THE DEVELOPMENT OF MILD COMBUSTION OPEN BURNER
EXPERIMENTAL SETUP

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ABSTRACT

This paper discusses the development of the combustion furnace for the Moderate and Intense Low oxygen Dilution (MILD) combustion. The development was started with using Computational Fluid Dynamics (CFD) software. ANSYS Fluent was used to simulate preliminary designs for the burner before the final design sent to workshop to build it. The requirement of MILD combustion are air fuel mixture preheat and dilute the oxygen content in the oxidant stream. In order to achieve this condition, Exhaust Gas Recirculation (EGR) was utilised. The burner requirement is in non-premixed and open burner. To capture and used the exhaust gas, the burner was enclosed with large circular shape wall with open at the top. External EGR pipe was used to transport the exhaust gas and mixed with the fresh oxidant (normal air or syntactic air). Butterfly valve was installed at the top opening as damper to close the exhaust gas flow at the certain ratio for EGR and exhaust out to atmosphere. This damper must be long enough to prevent from backflow of normal air into the combustion chamber. The R-type and K-type thermocouple wire was used to measure the temperature inside the combustion chamber and the EGR pipe. The lambda and gas sensor was installed to measure the gas compositions. Data acquisition system used to collect the temperature and gas compositions in combustion chamber, EGR pipe and exhaust gas. Three high temperature glass windows (fused silica) were installed to view and capture the image of the flame and analysed the flame propagation. The furnace development completed and ready to be tested.

Keywords: experimental setup, computational fluid dynamics, bluff-body MILD burner

INTRODUCTION

The majority of current energy production through combustion process was producing high pollution emissions and greenhouse gases (IEA, 2002, 2011; EIA 2007, 2011; IPCC, 2007; Ghoniem, 2011) and will effect on the climate change. The global temperature and the CO\textsubscript{2} concentration reported to increase significantly since the era of industrialization (IPCC, 2007). This is directly proportional with energy production. The solutions to this problem included energy conversion improvement, carbon capture, transport and storage (CCTS) and the use renewable resources such as solar, wind, hydro, biomass and geothermal energy. On the energy demand, combustion of fossil fuel projected at the year 2030 still account about 80% from global needs (Maczulak, 2010). Transport fuel in 2030 remains dominated by oil (87%) and biofuels (7%), natural gas (4%) and electricity (1%) in 2030 (British Petroleum, 2012). The combustion of fossil fuel is still a very important source of energy. Due to the energy
needs and pollution emission, the combustion researchers are focusing on the improvement of the combustion efficiency, new combustion technology and combustion modeling (Merci et al., 2007; Smith and Fox, 2007; Noor et al., 2012a).

MILD combustion is one of the new combustion technology that produce lower pollution emission and increase the thermal efficiency (Dally et al., 2002, 2010; Cavaliere and Joannon, 2004; Christo and Dally, 2004; Weber et al., 2005; Noor et al., 2012a). This combustion also called flameless oxidation or FLOX (Wünning, 1991, 1996, 2004, 2005; Wünning and Wünning, 1996, 1997; Milani and Wünning, 2007; Mancini et al., 2002, 2007), low NOX (Orsino et al., 2001) and high-temperature air combustion (HiTAC) (Katsuki and Hasegawa, 1998; Tsuji et al., 2003). MILD combustion has been investigated experimentally (Hardestry and Weinberg, 1974; Plessing et al., 1998; Lille et al., 2005; Cabra et al., 2005; Rafidi and Blasiak, 2006; Derudi et al., 2007; Derudi and Rota, 2011; Li et al., 2011a, 2011b) and numerically (Coelho and Peters, 2001; Park et al., 2003; Yang and Blasiak, 2005a, 2005b; Awosope et al., 2006; Zhenjun et al., 2010; Parente et al., 2011; Szegö et al., 2011; Noor et al., 2012d) in various industrial applications. The main requirement for MILD combustion is oxygen dilution in the oxidant stream and temperature mixture temperature is above the self-ignition for the fuel. The oxygen dilution and the heating of the oxidiser can be achieved by the used of exhaust gas recirculation (EGR) (Katsuki and Hasegawa, 1998; Noor et al., 2012b; Yusaf et al., 2013). The hot EGR will dilute the oxygen in the oxidant and preheat it. The oxygen content in the fresh air will reduce depending on the ratio of the fresh air and EGR.

