MILD COMBUSTION: THE FUTURE FOR LEAN AND CLEAN COMBUSTION

Talal Yusaf[1,2], M.M.Noor[2,3]and Andrew P.Wandel[3]

[1]National Centre for Engineering in Agriculture, USQ, Australia
[2]Faculty of Mechanical Engineering, Universiti Malaysia Pahang (UMP), Malaysia
[3]Computational Engineering and Science Research Centre, Department of Mechanical and Mechatronic Engineering, University of Southern Queensland (USQ), Australia
Email: talal.yusaf@usq.edu.au, muhamad@ump.edu.my, Phone: +607-46311783

ABSTRACT

Energy security is becoming an important and intergovernmental issue due to the depletion of fossil fuel. This paper discusses the energy needs and the new combustion technology that will aid in achieving lean and clean combustion.In 2001, British Petroleum estimated the total natural gas reserves to be 187.5 trillion cubic meters, which can supply up to $7x10^{15}$ MJ of energy. The total petroleum reserves can supply up to 1,383 billion barrels which amounts to $8.4x10^{15}$ MJ of energy. Due to the increasing population and economic development, these fuel reserves will not last long. Energy efficiency and greenhouse gas emissions are two important and critical issues. The new combustion technology, moderate and intense low oxygen dilution (MILD) combustionprovides a feasible solution. MILD, also known as flameless oxidation (FLOX) and high temperature air combustion (HiTAC) was discovered by Wünning in 1989. The thermal efficiency of combustion can be increasedby about 30% and NO_x emission reduced by 50%. MILD also can be achieved using different types of fuel such as gas fuel, liquid fuel and industrial waste fuel (saw dust).MILD combustion will be an important futurecombustion technology due to it producing higher efficiency and very low emissions.

Keywords: energy security; MILD combustion; biogas; world energy policy

INTRODUCTION

The demand for energy is dramatically increasing due to the world's population growth and substantial global economic development.Theworld energy demand is highly dependent on the combustion of fossil fuel: projected to fulfill about 80% of the energy requirements (IEA, 2009 and Maczulak, 2010). With the current consumption rate, the fossil fuel will have been depleted by 2042 (Shafie and Topal, 2009). Environmental issues and concerns are also motivating factors for innovation in combustion technology employed in transportation and stationary power-generation applications. Among the fossil fuels, natural gas combustion is the most attractive as it produces less harm to the environment because it releases less carbon dioxide, nitrogen oxide, sulphur dioxide, particulate and mercury per unit energy compared to oil and coal (US EIA, 1999).Some of the major challenges are to provide efficient energy and limit greenhouse-gas (GHG) emissions. In US energy generation, combustion of fossil fuel is projected to fulfil about 64% of this energy needs (Figure 1). The more efficient use of fuel with low GHG emissions as well as carbon capture and storage (CCS) might be effective ways to gradually reduce the overall GHG emissions (IEA, 2006 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.

