TRENDS REGARDING THE DEVELOPMENT OF HIGH THERMIC EFFICIENCY AND LOW LEVEL OF POLLUTING EMISSIONS COMBUSTION SYSTEMS

MARIUS-ION STĂNILĂ[1*], VALENTIN NEDEFF[1]

[1] *"Vasile Alecsandri" University of Bacau, Calea Marasesti 156, Bacau, 600115, Romania*

Abstract: Flameless combustion, or moderate or intense low oxygen dilution combustion, is an advanced technology that meets all the conditions for being an important actor in the researchers' efforts to develop low level of polluting emissions and high thermic efficiency combustion systems. Because all the factors that contribute to the emerge of this kind of combustion are not completely understood, there is the suspicion that this type of combustion could be achieved only by overheating the combustion air, which generates the limitation of this technology's application area. After all the last years conducted research, it came to the conclusion that the requirements for this combustion are less severe than they were believed to be. The recent research is conducted towards the use of this type of combustion for all type of fuels, gas, liquid and solid.

Keywords: overheated air combustion, flameless oxidation, flameless combustion, oxy-fuel combustion

1. INTRODUCTION

The last century's last decades have shown a certain ebullience in finding the proper solutions in order to answer to the requirements regarding the increase of combustion processes' thermic efficiency and, in the same time, to the constraints regarding the resultant pollutant emissions. Sadly, more than often, the decrease of pollutant emissions brings on a decrease in the thermic efficiency of the combustion process. To the contrary, the increase of thermic efficiency by increasing the combustion temperature and using a stable flame, generates the increment of the NO_x emissions level.

Combustion technologies that comply with these requirements were developed, such as pure oxygen combustion (the combustion air was replaced by oxygen), in which case the NO_x emissions are at a very low level and, at the same time, have a high level of combustion thermic efficiency, with a stabile flame and a high combustion temperature. Another great advantage of this technology is the possibility to easily seize the carbon dioxide resulted from combustion. The disadvantage is that of the high price of the oxygen needed for the combustion. Another technology used in order to obtain a low level of NO_x is the „cooling" flame technology [1], which, because of the low combustion temperature, can cause combustion instability that determines an incomplete combustion and the increment of CO emissions [2]. The substantial decrease of NO_x emissions can also be achieved by using the staged combustion technology, which implies the decrease of oxygen concentration in the first combustion area, which results in the decrease of NO_x and the increase of the reduction agents for NO_x quantity [3]. The addition of air in the first and third area of the primary flux leads to the reduction of the peak temperature and also to the reduction of thermic NO_x generation. The oxygen deficiency in the primary area and the low temperatures in the secondary area contribute to the reduction of NO_x emissions. In the case of natural

* Corresponding author, email: mstanila63@gmail.com

gas combustion, by using this staged combustion technology, the NO_x emissions can be reduced with more than 60% [3]. Sadly, in this case too, we can talk about a reduction in the thermic efficiency of the combustion process caused by the decrease of the combustion intensity [2]. Fluidized bed combustion technology has the advantage of using the fuels with low thermal power, low NO_x emissions; instead it has the disadvantage of low thermic efficiency caused by the combustion's low temperature [4].

Moderate or Intense Low Oxygen Dilution – MILD combustion seems to be a credible candidate for the simultaneous achievement of the established objectives, namely high thermic efficiency and low level of emissions. The combustion occurs in a peculiar manner, when dealing with this type of combustion, without a visible flame [1, 5, 6, 7], and that is why it is also called "flameless combustion" or "flameless oxidation" (FLOX) [1]. In the professional literature, this type of combustion is also called "High Temperature Air Combustion" (HiTAC) [6, 7], that is because, in the industrial regenerative systems, the air is usually preheated at temperatures around 1,000°C. The MILD combustion system is defined by the heat and the exhaust gases recirculation.

