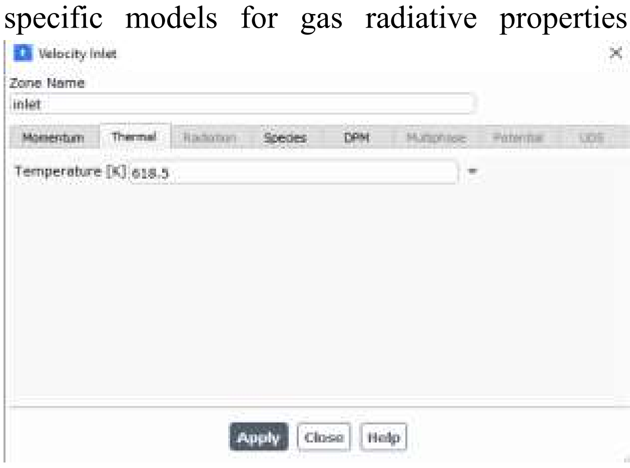
Meshingof3Dmodeloffurnace

CFDMODELLING

Coalcombustion:

AcommercialCFDprogram,ANSYSFluentversion2021 R1, was used to simulate the oxycoal combustionprocessinthereactionzoneoftheEFR.Theco mputationswereperformedinathree-dimensionalstructuredgridconsistingof~75,000cells,wh osedetails

have been reported previously. The CFD code solved theappropriate transport equations for the continuous phase,and a Lagrangian approach was used to calculate particletrajectoriesthroughthecalculatedgasfield. TheRealizable k-ε turbulence model was employed to modelthe dynamic of the flow. Heat transfer by radiation wasaccountedforbytheDiscreteOrdinateModelbe causeof the higher accuracy and smaller optical length of theEFR,togetherwiththecellbasedWeighted-Sum-ofGray-GasesModel(WSGGM)fortheradiativeproperties ofthegases.Otherresearchershavedeveloped specific models for gas radiative properties inoxy-fuelenvironmentsimplementedanewgaseousradia tivepropertiesmodelinCFDsimulationsinalaborat ory-scale0.8MWfurnaceandfoundlittledifference in the radiation source in comparison with theWSGGM model. They concluded that the two modelsmadenegligibledifferenceinthesimulation resultswhenappliedtosmall-scaleoxy-fuelcombustionmodelling,buttheirimplantationis necessaryinmodellinglarge-scaleoxy-fuelfurnaces.



InletBoundaryConditions

BoundaryConditions:

The boundary conditions were obtained from the dailyoperational data at 100% Boiler Maximum ContinuousRate (BMCR). The inlet conditions are the air and coalflows entering the domain from the burner nozzles. Coalflowrateandcombustionstoichiometricratioweres etas30m/sand1.2respectively.Temperaturesofcombus tion air are set as 345 °C. Pulverized coal sizewas modelled by a Rosin-Rammler distribution between300µm. The outlet conditions is the flue gas passage atboilerrearpass.

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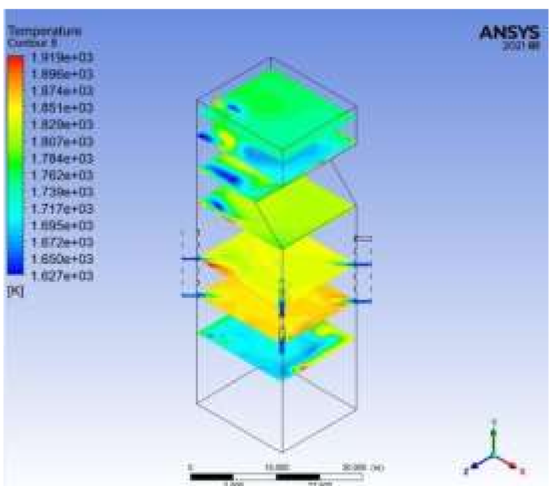
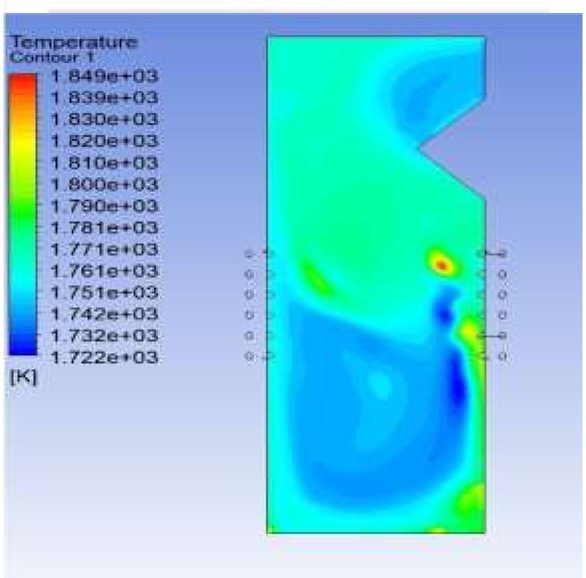
After initializing the cfd model, run thr calculation. Setthe umber of iterations 2000 and run the solution