The comparison of the flame temperature for the conventional and MILD combustion is shown in Figure 1. The different between minimum and maximum temperature (AT) for the conventional combustion is high compare to MILD combustion. The temperature distribution was more homogenous and this characteristic will give advantage to MILD combustion for many applications that need stable and distributed temperature throughout the combustion chamber.

![Figure 1. Comparison for conventional and MILD combustion (Wünning, 2003)](image)

This paper discussed about the development of the MILD burner for non-premixed open flame. The burner was design by using ANSYS Fluent 13.0, 14.0 and
14.5. Then the burner was built at USQ mechanical workshop. The testing and experimental work will be using methane, biogas and coal seam gas (CSG).

**COMBUSTION EQUATION**

In order to design the combustion chamber, the basics of combustion equation must be used to calculate the air fuel ratio (AFR). The study of AFR using computational fluid dynamics (CFD) commercial package (ANSYS Fluent) was done to design the air and fuel inlet diameters and volume flow rates (Noor et al., 2012b). The balance combustion process will not produce unburned hydrocarbon (UHC) in the exhaust gas. That shows the combustion process consume all the fuels. The combustion process can be written in general hydrocarbon stoichiometric combustion equation:

\[
C_n H_m + \left( n + \frac{m}{4} \right) (O_2 + 3.76N_2) \rightarrow n CO_2 + \frac{m}{2} H_2 O + 3.76 \left( n + \frac{m}{4} \right) N_2 \quad (1)
\]

Stoichiometric combustion equation without EGR for low calorific value gas consists of 50% methane, 20% hydrogen and 30% carbon dioxide by volume (Noor et al., 2012c).

\[
(0.5 CH_4 + 0.2 H_2 + 0.3 CO_2) + (1.1 O_2 + 4.1 N_2) \\
\rightarrow (0.8 CO_2 + 1.2 H_2 O + 4.1 N_2) \quad (2)
\]

In more general form, the combustion equation without EGR is

\[
(i CH_4 + j H_2 + k CO_2) + (2i + 0.5j)(1.0 O_2 + 3.8 N_2) \\
\rightarrow (i + k) CO_2 + (2i + j) H_2 O + 4.1 N_2 \quad (3)
\]

For lean combustion, take equivalent ratio, \( \phi = 0.5 \) and fuel composition are \( i = 0.5, j = 0.2 \) and \( k = 0.3 \),

\[
(0.25 CH_4 + 0.1 H_2 + 0.15 CO_2) + (1.1 O_2 + 4.1 N_2) \\
\rightarrow 0.4 CO_2 + 0.6 H_2 O + 4.1 N_2 \quad 0.5 O_2 \quad (4)
\]

For rich combustion, take equivalent ratio, \( \phi = 1.5 \) and fuel composition are \( i = 0.5, j = 0.2 \) and \( k = 0.3 \),

\[
(0.75 CH_4 + 0.3 H_2 + 0.45 CO_2) + (1.1 O_2 + 4.1 N_2) \\
\rightarrow 1.2 CO_2 + 1.8 H_2 O + 4.1 N_2 + 0.5 CH_4 + 0.5 H_2 \quad (5)
\]

and the combustion equation with EGR is

\[
(i CH_4 + j H_2 + k CO_2) + (2i + 0.5j)(1.0 O_2 + 3.8 N_2) \\
+ \lambda ((i + k) CO_2 + (2i + j) H_2 O + 3.8(2i + 0.5j)N_2) \\
\rightarrow (\lambda + 1)((i + k) CO_2 + (2i + j) H_2 O + 3.8(2i + 0.5j)N_2) \quad (6)
\]

where \( i, j \) and \( k \) is the mole fraction of the methane, hydrogen and carbon dioxide respectively and \( \lambda \) is the EGR ratio. The stoichiometric combustion equation for low calorific value gas consists of 50% methane, 20% hydrogen and 30% carbon dioxide by volume, half of flue gas will flow back to the chamber and lower the oxygen level in the oxidizer stream. An example, for this composition at stoichiometric condition, \( \phi \) is 1.0, and 75% EGR, the balance equation is

\[
(0.5 CH_4 + 0.2 H_2 + 0.3 CO_2) + (1.1 O_2 + 4.1 N_2)
\]
\[ + (2.4CO_2 + 3.6H_2O + 12.4N_2) \rightarrow (3.2CO_2 + 4.8H_2O + 16.5N_2) \]  

