Faculty of Health, Engineering and Sciences
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Experimental and Numerical Study of MILD Combustion in an Open-End Furnace with Exhaust Gas Recirculation using Methane and Biogas

A Dissertation Submitted by

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Abstract

The world's energy demand by 2042 is estimated at about 18 billion tons of oil equivalent with 80 % fulfilled by the combustion of fossil fuel. Combustion is predicted to be the most important way of generating energy to cater for these energy needs. The need to address energy sustainability (fuel depletion) and environmental pollution (emission) has led to an increased interest in energy efficiency improvement. Combustion technologies with higher thermal efficiency and biogas (renewable) fuels are possible long-term solutions. The Moderate or Intense Low oxygen Dilution (MILD) combustion technology can play a significant role to produce higher thermal efficiency and reduce emissions. MILD combustion has achieved great success, however it needs further fundamental study due to the current limited research on open-end furnaces.

In this study, an open-end furnace with an enclosure wall was used to capture the exhaust gas and utilised it as Exhaust Gas Recirculation (EGR). The EGR recirculates a portion of exhaust gas back to the combustion chamber to dilute the oxygen before the oxidant is mixed with the fuel and increases the reactant temperature. This setup is an open-end furnace because it allows a portion of the exhaust gas to flow out and be utilised as external EGR. In the case of a closed furnace, the exhaust gas is recirculated internally to dilute the reactants and increase their temperature. The wall thickness for the open-end furnace is very thin compared to the closed furnace which normally has a thick wall. The development and operating cost for the open-end furnace is cheaper than the closed furnace but the external EGR structure is an additional installation for the open-end furnace. The main objectives of this thesis are to conduct numerical modelling using Computational Fluid Dynamics (CFD) to design and develop the furnace, to develop and fabricate the new open-end furnace combustion chamber and to optimise the furnace performance to achieve MILD combustion.

The numerical modelling for the MILD combustion using CFD has been extensively conducted on different burners and different scale furnaces. In this study, the three-dimensional CFD model was utilised to develop and optimise the furnace. The Reynolds–Averaged Navier–Stokes (RANS) equations were solved using realisable k–ε turbulent models which has been shown by others to be a reasonably accurate model to predict the combustion temperatures and combustion products. In this research, the results of the simulation slightly over-predict the flame temperatures by about 2 % compared to the experimental results. The non-premixed, partially premixed and premixed combustion with chemical equilibrium and non-adiabatic energy treatment for the thermo-chemical database were used. The Discrete Ordinates (DO) model was used to solve the radiative transfer equation for a finite number of discrete solid angles in the Cartesian coordinate system. The Weighted Sum of Gray Gas Model (WSGGM) was used for the absorption coefficient. The method of meshing was tetrahedrons patch conforming with advanced sizing function of proximity and curvature. The active assembly, fine span angle centre and fine relevance centre setting were used for all grids. All the governing equations were solved using the second order upwind discretisation scheme for higher accuracy of the calculation. The pressure-velocity coupling scheme with a least-squares cell-based gradient was used and presto was used as the pressure discretisation scheme. The early stage of the combustion chamber development started with a CFD simulation of a basic enclosed wall and top open combustion chamber. After analysing the results, two external EGR pipes were added. Then two more EGR pipes were added to make a total of four EGR pipes. The final model was improved with regard to the pipe size and the top part of the chamber design to ensure it collected an appropriate amount of the exhaust gas. This model was later used for the experimental and numerical modelling.

The laboratory scale combustion chamber (total volume of $0.33\,m^3$ and thermal intensity of $18.8\,kW/m^3$ atm) was developed and fabricated. In this study, the air and fuel supply system was also developed especially for this furnace operation. The parameters for the experimental study were the fuel compositions and the equivalence ratio. The experimental data was collected with 42 thermocouples (R-type and K-type), a gas analyser, an oxygen sensor and pressure transducers. The EGR flow rates were determined based on the pressures and temperatures in the EGR pipes. A National Instruments compact data acquisition system was used with analogue to digital converter modules and controlled by Labview software. Experimental tests were conducted where the secondary air supply was heated and non-heated while the reactants were varied to produce non-premixed, partially premixed and premixed flames. Methane fuel ignited more quickly than biogas due to its higher calorific value and lower self-ignition temperatures. The combination of heated secondary air with partially premixed fuel was the quickest to ignite. The combustion chamber, EGR and exhaust temperatures and the exhaust gas species were experimentally studied for the various equivalence ratios. The flame temperature for the biogas is lower than methane due to the lower calorific value of the fuel. Both methane and biogas flames produced very low NO_x (2 ppm) for all flow rates whereas for carbon monoxide, biogas produced almost zero once the flame became steady.

