Investigation of Biogas
Moderate or Intense Low Oxygen Dilution (MILD) Combustion on Open Furnace Bluff-body Burner

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Outline

1. Introduction
2. Research Focus
3. Methodology
4. Current Status
5. Conclusions
Energy demand increase - growth of the world's population and substantial economic development (e.g. China and India).

Challenges - efficient energy and limit greenhouse-gas (GHG).

Combustion of fossil fuel - fulfil about 80% (IEA, 2009).

Low Pollutants Emissions (Kyoto Protocol, 1997)

- New combustion technology - Moderate or Intense Low Oxygen Dilution (MILD) combustion produces high combustion efficiencies with very low emissions. (Tsuji et al., 2003).
- One of the most promising combustion technology (Tsuji et al., 2003 and Cavaliere and de Joannon, 2004, Dally et al., 2004).
In 1989, Wünning (1991) observed a surprising phenomenon during experiments with a self-recuperative burner.

Furnace: 1000°C and 650°C air preheat temperature, - No flame could be seen, Fuel was completely burnt, CO was below 1ppm in the exhaust

Called that condition “flameless oxidation” or FLOX

This new combustion technology was also named:

Moderate or Intense Low-oxygen Dilution (MILD) combustion (Dally et al., 2002, Cavaliere and de Joannon, 2004).

High Temperature Air Combustion (HiTAC) (Katsuki and Hasegawa, 1998 and Tsuji et al., 2003).
MILD combustion summary (Li et al., 2011b):

- High temperature pre-heat of combustion air and high-speed injections of air and fuel. (Key requirement)
- Strong entrainments of high-temperature exhaust gases, dilute fuel and air jets. (Key tech. to maintain MILD)
- Oxygen dilution: 3%–13%.
- Reactant temperature is greater than fuel self-ignition. (N₂ and CO₂-rich exhaust gas)
- Regenerator - thermal efficiency can increase by 30%, reduce NOₓ by 50% (Tsuji et al., 2003).
Comparison MILD and Conventional

(a) Conventional flame (natural gas)
(b) MILD combustion (natural gas)
(c) Conventional combustion of sawdust
(d) MILD combustion of sawdust

Figure 2 MILD and Conventional combustions on natural gas and sawdust (Dally et al., 2010).

Figure 3 MILD furnace and parallel jet burner (Szegö et al., 2008).
MILD Combustion

Figure (New) The comparison between Recuperator and Regenerator (Tsuji et al., 2003)

Schematic of two-flame and one-flame type regenerative burning systems. (Zhenjun et al., 2010)

Figure (New) Combustion air temperature of 1100 °C and O₂ concentration (Gupta et al., 1999)

21% 8% 2%
Exhaust Gas Recirculation

- EGR works by recirculating a portion of the exhaust gas back to the combustion chamber.

- The main purpose is to dilute oxygen and heat the mixture.

Dilution ratio, $K_V = \frac{M_E}{(M_F + M_A)} = \frac{(M_T - M_F - M_A)}{(M_F + M_A)}$

$M_T = \text{Total mass flow rate}$

$M_E = \text{EGR mass flow rate}$

$M_F = \text{Fuel mass flow rate}$

$M_A = \text{Air mass flow rate}$

(Wünning and Wünning, 1997, Cavigiolo et al., 2003 and Galletti et al., 2009)

Conventional System **Efficiency:** 37.4%

EGR System **Efficiency:** 72.4%

Kraus and Barraclough, 2012
The maximum temperature increase due to the combustion \((\Delta T = T_{\text{max}} - T_{\text{in}})\) is lower than the mixture self-ignition temperature \((T_{\text{si}})\) (Cavaliere and de Joannon, 2004).

Figure 1: Principles of standard combustion (top) and flameless oxidation (bottom). On the right hand side, the temperature evolution is shown [2].  
(Wunning, 2003).
Significantly, both the reacting and non-reacting zones for the MILD case are bigger compared to the conventional case.