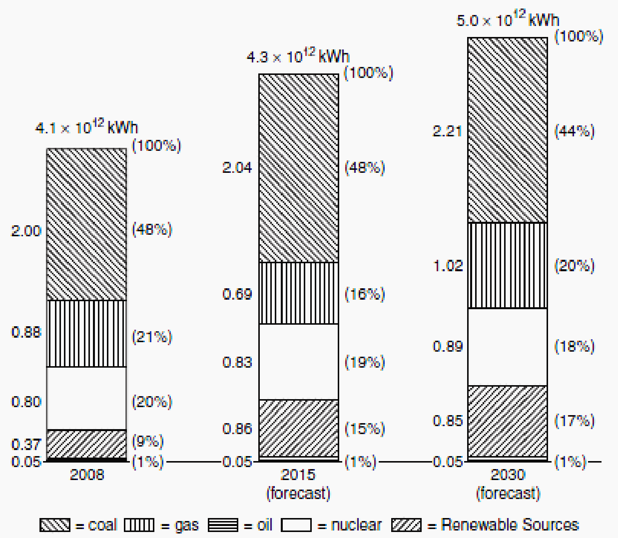
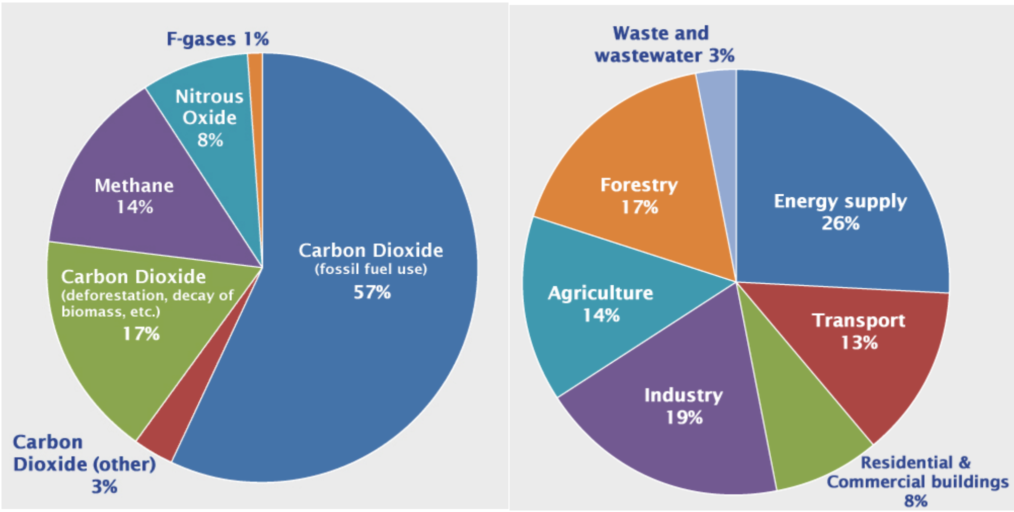


Figure 1. US electrical energy generation (US EIA, 2010).

Table 1 compares the pollutants from natural gas, oil and coal. The use of natural gas will reduce the impact of fossil fuel combustion on climate change. In order to further reduce NO_x and other harmful pollutants, lean mixtures will reduce the combustion temperature and decrease the formation of NO_x. Pollutant emissions are reduced because flame temperatures are typically low, reducing thermal NO_x formation.Beside fuel NO_x and prompt NO_x,thermal NO_x is the key NOx formation that will increase rapidly after the combustion temperature reaches 1573 K (EPA, 1999) and 1810 K (AET, 2012). Figure 2 illustrates the GHG emissions by type of gas and source. Figure 2(a) clearly indicates that carbon dioxide from fossil fuel combustion accounts for 57%, the majority of the GHG emissions. Figure 2(b) shows that 26% of GHG emissions originated from energy production.

Table 1. Pollutants from fossil fuel (US EIA, 1999).

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



(a) (b)

Figure 2. Global greenhouse gas emissions a) by type of gases, b) by type of sources (IPCC, 2007).

Figure 3 plots the formation of NO_x. In order to achieve low NO_x emissions, the flame temperature of the combustion must be below 1425°C (1698 K). Above that temperature, the NO_x formation will be very high.

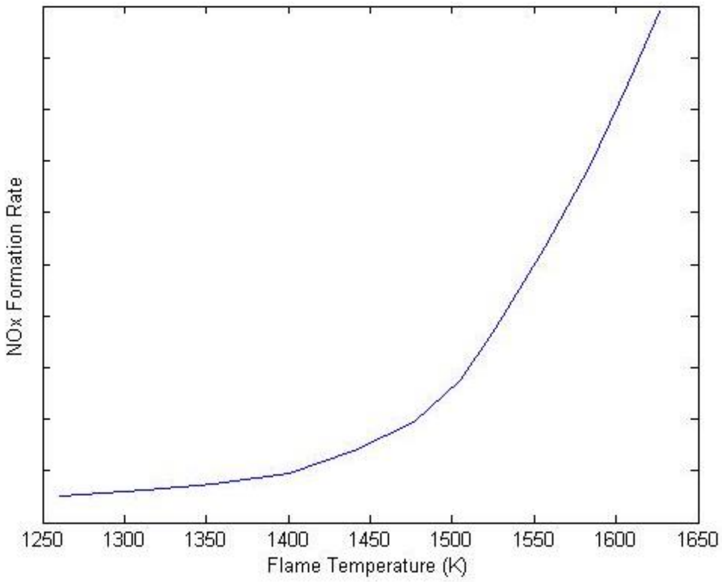


Figure 3. The rate of NO_x formation forflame temperature (AET, 2012).