For lean combustion, the excess oxygen and nitrogen will not be involved in combustion and exhaust through the flue gas. These excess can be seen in an example (Equation 8) of \( \phi \) is 0.5, and 33% EGR, the balance equation is

\[ (0.25CH_4 + 0.1H_2 + 0.15CO_2) + (1.1O_2 + 4.1N_2) \]
\[ + 0.2CO_2 + 0.3H_2O + 2.1N_2 0.4O_2 \rightarrow 0.6CO_2 + 0.9H_2O + 6.2N_2 + 1.1O_2 \]  

In the rich combustion process, due to not enough oxygen to burn high mass fraction of CH\(_4\), excess methane and hydrogen will not be involved in combustion and becoming unburned hydrocarbons. These conditions can be seen in an example (Equation 9) of \( \phi \) is 1.5, and 66% EGR, the balance equation is

\[ (0.75CH_4 + 0.3H_2 + 0.45CO_2) + (1.1O_2 + 4.1N_2) \]
\[ + 2.4CO_2 + 3.6H_2O + 8.3N_2 + 1.1CH_4 + 1.1H_2 \rightarrow \]
\[ 3.6CO_2 + 5.4H_2O + 12.4N_2 + 1.7CH_4 + 1.7H_2 \]  

If the fuel is biogas with only methane and carbon dioxide, the general form of the combustion equation with EGR is

\[ (iCH_4 + kCO_2) + 2i(1.0O_2 + 3.8N_2) + \lambda[(i + k)CO_2 + 2iH_2O + 7.6iN_2] \]
\[ \rightarrow (\lambda + 1)[(i + k)CO_2 + 2iH_2O + 7.6iN_2] \]  

**COMPUTATIONAL FLUID DYNAMICS**

CFD is an important design tool that has been extensively used to explore and design the engineering hardware (Baukal et al., 2001; Davidson, 2002, Noor et al., 2012a; Najja et al., 2012a, 2012b) including combustion chambers. CFD was increasingly being used for the optimisation of gas burner (Scharler and Obernberger, 2000) and industrial gas furnace (Dally et al., 2004; Riahi et al., 2012; Noor et al., 2013) or coal combustion (Calchetti et al., 2007). In this study, the CFD package ANSYS FLUENT 13.0, 14.0 and 14.5 was used to model MILD combustion in the mode of non-premixed combustion.

A governing equations used including mass, momentum, energy and species in addition to the turbulence transport and combustion model were discretized in the whole domain using the second-order schemes. The realizalbe k−ε turbulence model (Shih et al., 1995) [that developed based on standard k−ε turbulence model (Launer and Spalding, 1974)] was used for turbulence model (Peters, 2000; Pope, 2000) and discrete ordinate (DO) model (Chui and Raithby, 1993) for radiation model. DO model is applicable to a wide range of optical thicknesses. The optical thickness for MILD combustion flames is not well defined makes DO model a good selection for the radiation model. This model solves a radiative transfer equation. Weighted sum of gray gas model (WSGGM) was used for the absorption coefficient which was conceptually developed in 1967 (Hottel and Sarofim, 1967) and used for spray combustion (Choi and Baek, 1996) and gas furnace (Liu et al., 1998). The WSGGM is having reasonable compromise between the oversimplified gray gas model and a complete model.

The MILD combustion open furnace was model and the flame behaviour, temperature distributions, flow velocities, turbulent behaviour and EGR flow was analysed. The early design of the combustion chamber was with 2 EGR and 4 small
EGR pipe (Figure 2) to transport the exhaust gas to mix it with fresh air. Those 2 models was not success to ensure the exhaust gas get into the EGR pipe and flow down. For the early design (Figure 2(a)), this is due to the EGR in the inlet of EGR at the top is not helping the fluid flow. The 90° inlet angle was not letting the exhaust gas flow into the EGR pipe as plan.