The numerical modelling for the partially-premixed methane and biogas using the same geometry and conditions as the experimental work is conducted and the flame temperatures are 1,499 K and 1,368 K respectively. These can be compared to the experimental flame temperatures for methane and biogas which are 1,483 K and 1,358 K respectively. The numerical modelling over-predicts by 1.13 % and 0.73 % respectively, which is good agreement. The exhaust gas species (CO_2, H_2O, O_2 and NO_x) were analysed at the exhaust pipe and the downstream of the EGR pipes. Both methane and biogas flames are lean. The combustion is completed with zero unburned hydrocarbons detected and excess oxygen was recorded for both the exhaust pipe and the downstream of the EGR pipes. At the downstream end of the EGR pipes, the excess oxygen is much higher due to the fresh supply of secondary air diluting the exhaust gas as expected. The NO_x emissions for methane and biogas are very low (< 3 ppm) for both locations. The numerical sensitivity test was conducted to study the effect of the chamber wall temperature boundary condition on the flame temperature. The results show that the flame temperature is very sensitive to the combustion chamber wall boundary conditions. It concluded that biogas has advantages over methane due to lower peak temperature making the combustion chamber and burner last longer and be more economical to operate. More numerical modelling was conducted for the experimental furnace geometry; when appropriate oxygen dilution (3–13 %) and the preheated oxidant were applied, the model could achieve the MILD regime. The limitation of the developed experimental furnace was discussed where it required a minimum of 0.1 MW/m^3 atm thermal density to achieve and sustain MILD combustion.

Further simulations were conducted using the same furnace geometry except a bluff-body air-fuel nozzle to successfully achieve MILD combustion. The oxygen mole fraction is diluted between 3 % and 13 % and the oxidant supply is preheated to achieve the overall reactant temperature above the fuel self-ignition temperature. The average and maximum chamber temperatures were almost identical at 3 % inlet oxygen mole fraction. The chamber temperature uniformity ratio was $\leq 20\,\%$ when the oxygen mole fractions were $\leq 13\,\%$. The conventional flame was produced (the uniformity ratio of the chamber's temperature was $> 20\,\%$) when the oxygen mole fraction reached $> 14\%$.

A new open-end furnace was designed, fabricated and tested experimentally as well as numerically. The open-end furnace with the enclosed chamber numerically operated in the MILD combustion regime for both the industrial burner and the bluff-body burner. These results can be utilised by the heating industry and also for further studies by combustion researchers. It is recommended that future work to extend this study be carried out experimentally and numerically. The further studies can be undertaken using different fuel compositions, a new gas burner, higher secondary air preheating temperatures and a modified combustion chamber.

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated. [3ex]

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Date

ENDORSEMENT

Supervisory Team

Dr. Andrew P. Wandel	Professor Dr. Talal Yusaf
Signature of Principal Supervisor	Signature of Associated Supervisor
Date	Date

Dedication

Thee my Lord to be satisfied
To my father: Haji Mat Noor Adam
To my mother: Hajjah Che Thom Haji Yaacob
To my wife: Puan Daswati Haji Ghazali
To my kids: Muhammad Nur Amiruddin, Nurul Ain Nafisah,
Nurin Aisyah, Nurina Amni and Nurin Aqila
To my brothers : Sanusi, Azmi, Shaifol, Zamani,
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To my sisters : Noriah and Suzarmaini

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List of Publications and Presentations

