Extinction Limits of Opposed Jet Turbulent Premixed Methane Air Flames with Water Mist

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ABSTRACT

An experimental study on water mist extinction of turbulent premixed flames is described. The aim of the study is to compare the extinction limits of opposed jet turbulent methane/air flames with and without the addition of water mist, and to study the influence of several parameters including the structure of water mist in terms of droplet size and mass fraction of the condensed phase, mean strain rate, equivalence ratio and turbulence. An existing opposed jet turbulent premixed flame experimental set-up is modified to include a water mist production system. An air assisted atomizer is developed to produce and control the water mist. The structure of the water mist is characterized by a Phase Doppler Anemometer. Water mist interaction with three different configurations of opposed jet premixed flames is explored and the results are discussed by introducing a parameter representing the water mist efficiency.

KEYWORDS : Water mist, Flame extinction, Turbulent premixed flames

INTRODUCTION

Water mists as fire suppression systems have been an active area of research and development in recent years, and many commercial systems are available or in development **[1, 2]**. As one of the most effective fire suppression solutions, water mists have many advantages as they are : inexpensive, non toxic, pose no environmental problems, can be used to suppress various kinds of fires, utilize water quantities lower than sprinklers and hence have reduced collateral damage, can be made to perform functionally in some applications like total flooding activated by a variety of means, may be non-electrically conductive, and may also have applications as inerting or in explosion suppression systems.

Early research in the 1950's identified the dominant mechanisms of extinction by water mist [3, 4] as gas phase cooling, oxygen displacement or dilution, wetting of fuel surfaces, and attenuation of radiative heat transfer. More recently, Mawhinney et al [5] and Jones and Thomas [6] confirmed these primary mechanisms, which are all involved to some degree in fire suppression by water mist. The relative importance of each mechanism depends on the flame configuration and the mist characteristics. Therefore, optimal water mist properties should be determined for each flame configuration. For example, in a recent numerical study, Lentati and Chelliah [7] found an optimal droplet diameter of about 20 μm for diffusion flame extinction by water mist. Similarly, Lacas and Higgins [8] aim to determine the optimum droplet diameter to reduce the laminar flame velocity for premixed flames. Coppalle et al [9] determined the optimum and the most effective droplet sizes which maximize the attenuation of radiation of a fire. The water loading is another parameter which should be optimized for efficient fire suppression strategies.

A recent study on the effects of water mists and NaCl-water solutions on the extinction of laminar premixed methane-air counterflow flames has been conducted [10]. The burners used consist of two opposed nozzles each with an inner diameter of 25 mm at the exit. In the lower part of the burner, a pressure atomizer is centrally located near the bottom. The D_{32} measured by PDPA range from 14 μm to 25 μm. Of particular interest of the study is the combination of flame stretch and water mist concentration which reduce the reaction rate, corresponding to the local extinction of the flame. The higher the mist concentration the more easily the flame can be extinguished by stretch. Mist containing NaCl/water solutions were found to be more effective than pure water mist in promoting premixed flame extinction.

The present study also concerns water mist extinction of opposed jet premixed flames but in the turbulent regime. Recently, an experimental study of turbulent premixed combustion in opposed jet flows has been conducted in our laboratory [11, 12]. Measurement techniques based on a two-component Laser Doppler Velocimetry system and Mie scattering have been used to characterize flow velocities and to measure the mean burning rate. In the present study we use the same set-up to determine the flame extinction limits with and without the addition of water mist, in order to characterize the fire suppression efficiency of water mists The existing set-up has been modified to include a water mist production system which consists of a twin fluid air assisted atomizer. The water mist structure is determined using phase Doppler anemometry (PDA). The extinction limits of methane/air opposed jet flames are determined under various turbulence, mean strain rate and equivalence ratio conditions, with and without water mist. The final objective of the study is to determine the modification of the extinction limits of the investigated flames when they interact with water mist, for varying mist concentration and structure (droplet size distribution) and for different configurations of the opposed turbulent jet flames (see below). In a previous companion study [13], we determined the effects of turbulence on water droplet vaporization, which takes its rational from experimental observations showing that smaller flames are more difficult to extinguish by water mist than large flames [1]. One explanation of such an observation might indeed be related to the strongly turbulent nature of large flames.