The design for the EGR inlet was change (Figure 2(b)) with the inlet is direct in the vertical direction. This is in line with the flame and exhaust gas direction and easy for the exhaust gas to flow into the EGR pipe. The outlet for the exhaust move downward to make the inlet for EGR is bigger and can be seen in Figure 2(b) and 3(a). The small EGR pipe (Figure 2(b)) only allows small volume of exhaust gas flow downward. In order to increase the volume of exhaust gas flow, the EGR pipe increase from 25 mm to 50 mm diameter (Figure 3(b)). The same principle as EGR pipe inlet, the EGR pipe outlet also finally install at the side of each EGR to help the EGR flow (Figure 3(a) and 3(b)). This design also to ensure the exhaust gas mix properly before enter the combustion chamber. Nakamura et al. (1993) and Weber et al. (2000, 2001) experimentally studied pilot-scale furnaces equipped with heat exchangers and demonstrated that heat transfer was affected by the port locations and angles.

The simulation was done on the final model (Figure 3(b)) for the ignition location study (Noor et al., 2013), air fuel ratio study (Noor et al., 2012b) and other parametric study (Noor et al., 2012d, 2012e) on the MILD combustion using biogas as a fuel. Difference combination of air and fuel compositions injected to the chamber giving different result. When the oxygen level is from 3 to 13% before mixed with fuel, then MILD combustion will be achieved (Figure 4(b)). Otherwise the combustion is not achieved MILD state (Figure 4(a)). Figure 5 shows the velocity magnitude of the flow in the chamber. This flow shows that the chamber is open and the pressure in the chamber is at atmospheric pressure since the chamber is open on the top. This open chamber is considered as open MILD combustion furnace.

![Figure 2. MILD burner early development in CFD in early design stage (a) with 2 EGR pipe (b) with smaller EGR pipe and 4 fuel inlet](image-url)
Figure 3: Final design with bigger EGR pipe (a) 2D schematic diagram (b) 3D image

Figure 4: MILD combustion state (a) not achieved (b) achieved
MODEL DEVELOPMENT

The development of the burner was done at USQ mechanical workshop. The schematic diagram for the overall gas system and burner is shown in Appendix A. There are consisting of 3 main parts which are gas system, burner and data acquisition. The gas system is including 5 gas cylinder, gas supply line and valve and gas control panel. The gas control panel was the place where the gas will be mixed and the flow rate will be controlled. The burner system including burner, ignition system and EGR pipe are shown in Figure 6. The data acquisition system will be discussed in the next section.

The ignition process was designed using spark ignition in the recirculation zone (Noor et al., 2013). A study on recirculation zone for the ignition location was done using CFD. Figure 7(a) shows the flame flow field with Figure 7(b) as the mixing recirculation zone. Figure 7(b) shows that there are two types of recirculation zone: the inner recirculation zone (IRZ) formed in between the air and fuel jet flow of bluff-body and the outer recirculation zone (ORZ) formed outside the annulus air flow. The recirculation of the mixture of fuel and air was important due to that process will create the turbulent flow of the mixture which will enhance the mixing process. Mastorakos (2009), Triantafyllidis et al. (2009), Neophytou et al. (2012) and Noor et al. (2013) concluded that the best location for ignition was in the centre of inner recirculation zone where the recirculation velocity is almost zero.

This is important to ensure the spark energy supplied by the tungsten rod was not flushed away, thereby giving sufficient time for the spark energy to ignite the mixture of fuel and oxidant. The ignition system was design and install as Figure 8 and 9. The ignition system comes with 2 tungsten rod with each diameter 2.4 mm. At the end of the tungsten rod, the sharp edge was gap at 2.0 mm. Ignition coil was used to increase the voltage from the car battery and used to ignite the mixing. The ignition installation is as shown in Figure 9.
Figure 6. MILD burner setup (a) burner (b) high temperature glass window (c) external safety covers for the burner

Figure 7. Schematic diagrams for bluff-body burner, (a) flame flow field with central fuel jet and annulus air co-flow, (b) flow field re-circulation zone
The furnace was installed in the USQ combustion laboratory (building called P7). The furnace shares the room with remote access laboratory (RAL) engine for the remote access experiment. The room layout was shown in Figure 10. The layout for MILD combustion system burner consist of the burner, exhaust system, data acquisition system equip with one computer and gas control panel. The data acquisition system will be discussed later in this paper. The gas control panel is for the gas supply to control the gas flow rate and mixing of gas. The gas supplies are methane, hydrogen, carbon dioxide, oxygen and nitrogen. Methane and carbon dioxide was use to mix and create biogas with the composition of 60% methane and 40% carbon dioxide. More study can be done with the effect of hydrogen mix with methane and carbon dioxide as a fuel. Oxygen and nitrogen is used to create the synthetics air supply with 5% to 30% of oxygen level in the mixing.