One of the techniques for improving thermal efficiency and reducing NO_x is moderate and intense low oxygen dilution (MILD) combustion (Dally et al., 2002, 2004 andCavaliere et al., 2004, 2008). This technique isalso known as flameless oxidation (FLOX) by Wünning (1991, 1996, 1997), high-temperature air combustion (HiTAC) by Katsuki and Hasegawa (1998), Tsuji et al. (2003) and colourless distributed combustion (CDC) by Arghode and Gupta (2010, 2011). The main characteristic of MILD combustion is an elevated temperature of reactants and low temperature increase in the combustion process. To increase the reactant temperature, the exhaust gas recirculation concept and input air preheat was normally implemented. The hot exhaust gases will be utilised to heat up the temperature and dilute the oxygen in the injected fresh air.

This paper willdiscuss the future of MILD combustion and its ability toprovide lean and clean combustion.The continualsignificant demand for cheap and clean energy coupled with the unclear fossil fuel reserves and limitations on other source of energy provides increasing pressure for the combustion community to improve the overall combustion efficiency with minimum pollution emission.

LEAN COMBUSTION AND CLEAN COMBUSTION

Lean combustion is defined as achieving the combustion stability process with a minimum amount of fuel. Whereas clean combustion is to achieve the lean combustion process with zero or minimum unwanted pollutants. Lean combustion is applicable and used in all combustion equipment at both laboratory and industrial scale including internal combustion engines, burners, gas turbines, furnaces, boilers and kiln. This is to take advantage of the combustion processes that operates with minimum or lean conditions with very low pollutant emissions and very high efficiency.

In the hazard of combustion study, like explosive, hazard and flammability limit, lean combustion are very important for the setting of any fuel's limit of inflammability.Davy (1816) studied lean combustion to prevent explosions of methane gas in coal mines. Davy reported that the limits of inflammability were between 6.2 and 6.7%, which is same as an equivalence ratio range for methane between 0.68 and 0.74. The challenging behaviours of lean flames include sensitivity to fuel composition and relatively weak reaction fronts in highly dynamic fluid flows (Rankin, 2008). Lately beside the combustion process, fuel studies also get attention for lean and clean research. A Maryland-based independent power provider (IPP) combustion company has developed an innovative patented technology for Lean, Premixed, Prevaporised (LPP) combustion of fuels, hence, these fuels burn cleanly in gas-fired power turbines and other combustion devices (IFP, 2010). Biofuel is also part of the fuel study for better performance with lower exhaust emission (Ghobadian et al., 2009; Yusaf et al., 2011; Najafi et al., 2011; Noor et al., 2012a).

MILD COMBUSTION REGIME

MILD combustion is a revolutionary mode of burning that dramatically improves the efficiency of a furnace while substantially reducing the pollutants that are produced (Tsuji et al., 2003; Choi and Katsuki, 2001; Dally et al., 2004; Medwell et al., 2007; Noor et al., 2012c; Abtahizadeh et al., 2012). While most research has focussed on "closed furnaces", which have a simpler configuration at a substantially increased cost of construction, USQ is developing an "open furnace" system, which is similar to many furnaces currently in use (Noor et al., 2012c). Retrofitting an open furnace system to operate under MILD conditions is relatively straightforward: it merely requires the addition of recirculation pipes (Exhaust Gas Recirculation, EGR) (Noor et al., 2012c) making this an appealing option.

The low oxygen concentration and mixture temperature higher than the fuel auto ignition are two important points for MILD combustion. The combustion regime (figure4) indicates that oxygen content in reaction is about 3-13% and after 13%, the region becomes lifted flame, hot flame and above 21% it is normal conventional oxygen rich combustion. The original figure from Rao (2010), updated by Chen et al. (2012), shows that Medwell from Adelaide University was able to achieve MILD combustion in the area of 700 to 900 K and oxygen dilution below 9% (Figure 4).

The oxygen dilution plays the most important rolein achieving MILD combustion as shown in a step by step illustration of oxygen dilution in Figure 5. Recent applications of MILD combustion have been in research and development of gas turbines (Duwig et al., 2008; Arghode and Gupta, 2010, 2011) 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.