In the following we first present the experimental set-up for turbulent premixed flame extinction studies, the water mist production system and the characterization of the mist structure. Preliminary results are then reported on the water mist extinction efficiency with three flame configurations.

EXPERIMENTAL SET UP FOR THE STUDY OF WATER MIST EXTINCTION OF TURBULENT PREMIXED FLAMES IN OPPOSED JET CONFIGURATION

In order to determine the modifications in the extinction limits of the previously investigated opposed turbulent jet premixed methane-air flames when they interact with water mist, an experimental set up has been developed in the laboratory, using the burners described in ref. [11] with the same conditions of the flow field. **Figure 1** shows the general configuration of the set-up for the present study:

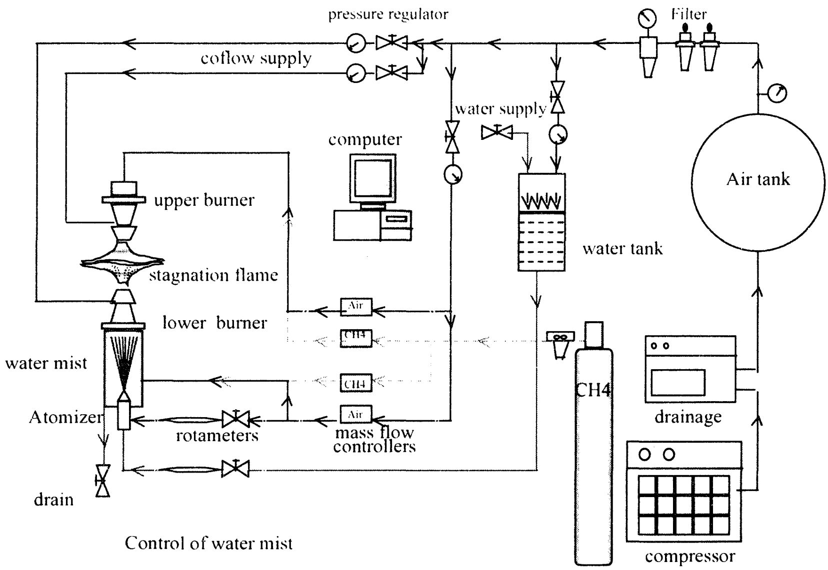

FIGURE 1 Schematic representation of the experimental set-up for the study of opposed jet turbulent premixed flames extinction with water mist

Flame generation

Two geometrically identical burners of 30mm inner diameter D are supplied with identical premixed methane/air mixtures. The nozzles are placed such that the generated opposed jet flow field produces an axisymetric free stagnation plane, where reactants (methane/air mixture) form a turbulent stretched premixed flame stabilized between the two nozzles. In order to explore the stability regimes of the flame by varying the equivalence ratio and the strain rate (imposed by the reactant velocity at the exit of the burner for fixed nozzle separation), the flow rate of reactants is controlled with mass flow controllers piloted with a computer. The jets are surrounded by a co-flow of air with an external diameter of 50mm. The use of the co-flow has been shown to stabilize the flames by reducing the interactions with surrounding air and to homogenize the turbulence and reduce the effect of buoyancy on the flames. Perforated plates with different hole diameter and mesh sizes are placed 40mm upstream of the nozzle exit to generate various turbulence conditions. The perforated plate used in the present study has a mesh of 3.8mm and a hole diameter of 2.5mm, which produces a turbulence with an integral length scale L_u of 6.1mm and a turbulence intensity u'/U of 12%. The extinction limits of the flame have been determined under various mean strain rate and equivalence ratio conditions. The separation distance between the upper and the lower nozzle exits H can be varied from 20mm to 60mm; in the present study it is fixed at 40mm .

