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MILD Combustion: The Future for Lean and Clean Combustion Technology

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Abstract – *The future of today's society is greatly depending on the energy development. Due to the depletion of fossil fuel and the gradual development of energy generation from renewable sources, energy security becomes an important intergovernmental issue. 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 7x1015 MJ of energy. The total petroleum reserves can supply up to 1,383 billion barrels which amounts to 8.4x1015 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) combustion provides 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 increased by about 30% and NOx 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 future combustion technology due to it producing higher efficiency and very low emissions.*

***Keywords**: energy security, MILD combustion, biogas, world energy policy*

I. Introduction

The current society will continue to greatly depend on energy and its development. The demand for energy is dramatically increasing due to the world's population growth and substantial global economic development. The world energy demand is highly dependent on the combustion of fossil fuel: projected to fulfill about 80% of the energy requirements [1-2]. With the current consumption rate, the fossil fuel will have been depleted by 2042 [3].

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 [4]. Some of the major challenges are to provide efficient energy and limit greenhouse-gas (GHG) emissions [5-6]. In US energy generation, combustion of fossil fuel is projected to fulfil about 64% of this energy needs (Fig. 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 emission [7-8]. IEA/OECD [9] and Jonathan [10] 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.

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.

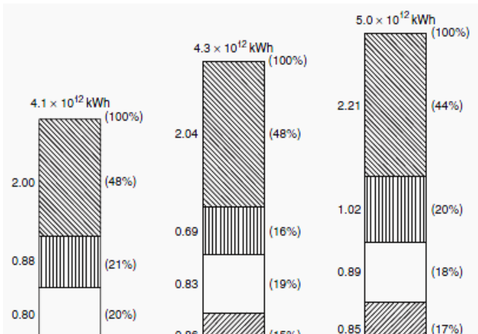

Fig. 1. US electrical energy generation [11].

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 [12] and 1810 K [13]. Fig. 2 illustrates the GHG emissions by type of gas and source. Fig. 2(a) clearly indicates that carbon dioxide from fossil fuel combustion accounts for

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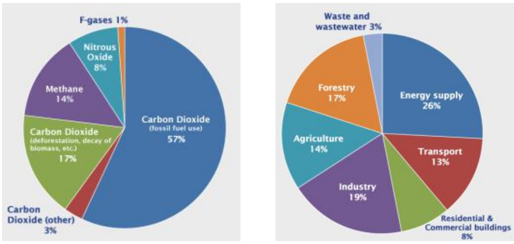
57%, the majority of the GHG emissions. Fig. 2(b) shows that 26% of GHG emissions originated from energy production.

Fig. 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.



(a) (b)

Fig. 2. Global greenhouse gas emissions a) by type of gases, b) by type of sources [14].

Table 1. Pollutants from fossil fuel [4].

Pollutant	Gas	Oil	Coal
	(kg of pollutant per 109 kJ of energy input)		
Carbon dioxide	273,780	383,760	486,720
Carbon monoxide	94	77	487
Nitrogen oxide	215	1,048	1,069
Sulphur dioxide	2.34	2,625	6,063
Particulate	16.4	197	6,420
Mercury	0.00	0.016	0.037

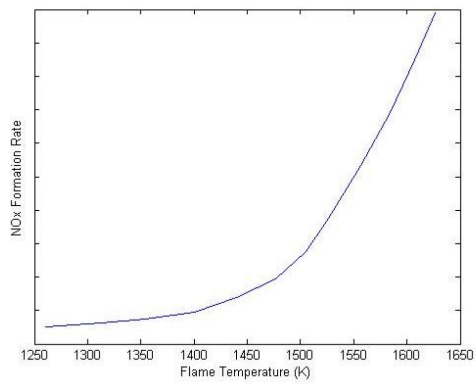


Fig. 3. The rate of NO_x formation for flame temperature [13]

One of the techniques for improving thermal efficiency and reducing NO_x is moderate and intense low oxygen dilution (MILD) combustion [15-18]. This technique is also known as flameless oxidation (FLOX) [19-21] high-temperature air combustion (HiTAC) [22-23] and colourless distributed combustion (CDC) [24-25]. 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 will discuss the future of MILD combustion and its ability to provide lean and clean combustion. The continual significant 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.