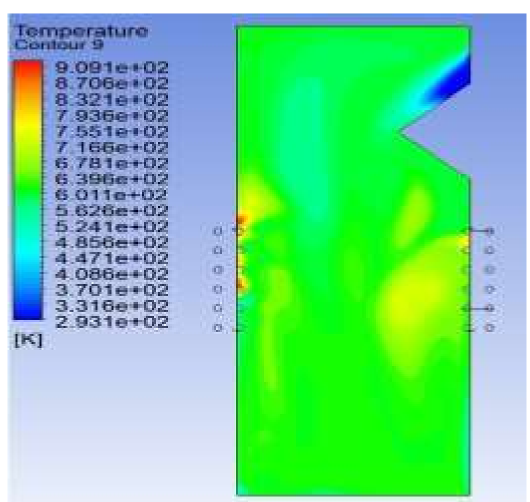
untiltheproblemisconverged.

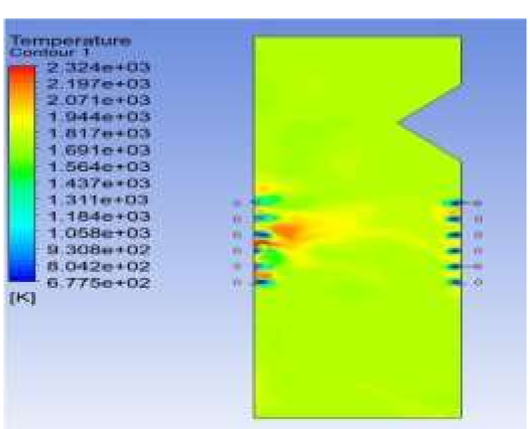
RESULTSANDDISCUSSION

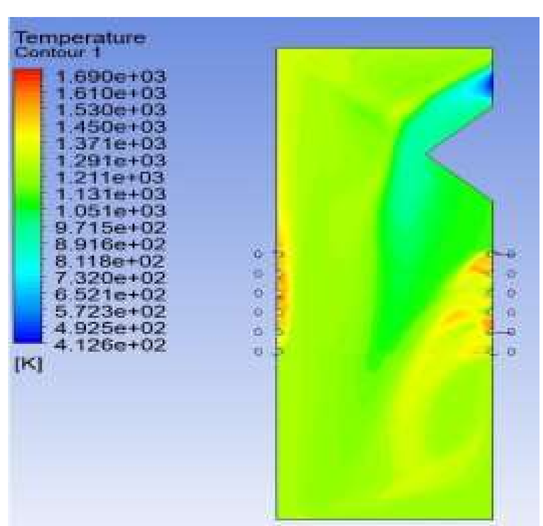
Temperature Distribution:Coalc:



