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# MILD COMBUSTION: A TECHNICAL REVIEW TOWARDS OPEN FURNACE COMBUSTION

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## ABSTRACT

Moderate or Intense Low oxygen Dilution (MILD) combustion is one of the best alternative new technologies for clean and efficient combustion. MILD combustion has been proven to be a promising combustion technology for industrial applications with decreased energy consumption due to the uniformity of temperature distribution, also producing low $NO_x$ and CO emissions. This article provides a review and discussion of the recent research and development in MILD. Furthermore, the problems and focuses are summarized with some suggestions and therefore presented on upgrading an application of MILD in the future. Currently MILD combustion has been applied in closed furnace. For closed furnace, the preheating supply air is no longer required since the recirculation inside the enclosed furnace will self preheats the supply air and self dilutes the oxygen in the combustion chamber. The possibility of using open furnace MILD combustion was discussed and reviewed.

***Keywords***: MILD combustion, turbulent combustion, open furnace

## INTRODUCTION

Chemical reaction through combustion still contributes to most of the energy needs. The demand of energy is dramatically increasing due to the growth of the world's population and substantial economic development in countries such as China and India. Some of the major challenges are to provide efficient energy and limit greenhouse-gas (GHG) emissions. Combustion of fossil fuel is projected to fulfil about 80% of these energy needs (IEA, 2009 and Maczulak, 2010). The pollution resulting from conventional combustion processes is linked with global warming and other associated changes such as abnormal weather patterns, rise in ocean levels and melting of ice the North and South Poles. The more efficient use of fuel with low GHGs emission as well as carbon capture and storage (CCS) might be effective ways to gradually reduce the GHG emissions (IEA, 2006, 2009 and Orr, 2005). IEA/OECD (2002) and Jonathan (2006) reported that $CO_2$ contributed 77% of the greenhouse gas emissions with combustion accounting for 27%, making it a major contributor to global climate change. To counter this issue, the improvement of combustion efficiency with lower emissions has led researchers to have more interest in new combustion technology and combustion modeling (Smith and Fox, 2007 and Merci et al., 2007). One of the methods to improve the combustion efficiency is to preheat the reactant by the hot flue gas. However, preheating the combustion air generally increases the flame temperature which results in more formation of thermal $NO_x$. A new combustion technology has been suggested that is able to solve this issue: Moderate or Intense Low Oxygen Dilution (MILD) combustion produces high combustion efficiencies with very low emissions.

Combustion processes require three basic elements which are fuel, oxidiser and heat or an ignition source. Fuel and oxidiser need to be mixed at the molecular level via a turbulent mixing process. In 1989, Wünning (1991) observed a surprising phenomenon during experiments with a self-recuperative burner. At furnace temperatures of 1273K and about 923K air preheat temperature, no flame could be seen and no UV-signal could be detected. The fuel was completely burnt and the CO was below 1ppm in the exhaust. The $NO_x$ emissions were almost zero with smooth and stable combustion. Wünning (1991) called that condition "flameless oxidation" or FLOX (Wünning, 1996, Wünning and Wünning, 1997 and Milani and Wünning, 2007). This new combustion technology was also labelled as Moderate or Intense Low-oxygen Dilution (MILD) combustion (Dally et al., 2002, Cavaliere and de Joannon, 2004). Katsuki and Hasegawa (1998) and Tsuji et al., (2003) found that high-temperature air combustion (HiTAC) is nearly the same as MILD combustion, besides operating at higher temperatures. MILD combustion has many beneficial features, especially on producing uniform temperature distribution, excellent combustion stability, very high efficiency and extremely low emissions of $NO_x$. The early research and development of MILD combustion came from Germany (Wünning and Wünning, 1997, Plessing et al., 1998, Mancini et al., 2002, 2007, Kim et al., 2008 and Zieba et al., 2010) and Japan (Katsuki and Hasegawa, 1998, Yuan and Naruse, 1999 and Tsuji et al., 2003). However all the combustion was studied for closed chamber or closed furnace.

Currently there is no record of studies for MILD combustion in open furnace. More understanding on flame structures are necessary to increase the application range of the MILD combustion (Medwell, 2007) especially on open furnace. Some histories, recent trends and researches on MILD were reviewed. The key topics discussed include MILD combustion regime, flame characteristics and properties, $NO_X$ emissions. Some early results on the modelling of open furnace of MILD combustion were discussed at the end of this paper.

## COMBUSTION REGIME

MILD combustion is greatly different from normal combustion mainly because of the low oxygen concentration and mixture temperature higher than the fuel autoignition point (Li et al., 2011b). Figure 1 indicates that the MILD combustion range for oxygen dilution is about 3-13% and the reactant temperature is above the auto ignition temperature.

The recirculation of hot flue gas to preheat the reactants and simultaneously diluted the oxygen was a key concept of MILD combustion (Tsuji et al., 2003). The maximum temperature increase due to the combustion is lower than the mixture self-ignition temperature (Cavaliere and de Joannon, 2004). Recent applications of MILD combustion have been into research and development of gas turbines (Duwig et al., 2008, Arghode and Gupta 2009, 2010a, 2010b, 2011a, 2011b) and gasification systems (Tang et al., 2010, 2011). This combustion mode can be very interesting in gas turbine applications due to low maximum temperatures (very close to the ones at the inlet of a gas turbine), noiseless characteristics, good flame stability and effectiveness in reducing pollution emissions. In contrast, the problems related to large scale application of MILD gas turbines are the characteristic time related to the chemical process (the ignition delay time) and the preheating of the fresh reactants (ultralean, superdiluted, highly preheated). Based on the study and compilation by Li et al. (2011b), common MILD combustion appears to be summarised as:

i. High temperature pre-heat of air and high-speed injections of air and fuel are the main requirements of achieving MILD combustion;
ii. Strong entrainments of high-temperature exhaust gases, which dilute fuel and air jets, are the key technology of maintaining MILD combustion;
iii. Important environmental conditions for the establishment of MILD combustion: local oxygen concentration is less than 5%-10% while local temperature is greater than that for fuel self-ignition in the reaction zone. These must be achieved by strong dilution of reactants with the flue gas ($N_2$ and $CO_2$-rich exhaust gas);
iv. When using the regenerator to recycle the waste heat of flue gases, the thermal efficiency of MILD combustion can increase by 30%, while reducing $NO_x$ emissions by 50% (Tsuji et al., 2003).