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Acronyms & Abbreviations

AD	:	Anaerobic digestion
ADC	:	Analogue to digital conversion
ALS	:	Australian laboratory service
ANOVA	:	Analysis of variance
AVC	:	Atmospheric Vent Combustion
BOD	:	Biological oxygen demand
BR	:	Blockage ratio
CCS	:	Carbon capture and storage
CDC	:	Colourless distributed combustion
CFD	:	Computational fluid dynamics
CMC	:	Conditional moment closure
CO	:	Carbon monoxide
CO_2	:	Carbon dioxide
COD	:	Chemical oxygen demand
EC	:	Electrical conductivity
EGR	:	Exhaust gas recirculation
FIR	:	Fuel induced recirculation
FOG	:	Fat, oil and grease
GHG	:	Greenhouse gas
GUI	:	Graphic user interface
HC	:	Hydrocarbon
HCCI	:	Homogeneous charge compression ignition
HHV	:	Higher heating value
HiTAC	:	High temperature air combustion
HPC	:	High performance computing
HTOC	:	High temperature combustion
IEA	:	International Energy Agency
IRZ	:	Inner recirculation zone
ISA	:	Instrument Society of America
JHC	:	Jet in hot co-flow
LDA	:	Laser Doppler Anemometry
LRS	:	Laser Rayleigh Scattering
LCV	:	Low calorific value
LES	:	Large eddy simulation
LHV	:	Lower heating value

LSD	:	Least significant difference
MFB	:	Mass fraction burn
MILD	:	Moderate or intense low oxygen dilution
MMC	:	Multiple mapping conditioning
MWTPs	:	Municipal waste water treatment plants
NI	:	National Instrument
NH_3-N	:	Ammonia as nitrogen
NO	:	Nitric oxide
NO_2	:	Nitrogen dioxide
NO_x	:	Nitrogen oxides
N_2O	:	Nitrous oxide
NPF	:	Non-premixed flame
OH	:	Hydroxyl
ORZ	:	Outer recirculation zone
ORP	:	Oxidation-reduction potential
PAH	:	Polycyclic aromatic hydrocarbons
PCA	:	Principal component analysis
PDE	:	Partial differential equation
PDF	:	Probability density function
PF	:	Premixed flame
PPF	:	Partially premixed flame
PM	:	Particulate matter
RH	:	Relative humidity
RME	:	Rapeseed ethyl ester
RoHR	:	Rate of heat release
RANS	:	Reynolds-averaged Navier-Stokes
SDE	:	Stochastic differential equation
SI	:	Spark ignition
SO_x	:	Sulphur oxides
SOC	:	Start of combustion
SPDL	:	Stochastic particle diffusion length
TKN	:	Total Kjeldahl nitrogen
TSS	:	Total concentration of suspended (non-soluble) solids
Tc	:	Chamber temperature
T_{in}	:	Inlet temperature
T_{si}	:	Self-ignition temperature
UCL	:	Upper calorific value
UHC	:	Unburned hydrocarbons
UV	:	Ultra violet
VFA	:	Volatile fatty acids
fps	:	frame per second

Nomenclature

R	:	gas constant
T	:	temperature
U	:	internal energy
V	:	volume
W	:	chemical source term
Y	:	mass fraction
Z	:	mixture fraction (a conserved scalar)
A_n	:	air nozzle outer diameter
C_p	:	specific heat at constant pressure
D_a	:	air nozzle outer diameter
D_b	:	bluff-body diameter
D_i	:	air/fuel nozzle inner diameter
F_n	:	fuel nozzle outer diameter
R_d	:	internal dilution ratio
R_{tu}	:	Temperature uniformity ratio
K_v	:	dilution ratio
T_r	:	temperature of the reactants
T_c	:	chamber temperature
T_{in}	:	inlet temperature
T_{si}	:	self-ignition temperature
d	:	fuel nozzle inner diameter
k	:	turbulent kinetic energy
$\dot{q}$	:	heat release rate
$\dot{m}$	:	mass flow rate
n	:	total number of species
σ	:	standard deviation
p_c	:	chamber pressure
t	:	time
	:	timescale
u	:	velocity
v	:	specific volume
	:	physical velocity
$\dot{v}$	:	volume flow rate
x, y	:	physical location
α	:	chemical species
δt	:	time interval

μ	:	mean
ν	:	kinematic viscosity
ρ	:	density or mean fluid density
$\dot{\omega}$	:	chemical reaction rate
ε	:	turbulent kinetic energy dissipation rate