![Figure 8. Schematic diagrams of combustion chamber, (a) ignition rod location, (b) location plan view and (c) location side view of ignition location and installation](image)

![Figure 9. Ignition system (a) ignition lead top view (b) bottom view](image)
The furnace power or heat release rate in unit Watt (W) can be calculated by mass flow rate (kg/s) times gas heating value (kJ/kg). The dimensional analysis is:

\[ W = \text{Nm/s} = \text{kg/s} \times \text{m}^2/\text{s}^2 = \text{kg/s} \times \text{kJ/kg} = \text{mass flow rate} \times \text{gas heating value} \]

Methane gas was injected through a 10 mm inlet diameter. The area of the fuel inlet is \(7.85 \times 10^{-5} \text{ m}^2\). The gas injected to the combustion chamber at the maximum rate of 25.0 litre/min. This is equal to \(4.16 \times 10^{-4} \text{ m}^3/\text{s}\). The fuel speed injected is 5.3 m/s. The mass flow rate is depending on the density of the fluid. The density of methane gas is 0.668 kg/m\(^3\) (at 293K and 101.325 kPa), thus the mass flow rate is

\[ m = \text{gas density} \times \text{volume flow rate} = 0.668 \text{ kg/m}^3 \times (4.16 \times 10^{-4} \text{ m}^3/\text{s}) = 2.78 \times 10^{-4} \text{ kg/s} \]

Heat release by the combustion of methane can be calculated as below. Methane heating value is 55.0 MJ/kg (Table 1).

\[ q = \text{mass flow rate} \times \text{gas heating value} = (2.78 \times 10^{-4} \text{ kg/s}) \times 55.0 \text{ MJ/kg} = 15.3 \text{ kW} \]

The power for the furnace for 25 litre/minute of methane volume flow rate is 15.3 kW. Methane thermal properties are including internal energy (u), enthalpy, (h), specific heat \((C_p)\), and heating value \((h_v)\). The heating value unit is J/mole or Joule/kg used to measure the maximum amount of heat can be generated by combustion with air at 25°C and 101.325 kPa. Table 1 shows the heating value for methane and compare with other fuel and gases (McAllister, 2011; Demirel, 2012; Noor et al., 2012e). The highest heating value is hydrogen which is 141.8 KJ/kg and methane is 55.5 KJ/kg, the highest among hydrocarbon fuel.

**Figure 10. MILD layout for the installation (plan view)**
Table 1. Fuel heating value to calculate furnace Watt power

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Composition</th>
<th>Molar mass g/mol</th>
<th>Specific heat MJ/kg</th>
<th>Specific heat KJ/mol</th>
<th>Specific heat BTU/lb</th>
<th>Density kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>2.01</td>
<td>141.8</td>
<td>286</td>
<td>61100</td>
<td>0.0899</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>16.04</td>
<td>55.5</td>
<td>890</td>
<td>23900</td>
<td>0.6680</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>30.07</td>
<td>51.9</td>
<td>1560</td>
<td>22400</td>
<td>1.2640</td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td>44.09</td>
<td>50.3</td>
<td>2220</td>
<td>21700</td>
<td>1.8820</td>
</tr>
<tr>
<td>Natural gas</td>
<td>-</td>
<td>18</td>
<td>50.0</td>
<td>900</td>
<td>21600</td>
<td>0.8000</td>
</tr>
<tr>
<td>Butane</td>
<td>C₃H₁₀</td>
<td>58.12</td>
<td>49.5</td>
<td>2877</td>
<td>20900</td>
<td>2.4890</td>
</tr>
<tr>
<td>Octane</td>
<td>C₄H₁₈</td>
<td>114.23</td>
<td>47.9</td>
<td>5470</td>
<td>20600</td>
<td>703.00</td>
</tr>
<tr>
<td>Decane</td>
<td>C₅H₂₂</td>
<td>142.28</td>
<td>47.6</td>
<td>6773</td>
<td>20500</td>
<td>730.00</td>
</tr>
<tr>
<td>Gasoline</td>
<td>C₅H₁₈₋₅₇₇₈</td>
<td>100-110</td>
<td>47.3</td>
<td>5400</td>
<td>20400</td>
<td>719.70</td>
</tr>
<tr>
<td>Diesel</td>
<td>C₆H₁₇₅₉₆</td>
<td>170-200</td>
<td>44.4</td>
<td>4480</td>
<td>19300</td>
<td>832.00</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>-</td>
<td>-</td>
<td>32.8</td>
<td>393.5</td>
<td>14100</td>
</tr>
<tr>
<td>Coal</td>
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<td>-</td>
<td>21</td>
<td>275</td>
<td>11000</td>
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<td>-</td>
<td>15</td>
<td>300</td>
<td>6500</td>
<td>650.91</td>
</tr>
</tbody>
</table>