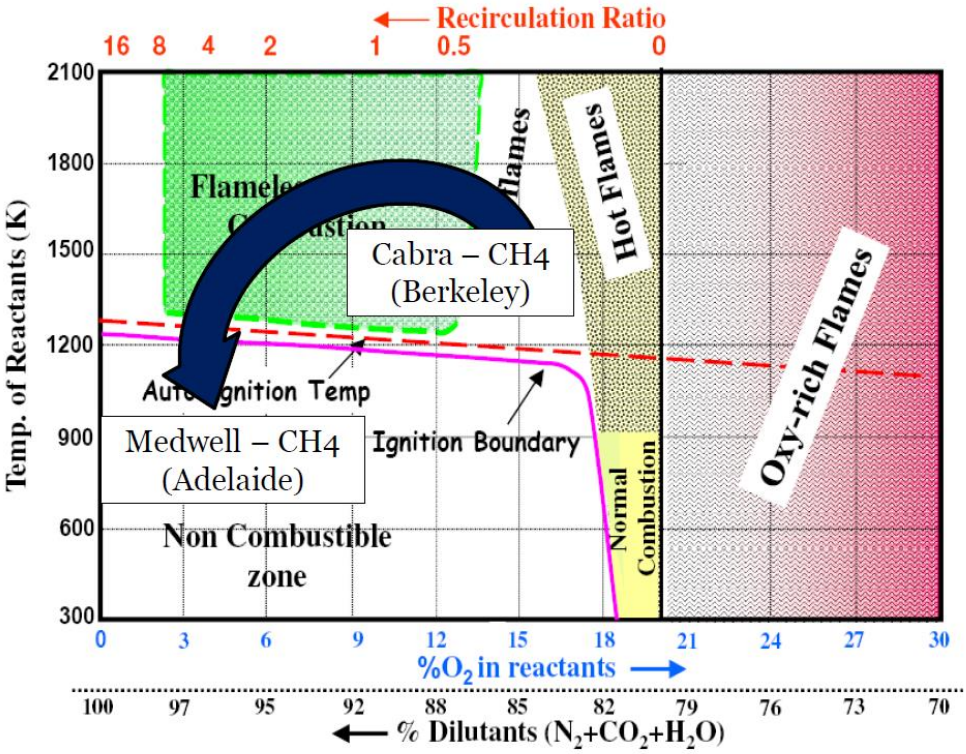


Figure 4. Schematic regime diagram for methane-air JHC flames (Rao, 2010 and Chen at al., 2012).

MILD combustion characteristics based on the study and compilation by Li et al. (2011), can be summarised as high temperature pre-heat of air and high-speed injections of air and fuel are the main requirements of achieving MILD combustion; strong entrainments of high-temperature exhaust gases, which dilute fuel and air jets, are the key technology for maintaining MILD combustion; 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 through strong dilution of reactants with the flue gas (N_2 and CO_2-rich exhaust gas) and when using the EGR or regenerator to recycle the heat fromexhaust gases, the thermal efficiency of MILD combustion can be increased by 30%, while reducing NO_x emissions by 50% (Tsuji et al., 2003).

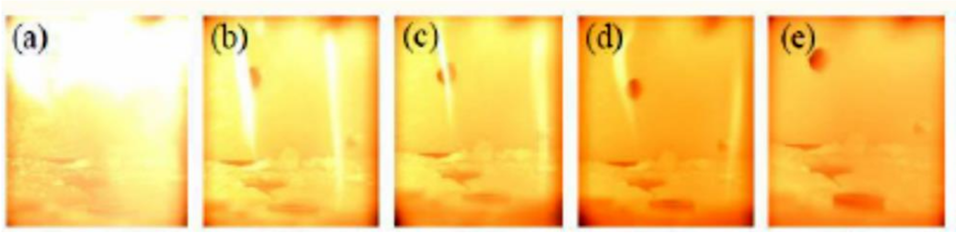


Figure 5. Step by step of MILD combustion a) combustion started, b) to d) progressively more dilute oxygen e) fully MILD combustion (Dally et al., 2012)

BIOGAS AND ENERGY BALANCE

Biogas is a clean and renewable energy whichisalow heating value gas,also known as low calorific value (LCV) gas. Biogas consists of a mixture of 55 to 65% of methane, 35 to 45% of carbon dioxide and 1-3% of hydrogen sulphide, nitrogen, hydrogen, oxygen and ammonia (Balat and Balat, 2009). Biogases are commonly produced from waste treatment, mainly agricultural waste (manure), industrial organic waste streams and sewage sludge (Hartmann and Ahring, 2005). Figure 6 shows the CO_2 cycle for biogas. Carbon dioxide produced from combustion will be used back by the crops and some of these crops are fed to animals. These crops and animal manure will be used to produce biogas. Table 2 shows the typical combustion properties of biogas. The average biogas ignition point is 700^{o}C but this depends on the percentage of methane. The higher the methane the lower will be the ignition temperature.