The reinsertion of hot exhaust gases in the combustion circuit leads to the local depletion of the oxygen concentration and the increase of the reactants' temperature. All this leads to the deceleration of the combustion reactions and results in the formation of a distributed reaction area. The heat distribution in a larger volume leads to the formation of an almost homogeneous heat distribution area, resulting in the reduction of the temperature's peaks [2]. As a result, the net radiation flow can be upgraded within almost 30% [7], the pollutant emissions are much lower than in the conventional flame case, where the calorification area is limited by the flame line [2]. Because of this almost homogeneous heat distribution, the hot points are eliminated, so that the thermic NO_x generation will be inhibited. The MILD combustion type shouldn't be mistaken with other emissions control technics used in conventional systems, such as staged combustion and exhaust gas recirculation-EGR or flue gas recirculation-FGR. Although there are similarities, the MILD system operates with dilution proportions around the stability limit value for the conventional flame. That is why, for sustaining the oxidation reactions in this dilution conditions, the MILD burners usually operate on preheated air [2]. The heat exchangers are usually used for recuperating the heat from the exhaust gases before these are discharged into the atmosphere, the heat being used for preheating the combustion air. This leads not only to the heating of the gas mixture and to the combustion reactions conservation, but also upgrades the thermic efficiency. These unique properties of the MILD combustion makes this technology overcome the obstacle of the simultaneous achievement of energy saving and of low emissions [2]. This combustion technology was discovered in the early 1990s, and was successfully used in the ferrous metallurgy and metallurgical engineering industry form many countries, such as: Germany, Italy, Japan, US, Sweden and China. The industrial applications of this method have shown that MILD regenerative combustion (known as HiTAC in Japan and FLOX in Germany) can upgrade the thermic efficiency with more than 30 % (also reducing the CO_2 emissions), at the same time with the reduction of NO_x emissions with more than 70 % [7]. In addition, the MILD combustion technology has a distinctive advantage in using the low thermal power fuel. This technology, because of the high energy saving and of the low emissions, was considered to be one on the most promising combustion technologies of the 21st century by the professional international community [5, 6, 7, 8].

2. BREAF HISTORY AND THE PRESENT STATE OF THE MILD COMBUSTION TECHNOLOGY (HiTAC, FLOX)

In order to enhance the thermic efficiency of a combustion system the heat extraction of the stack gases is needed, having a lower temperature than the exhaust gases, and their reinsertion in the combustion circuit, therefore reducing the heat losses. For that, recuperators or regenerators are used. These absorb the residual heat form the stack gases and reinsert it in the combustion system thus preheating the combustion air. The recuperator is able to preheat the air up to almost 1000 K whereas the regenerator is able to preheat the same air up to almost 1300 K temperature [7]. Anyway, in the conventional systems, a growth in the preheating temperature will for sure stimulate the NO_x generation, although the combustion intensity will probably be improved [2].

The German and Japanese researchers [7] have discovered, at the beginning of the '90s, that when the air is being preheated up to approximately 1600 K by using the regenerator and then this is being injected with a speed around 90 m/s, the visible flame disappears (Figure 1). It was then believed that no reaction takes place any longer, but the same researchers have determined that the level of oxygen concentration in the stack gases was very low, as in a complete combustion situation. This shows that, even if the flame wasn't visible, the chemical reactions took place. It was very important that the NO_x emissions' level was very different from the expectances based on the former knowledge, which shown that the NO_x level increases at the same time with the preheating temperature of the air [1]. In that experiment the NO_x levels up to maximum 80 ppm or even close to zero were measured [7]. Apparently, the application of the regenerator use not only makes the flameless combustion possible, recuperating the heat from the stack evacuated air, thus satisfying the requirements for thermic efficiency, but also achieves an important emission reduction (NO_x especially), thus also meeting the requirements for polluting emissions reduction.