**Figure 7** Schematic regime for methane-air jet in hot coflow flames (Rao, 2010).

Oxygen dilution is about 3-13% and the reactant temperature is above the self ignition temperature.

**Figure 8** Closed furnace reacting zone (Li and Mi, 2011).
### NOx & Pollutant from Fossil Fuel & Biogas

#### Table 1: Pollutant from fossil fuel (EIA, 1999)

<table>
<thead>
<tr>
<th>No.</th>
<th>Pollutant</th>
<th>Gas (kg of pollutant per 109 kJ of energy input)</th>
<th>Oil (kg of pollutant per 109 kJ of energy input)</th>
<th>Coal (kg of pollutant per 109 kJ of energy input)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Carbon dioxide</td>
<td>273,780</td>
<td>383,760</td>
<td>486,720</td>
</tr>
<tr>
<td>2.</td>
<td>Carbon monoxide</td>
<td>94</td>
<td>77</td>
<td>487</td>
</tr>
<tr>
<td>3.</td>
<td>Nitrogen oxide</td>
<td>215</td>
<td>1,048</td>
<td>1,069</td>
</tr>
<tr>
<td>4.</td>
<td>Sulphur dioxide</td>
<td>2.34</td>
<td>2,625</td>
<td>6,063</td>
</tr>
<tr>
<td>5.</td>
<td>Particulate</td>
<td>16.4</td>
<td>197</td>
<td>6,420</td>
</tr>
<tr>
<td>6.</td>
<td>Mercury</td>
<td>0.00</td>
<td>0.016</td>
<td>0.037</td>
</tr>
</tbody>
</table>

#### Biogas cycle

Figure 1: The rate of NOx formation. (a) flame temperature in Fahrenheit (2800 F is equal to 1810 K) (b) percentage of oxygen level in the oxidiser (AET, 2012).
1. Introduction

2. Research Focus

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MILD is still not fully commercialized and well adopted in furnace industry, need substantial fundamental and applied research (Cavaliere et al., 2008, Li et al., 2011b, Parente et al., 2011 and Danon, 2011).

The characteristic of MILD combustion is strong coupling between turbulence and chemistry (Parente et al., 2008). Mixing field homogeneity (de Joannon et al., 2010) and slower reaction rates - accurate modeling is challenging (Aminian et al., 2011), Fundamental study on the mixing quality is required.

Furnace efficiency - lean and clean operation and fuel cost is nearly 67% plant’s energy budget (Thomas, 2011).

More understanding on flame structure is necessary to widen the application range of the MILD combustion (Medwell, 2007) especially on open furnace.
Yes to Thermal Regeneration p.24
New Plasma Nitriding p.28
Nitriding Measurement Errors p.31
Additive Manufacturing p.34
Technology Spotlights p.37
Research Objectives

Investigate the possibility of using a new open furnace which can operate on MILD combustion.

Research work will consist of numerical and experimental.

The main objectives of this research are:

i. Evaluate the efficiency and exhaust gas emissions of the open furnace MILD combustion system using biogas fuel.

ii. Design and construct an open furnace with a bluff-body burner head (experimental technique).

iii. Optimise the burner head design using CFD modelling; validated against the experimental results.

iv. Investigate the impact of hydrogen additive on the operating conditions.
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Methodology: Proposed experimental setup

The parameter for the study will be:

i. EGR - dilute oxygen and preheat the reactant

ii. Supply air and fuel - velocity

iii. Nozzle and bluff body - design

iv. Hydrogen additive – reduce self ignition temperature

Three main parts:

i. Gas supply

ii. Combustion chamber

iii. Data acquisition system

The correct ratio of methane, carbon dioxide and nitrogen mixtures will produce natural gas, low calorific value gases like biogas and coal seam gas.