Table 2. Combustion properties of biogas (Balat and Balat, 2009).

Ignition temperature	700^{o}C
Density (dry basis)	1.2 kg/m^3
Ignition concentration gas content	6 -12%
Heat value	5.0 - 7.5 kWh/m^3

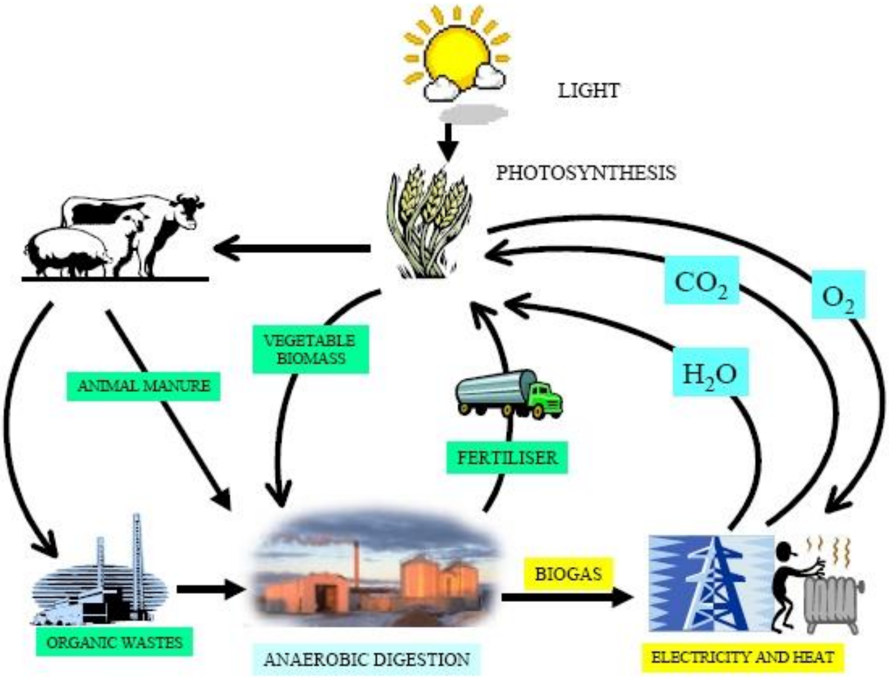


Figure 6. Carbon dioxide closed cycle for biogas (The Sietch, 2013).

Table 3 show a comparison of energy balance for natural gas with 97% methane. The summary was made for the furnace whichoperates in the flameless mode and conventional mode with natural gas. The supply of thermal energy was constant at about 21 kW for both conditions.

Table 3. Natural gas energy balance (Colorado et. al, 2010).

Combustion mode	Flameless mode	Conventional mode
Energy input (includingfuel + combustionair + cooling air) (kW)	21.31	21.02
Energy losses through the wall (kW)	3.07	3.20
Energy removed by thecooling tubes (kW)	14.99	8.71
Energy output throughthe chimney (kW)	1.39	8.25
Energy of the combustionproducts after theregenerative system (kW)	1.36	0
Efficiency (%)	70.0	41.4

The efficiency for the combustion with conventional mode is only 41.4% whereas for MILD mode it is 70%. The comparison for the efficiency of flameless mode and conventional mode for natural gas is 28.6%.

EXHAUST GAS RECIRCULATION

In conventional combustion, about 62% of the energy input to the combustion process will be lost through exhaust gas(figure 7).Part of these heat losses can be recovered by the concept of Exhaust Gas Recirculation (EGR).EGR works by recirculating a portion of the flue gas back to the combustion chamber through EGR pipe. Weinberg (1996) demonstrates this in his famous Swiss-roll burner by transferring the heat from burned products to the unburned fresh mixture.