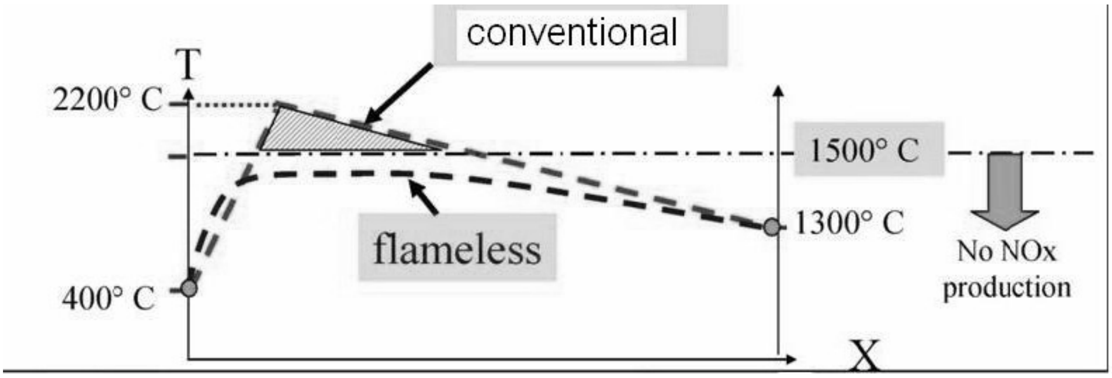

Fig. 1. Flameless combustion diagram [4].

Furthermore, it was confirmed that, in certain conditions of air preheating at high temperature and high injection speed, the combustion reaction is even, the thermic distribution is even and the heat transfer through radiation increases with almost 30% more [9], and the specific combustion noise also disappears.

The flameless combustion researchers (HiTAC, FLOX) from Germany and Japan] are the first to conduct the research and the development of this kind of combustion, being followed by those from Sweden, Italy, Holland, France, Australia, United States and China. Based on the previous researches, the consensus in the approach of this kind of combustion may be integrated as follows [2]:

1. The main requests for achieving this this type of combustion are the high preheating temperature of the air needed for the combustion and its high speed injection;
2. The technological key point for maintaining the MILD combustion is the dilution of the fuel and of the air jets having a strong high temperature exhaust gases flow;
3. The environmental conditions needed for MILD combustion are: local oxygen concentration lower than 5-10% at the same time with local temperature higher than that needed for the self-ignition in the reaction area. This is achieved by a strong dilution of the reactants by the exhausted gases (exhausted gases rich in N_2 and CO_2);
4. Using the regenerator for recirculating the heat in the exhausted gases may increase the thermic efficiency of the MILD combustion by more than 30% at the same time with the reduction of the NO_x emissions by more than 70% [7].

In order to measure the reactants dilution rate by the exhaust air, Wünning [1] has defined the internal recirculating relative rate (K_v) as being the fraction between the internal recirculating gas flow mass (M_E) and the initial fuel and air flow (M_F+M_A), namely:

$$K_v = \frac{M_E}{M_F + M_A} = \frac{M_J - \left(M_F + M_A\right)}{M_F + M_A} \qquad (1)$$

Where $M_E = M_J - (M_F + M_A)$ and M_J represents the total mass of the gas flow driven by the fuel and air jets. This indicator can quantify the effect of the gas recirculation over the flameless combustion. Figure 2 illustrates the axial evolution and the fuel-air jet dispersion, which results from the drive of the surrounding air and fuel gas and from their mixing. The reactants are being gradually diluted by the exhausted gases and being reintroduced in the system (CO_2 and H_2O) together with inert gas (N_2).

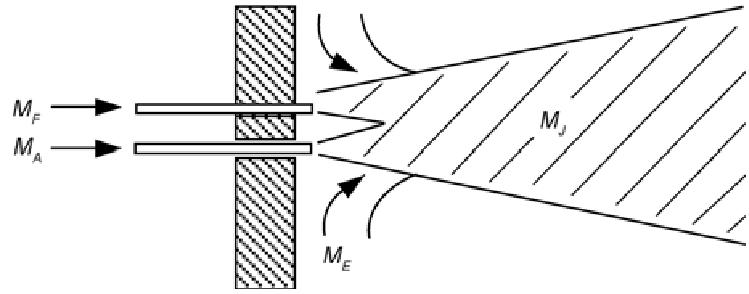

Fig. 2. Stability limits of the combustion without MILD premixing [1].

Wünning [1] has experimentally achieved a relation between K_v and the diffused combustion temperature, thus drawing a combustion stability diagram, diagram drawn for a no-premixing methane (CH_4) combustion in a particular combustion system (Figure 3). The vast majority of the former researches regarding the MILD combustion were conducted by examining the K_v influence over the combustion and its comparison, at times, with the diagram.