Water mist production system

To carry out the experiments of premixed flame extinction limits with water mist, we developed a twin fluid (water/air) pressure assisted atomizer, to control the droplet size and mass fraction of the condensed phase by varying the flow conditions [14]. The atomizer, shown schematically in **Figure 2**, consists of two concentric tubes. The inner one supplies the water and the outer the assisting air. The inner tube can be moved axially inside the outer tube so that the internal mixing chamber dimensions may be varied and different atomization regimes can be obtained with the same atomizer. The exit orifice is 3mm long and has a diameter of 1.2mm and the inside orifice has a diameter of 0.8mm. Distilled water is supplied from a pressurized water tank. Pressurized air is supplied from the compressed air line. Air and water are supplied to the atomizer with a pressure fixed at 6 bars. The flow rate of air and water are controlled with two rotameters with needle valve. A by pass is used at the exit of the air flow mass controller of the lower burner to supply the atomizer air, in order to keep constant the imposed equivalence ratio of the mixture. As shown on Figure 1, the atomizer is placed inside a flow tube below the lower burner. When the spray system is activated in the presence of the main flow of reactants, the water mist droplets are carried to the lower burner and reach the flame zone.

CHARACTERIZATION OF THE WATER MIST

The water mist structure is characterized by simultaneous two-component velocity and size measurements performed with a TSI phase Doppler anemometer (IFA 755). The 514.5nm and 488nm emission lines of an Ar^+ laser are used for the axial and radial velocity components, respectively. The optics and electronics of the PDA layout are schematized in **Figure 3**.

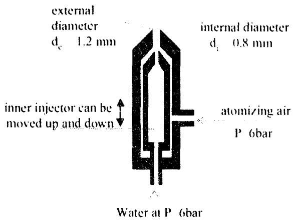

FIGURE 2 Detail of the atomizer

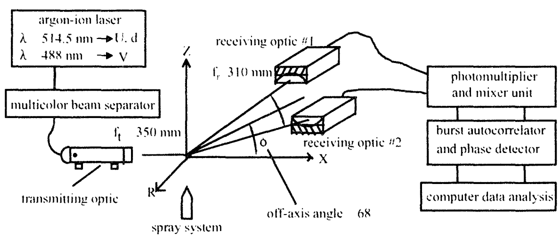

FIGURE 3 Apparatus layout for PDA measurements

Characterization of the water mist without the burner (only the atomizer)

The gas to liquid ratio by mass (GLR) is used to characterize the atomization conditions. The mass of air in this ratio concerns only that of the atomization air of the injector. The conditions explored in this study are summarized on TABLE 1. The atomizer without the burner for different GLR is first characterized by PDA. The measurements have been performed at 200mm from the exit of the atomizer. **Figure 4** shows the variation of D_{10} , D_{32} and the axial velocity of the droplets as a function of the GLR. D_{10} and D_{32} are respectively the mean and the Sauter mean droplet diameters. D_{10} and D_{32} decrease with the increase of GLR; on the other hand, the droplet velocity increases. **Figure 5** shows a typical drop size distribution of the water mist for GLR=6.96. **Figure 6** shows the characteristic droplet distribution produced by the injector alone at Z=200mm from the exit and for GLR=6.96, for different axial positions as a Rosin-Rammler plot. The parameters X and q used in the Rosin-Rammler relationship to describe the spray **[15]** have been respectively found equal to 9 and 4.

TABLE 1 Experimental conditions of the injector flow rates and GLR

q_{air} (l/min)	Q_{water} (ml/min)	GLR
3.1	12.3	1.79
3.1	6	3.68
3.1	3.2	6.85
5.8	6	6.96
9.3	6	11.14
5.8	3.4	12.10
13.7	6	16.36

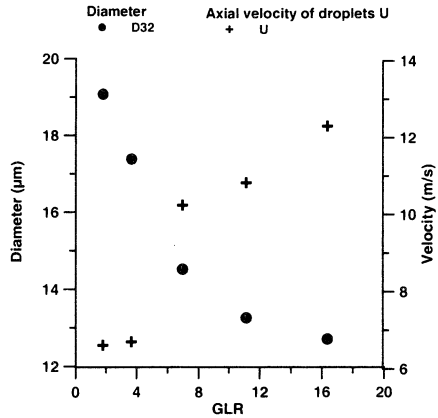

FIGURE 4 Variation of D_{10} and D_{32} and the axial droplet velocity U as a function of GLR