**DATA ACQUISITION SYSTEM**

The instrumentation in USQ Combustion Laboratory was mainly equipped with a National Instrument (NI) data acquisition system and LabVIEW software. The temperature was measured on 32 different locations on various combustion chambers’ components such as the main chamber, air inlet, EGR pipe and exhaust pipe. The temperature was measured by R-type and K-type thermocouple which was connected to a 32-channel NI connector box. The thermocouple specification can be referred to Appendix B (Noor et al., 2012e). Figure 11 shows the arrangement of the data acquisition system of the test engine. The measurement was displayed in a LabVIEW graphical user interface (GUI) and can be recorded as an MS Excel format. Figure 12 shows the LabVIEW graphical user interface used to display and recorded the data. In this experiment, National Instruments Data Acquisition (NIDAQ) system was used to measure and display the temperature measurement through thermocouples. LabVIEW software was used to manage and store the data collected. It consists of chassis NIDAQ 9178 with a number of signal conditioning amplifiers and analogue to digital conversion modules.

![Figure 11. Data acquisition system with National Instrument DAQ Card and computer](image)
Gas analyser was used to measure the gas composition in the combustion chamber, EGR pipe and exhaust ducting. The analysis of gas composition is very important to evaluate the NOx emission, unburned hydrocarbon (UHC) and excess oxygen in the exhaust gas.

![LabVIEW graphical user interface (GUI)](image)

**CONCLUSION**

The design of the MILD combustion open furnace was successful with the use of ANSYS Fluent. The simulation of the MILD combustion was successful to achieve MILD state. The combustion has to be enclosed to collect the exhaust gas and utilised it to dilute the oxygen in the oxidant stream and at the same time, increase the oxidant temperature. Four EGR pipes were added to bring down the exhaust gas and mixed with the inlet air. The building and development of the furnace was carried out at University of Southern Queensland mechanical workshop. The furnace was equipped with three high temperature glass window to monitor and record the flame propagation. The R-type thermocouple was used for the main chamber temperature measurement since it can withstand up to 2040K. K-type thermocouple that can withstand up to 1645K was used to measure the temperature of the exhaust gas at the exhaust gas pipe on the top of the chamber and EGR pipe. Data acquisition system was used to collect and record the data from the thermocouples. The composition for the exhaust gas in the exhaust pipe and EGR pipe was measured using gas analysers. The furnace power calculated for the 25 litre/minute of methane is 15.3 kW.

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**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS</td>
<td>Carbon capture and storage</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>FGR</td>
<td>Flue gas recirculation</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse-gas</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>Hydrogen peroxide</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>HTOC</td>
<td>High temperature combustion</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>LCV</td>
<td>Low calorific value</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>OH</td>
<td>Hydroxyl</td>
</tr>
<tr>
<td>SOₓ</td>
<td>Sulphur oxides</td>
</tr>
<tr>
<td>UHC</td>
<td>Unburned hydrocarbons</td>
</tr>
</tbody>
</table>
Appendix A. Schematic drawing for USQ MILD Bluff-body Burner

USQ Bluff-body Burner
1) Safety Valve
2) Gas Mixer
3) Pressure Regulator
4) Pressure Gauge
5) Flow Gauge
6) DAQ System
7) HS Camera
8) Charge Amplifier

750mm h x 600mm d, Clear Silica Quartz Cylinder

Safety Valve

Charge Amplifier

DAQ System

Non-premixed Bluff-body Burner
Muhamad CESRC, USQ
20 Dec 2011
### Appendix B. Thermocouple types (summarised by Noor et al., 2012e)