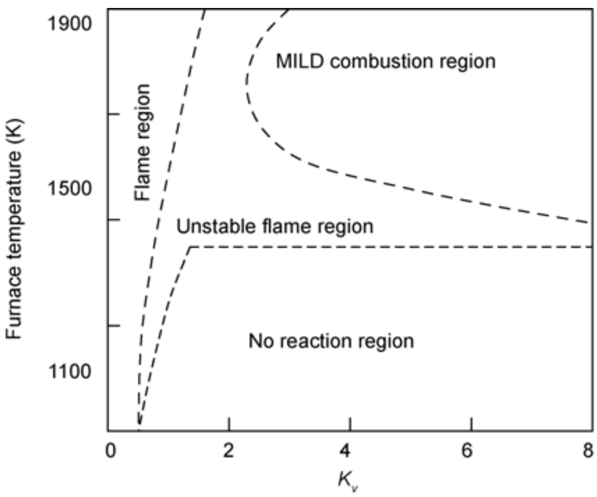

Fig. 3. The relation between K_v and the no-premixing methane (CH_4) combustion temperature [1].

The diagram illustrated in the Figure 3 shows that in the flameless combustion aria the internal recirculation rate (K_v) is higher than 2,5 whilst the exhaust gases temperature used in the dilution is higher than 1100 K. Cavigiolo et al. [10] has conducted a complete and detailed study about the K_v influence over the combustion reaction temperature and over the NO_x and CO formation in the natural gas combustion process. These researchers concluded that the specific NO_x and CO emission reduction factor is not changing at the same time with the exhaust gases temperature, the fuel type or its quality, because the flameless combustion is very stable. These researchers also discovered that because of the differences between the combustion points and the calorific powers of the different fuels, in order to achieve the flameless combustion, the critical values for K_v are different for different fuels.

The existing flameless combustion systems can be classified in two categories: regenerative and recuperative. A typical recuperative system used in the flameless combustion is the radiant tube [1], having a small internal chamber inside which a very high internal gas recirculation rate can be easily achieved [2].

The regenerative MILD combustion system (usually called HiTAC) has regenerators and reversing valves [6, 7]. These systems are largely applied in the ferrous metallurgy and in metallurgical engineering. As the Figure 4 shows, when the system is operating, inside a cycle, usually between 30 and 120 s, the regenerator absorbs the residual heat from the exhausted gases and conducts this heat over to the combustion air, then the cooled gases are released into the atmosphere. The cooled gases temperature is often lower than 450 K [2].

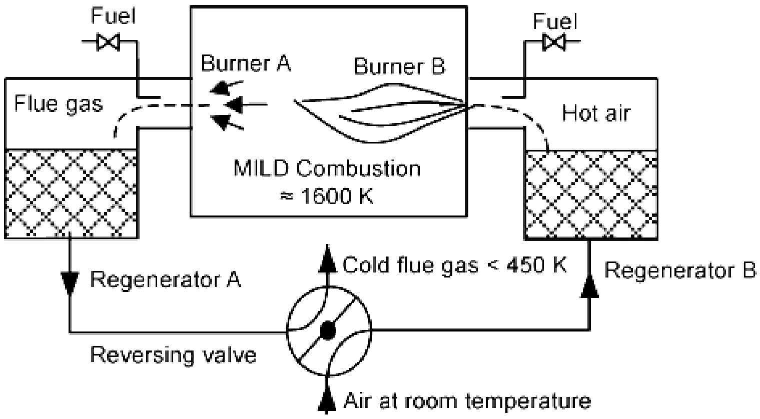

Fig. 4. MILD regenerative system [2].

As it has been shown above, this regenerative combustion system may lead to up to 30% or even more thermic efficiency improvement and may decrease up to 70 % the NO_x emissions. The misconception regarding the energy saving and the emissions reduction for the flameless combustion system must be clarified. The exhausted heat recovery may, indeed, very much improve the thermic efficiency, but this is the only reason for which the flameless combustion has such a high thermic efficiency. The conventional regenerative systems can also recover the exhausted heat, with a high thermic efficiency, but the flameless combustion system has two mechanisms that increase the thermic efficiency:

1. The flameless combustion is achieved at a much more constant temperature inside the combustion chamber, that leading to the reduction of the heat losses by combustion and thermic transfer [11];
2. Although the temperature peak for the flameless combustion is lower than the one achieved for the conventional combustion, in the flameless combustion case a higher temperature average is being achieved, thus improving the thermic transfer average, especially the thermic radiation transfer [7].