Characterization of the water mist with the burner (in the presence of the reactant flow)

Water mist is introduced from the lower burner under various main flow rate Q of the reactants for different GLR conditions of the atomizer placed inside the burner. For water mist characterization, the reactants flow is replaced by an air flow of equivalent flow rate. The droplet velocity and size measurements have been done at 470 mm from the exit of the atomizer (i.e. 30 mm upstream of the lower burner). **Figure 7** shows the variation of D_{10}, D_{32} diameters and the axial velocity of droplets U compared to the axial velocity of the main flow at the exit of the burner U_0 as a function of the main flow rate Q for different GLR. The size of droplets does not change significantly with the increase of the flow rate Q and the velocity of the water mist droplets is approximately the same compared to the main flow velocity U_0 at the

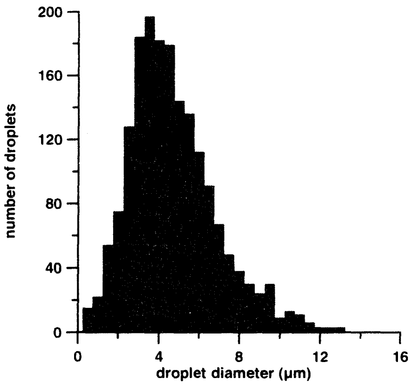

FIGURE 5 Typical drop size distribution of the water mist produced by the injector alone without the burner at Z=200 mm from the exit, for GLR=6.96

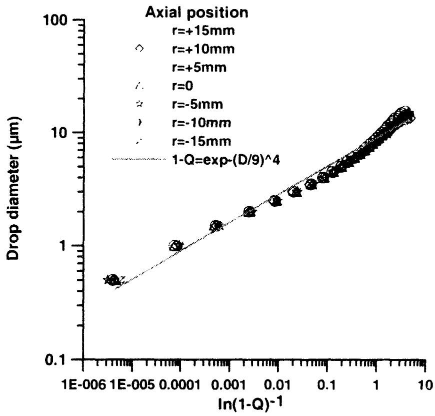

FIGURE 6 Characteristic droplet distribution produced by the injector alone at Z=200 mm from the exit and for GLR=6.96, for different axial positions as shown as a Rosin-Rammler plot

exit of the burner ; i.e. the water mist droplets are carried upwards by the main flow. PDA measurements have been performed to study the variation of D_{10} and D_{32} at different radial positions for the injector alone (at 200 mm from the atomizer exit) and the injector within the burner in the presence of the main flow (Q=12.71 m^3/h), 30 mm upstream of the lower burner exit. FIGURE 8 shows that the spray structure is homogenous in the two cases. It is observed that the droplet sizes are smaller compared to those with the isolated atomizer due to the longer distance traveled by the droplets inside the burner. **Figure 9** shows a typical drop size distribution of the water mist with the burner for Q=12.71m^3/h and GLR=6.96. In this study three values of GLR (6.96, 12.1, 16.36) have been chosen for water mist interaction with the flame. In order to determine the effective water loading that reaches the flame zone, we use a cotton layer to collect the water droplets which is weighed before and after collection. The weight difference gives the total liquid mass introduced from the lower jet. **Figure 10** shows the flow rate of water mist q_{eff}. at the exit of the burner for three GLR with the presence of the main flow (Q=12.7 m^3/h). The difference between the initial water flow rate injected through the atomizer and that collected at the exit of the burner comes from the droplets which impact the inner walls of the burner, the flow homogenization and turbulence grids, but also from the vaporized water fraction which is not retained by the cotton layer.