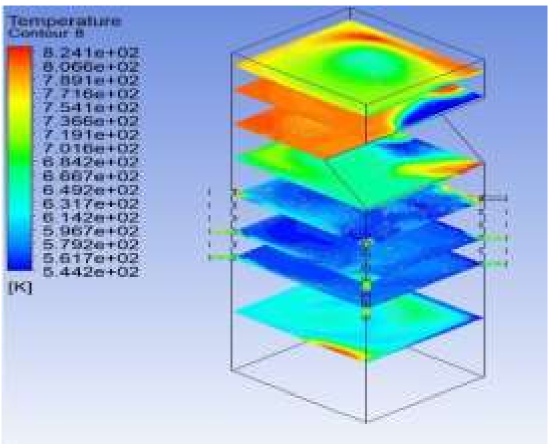




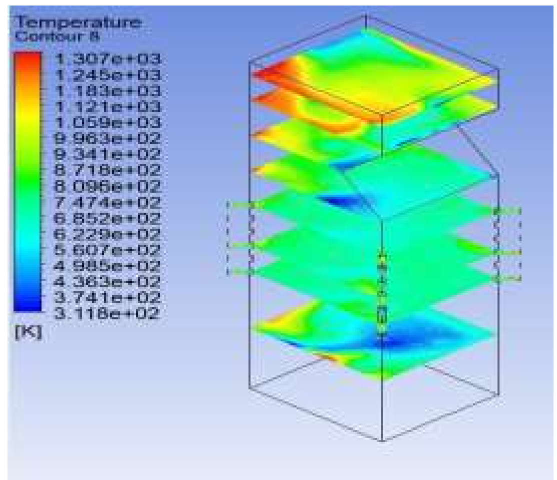


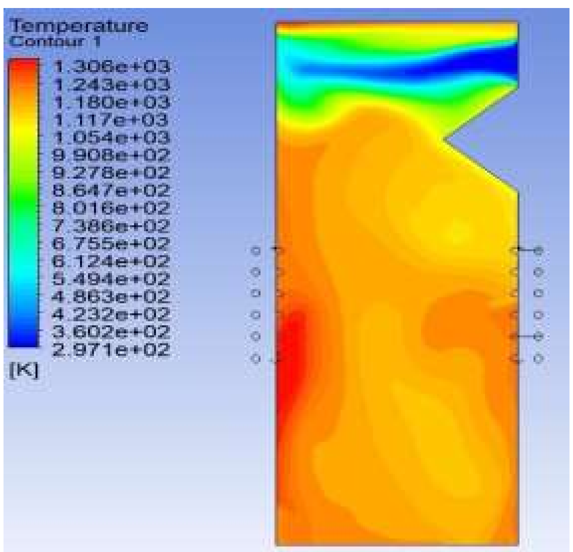


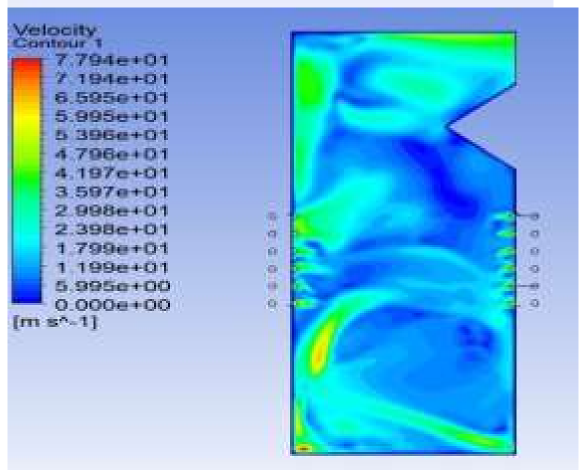
CoalB:

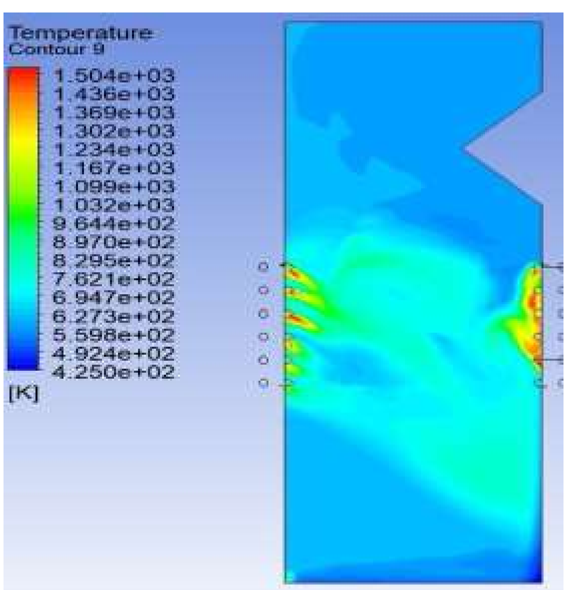


CoalA:









VelocityContours:

CoalC:

CoalB:

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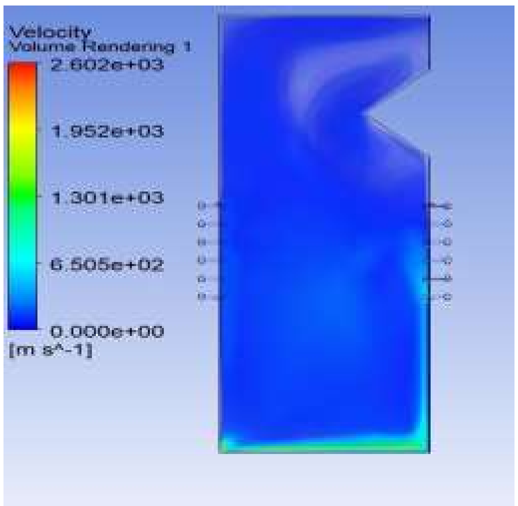
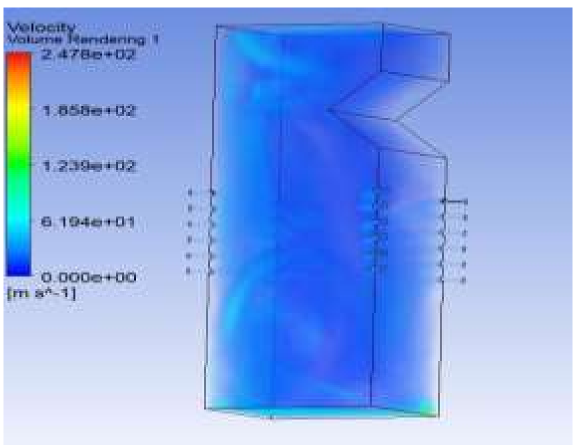
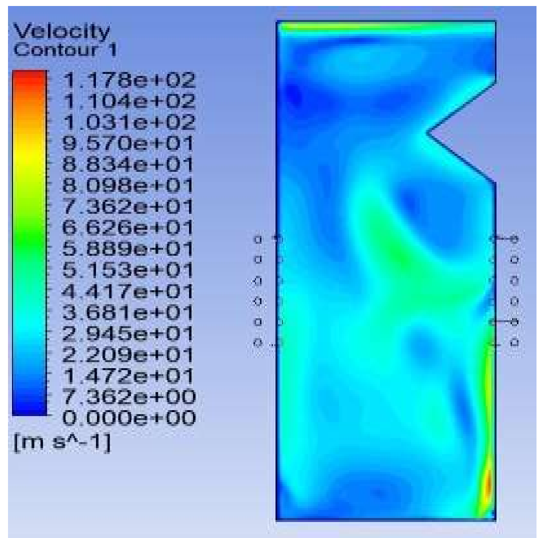


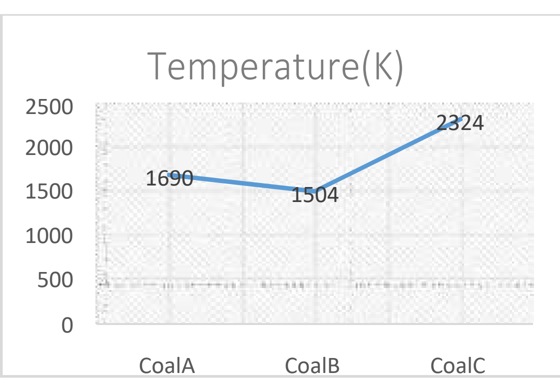
CoalA



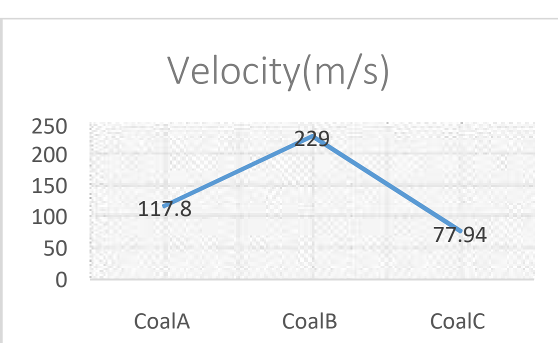


	Temperature (K)	Velocity (m/s)
Coal A	1690	117.8
Coal B	1504	229
Coal C	2324	77.94