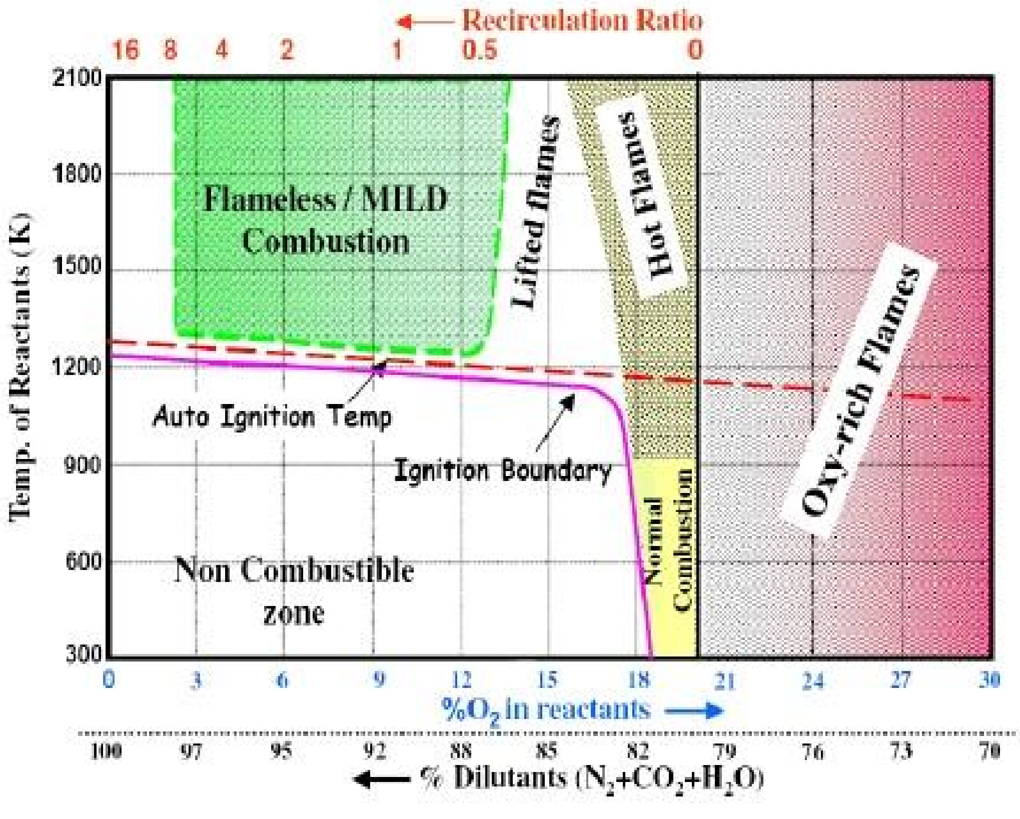
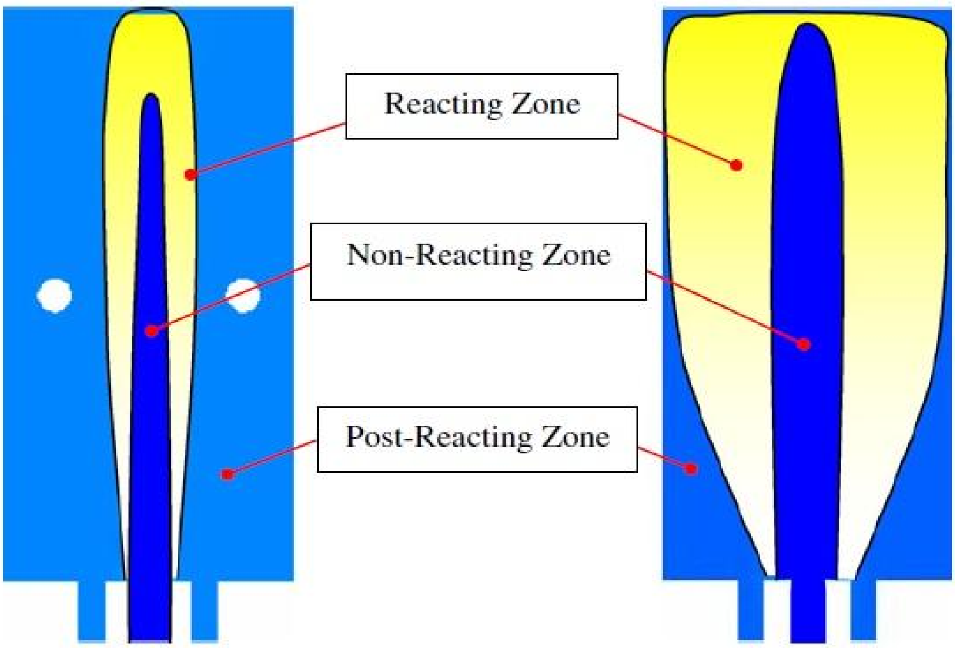



Figure 1. Schematic regime diagram for methane-air JHC flames (Rao, 2010).