The comparison of combustion with and without EGR can be seen in Figure 7 and 8. The furnace in Figure 7 is running without a regenerator (EGR) and 654 BTU of heat is lost through flue gas. The difference for Figure 8 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 of the 521 BTU of 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 and the system with EGR is 35% higher.

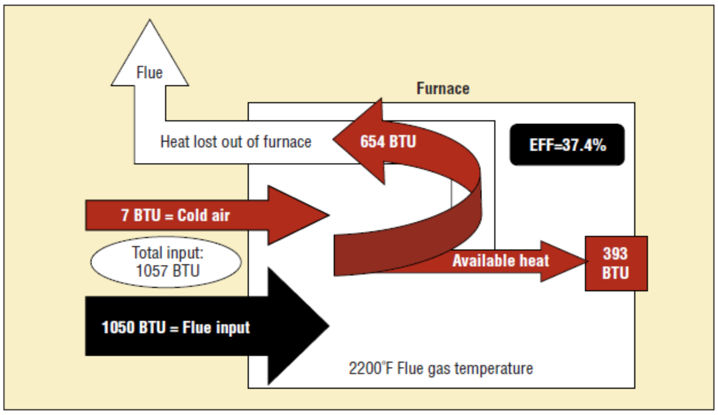


Figure 7. Efficiency of the heating system without EGR (Kraus and Barraclough, 2012).

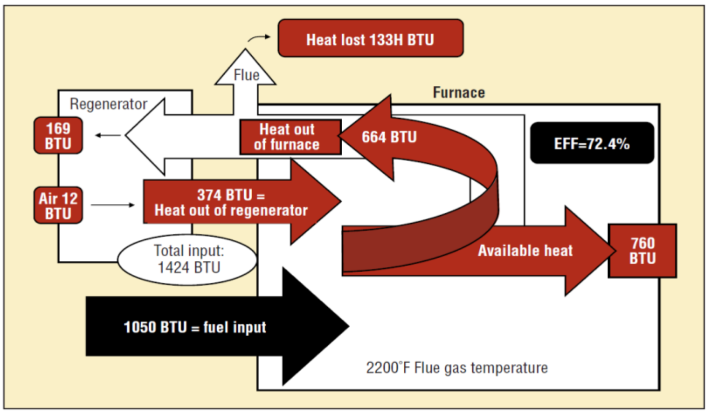


Figure 8. Efficiency of the heating system with EGR (Kraus and Barraclough, 2012).

EGR will increase the intake air temperatureand dilute the oxygen level in the combustion chamber. The recirculation volume flow into the combustion chamber depends on the level of air pre-heating and oxygen dilution needed. EGR will reduce NO_x emissions of the oxygenated fuels by more than 55% since it reduces both the pressure (Raj and Sendilvelan, 2010) and the maximum combustion temperature.

Figures 9 and 10 show the industrial furnace with the heat exchanger system and internal gas recirculation to utilize the flue gas.