FLAME EXTINCTION WITH AND WITHOUT WATER MIST

In this paper, the extinction limits of opposed jet turbulent premixed methane air flames have been studied for several parameters including strain rate (velocity of the reactants flow), equivalence ratio, with and without the addition of water mist, with three water flow rates and for three configurations (**Figure 11**). For each flame configuration, different mechanisms control flame extinction by water mist. In configuration 1, upper and lower flames are ignited and water mist is introduced from the lower burner. In configuration 2, only the upper flame is ignited, and air (with a flow rate equivalent to that of the reactants) and water mist are introduced from the lower burner. In configuration 3, only air is introduced from the upper burner, whereas the lower flame is ignited and water mist is introduced from the lower burner.

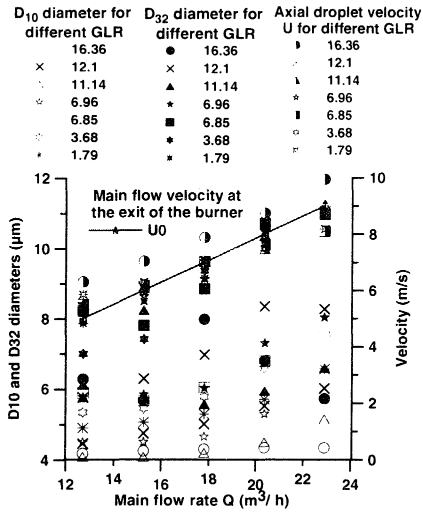

FIGURE 7 D_{10}, D_{32} and the axial droplet velocity compared to the velocity of the main flow at the exit of the burner for different GLR

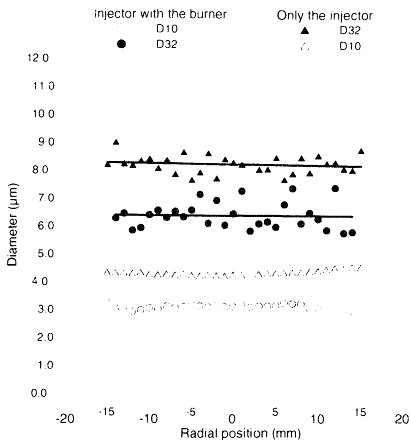

FIGURE 8 Variation of D_{10} and D_{32} at different radial positions for the injector alone and with the burner in the presence of the main flow (Q=12.71 m^3/h,GLR=6.96)

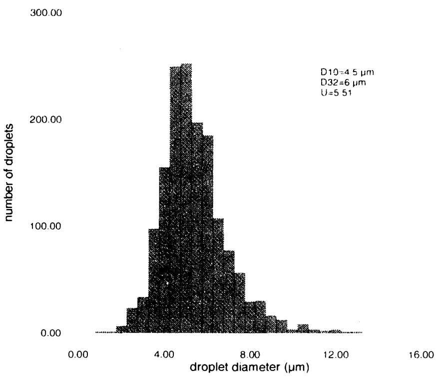

FIGURE 9 Typical drop size distribution with the burner at Z=470 mm. Q=12.71 m^3/h, GLR=6.96

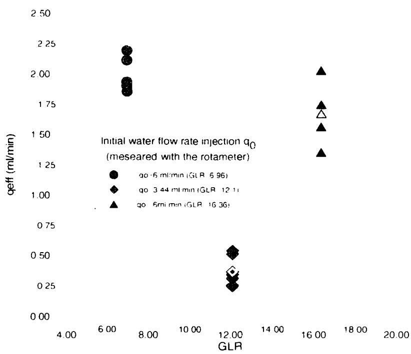

FIGURE 10 Effective flow rate of water mist at the exit of the burner with the presence of the main flow (Q=12.7 m^3/h)