The supply air needs to be heated by using a recuperator or regenerator to absorb waste heat from the flue gas. A recuperator can preheat the air to 1000K while the regenerator can heat the combustion air to about 1600K (Tsuji et al., 2003). It shows that there are four main regimes: a clean MILD combustion region, where MILD is easily sustained without any significant emissions; an unstable flame region, where low-emission MILD conditions can be achieved by suitably selecting some key operating parameters, such as the combustion air temperature; a conventional (normal) flame combustion region and a no-combustion or extinction zone. The more usual representations (Cavigiolo et al., 2003 and Wünning and Wünning, 1997) identify different regimes of stable and unstable flame combustion and a flameless oxidation region. The oxygen concentration and the temperature of the air preheated will affect the MILD flame colour as shown in figure 2. The flame became green and generally less visible when the oxygen level decreased to 2%, (Gupta et al., 1999). When MILD combustion started, the furnace was bright and transparent (Wünning and Wünning, 1997, Tsuji et al., 2003 and Cavaliere and de Joannon, 2004).

(a) 21% (b) 8% (c) 2%

Figure 2. Combustion air temperature of 1100 °C and percentage of $O_2$ concentration (Gupta et al., 1999)




(a) (b)

Figure 3. Closed furnace reacting zone for (a) conventional and (b) MILD combustion (Li and Mi, 2011)

Recently Parente et al. (2009, 2011b) studied the MILD combustion regime using a novel methodology based on Principal Component Analysis (PCA), investigates the main features for the characterisation. PCA can effectively identify low dimensional representations of the $CH_4$ / $H_2$ experimental dataset. Figure 3 illustrates the flame region for MILD and conventional combustion based on the [OH] contours. Significantly, both the reacting and non-reacting zones for the MILD case are bigger compared to the conventional case. The best combustion process is lean combustion. This is due to lean combustion use of less fuel and the impact is less cost of combustion. MILD lean combustion means that the combustion with less fuel and less oxygen level. In between the ratio of oxygen from 3 to 13%, auto ignition temperature is reducing with the increase of oxygen level.

## COMBUSTION EFFICIENCY

Combustion efficiency is the ratio of the heat received by the target material to be heated (useful output) to the supply heat provided to the combustor (in the form of fuel or electricity supply). Industrial burners need a stable and efficient flame for an economical and safe heating process. In the industrial scale, diffusion or non-premixed combustion is commonly used due to its controllability and safety (Peters, 2000 and Tsuji et al., 2003). Bluff-body burners can offer a stable burner as required. There are many different shapes and geometries such as cone, cylinder, vee gutter, disk and sphere. The geometry will affect the recirculation zone (flame bluffing zone). Furnace lean and clean operation is very critical since two thirds of the plant's energy budget is allocated for the fuel cost (Thomas, 2011). Combustion thermal efficiency in the furnace can be improved by recycling the exhaust gases (Li et al. 2011a, 2011b).

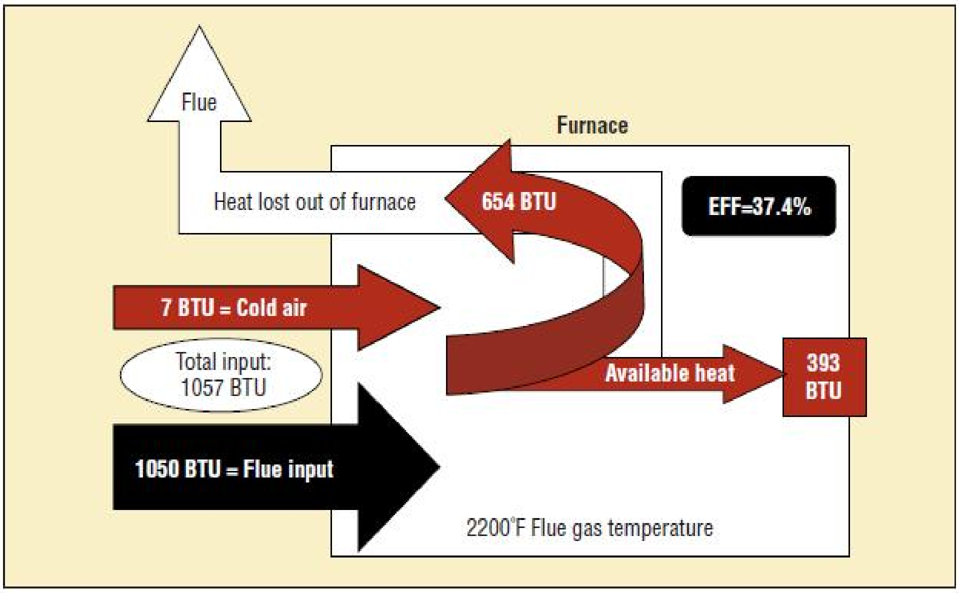



Figure 4. Efficiency of the heating system without EGR (Kraus and Barraclough, 2012).

MILD combustion has proved to produce clean and efficient combustion. Recent studies by Colorado et al. (2009) and Danon et al., (2010) on low calorific value fuels used in MILD combustion show that low $NO_x$ emissions were achieved. The fundamental parameters of MILD combustion are the average combustion chamber temperature ($T_c$), dilution ratio ($K_V$), and jet velocity (Derudi et al., 2007a). $K_V$ is a key parameter for the MILD combustion operating conditions. Several other researchers (Wünning and Wünning, 1997, Katsuki and Hasegawa, 1998, Cavigiolo et al., 2003, Dally et al., 2008 and Galletti et al., 2009) defined $K_V$ as the ratio between the recycled exhausts and the incoming air and fuel flow rates. MILD combustion has many advantages, such as producing very high thermal efficiencies and low emissions of $NO_x$. It produces a uniform temperature distribution, excellent combustion stability and has been considered as one of the new-generation, clean and efficient combustion technologies. It has great potential to be implemented in many industrial applications.