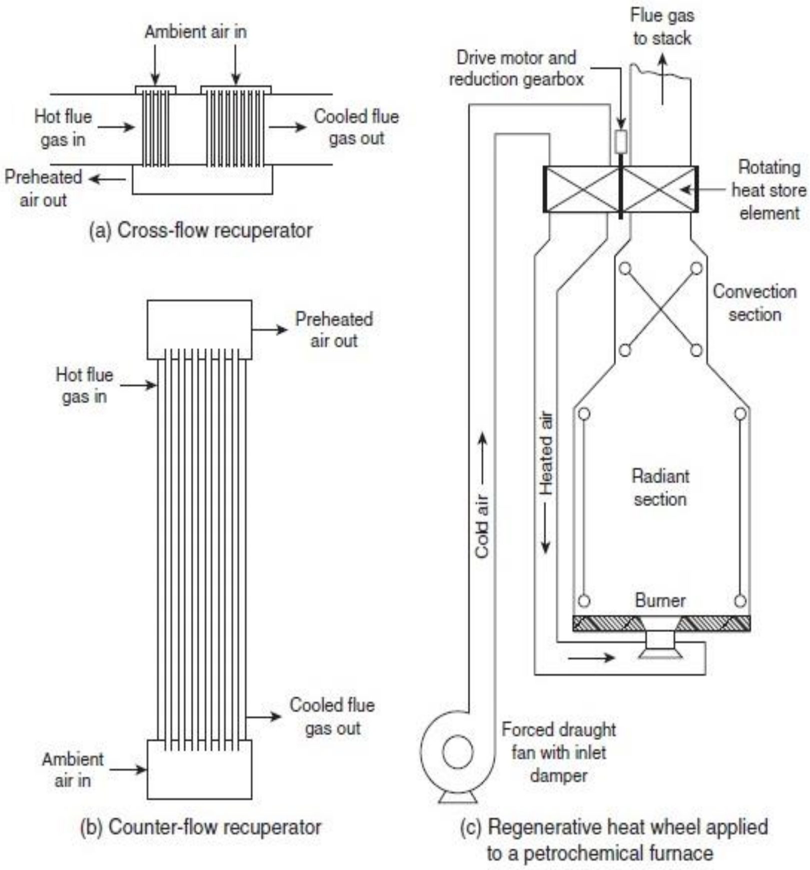


Figure 9. Industrial furnaces with heat exchanger system (Mulliger and Jenkin, 2008).

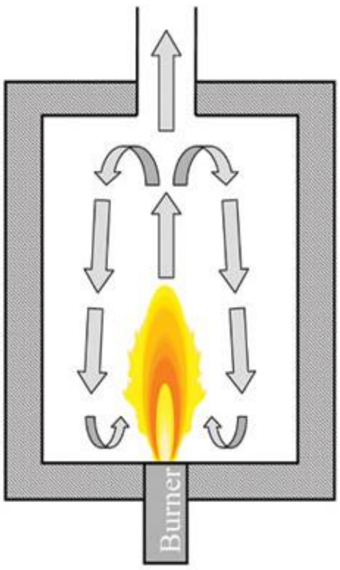
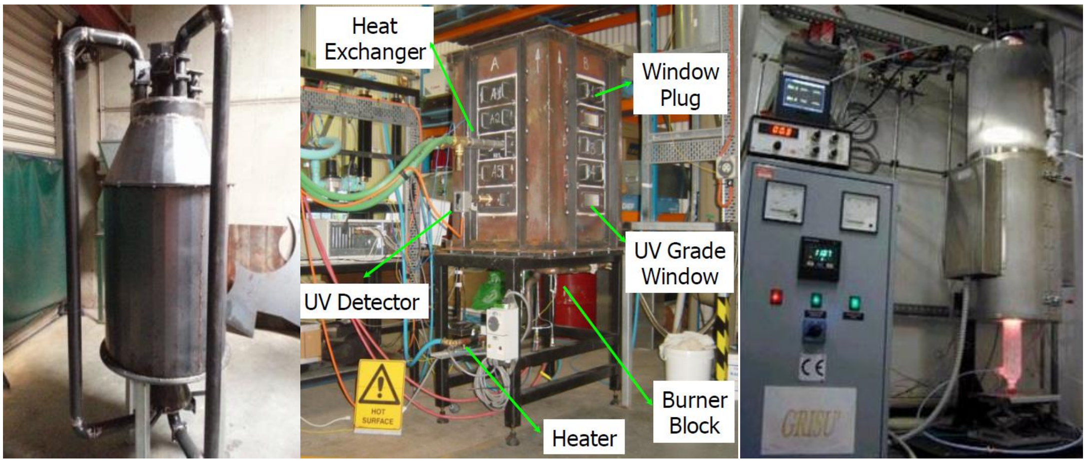


Figure10. Industrial furnaces with internal EGR system (Metal Finishing, 2013).

MILD COMBUSTION FURNACE

MILD combustion technology is new to the furnace industry and it is not fully commercialized and well adopted in furnace industry.In the Jan 2012 edition of Industrial heating magazine, it is written that new configurations (utilisation of EGR) may make it harder to say no to thermal regeneration (Kraus and Barraclough, 2012). To further improve the combustion process, it is very important to conduct substantial fundamental and applied research (Cavaliere et al., 2008, Yusaf et al., 2010, Li et al., 2011, Parente et al., 2011,Danon, 2011, Rahman et al., 2011,Kamil et al., 2011, 2012,Noor et al., 2012a; Hamada et al., 2013).To achieve MILD combustion, the fuel and oxidant mixing is very important. The mixing process is coupled between turbulence and chemistry (Parente et al., 2008) occurring at similar timescales (Plessing et al., 1998; Galletti et al., 2007), thus, the turbulence-chemistry interactions should be treated with finite-rate approaches. The level of homogeneity of the mixing field (Joannon et al., 2010) and slower reaction rates make the accurate modelling of this combustion regime challenging (Aminian et al., 2011). This is especially the case for the heat release rate, NO_x and soot formation, thus, a fundamental study on the mixing quality is required.