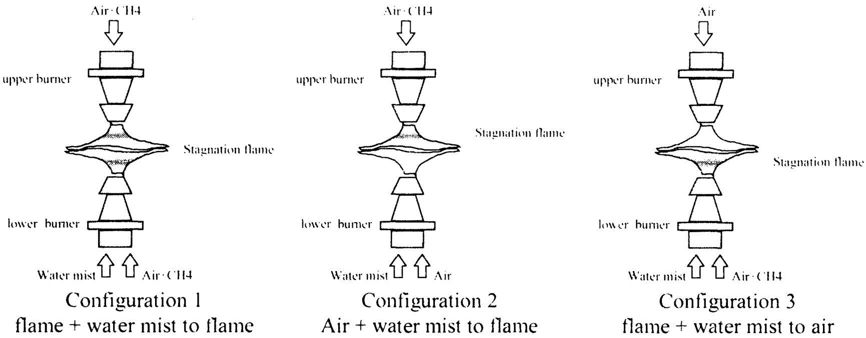

FIGURE 11 Different configurations for flame/water mist interaction studies

In the following, the equivalence ratio is given as $\Phi=9.524Q_{CH4}/Q_{air}$, where Q_{CH4} and Q_{air} are respectively methane and air flow rates. The total flow rate of reactants is therefore given by $Q=Q_{CH4}+Q_{air}$. The velocity U_0 of the mixture at the exit of the burner can be calculated with $U_0=Q/S$ where S is the burner exit surface area. The strain rate is estimated by the expression $2U_0/H$ **[12]**.

Extinction limits of the flames without water mist

Figure 12 shows the flame extinction limits for each configuration without water mist addition as a function of equivalence ratio and the mean strain rate for different flame configurations. This figure allows the comparison of the stability domains for each flame configuration. The flames of configuration 1 are the most stable because of the presence of twin back-to-back flames (reactants from the upper and the lower burners) which reduces heat losses from burnt gases.

For configurations 2 and 3, rich flames are more robust. These results confirm the existing knowledge on the stability limits of opposed jet turbulent flames.

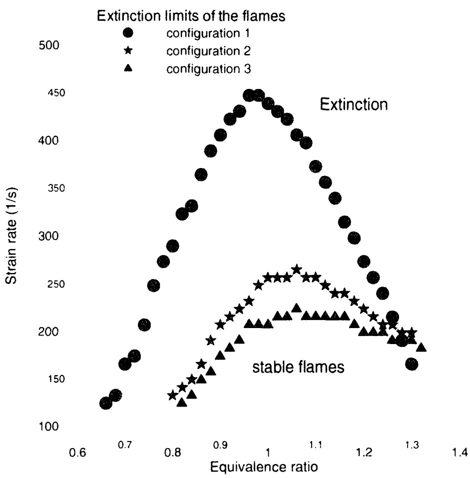

FIGURE 12 Flame extinction limits without water mist as a function of equivalence ratio and the mean strain rate for different configurations of the flame

Extinction limits of the flames with water mist

Configuration 1

Figure 13 shows the extinction limits of the flame with and without the water mist as a function of equivalence ratio and strain rate, for configuration 1. It is clearly observed that the flames are weakened by the addition of water mist. In order to optimize the amount of the injected water, we used in these experiments three water flow rates (q_{eff}=2ml/min, q_{eff}=1.5ml/min, q_{eff}=0.4ml/min). For each effective water flow rate, the droplet mass fraction is calculated as Y=H_2Omass/Total mass. The droplet mass fraction increases with increasing q_{eff} but remains approximately constant for equivalence ratio values comprised between the extinction limits. The extinction efficiency of water mist increases with q_{eff}. Rich flames are more difficult to extinguish than lean ones. In order to quantify the water mist efficiency for premixed flame extinction, we define a parameter η expressed in % and called Water Mist Efficiency (WME) Its definition is based on the strain rate at extinction a_E, without the addition of water mist and in the presence of water mist a_{Emist} for the same equivalence ratio ϕ. WME is therefore given by $\eta=(a_E-a_{Emist})100/a_E$. **Figure 14** shows the the variation of WME in terms of reactant flow velocity for three q_{eff}. as a function of equivalence ratio for configuration 1. For each effective water flow rate q_{eff} the extinction is more easier for lean flames than rich ones, especially for near stoechiometric flames. The figure shows also that the increase of q_{eff} increases the efficiency of the water mist.