II. 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 [26] studied lean combustion to prevent explosions of methane gas in coal mines. Davy [26] 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 [27]. Lately beside the combustion process, fuel studies also get attention for lean and clean research. A Maryland-based independent power provider (IPP) 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 [28]. Biofuel is also part of the fuel study for better performance with lower exhaust emission [29-32].

III. 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 [16,23,33-36]. 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 [32,37]. 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) [38] 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 (Fig. 4) 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 Fig. from Rao [39], updated by Chen et al. [40], shows that Medwell [34] from Adelaide University was able to achieve MILD combustion in the area of 700 to 900 K and oxygen dilution below 9% (Fig. 4).

The oxygen dilution plays the most important role in achieving MILD combustion as shown in a step by step illustration of oxygen dilution in Fig. 5. Recent applications of MILD combustion have been in research and development of gas turbines [24-25,41] and gasification systems [42-43]. 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.

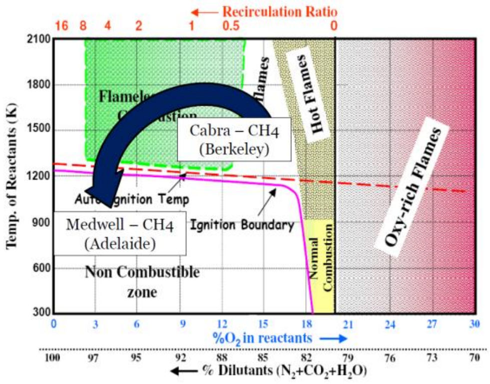


Fig. 4. Schematic regime diagram for methane-air JHC flames [39-40].

MILD combustion characteristics based on the study and compilation by Li et al. [44], 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 from exhaust gases, the thermal efficiency of MILD combustion can be increased by 30%, while reducing NO_x emissions by 50% [22].

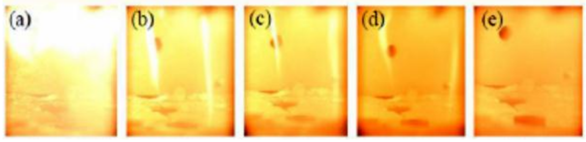


Fig. 5. Step by step of MILD combustion a) combustion started, b) to d) progressively more dilute oxygen e) fully MILD combustion [45].

IV. BIOGAS AND ENERGY BALANCE

Biogas is a clean and renewable energy which is a low 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 [46]. Biogases are commonly produced from waste treatment, mainly agricultural waste (manure), industrial organic waste streams and sewage sludge [47]. Fig. 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°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 [46].

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

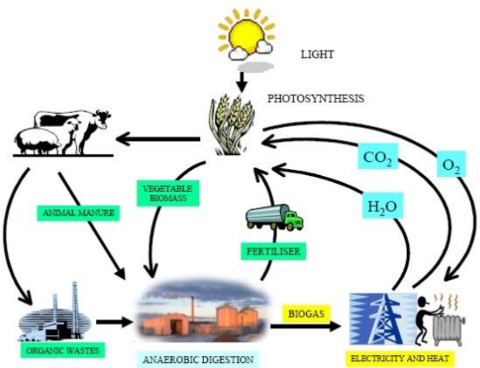


Fig. 6. Carbon dioxide closed cycle for biogas [48].

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

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%.

Table 3. Natural gas energy balance [49].