Figure 14 Proposed experimental setup
Methodology: Image of Experimental setup

Figure 15 The image of (a) experiment setup with high speed camera and data acquisition computer (http://www.uni-due.de), (b) the burner head with 1mm fuel jet (Derudi et al., 2007b)

Burner head design will be selected by using CFD modelling, before experimental work.

Supply air will be preheated using regenerator or electrical heater (if $T_{mix} < T_{si}$)
Sensitivity to turbulence model (e.g. standard $k$-$\varepsilon$ model (Launder and Sharma, 1974)) will be investigated.

The parameters for the modelling works after the experiment:

i. Temperature, velocity and the angle of the supply air
ii. Temperature, velocity and the angle of the fuel
iii. Percentage of EGR
iv. Location of the EGR input to supply air
v. Burner head design and fuel properties
4. Current Status
Early Furnace Design

Figure 3: First combustion chamber model (a) No EGR (b) with 2 EGR pipe (c) with 2 EGR pipe and EGR inlet modified

Table 2: Typical data for furnace and burner in figure 3(c) above

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>0.5CH(_4) + 0.2H(_2) + 0.3CO(_2)</td>
</tr>
<tr>
<td>Oxidiser</td>
<td>Atmospheric air, heated to 800 K</td>
</tr>
<tr>
<td>Fuel inlet</td>
<td>Round 1,256 mm(^2), 40~50 m/s each</td>
</tr>
<tr>
<td>Air inlet</td>
<td>Annulus 5,140 mm(^2), 80~100 m/s each</td>
</tr>
<tr>
<td>Chamber size</td>
<td>Diameter 375mm, Height 650mm</td>
</tr>
<tr>
<td>EGR</td>
<td>2 EGR with 386.9 mm(^2) each inlet</td>
</tr>
<tr>
<td>Mesh method</td>
<td>Tetrahedrons (Patch conforming method) with 92,034 nodes and 421,172 elements</td>
</tr>
<tr>
<td>Radiation model</td>
<td>Discrete Ordinate (DO) model. Absorption coefficient: Weighted Sum of Gray Gas (WSGGM) model.</td>
</tr>
</tbody>
</table>
Furnace Design (Jun 2012)

Figure 4: Final model with 4 EGR. (a) Air inlet internal diameter is 22 mm. (b) Air inlet internal diameter is 5 mm.

Combustion temperature in the chamber for figure 4(b)

Table 3: Typical data for furnace and burner in figure 4(b)

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>(0.5\text{CH}_4 + 0.2\text{H}_2 + 0.3\text{CO}_2)</td>
</tr>
<tr>
<td>Oxidiser</td>
<td>Atmospheric air, heated to 800 K</td>
</tr>
<tr>
<td>Fuel Inlet</td>
<td>4 x 19.6 mm(^2), 20 m/s each</td>
</tr>
<tr>
<td>Air Inlet</td>
<td>4 x 19.6 mm(^2), 80 m/s each</td>
</tr>
<tr>
<td>Chamber size</td>
<td>Diameter 600mm, Height 860mm</td>
</tr>
<tr>
<td>EGR</td>
<td>4 EGR with 386.9 mm(^2) each inlet</td>
</tr>
<tr>
<td>Mesh method</td>
<td>Tetrahedrons (Patch conforming method) with 111,975 nodes and 501,831 elements</td>
</tr>
<tr>
<td>Radiation model</td>
<td>Discrete Ordinate (DO) model. Absorption coefficient: Weighted Sum of Gray Gas (WSGGM) model.</td>
</tr>
</tbody>
</table>
AFR Study 1 – MPC2012

The fuel mole fraction to produce Lower Calorific Value (LCV) is 53.44% CH\textsubscript{4}, 13.36% H\textsubscript{2}, 30.00% CO\textsubscript{2}, 1.30% N\textsubscript{2}, 1.70% C\textsubscript{2}H\textsubscript{6}, 0.01% C\textsubscript{3}H\textsubscript{8} and 0.01% C\textsubscript{4}H\textsubscript{10}.

