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EXPERIMENTAL STUDIES ON THE FLAMMABILITY AND STABILITY LIMITS OF GASEOUS COMBUSTION AT DIFFERENT LEVELS OF DILUTION AND PREHEATING LEVELS OF THE OXIDIZER

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În urma cercetărilor experimentale realizate pentru această lucrare au fost determinate limitele de aprindere ale unei flăcări de metan, cu amestec parțial al combustibilului şi diferite grade de diluare cu azot a oxidantului. Ca aplicație industrială acest tip particular de ardere poate fi găsit în generatoarele de abur recuperatoare (GAR) cu ardere suplimentară folosite în ciclurile mixte gaze-abur, gazele de ardere evacuate de către turbina cu gaze având rolul de oxidant pentru combustibilul suplimentar ars. Aceste gaze de ardere folosite ca oxidant sunt deficiente în oxigen şi au o temperatură ridicată.

Based on the experimental studies completed for this paper the flammability limits of a partially premixed methane flame at different levels of dilution with nitrogen and preheating levels of the oxidizer are reported. As an industrial application this particular type of combustion may be found in the supplementary fired heat recovery steam generators (HRSG), used in the combined gas-steam cycles, the exhaust gases from the gas turbine acting as an oxidizer for the supplementary fuel burned. The exhaust gases used as an oxidizer are deficient in oxygen and have a high temperature.

Keywords: flammability limits, low oxygen content, hot oxidizer, experimental study.

1. Introduction

The combustion of a gaseous fuel in a hot and low oxygen concentration atmosphere was previously studied by other authors. All of them concluded that this is possible and also that this type of combustion has a series of advantages like: reduction in the fuel consumption and, directly, reduction in the carbon dioxide and the nitrogen oxides produced in the reaction, high uniformity of the heat flux in the combustion chamber, larger flame volume, lower combustion noise etc.

The applications in the industry of this type of combustion are limited to just a couple of domains. One of the most important applications is in the combined gas-steam cycles used for energy and heat generation. To increase the

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thermal power of the heat recovery steam generator and directly the power of the steam cycle, a supplementary quantity of fuel can be burned inside the steam generator. This additional fuel will use as an oxidizer the hot and oxygen deficient flue gases from the gas turbine. Since the gas turbine must not be affected by this additional combustion, some measures are taken. Partial premixed combustion is used, usually in coflow conditions, the fuel being directly injected in the oxidizer flow with the help of a duct burner. It is known that the stability of a flame is greatly influenced by the geometry of the burner and the parameters of the reactants (turbulence, velocity, temperature etc.). Since in these conditions the combustion isn't as stable as in normal conditions, the flame must be surface stabilized.

The low oxygen content and the temperature of the oxidizer have a significant impact on the flammability limits of the combustion process. Knowing these new limits significant progress can be made in the design of the burners used in these conditions and implicitly a higher efficiency of both the combustion process and the equipment itself.

2. Experimental setup

Other authors studied the combustion in a low oxygen content and hot oxidizer of a single jet [1-4]. This gives valuable theoretical information about the flame properties, but this isn't enough for designing an efficient burner. To get results applicable to industrial applications the burner used in the experimental setup must be similar to the existing burners design already proposed by different companies for this type of combustion. The burner designed for the experimental study, presented in Fig. 1, is a simplified one similar to most of the designs presented by different companies for applications related to the subject of this paper. The fuel used in the experimental setup was methane and the oxidizer was air diluted with nitrogen to concentrations comparable with those found in industrial applications. The oxidizer enters the burner through a single circular inlet and the methane through 9 nozzles.

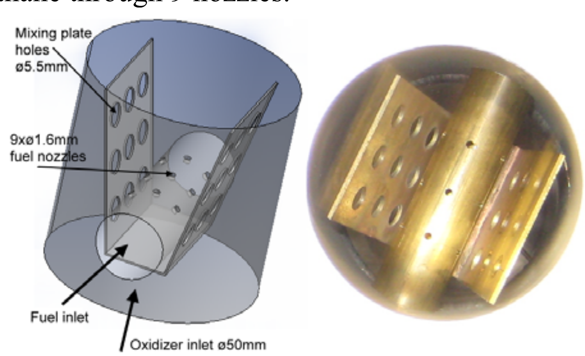


Fig. 1. Experimental setup burner.