Combustion mode	Flameless mode	Conventional mode
Energy input (including fuel + combustion air + cooling air) (kW)	21.31	21.02
Energy losses through the wall (kW)	3.07	3.20
Energy removed by the cooling tubes (kW)	14.99	8.71
Energy output through the chimney (kW)	1.39	8.25
Energy of the combustion products after the regenerative system (kW)	1.36	0
Efficiency (%)	70.0	41.4

V. EXHAUST GAS RECIRCULATION

Using conventional combustion the heat loss is very high. As presented in Figure 7, during the combustion process, about 62% of the energy input will be lost through exhaust gas. 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 [50] demonstrates this in his famous Swiss-roll burner by transferring the heat from burned products to the unburned fresh mixture.

The comparison between combustion with and combustion without EGR are presented in Figures 7 and 8. Kraus and Barraclough [51] reported that the burner can gain high energy saving by applying preheat using exhaust gas. The furnace in Fig. 7 is running without a regenerator (EGR) and 654 BTU of heat is lost through flue gas. The difference for Fig. 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.

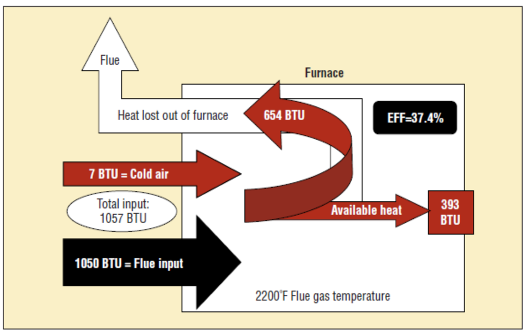


Fig. 7. Efficiency of the heating system without EGR [51].

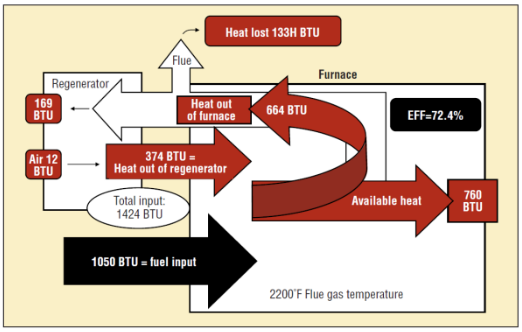


Fig. 8. Efficiency of the heating system with EGR [51].

EGR will increase the intake air temperature and 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 [52] and the maximum combustion temperature. Figs 9 and 10 show the industrial furnace with the heat exchanger system and internal gas recirculation to utilize the flue gas.

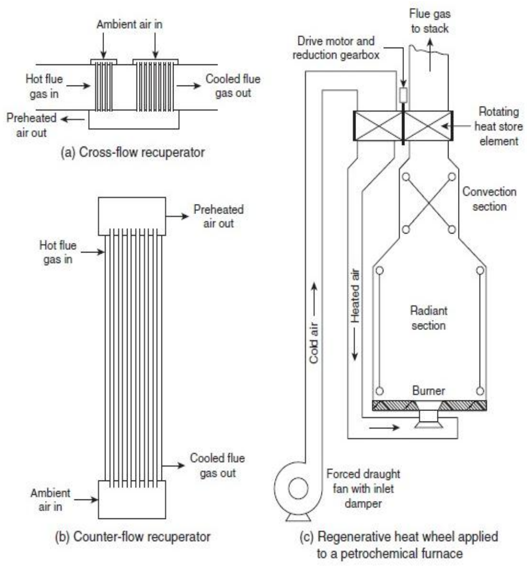


Fig. 9. Industrial furnaces with heat exchanger system [53].