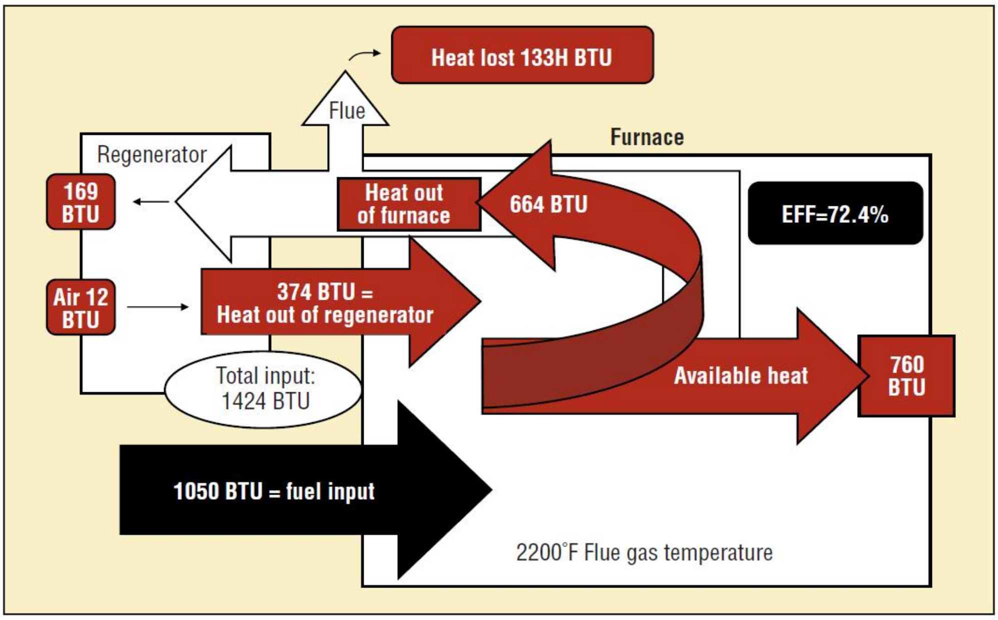



Figure 5. Efficiency of the heating system with EGR (Kraus and Barraclough, 2012).

The advantages of MILD combustion are implemented by the heating industries. Danon (2011) reported an increase in demand for expertise on the implementation of MILD combustion, especially for large-scale furnaces equipped with multiple burners. MILD combustion was achieved experimentally (Yuan and Naruse, 1999, Ertesvag and Magnussen, 2000, Weber et al., 2000, Özdemir and Peters, 2001, Hasegawa et al., 2002, Cabra et al., 2003, 2005, Rafidi and Blasiak, 2006, Sabia et al., 2007, Derudi et al., 2007a, 2007b, 2007c, Mörtberg et al., 2007, Kumar et al., 2007, Dally et al., 2008, Li and Mi, 2010, Mi et al., 2010, Zhenjun et al., 2010, Li et al., 2010a, 2010b, Oldenhof et al., 2010, 2011, Derudi and Rota, 2011 and Kraus and Barraclough, 2012) and numerically (Ertesvag and Magnussen, 2000, Coelho and Peters, 2001, Park et al., 2003, Cabra et al., 2003, 2005, Kim et al., 2005, Awosope et al., 2006, Kumar et al., 2007, Galletti et al., 2009, De et al., 2010, Frassoldati et al., 2010, Oldenhof et al., 2010, Zhenjun et al., 2010, Szegö, 2010, Parente et al, 2011a, 2011b and Kraus and Barraclough, 2012) in premixed, partially-premixed and non-premixed combustion modes. For the furnace combustion, simultaneous increase in radiant heat transfer and reduced $NO_x$ emissions are possible with careful control of the fuel and air mixing (Mulliger and Jenkin, 2008). Nakamura et al. (1993) and Webber (2001) experimentally studied several pilot-scale furnaces equipped with heat exchangers. They demonstrated that the port angles and locations will affect the heat transfer behaviour. The comparison of combustion with and without EGR can be seen in Figure 4 and 5. The furnace in Figure 4 is running without regenerator (EGR) and 654 BTU of heat lost through flue gas. The difference for Figure 5 is the furnace running with the regenerator (EGR) and from 654 BTU of heat in the flue gas; only 133 BTU is lost through flue gas to the atmosphere. Some 521 BTU of the heat is returned back to the system via the regenerator. The efficiency is 37.4% for the system without EGR and 72.4% for the system with EGR.

## MILD RECENT TREND

The concept of MILD combustion has been extensively studied experimentally and numerically. However the challenge still remains to accurately model the MILD combustion regime due to the homogeneous mixing field effect by turbulence mixing and slower chemical reaction rates. MILD combustion is characterised by a strong relation between turbulence and chemistry, occurred at similar timescales (Plessing et al., 1998 and Galletti et al., 2007). The turbulence chemistry interactions should be treated with finite rate approaches. The non-premixed mode occurred when the fuel and preheated air are injected to the enclosure furnace through different ports and mixing and combustion proceed inside the chamber. Nathan et al. (1992) and Parham et al. (2000) reported that by controlling the mixing through their precessing gas jet, a simultaneous reduction in $NO_x$ emissions by 30–50% and an increase in heat transfer by 2–10% were achieved. Szegö et al. (2008) used a furnace with 20kW supplied by the fuel and 3.3kW from the pre-heated air. This closed furnace used parallel air and fuel jets with one central air nozzle, four fuel jets and four exhausts. All the nozzles and exhausts were at the bottom of the furnace. This MILD combustion setup has produced data on various experiments including fuel tests, flame tests, $NO_x$ tests, and heat exchanger tests (Maruta et al., 2000, Flamme, 2004, Park et al. (2004), Christo and Dally, 2004, 2005, Medwell et al., 2007, 2008, Mörtberg et al., 2006, Stankovic, 2006, Lou et al., 2007, Dally et al., 2002, 2004, 2008, 2010, Colorado et al., 2009, Mi et al., 2009, de Joannon et al. 2009, 2010, Li et al., 2011b, Oryani et al., 2011).