The furnaces for MILD combustion are greatly invested at a laboratory scale and at industrial scale;gradual adaptations are taking place for this new technology. Worldwide there are many research labs and universities are conducting further research, an example of this is shown below in Figure 11. Figure 11(a) is MILD combustion in an open furnace at University of Southern Queensland (USQ), Australia (Noor et al. 2012c). This is the first to be declared as a MILD combustion open furnace since the opening at the top allows substantial exhaust gas to flow out. Figure 11(b) is the closed furnace of MILD combustion at University of Adelaide, Australia. The furnace is also successful in using saw dust as a fuel as an alternative to normal gaseous fuels (Dally et al. 2010). Figure 11(c) is the MILD setup at Politecnico di Milano, Italy (Derudi and Rota, 2011). This MILD burner is using a double nozzle for jet fuel.



a) b) c)

Figure 11.MILD combustion furnace, a)University of Southern Queensland, Australia (Noor et al., 2012a), b) University of Adelaide, Australia (Szego et al., 2008; Dally et al., 2010, 2012), c) Politecnico di Milano, Italy (Derudi and Rota, 2011)

The results for the Computational Fluid Dynamics (CFD) on open furnace are as Figure 12. The temperature distribution in the combustion chamber is homogeneous.

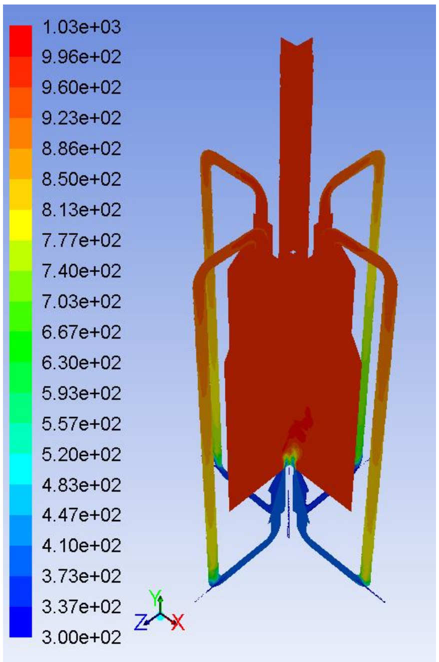


Figure 12. MILD combustion achieved (Noor et al., 2012a).

For theUSQ combustion group, the experimental setup is not only for MILD combustion but can be used for a wide range of combustion and ignition studies in the future: testing the characteristics of alternative fuels under combustion, including natural gas, biogas and coal seam gas. Biogas and LCV fuels are difficult to burn in a conventional combustor, but are readily burned in MILD mode (Colorado et al., 2010, Dally et al., 2010), so the potential exists to lead the world in both open furnace MILD systems and the usage of alternative fuels (Noor et al., 2012a, 2012b, 2012c). This also has great potential for consulting work with local industries to improve their green characteristics, and therefore, could lead to substantial future research and development opportunities.

CONCLUSION

Lean and clean combustion is a must in today's energyproduction in order to cater the critical energy supply. The other critical issue is the demand for agreener world leads to the reduction of greenhouse gases and more environmental friendly energy production. MILD combustion technology and its characteristicsare very impressive and ithas the potential to be the real future of combustion for lean and clean energy. MILD combustion produced a 30 to 35% improvement in thermal efficiency through the re-use of heat from exhaust gas. At the same time, MILD combustion also reduced the NO_x emissions by 50%. USQ combustion group is the first to research the MILD combustion in an open furnace.

Biogas is one of the most suitable alternative energy sources since it is renewable and producesa combustion product, which is carbon dioxide, that is recyclable. Carbon dioxide will be used back as the source of biogas energy.MILD combustion techniquescoupledwith the use of biogas as a fuel proves to be the perfect match for the future of lean and clean combustion technology.

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