The air mole fraction is 21.008% O\textsubscript{2} and 78.992% N\textsubscript{2}.

<table>
<thead>
<tr>
<th>Air (m/s)</th>
<th>Fuel (m/s)</th>
<th>AFR</th>
<th>UHC CH\textsubscript{4} mole fraction</th>
<th>UHC CH\textsubscript{4} mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50</td>
<td>1:0:1</td>
<td>0.1069</td>
<td>0.0615</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>2:0:1</td>
<td>0.0450</td>
<td>0.0258</td>
</tr>
<tr>
<td>90</td>
<td>40</td>
<td>2:3:1</td>
<td>0.0390</td>
<td>0.0215</td>
</tr>
<tr>
<td>75</td>
<td>30</td>
<td>2.5:1</td>
<td>0.0351</td>
<td>0.0201</td>
</tr>
<tr>
<td>100</td>
<td>40</td>
<td>2.5:1</td>
<td>0.0327</td>
<td>0.0185</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
<td>3:0:1</td>
<td>0.0240</td>
<td>0.0119</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>3:3:1</td>
<td>0.0146</td>
<td>0.0082</td>
</tr>
<tr>
<td>55</td>
<td>15</td>
<td>3.7:1</td>
<td>0.0097</td>
<td>0.0056</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>4:0:1</td>
<td>0.0058</td>
<td>0.0033</td>
</tr>
<tr>
<td>65</td>
<td>15</td>
<td>4.3:1</td>
<td>0.0027</td>
<td>0.0015</td>
</tr>
<tr>
<td>70</td>
<td>15</td>
<td>4.7:1</td>
<td>0.0004</td>
<td>0.0002</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>5:0:1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>16</td>
<td>5:0:1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>5:0:1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>13</td>
<td>5.4:1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>15</td>
<td>6:0:1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

When AFR reach 5:1, CH\textsubscript{4} mole fraction in EGR pipe is Zero.

The CH\textsubscript{4} mole fraction between 0 to 0.15 with UHC in the EGR pipe.

Comb. temperature with unwanted burning in EGR pipe due to unburned CH\textsubscript{4} in EGR.
AFR Study 2 – SREC2012

Figure 1: Open furnace with 4 EGR (a) total geometry (b) air (outer) and fuel (inner) bluff body nozzle

Figure 2: Meshing for open furnace with 4 EGR (a) 911,669 mesh element and 189,372 mesh nodes (b) mesh element refinement air and fuel nozzle
LCV is 50% CH$_4$, 20% H$_2$, 30% CO$_2$

The air mole fraction is 21.008% O$_2$ and 78.992% N$_2$.

When AFR reach 4:1, CH$_4$ mole fraction in EGR pipe is become Zero
Calculation & Residuals

Time taken for:
Coarse mesh : 20 – 40 second per step
Medium mesh : 45 – 100 second per step
Fine mesh : 120 – 300 second per step

Problem – floating point, computer hang, divergence
Latest Result

LCV is 50% CH₄, 20% H₂, 30% CO₂

Normal Air 21.008% O₂ and 78.992% N₂.

Low Oxygen Air: 7.0% O₂ and 93.0% N₂.

Air 200 m/s 400K and Fuel 120 m/s 800K

Conventional

MILD

(Wunning, 2003)
Streamline from Air Inlet (10mm exhaust)  
Streamline from Chamber (10mm exhaust)  
Streamline from Air Inlet (100mm exhaust)  
Streamline from Chamber (100mm exhaust)  

Velocity Magnitude  
Oxygen mole fraction  
CH4 mole fraction (Not zero in EGR and exhaust)  
EGR flow down still not strong enough to dilute oxygen in fresh air
1. Introduction
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5. Conclusions
1) CFD Progress to design and develop the parameter for open furnace

2) The experimental setup is in progress
Thankyou