<table>
<thead>
<tr>
<th>SLD&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Popular name</th>
<th>Materials (colour code)&lt;sup&gt;b&lt;/sup&gt; (positive material appears first)</th>
<th>Typical range&lt;sup&gt;c&lt;/sup&gt; (Kelvin)</th>
<th>Thermo power at 373K</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Copper-constantan</td>
<td>Copper (blue) and a Copper-Nickel alloy&lt;sup&gt;d&lt;/sup&gt; (red)</td>
<td>0 to 673K</td>
<td>46.8</td>
</tr>
<tr>
<td>J</td>
<td>Iron-constantan</td>
<td>Iron (white) - a slightly different Copper-Nickel alloy&lt;sup&gt;e&lt;/sup&gt; (red)</td>
<td>63 to 1033&lt;sup&gt;f&lt;/sup&gt;</td>
<td>54.4</td>
</tr>
<tr>
<td>E</td>
<td>Chromel-constantan</td>
<td>Nickel-Chromium alloy&lt;sup&gt;g&lt;/sup&gt; (yellow) and Nickel-Aluminium alloy&lt;sup&gt;i&lt;/sup&gt; (purple) vs. a Copper-Nickel alloy&lt;sup&gt;h&lt;/sup&gt; (red)</td>
<td>0 to 1273K</td>
<td>67.5</td>
</tr>
<tr>
<td>N</td>
<td>Nicrosil-Nisil</td>
<td>Nickel-Chromium-Silicon alloy&lt;sup&gt;i&lt;/sup&gt; (orange) vs. Nickel-Chromium-Magnesium&lt;sup&gt;i&lt;/sup&gt; alloy (red)</td>
<td>0 to 1570K</td>
<td>29.6</td>
</tr>
<tr>
<td>K</td>
<td>Chromel-Alumel</td>
<td>Nickel-Chromium alloy&lt;sup&gt;g&lt;/sup&gt; (red) and Nickel-Aluminium alloy&lt;sup&gt;i&lt;/sup&gt;</td>
<td>0 to 1645K</td>
<td>41.4</td>
</tr>
<tr>
<td>M</td>
<td></td>
<td>Nickel-Molybdenum (18%) and Nickel Cobalt (0.8%)</td>
<td>273 to 1673K</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td></td>
<td>Platinum (10%) Rhodium and Platinum&lt;sup&gt;j&lt;/sup&gt;</td>
<td>223 to 2040K</td>
<td>7.3</td>
</tr>
<tr>
<td>R</td>
<td></td>
<td>Platinum (13%) Rhodium and Platinum&lt;sup&gt;j&lt;/sup&gt;</td>
<td>223 to 2040K</td>
<td>7.5</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Platinum (30%) Rhodium and Platinum&lt;sup&gt;j&lt;/sup&gt; (6%) Rhodium</td>
<td>273 to 2093K</td>
<td>0.9</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>Tungsten (5%) Rhenium and Tungsten&lt;sup&gt;j&lt;/sup&gt; (26%) Rhenium</td>
<td>273 to 2593K</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup>SLD is stand for Standardized Letter Designation. The letter designation is for the combined thermocouple with each individual thermo-element designated by P or N for positive or negative legs, respectively, for example, SN stands for platinum, TP stands for copper.

<sup>b</sup>The color codes given in parentheses are the colour of the duplex-insulated wires (ISA, 1982). Colour codes are not available for the noble metal types (S, R, and B). For the base metal types (T, J, E, and K), the overall insulation colour is brown.

<sup>c</sup>These temperature ranges are taken from (Burn et al., 1993)

<sup>d</sup>This copper-nickel alloy is the same for both EN and TN, often referred to as Adams constantan or constantan.

<sup>e</sup>This copper-nickel alloy is used in JN. It is similar to, but not always interchangeable with, EN and N. By SAMA specifications, this substance is often referred to as SAMA constantan or constantan.

<sup>f</sup>Even though EMF-temperature values are available up to 1473K (Burn et al., 1993), thermo-physical properties of type J thermocouples are not stable above 1030K.

<sup>g</sup>EP and KP is a nickel-chromium alloy that is usually referred to by its trade name, Chromel (HMC2012).

<sup>h</sup>KN is a nickel-aluminium alloy usually referred to by its trade name, Alumel (HMC2012).

<sup>i</sup>See ref. (Burley et al., 1978) for more details.

<sup>j</sup>See ref. (Goldstein et al., 1998) for more details.