MILD combustion technology is still not fully commercialized and well adopted in furnace industry, thus it is very important to conduct substantial fundamental and applied research (Cavaliere et al., 2008, Li et al., 2011b, Parente et al., 2011a, 2011b and Danon, 2011). The fuel-air mixing in MILD combustion has become one of the interests of studies (Tsuji et al., 2003). Precise prediction of turbulent mixing is important in modelling turbulent combustion because it has a large effect on the flow field and turbulence–chemistry interaction (Shabanian et al., 2011). Galletti et al. (2007) claimed that the reactants' jet velocity and their angles are the main parameters affecting the quality of the air-fuel mixture. The characteristic of MILD combustion is strong coupling between turbulence and chemistry (Parente et al., 2008), occurring at similar timescales (Plessing et al., 1998 and Galletti et al., 2007) thus the turbulence-chemistry interactions should be treated with finite-rate approaches. The level of homogeneity of the mixing field (de Joannon et al., 2010) and slower reaction rates make the accurate modeling of this combustion regime challenging (Aminian et al., 2011), especially for the heat release rate and $NO_x$ and soot formation, thus a fundamental study on the mixing quality is required. To achieve MILD combustion, the air supply has to be preheated (Wünning and Wünning, 1997). Many researchers claim that regenerative heating or preheating is an important element in MILD combustion applications, which may add some complexity when retrofitting systems. However, a recent study by Li et al. (2011a, 2011b) showed that preheating is not required in the case of a closed furnace. The use of an open furnace operating in MILD combustion mode was investigated. Generally, the setup for open furnace is simpler and cheaper than closed furnace because the latter needs a thick and solid wall. However, open furnaces have additional complexity because of their requirement for preheating of the reactants. Oldenhof et al. (2011) claimed that studying flameless combustion in an open and unconfined setup might give valuable insights. The combination of open furnace and preheating as well as the effect of air-fuel mixing (Oldenhof et al., 2011) need to be fully addressed. It is believed that there is no reported data about MILD combustion in open furnace applications.

Biogas is an attractive alternative to replace the dependency on fossil fuels. Recently Colorado et al. (2009) studied MILD combustion using biogas (methane diluted with inert gases) and reported that $NO_x$ and soot emissions were reduced but CO emission was increased. This was possibly due to the high fuel dilution and low coflow oxygen level. $NO_x$ emission could be reduced effectively by means of low-oxygen concentration combustion (Suzukawa et al., 1997, Gupta, 2000 and Fuse et al., 2002). $NO_x$ strongly depends on the mixing processes between fuel and air. The recirculation flue gases are entrained with combustion air and fuel before combustion occurs to depress higher peak temperature. As a result, thermal $NO_x$ is suppressed. There are parameters to be measured to achieve the desired MILD combustion which are dilution ratio ($K_v$) and temperature inside the combustion chamber. The minimum dilution ratio to achieve MILD combustion is 2.5 (Wünning and Wünning, 1997). The MILD combustion key control strategies are the heating requirement by the furnace. Based on the heating requirement, the dilution ratio and fresh air supply was controlled by. EGR, fresh air and fuel supply are controlled based on the dilution ratio required. Fuel consumption is the key to measure the efficiency of the system. Thermocouples are used to measure the heat produced by the flame.

## EXHAUST GAS RECIRCULATION

Thermal efficiency of furnace and other heating equipment, such as kilns, ovens and heaters are very critical issue. Large amount of the heat is wasted in the form of flue gases and small amount of wall loss, opening loss, store heat and cooling water loss. Exhaust gas recirculation (EGR) is one of the methods to recover these losses. EGR behaves differently to heat regenerators. EGR works by recirculating a portion of the exhaust gas back to the combustion chamber. The main purpose of EGR is that the oxygen in the combustion chamber will be diluted by the hot flue gas and the mixture heated directly. The volume of hot flue gas to be injected back into the system depends on the level of oxygen dilution needed. EGR with MILD combustion was used by Wünning and Wünning (1997), Katsuki and Hasegawa (1998) and Cavaliere and de Joannon, (2004) as a solution to avoid $NO_x$ and soot formation. Wünning and Wünning (1997) calculated the dilution ratio $K_V$ with EGR as:

$$K_V = \frac{M_E}{(M_F + M_A)} = \frac{(M_T - M_F - M_A)}{(M_F + M_A)} \quad (1)$$

The total mass flow rate ($M_T$) is calculated by adding up the EGR mass flow rate ($M_E$), fuel mass flow rate ($M_F$) and fresh air mass flow rate ($M_A$). The dilution ratio ($K_v$) and temperature inside the combustion chamber are to be measured when combustion achieve steady state. The minimum dilution ratio is 2.5 (Wünning and Wünning, 1997). The control strategy is the heating required by the furnace which will determine the required dilution ratio. The damper blade will act as a control valve at the furnace stack. The damper blade will use to control the outflow from the furnace and the percentage of the opening size will determine the percentage of the exhaust gas recirculation (EGR). The EGR and the fresh air mixing will determine the dilution ratio of the system. The total flue gas out of the system must be equal to the quantity of the fresh air and fuel supply. The research on utilising EGR to reduce the emission and increase the efficiency of the combustion extensively progress. EGR was reported giving effect on the reduction of the emission for the internal combustion engine (Abdullah et al., 2009, Mamat et al., 2009 and Yasin et al., 2011).

## BIOGAS: LOW CALORIFIC VALUE GAS

Considering biogas with the standard methane content of 50%, the heating value is 21 MJ/Nm³, the density is 1.22 kg/Nm³ and the mass is similar to air at 1.29 kg/Nm³ (Al-Seadi et al., 2008). The use of gas is predicted to continue to replace coal for electricity generation as it is a cleaner fuel producing lower greenhouse gases. Coal usage is predicted to increase by 50%, whereas gas is expected to increase by 88% (Scragg, 2009). Biogas can be produced from the biodegradation of organic materials of biological origin (biomass) in anoxic environments, such as swamps, wetlands, sediments, and in the rumen of ruminant animals. Methane production in engineered anaerobic digestion (AD) systems has been employed for more than a century to treat municipal sludge generated by municipal wastewater treatment plants (WWTPs), beside renewable resources and reduce greenhouse gas emissions, biogas also benefit to the farmers. It will reduce biomass waste and digestate is an excellent fertiliser since its rich of nitrogen, phosphorus and potassium. Besides many advantages of biofuel and biogas, currently there are some debates on the sustainability of biofuel resources (RACQ, 2008) including the risk of food supply and shortage of biomass due to floods and other circumstances.