A mixing plate helps in surface stabilizing the flame and also in partially premixing the fuel and oxidizer through a series of holes drilled into it. A quartz glass tube was used to limit the effects of the atmospheric air on the flame and to allow photos to be taken.

The oxidizer was obtained by diluting atmospheric air with industrial pure nitrogen. Two mass flow controllers (MFC) were used to mix the air and nitrogen flows up to the desired oxygen concentration C_{Ox} and a third one to regulate the flow of methane into the burner. A program was written to control the mass flow controllers trough a computer so that the desired equivalence ratio would be obtained at any flow magnitude. The program controls the equivalence ratio of the mixture by either changing the flow of fuel or by changing the flow of nitrogen and directly the oxygen excess. A gas analyzer was used to confirm the concentration of oxygen at the burner inlet. Also a thermometer was used to confirm the preheat temperature of the oxidizer. Figure 2 shows the schematics of the experimental setup.

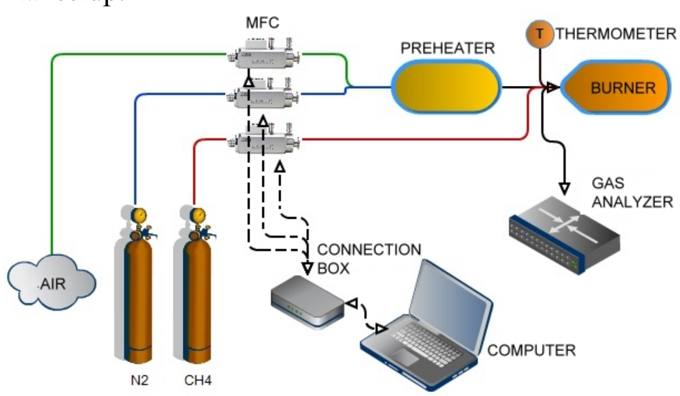


Fig. 2. Schematics of the experimental setup.

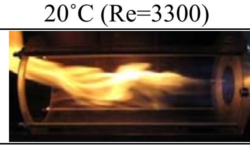
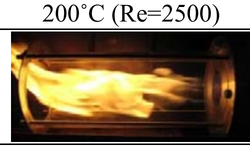
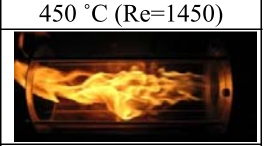
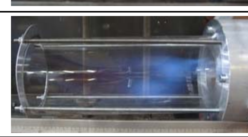
3. Results and discussion

All the observations were done for lean combustion conditions for an equivalence ratio ϕ between 0.1 and 1 and for three different preheat temperatures of the oxidizer: 20, 200 and 450°C. The equivalence ratio of a system is defined as the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio. A velocity of 1 m/s was calculated for the oxidizer (at normal conditions) by setting the volumetric flow to 117.75 l/min (~0.001963 m^3/s) for a known inlet diameter of 50 mm. This speed increases with the preheat temperature (the volume increases) up to approximately 2.3 m/s. The methane velocity was calculated to be situated between 0.8 m/s (C_{Ox}=15%, ϕ=0.1) and 11.3 m/s (C_{Ox}=21%, ϕ=1) depending on the stoichiometry needed given by the oxygen concentration and equivalence ratio ϕ. The fuel velocity remained constant with the increase of the preheat temperature since the injection point was situated downstream after the preheater. The equivalence ratio is lowered by decreasing the flow of fuel injected into the burner.

Table 1 shows the flame aspect for different oxygen concentrations, equivalence ratios and oxidizer preheat temperatures. As expected, the flame length and volume decrease when the flow of methane is reduced. On the other hand, the flame length and volume increases with the reduction in the oxygen concentration although the fuel quantity is also decreased. A flame at a given ϕ and preheat temperature, in a 21% oxygen atmosphere is similar in size with a flame at the same ϕ and preheat temperature in a lower oxygen concentration.