This is why the flameless combustion thermic efficiency is higher than the one from the conventional combustion, not taking into consideration the thermic efficiency reversibility or the heat transfer. Regarding the NO_x emissions reduction, the mechanism for this type of combustion (MILD, HiTAC, FLOX) is the invisible flame and the low temperature peak. It is well known the fact that the thermic NO_x is being formed at temperatures higher than 1500°C. That is why the fact that through flameless combustion (MILD, HiTAC, FLOX) the heat lost in the exhausted gases being recovered is not important, this type of combustion achieving the performance of energy saving and of reduced emissions. There are several aspects that, of course, need further research, such as combustion phase convection and radiation thermic transfer [2].

3. APPLICATIONS DEVELOPMENT FOR THE FLAMELESS COMBUSTION SYSTEM (MILD, HiTAC, FLOX)

It seems that, presently, there aren’t major constraints for advanced flameless combustion systems development to have a large application area, less limitative conditions, identical heat recovery capacities and a lower cost. One of the major constraints, eliminated for now through experimental studies and numerical simulations, is the one regarding the combustion air preheating. Without being basic, these researches are a starting point in this technology’s application in a wide range of activities. The results of these researches have been presented by authors such as: Kumar et al. [12], Krishnamurthy et al. [13], Rottier et al. [14, 15] and Lin et al. [16]. Experimental researches and numerical simulations have been carried out by Chinese researchers too [17, 18] regarding the MILD combustion achievement without preheating the air, so this is no longer a development barrier. It is the interested companies’ duty to take the next step further in order to put into practice these technologies in different industries [2]. Nowadays, the researches regarding the application of MILD combustion technologies in gas turbines, in gasification systems and in no-preheating industrial ovens [2] have started. Figure 5 presents a possible application area for this combustion technology.

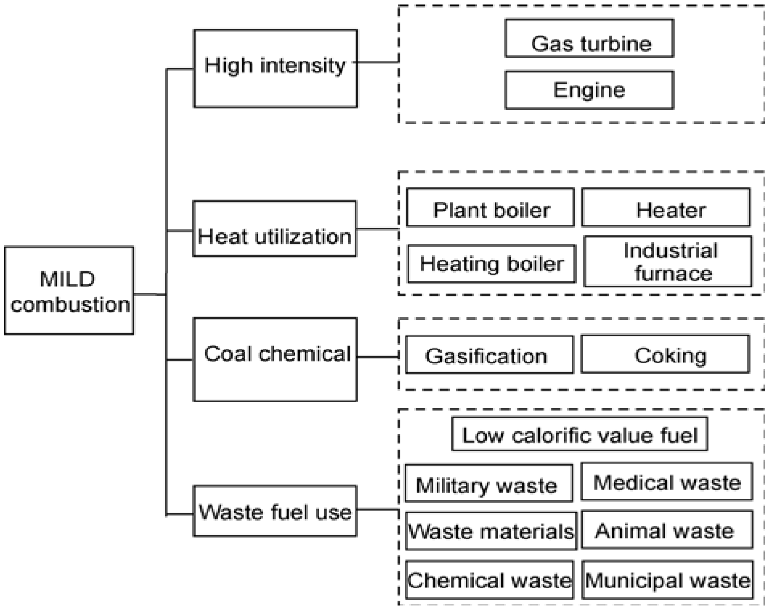

Fig. 5. The possible industrial application area for the MILD combustion technology [2].

All these applications need a high combustion stability, a very high thermic efficiency, a uniform temperature distribution, and very low NO_x emissions.

3. CONCLUSIONS

Presently, the basic knowledge regarding the flameless combustion formation, its characteristics and its control parameters are very low. This is the reason for which the industrial application of this technology is limited. The recent studies show, without a doubt, that flameless combustion may be achieved for gaseous, liquid and solid fuels without external pre-heating, now being the equipment producers turn to put these technologies into practice.

The existence of researches in the high thermic efficiency and low polluting emission combustion field creates the premises for new industrial equipment emergence that will be used in industries with a very high level of pollution.

Important steps towards the implementation of these combustion technologies have been also made regarding modern energy equipment, namely gas turbines, where the technological leap is significant, these gas turbines' efficiency reaching record levels and, at the same time, the NO_x emission level tending towards zero.