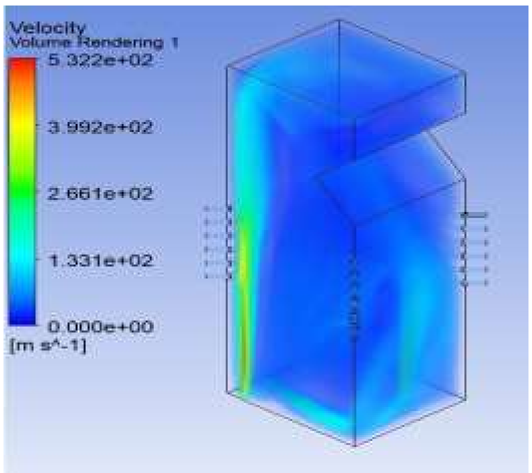
Table



CoalsamplevsTemperature



CoalsamplevsVelocity



Fromtheabovecontourplots,

Conclusion:

To get a better grasp on how various sub-bituminous coals burn inside the boiler, computational fluid dynamics (CFD) simulations of flow and combustion in a full-scale power station furnace have been conducted. Predicted findings reveal a relationship between the coal types and the distributions of temperature, velocity, O2, and CO species; three appropriate coals were used for boiler burning. A high furnace temperature is the result of burning coal with a high calorific value, which releases more energy during combustion. Another important factor that may affect the temperature distribution is the fuel ratio. The compositions of the flue gases are affected by the combustion behaviour in the boiler, which in turn affects the distributions of CO and O2. Validation of the model was done using data from the boiler's performance, including boiler exit gas temperature, O2, and CO %, and the results show that the temperature and velocity profile match the expected behaviour of a tangential-fired boiler.

This effort should keep simulating with a larger variety of sub-bituminous coal qualities in order to better understand the complicated physical and chemical reactions within boilers. Further research into how different operational conditions impact combustion outcomes is required. The boiler's performance may be optimised by adjusting its specifications to accommodate a broad variety of coal qualities.

• Coal Sample C reaches a maximum temperature of 2324 k, whereas samples A and B reach temperatures of 1690 and 1504 K, respectively. The reason for this is the higher amount of coal (fuel) in samples A to C. Coal A has a lower coal concentration relative to the oxygen in the mixture. Use of coal sample A results in oxygen waste.

• The proportions of coal and oxygen in the combination are enough for coal B. As a result, using coal sample B does not result in any oxygen or coal waste.

• The coal concentration is higher than the oxygen provided in the mixture when dealing with coal C. Wasted coal is the result of using coal sample A. The result will be additional pollution due to incomplete combustion.

From an operational standpoint, it is possible for scales to form in the tubes as the boiler temperature rises, which will decrease the boiler's efficiency. Coal sample B, however, produces the best results out of the three. However, we may use Coal sample A if the boiler's capacity is large.

FutureScope:

The temperature at the intake, the amount of coal and oxygen in the mixture, the flow rate, the pressure of the mixture, the furnace's height, and the coal's calorific value are all factors that affect the efficiency of coal combustion. Thus, according to the boiler's design circumstances, the efficiency of the furnace may be changed by adjusting the aforementioned factors.

As a result, there is always room for improvement in terms of combustion efficiency. This is a partial list of some of them:

1. Increasing the availability of oxygen for full combustion may improve combustion efficiency. Which can be done in two ways.

• Adding more oxygen to the oxy-coal mixture. • Making sure the burner has enough oxygen by using a secondary channel.

2. To enhance efficiency, you may change the speed of the incoming oxy-coal mixture.

3. Enhancing efficiency may be achieved by modifying the inflow oxy-coal mixture's temperature conditions.

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