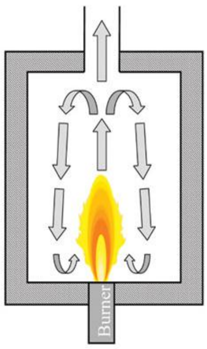
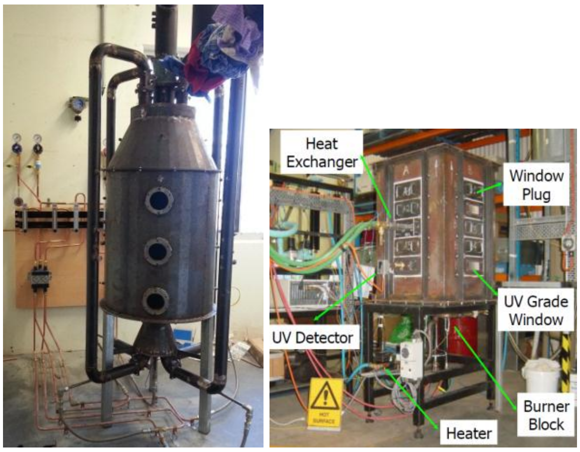


Fig. 10. Industrial closed furnaces with internal EGR system [54].

VI. 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 [51]. To further improve the combustion process, it is very important to conduct substantial fundamental and applied research [18,31,44, 55-61]. To achieve MILD combustion, the fuel and oxidant mixing is very important. The mixing process is coupled between turbulence and chemistry [62] occurring at similar timescales [63-64], thus, the turbulence-chemistry interactions should be treated with finite-rate approaches. The level of homogeneity of the mixing field [65] and slower reaction rates make the accurate modelling of this combustion regime challenging [66]. 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 Fig. 11. Fig. 11(a) is MILD combustion in an open furnace at University of Southern Queensland (USQ), Australia [31].



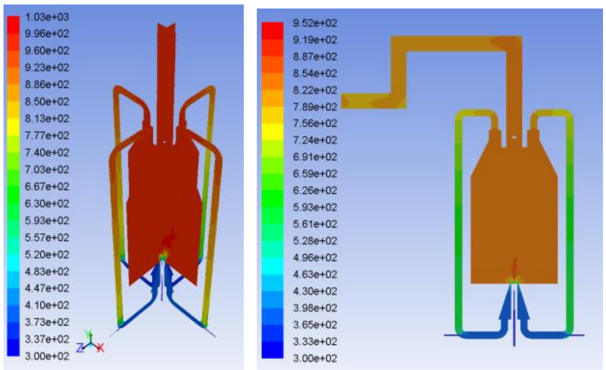
(a) (b)

(c)

Fig. 11. MILD combustion furnace, a) University of Southern Queensland, Australia [32] b) University of Adelaide, Australia [44,67,70] c) Politecnico di Milano, Italy [68].

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. Fig. 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 [67]. Fig. 11(c) is the MILD setup at Politecnico di Milano, Italy [68]. This MILD burner is using a double nozzle for jet fuel. USQ burner was designed and developed using Computational Fluid Dynamics (CFD) which was built after obtaining stable results from the CFD [69].

The results for the CFD on open furnace are as Fig. 12. The temperature distribution in the combustion chamber is homogeneous.



(a) (b)

Fig. 12.Temperature distribution for MILD combustion (a) 3D view (b) 2D view.

The design of the burner can be used for various purposes. For the USQ combustion group, the experimental setup is not only for MILD combustion but is also applicable for future studies on combustion and ignition including testing the characteristics of alternative fuels under combustion, for example 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 [4,67], so the potential exists to lead the world in both open furnace MILD systems and the usage of alternative fuels [32,38]. 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.

VII. CONCLUSION

The need for low cost energy is very important since there is an increase in demand for energy. Lean and clean combustion is a necessity in today's energy production in order to cater the critical energy. The other critical issue is the demand for a greener world leads to the reduction of greenhouse gases and more environmental friendly energy production. MILD combustion technology and its characteristics are very impressive and it has 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 produces a combustion product, which is carbon dioxide, which is recyclable. Carbon dioxide will be used back as the source of biogas energy. MILD combustion techniques coupled with the use of biogas as a fuel proves to be the perfect match for the future of lean and clean combustion technology.

Acknowledgments

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