Methane is the main component of natural gas and biogas and is the most abundant organic compound on earth. Natural gas is a promising alternative fuel to meet strict combustion emission regulations in many countries. The combustion run on natural gas can operate at lean burn and stoichiometric conditions with different combustion and emission characteristics. Table 1 shows the differences in natural gas composition between some countries compiled by Hairuddin et al. (2010). Natural gas, methane or hydrogen is commonly used for industrial burners. Hydrogen is the most clean and very low emission in combustion. Hydrogen's low density giving a challenging medium for the storage (requires very high pressures tank). By adding hydrogen to the fuel blend, the influence of molecular diffusion will increase with increasing hydrogen (Mardani et al. 2010b). Recently Mardani et al. (2010a, 2010b) and Wang et al. (2011) investigated the effects of hydrogen addition and found that MILD combustion occurred more easily. Yu et al. (2010) found that pure hydrogen could not reduce thermal $NO_x$ emission in the flameless combustion regime. Hydrogen properties show a lot of advantages over fossil fuels. Hydrogen is produced mainly from fossil fuel resources and only 4% generated by electrolysis (Stoots, 2011). In the future, when fossil fuel depleted, the raw material will be changed to water and biomass (Hollinger and Bose, 2008). The purpose of the fuselage (enclosure) is to capture the flue gas to use as EGR. This configuration is not fully enclosed due to there being an opening at the top of the furnace. Therefore this setup is considered an open furnace.

Table 1. The difference in natural gas composition between some countries (Jonathan 2006, Kong & Reitz 2002, Olsson et al. 2002, Papagiannakis and Hountalas 2004).

| **Components** | **Volume (%)** | | | |
|---|---|---|---|---|
| | **Australia** | **Greece** | **Sweden** | **USA** |
| Methane ($CH_4$) | 90.0 | 98.0 | 87.58 | 91.1 |
| Ethane ($C_2H_6$) | 4.0 | 0.6 | 6.54 | 4.7 |
| Propane ($C_3H_8$) | 1.7 | 0.2 | 3.12 | 1.7 |
| Butane ($C_4H_{10}$) | 0.4 | 0.2 | 1.04 | 1.4 |
| Pentane ($C_5H_{12}$) | 0.11 | 0.1 | 0.17 | - |
| Hexane ($C_6H_{14}$) | 0.08 | - | 0.02 | - |
| Heptane ($C_7H_{16}$) | 0.01 | - | - | - |
| Carbon Dioxide ($CO_2$) | 2.7 | 0.1 | 0.31 | 0.5 |
| Nitrogen ($N_2$) | 1.0 | 0.8 | 1.22 | 0.6 |

## CFD MODELLING

The application of computer simulation techniques to improve combustion process has been rapidly expanding over the last decade. These techniques offer reliable predictions on the effect of various parameters on combustion performance. Moreover, the computational simulation frequently presents information on physical quantities that are quite difficult to measure. CFD is the tool to model the fluid flow problems numerically and reduce the excessive cost of experimental work. Galletti et al. (2007) reported that beside the experimental characterization of MILD combustion burners, the industry also shows the interest on CFD modeling. CFD may help in optimizing burners' performances such as injection nozzles and flue gas recirculation.

CFD alone is not fundamentally strong without validation of their result with the experimental work. MILD combustion in setups on many different scales has been extensively simulated using CFD software over the last decades (Danon, 2011). The configuration of reactants and exhaust ports was optimized using a CFD modeling study (Szegö, 2003). Mollica et al. (2009) using CFD to study the effect of preheating, further dilution provided by inner recirculation and of radiation model for a hydrogen-air MILD burner. Oryani et al, (2011) numerically analyse and comparing the flue gas recirculation (FGR) and fuel induced recirculation (FIR) conditions in the case of $N_2$, $CO_2$ and $H_2O$ dilution and found that with small amounts of dilution, FIR is more effective in NOx reduction. The established turbulent model in fluent was utilised. The continuous fluid flow and chemical reactions are simulated in a discretization mode. A mesh or numerical grid of the physical geometry for burner head and boundary wall are generated. The fluid flow and heat transfer transport equations, which are conservation of mass, momentum, heat and species, are solved. Recently Szegö et al (2011) using CFD to model MILD combustion in furnace and found that there is a strong coupling between the furnace aerodynamics and the reaction zone. CFD modelling is useful to pre-determine the control parameters. Sensitivity to turbulence model (e.g. standard $k$-$\varepsilon$ model (Launder and Sharma, 1974)) normally was investigated. The control parameters for the modelling works are temperature, velocity and the angle of the supply air; temperature, velocity and the angle of the fuel; percentage of EGR; location of the EGR input to supply air; burner head design and fuel properties.

Turbulent flow occurs at high Reynolds numbers and very complex process and even more complex when involve with combustion reaction or other chemical reaction. Tennekes and Lumley (1972) characterised the nature of the turbulence as irregularity, large Reynolds numbers, diffusivity, three-dimensional vorticity fluctuations and continuum phenomenon. In the combustion process, particle interactions are very important in the fuel and air mixing process: usage of mixing models is required to close the molecular diffusion term in the probability density function (PDF) transport (Pope, 1985):

$$\frac{\partial \rho P}{\partial t} + \frac{\partial \rho u_i P}{\partial x_i} + \frac{\partial \rho S_k P}{\partial \psi_k} = -\frac{\partial}{\partial x_i}\left[\rho \langle u_i^{"} | \psi \rangle P\right] + \frac{\partial}{\partial \psi_k}\left[\frac{1}{\rho}\langle \frac{\partial J_{i,k}}{\partial x_i} | \psi \rangle P\right] \tag{2}$$