Table 1

Methane flame aspect for different oxygen concentrations, equivalence ratios and oxidizer preheat temperatures. $V_{Oxidizer}$=117.75 l/min, oxidizer inlet diameter ϕ_{Ox}=50 mm, fuel nozzle diameter 9 x $ø_{fuel}$=1.6 mm.

O_2 [%]	Re CH_4	ϕ	Oxidizer preheat temperatures		
			20˚C (Re=3300)	200˚C (Re=2500)	450 ˚C (Re=1450)
21	1100□	1			
	660	0.6			
□17	900	1			
	540	0.6			
□15	790	1			
	470	0.6	No ignition		
13	690	1	No ignition		

The color of the flame changes with the decrease in the oxygen concentration from intense yellow to almost invisible blue. The flammability limits are greatly affected by the reactants velocity ratio. When ϕ is lowered, the fuel velocity decreases and since the velocity of the oxidizer is constant (independent of ϕ) for a lower ϕ the flame is blown-off. The preheat temperature of the oxidizer has major effects on the combustion process. By increasing the oxidizers preheat temperature the mixture ignites for lower oxygen concentrations even when, at normal conditions, the mixture doesn't ignite. Also the flame color is affected by the preheat temperature.

Figure 3 shows the flammability limits of methane, obtained using the experimental setup, as a function of oxygen concentration, oxidizer temperature and equivalence ratio. The oxygen concentration was obtained by mixing air and nitrogen and the equivalence ratio by decreasing the fuel flow.

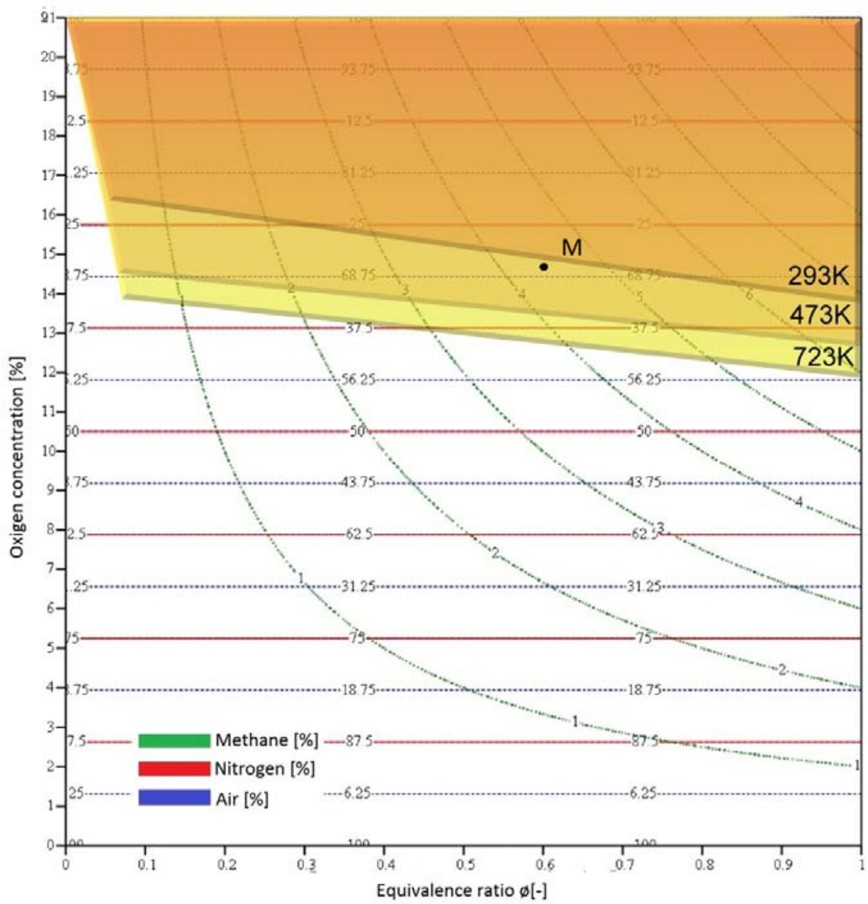


Fig. 3. Flammability limits of methane for the experimental setup.