REFERENCES

[1] Wünning, J.A., Wünning, J.G., Flameless oxidation to reduce thermal no-formation. Prog Energy Combust Sci, vol. 23, no. 1, 1997, p. 81–94.

[2] PengFei, L., JianChun, M.I., Dally, B.B., FeiFei, W., Lin W., ZhaoHui, L., Sheng, C., ChuGuang, Z., Science China Technological Sciences, vol. 54, no. 2, 2011, p. 255-269.

[3] http://cleanboiler.org/Workshop/RCTCombustion.htm (11.03.2013).

[4] Koornneef, J., Junginger, M., Faaij, A., Development of fluidized bed combustion-An overview of trend, performance and cost, Prog Energy Combust Sci, vol. 33, no. 1, 2007, p. 19–55.

[5] Cavaliere, A., Joannon, M., Mild combustion, Prog Energy Combust Sci, vol. 30, no. 4, 2004, p. 329–366.

[6] Katsuki, M., Hasegawa, T., The science and technology of combustion in highly preheated air, Proc Combust Inst, vol. 27, no. 2, 1998, p. 3135–3146.

[7] Tsuji, H., Gupta, A., Hasegawa, T., Katsuki, M., Kishimoto, K., Morita, M., High Temperature Air Combustion, From Energy Conservation to Pollution Reduction, Florida, CRC Press, 2003.

[8] Joannon, M., Langella, G., Beretta, F., Mild combustion, Process features and technological constrains. Combust Sci Technol, vol. 153, no. 1, 2000, p. 33–50.
[9] Zieba, M., Brink, A., Schuster, A., Hupa, M., Scheffknecht, G., Ammonia chemistry in a flameless jet. Combust Flame, vol. 156, no. 10, 2010, p. 1950–1956.
[10] Cavigiolo, A., Galbiati, M. A., Effuggi, A., Gelosa, D., Rota, R., Mild combustion in a laboratory-scale apparatus, Combust Sci Technol, vol. 175, no. 8, 2003, p. 1347–1367.
[11] Som, S. K., Datta, A., Thermodynamic irreversibilities and exergy balance in combustion processes, Prog Energy Combust Sci, vol. 34, no. 3, 2008, p. 351–376.
[12] Kumar, S., Paul, P. J., Mukunda, H. S., Studies on a new high-intensity low-emission burner, Proc Combust Inst, vol. 29, no. 1, 2002, p. 1131–1137.
[13] Krishnamurthy, N., Paul, P. J., Blasiak, W., Studies on low-intensity oxy-fuel burner, Proc Combust Inst, vol. 32, no. 2, 2009, p. 3139–3146.
[14] Rottier, C., Lacour, C., Godard, G., Taupin, B., Porcheron, L., Hauguel, R., Carpentier, S., Boukhalfa, A.M., Honore, D., An aerodynoamics way to reach mild combustion regime in a lab-scale furnace, In: Proceedings of the European Combustion Meeting, Chania, Crete, 2007.
[15] Rottier, C., Lacour, C., Godard, G., Taupin, B., Porcheron, L., Hauguel, R., Carpentier, S., Boukhalfa, A.M., Honore, D., On the effect of air temperature on mild flameless combustion regime of high temperature furnace. In: Proceedings of the European Combustion Meeting. Vienna, Austria, 2009.
[16] Xing, X.J., Lin, Q.Z., Research on NOx formation in normal temperature air flameless combustion, Acta Scientiae Circumstantiae, vol. 26, no. 10, 2006, p. 1671–1676.
[17] Li, P.F., Mi, J.C., Dally, B.B., Craig, R.A., Wang, F., Effect of equivalence ratio and reactants mixing pattern on flameless combustion, In: Chinese Society of Engineering Thermophysics Conference, Guang Zhou: Chinese Society of Engineering Thermophysics, 2010.
[18] Mi, J.C., Li, P.F., Dally, B.B., Craig, R.A., Alexander, R., Importance of initial momentum rate and air-fuel premixing on moderate or intense low oxygen dilution (MILD) combustion in a recuperative furnace, Energy Fuels, vol. 23, no. 11, 2009, p. 5349–5356.