Particle mixing is becoming more important to study for the mixing process. Recently Wandel (2011) has proposed a new turbulent mixing model which randomizes the interaction of the particles in a local manner. The proposed model was called SPDL or Stochastic Particle Diffusion Length (Wandel, 2011) model, which is based upon the practical localness of the random inter-particle distance (Noor et al, 2011). The configuration of reactants and exhaust ports was optimized using a CFD modelling study (Szegö et al., 2003, Khoshhal et al., 2011, Noor et al, 2012a, 2012b). Mollica et al. (2009) used CFD to study the hydrogen-air MILD burner. They reported about the effect of preheating, further dilution provided by inner recirculation and radiation model. Numerical method was utilised on the flue gas recirculation (FGR) and fuel induced recirculation (FIR) analysis (Oryani et al., 2011). In the small amounts of $N_2$, $CO_2$ and $H_2O$ dilution, FIR is more effective in $NO_x$ reduction. Recently Szegö et al. (2011) used CFD to model MILD combustion in furnace and found that there is a strong coupling between the furnace aerodynamics and the reaction zone.

## OPEN FURNACE

MILD Combustion in closed furnace was established for many years; however, many fundamentals still need further study and resolution. Open furnace combustion for MILD is still a new approach. Open furnace combustion needs the enclosed chamber to collect the flue gas and use it as EGR. The oxygen in the fresh air supply needs to be diluted and EGR must be used for this purpose. The concept of open furnace is due to the opening at the top of the furnace and the flue gas that is not used for EGR was released from this top opening. Figure 6 shows the open furnace (Noor et al, 2012a, 2012b) used to numerically study the MILD combustion. The opening on the top of the furnace chamber can be controlled and adjusted in order to control the amount of EGR and dilution ratio. The dilution ratio was controlled by the opening of the damper. The damper at the furnace stack was used to control the outflow from the furnace and the percentage of the opening size was determined by the percentage of the exhaust gas recirculate (EGR). The main purpose of EGR is to dilute fresh air with exhaust gas; and therefore will reduce the peak combustion temperature and pressure which will consequently reduce the amount of $NO_x$ (Santoh et al., 1997, Abd-All et al., 2001, Agarwal et al., 2006, Hountalas et al., 2008). The EGR and the fresh air mixing will determine the dilution ratio of the system.

The total flue gas emitted from the system must be equal to the quantity of fresh air supply. In order to capture the combustion image and the flame propagation, high speed camera was utilised in the early state of the combustion and establishment phase. When the flame reaches a steady state and invisible to the naked eye, the high speed camera will capture the flame luminescence (Oldenhof, et al., 2010, 2011). This process is important for the MILD combustion non premixed lifted flame. In normal jet flames, the lift-off height is the axial height of the sharp flame interface. To determine lift-off height, a certain threshold level for an averaged quantity is defined. Example using the quantities like temperature (Kumar et al., 2007), OH concentration (Cabra et al., 2003 and Ertesvag and Magnussen, 2000) or luminescence (Cabra et al., 2005) was proposed.

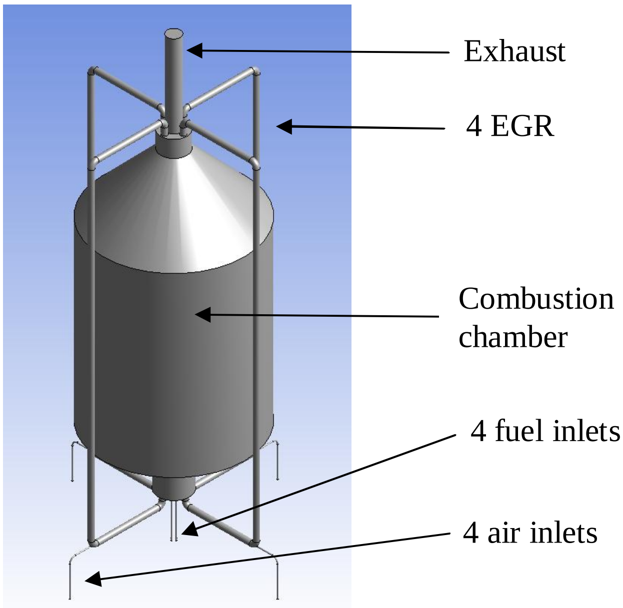



Figure 6. Open furnace with 4 EGR and top chamber opening.

Open furnace through the combination of the study parameters: preheating the reactants using EGR to dilute the oxygen in air supply, high reactant jet velocity, hydrogen additive to the biogas to reduce the mixture self ignition temperature and turbulent mixing of the reactant, optimisation of MILD combustion in an open furnace can be achieved. CFD was utilised to simulate the combustion with low calorific value gas call biogas. In this simulation, 50% of methane was mixed with 20% of hydrogen and 30% of carbon dioxide to form the low calorific value gas. The result for the combustion temperature and combustion radiation zone is shown in figure 7 and 8. The result from the simulation shows that MILD combustion can be achieved using an open furnace combustion with the enclosed chamber to capture and utilised flue gas as EGR.

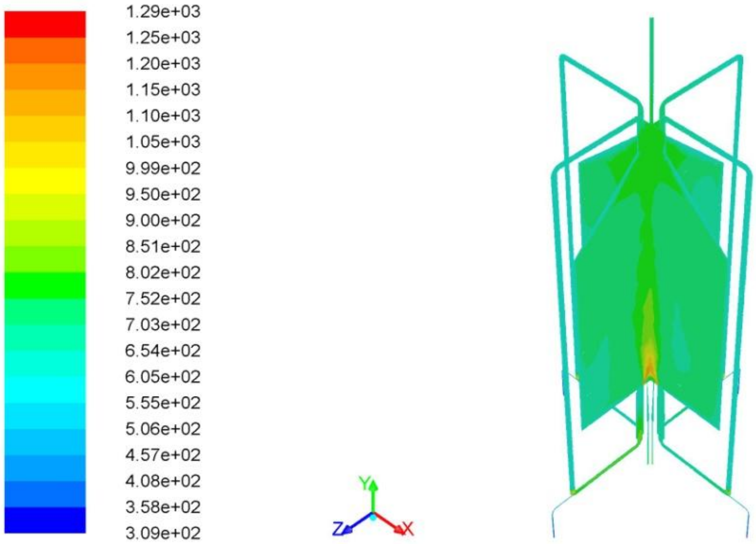



Figure 7. Combustion temperatures for low calorific value gas.