To explain the link between the diagram presented in Fig. 3 and the flames in *Table 1* the next specific case is chosen. For the experimental case, when the oxygen concentration was lowered to 15%, by diluting air with nitrogen, and the equivalence ratio was set to 0.6 by decreasing the fuel flow to the burner, the oxidizer preheat temperature was raised from room temperature to the conditions found at the exhaust of a gas turbine (450°C). According to *Table 1,* the mixture doesn't ignite at room temperature but it will burn at higher temperatures. In Fig. 3 the point M(ϕ, C_{O_2}) corresponding to the conditions just mentioned was drawn. It is obvious that a mixture with its characteristics situated in the area of point M will not ignite at room temperature but at higher preheat temperatures of the oxidizer the combustion becomes possible. This diagram can be used to approximate the flammability limits of methane in an oxidizer with a low oxygen concentration.

The ignition can be limited beside the limiting oxygen concentration by the fuel-oxidizer velocity ratio. By adjusting this ratio the combustion process can be stabilized at lower preheat temperatures of the oxidizer and oxygen concentrations. The limiting oxygen concentration (LOC) is defined as the concentration of oxygen below which combustion is not possible, independent of the concentration of fuel. LOC is also dependent of the inert gases found in the combustible mixture. Figure 4 shows the flammability diagram for methane, in a ternary plot.

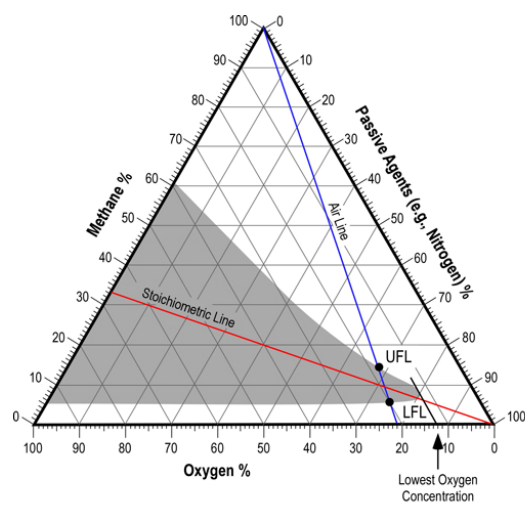


Fig. 4. Flammability diagram of methane with the stable combustion region and upper and lower flammability limits highlighted (at room temperature and atmospheric pressure).

The autoignition temperature of methane is situated around 540˚C but, in the conditions of low oxygen concentration, this value increases significantly to a point where a pilot flame is necessary. As said before the flame has a bigger volume at a lower concentration of oxygen and because of this a surface stabilisation method is absolutely necessary so that a stable combustion can be achieved.

4. Conclusions

The flammability limits of methane combusted in a hot, low oxygen atmosphere were experimentally investigated. The burner and the initial parameters used were similar to those used in the specific industrial applications. When the oxidizers preheat temperature is increased the mixture ignites for lower oxygen concentrations even when, at normal conditions, the mixture doesn't ignite.

The flame has a bigger volume at a lower concentration of oxygen for the same quantity of fuel burned. This is an advantage because of the enhanced temperature uniformity and heat transfer and the consequences are that the equipment will be downsized and the NO_x and CO_2 emissions are reduced due to the fuel consumption reduction. Also the flammability limits are affected by the velocity ratio of the reactants independent of the limiting oxygen concentration.

For the burner used in the experimental study the lowest oxygen concentration of the oxidizer that allowed the fuel to ignite was situated around 12% for an equivalence ratio of 1 and a preheat temperature of 450°C. Since in the case of a HRSG the concentration of oxygen in the exhaust gases from the gas turbine is situated around 14-16% and the temperature can easily reach 400°C one of the conclusions is that this type of combustion can be applied directly to the HRSG without adding supplementary air. The disadvantage is that the total efficiency of the combined cycle decreases indirectly proportional with the quantity of supplementary fuel burned and the advantage is that the power of the steam turbine can be increased directly dependent on the same quantity of fuel burned. The only thing that limits the increase in power of the steam turbine is the available oxygen in the exhaust gases of the gas turbine. This inconvenience can be removed by adding supplementary air to the HRSG to increase the oxygen available for the combustion process.

Further development is needed in this domain to improve this sector of industry since this type of combustion has some clear advantages

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