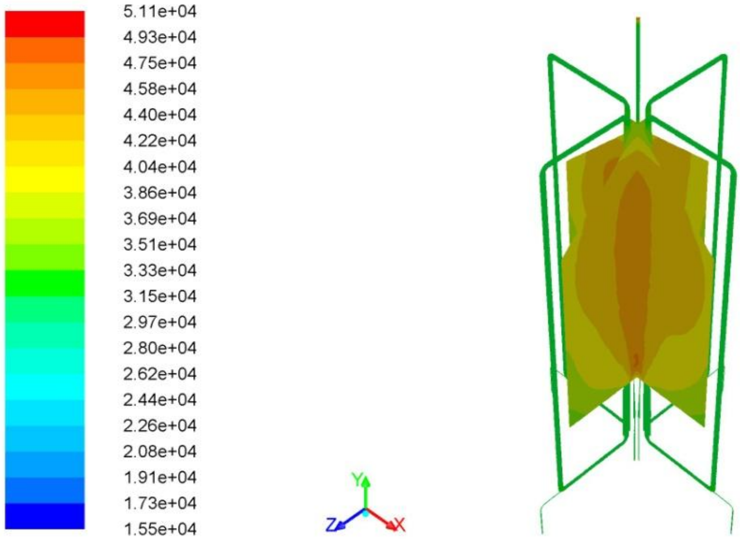



Figure 8. Combustion radiation zone.

## CONCLUSION

The review of MILD combustion toward open furnace was discussed. MILD or flameless combustion produces higher efficiency with lower emissions. The MILD combustion provides many benefits to the furnace and burners in heating industries. Despite the benefits, the fundamental of the combustion is not properly well established and needs further research especially on the control parameters, combustion behaviour, combustion characteristics, exhaust gas recirculation and dilution required. Heating industries are still in early stages to adopt MILD or flameless technology to their burners. Most of the burners are still using conventional combustion technology since it is fundamentally stable, strong knowhow and relatively high experience. In January 2012 issue of Industrial Heating journal, Kraus and Barraclough discussed about the utilisation of thermal regeneration for the industrial furnace is a must in order to increase the thermal efficiency of the burners. Biogas is one of the best alternatives for the fuel depletion issue. Fuel from bio resources is very environmental friendly since the cycle of $CO_2$ is properly closed. Hence the biogas with MILD combustion is the one of the best combustion for future energy and heating industries. CFD are good tools to simulate and predict the parameter before the experimental work take place. Simulations were the best option to reduce the experimental cost. Recent trend shows that MILD can be achieved by closed furnace. The dilution and preheating process happened internally in the closed combustion chamber. This will make the constructions of the combustion chamber simpler without external EGR needed but still closed furnace need thick wall. At this stage, there are no results of experimental or numerical records for open furnace MILD combustion. In this study, the open furnace with EGR to dilute and pre-heat the oxidant was numerically studied. MILD combustion was achieved for open MILD combustion. This result needs to be validated by an experimental technique.

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**Nomenclature**

| | |
|---|---|
| CCS | Carbon capture and storage |
| CFD | Computational fluid dynamics |
| CMC | Conditional moment closure |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| FGR | Flue gas recirculation |
| GHG | Greenhouse-gas |
| HC | Hydrocarbon |
| HiTAC | High temperature air combustion |
| HTOC | High temperature combustion |
| JHC | Jet in hot coflow |
| LCV | Low calorific value |
| MILD | Moderate or intense low $O_2$ dilution |
| $NO_x$ | Nitrogen Oxides |
| OH | Hydroxyl |
| PDF | Probability density function |
| $SO_x$ | Sulphur Oxides |
| SPDL | Stochastic particle diffusion length |
| UHC | Unburned hydrocarbons |

**Symbols**

| | |
|---|---|
| $B$ | Diffusion coefficient |
| $K_T$ | Total number of particles |
| $\bar{W}$ | Mean molecular weight of mixture |
| $W_I$ | Molecular weight of species I |
| $\dot{q}$ | Heat release rate |
| $N$ | Total number of species |
| $P$ | Favre joint PDF of composition |
| $P_b$ | Position of particle |
| $R$ | Gas constant |
| $R_d$ | Internal dilution ratio |
| $T$ | Temperature |
| $T_c$ | Chamber temperature |
| $V$ | Volume |
| $K_v$ | Dilution ratio |
| $Y$ | Mass fraction |
| $Z$ | Mixture fraction |
| $d$ | Constant |
| $k$ | Turbulence kinetic energy |
| $m_{in}$ | Mass flow rate |
| $t$ | Time |
| $u$ | Velocity |
| $v$ | Specific volume |
| $w$ | Importance weight |

**Greek Symbols**

| | |
|---|---|
| $u_i$ | Favre mean fluid velocity vector |
| $\delta t$ | Time interval |
| $S_k$ | Reaction rate for species k |
| $\varepsilon$ | Dissipation rate |
| $\psi_k$ | Composition space vector for specie k |
| $u_i''$ | Fluid velocity fluctuation vector |
| $J_{i,k}$ | Molecular diffusion flux vector |
| $\nu$ | Kinematic viscosity |
| $\xi$ | Reference variable |
| $\rho$ | Density or mean fluid density |
| $\emptyset$ | Composition of particle |
| $\dot{\omega}$ | Chemical reaction rate |
| $\beta$ | Index of composition variable |
| $\alpha$ | Model parameter |