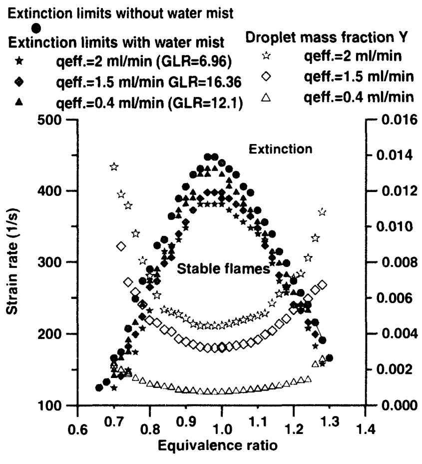

FIGURE 13 Extinction limits of the flame with and without water mist and droplet mass fraction for different q_{eff} as a function of equivalence ratio and strain rate a_b for configuration 1

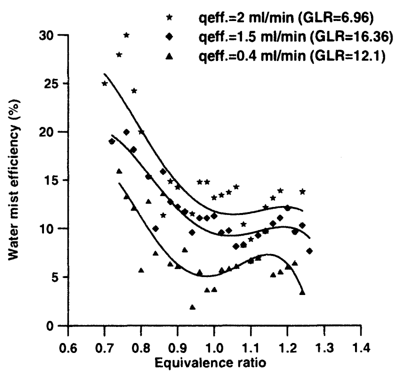

FIGURE 14 Water mist efficiency for different q_{eff}. as a function of equivalence ratio for configuration 1

Configuration 2

In configuration 2 we stabilize a single flame by injecting the reactants flow from the upper burner, and only air and water mist from the lower burner (**Figure 11**). For this configuration we only used q_{eff}=2ml/min. In this configuration, the water mist approaches the flame from the burnt gases side and it is clearly observed that all the droplets vaporize at the flame front and therefore considerably cool the burnt gases. **Figure 15** shows the extinction limits of the flame with and without water mist and droplet mass fraction as a function of equivalence ratio and strain rate. A large difference is observed between the extinction limits with and without addition of water mist.

Configuration 3

In configuration 3, we stabilize a single flame by injecting the reactants and water mist from the lower burner, and only air from the upper burner. In this configuration, water mist is carried along the cold gases and contribute mainly to the dilution of the premixture. In **Figure 16** flame extinction limits with and without water mist for q_{eff}=2ml/min (GLR=6.96) and droplet mass fraction as a function of equivalence ratio and strain rate are presented for this configuration, where the difference between the extinction limit curves with and without addition of water mist is less than configuration 2.

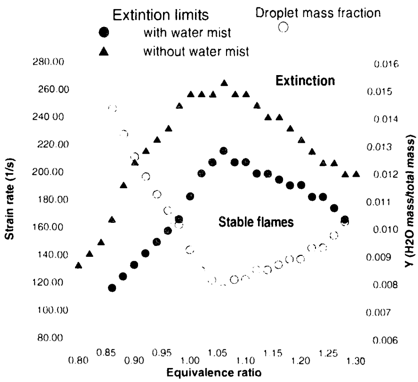

FIGURE 15 Flame extinction limits with and without water mist for q_{eff}=2ml/min (GLR=6.96) and droplet mass fraction as a function of equivalence ratio and strain rate for configuration 2

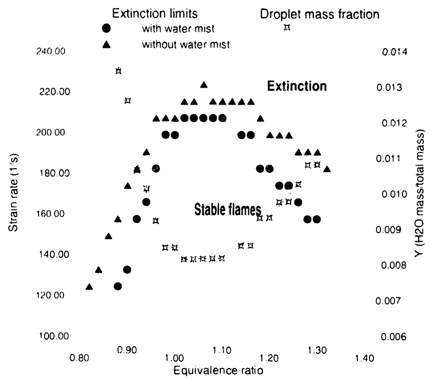

FIGURE 16 Flame extinction limits with and without water mist for q_{eff}=2ml/min (GLR=6.96) and droplet mass fraction as a function of equivalence ratio and strain rate for configuration 3.

Comparison between the three configurations

Figure 17 shows the water mist efficiencies for different flame configurations as a function of equivalence ratio for q_{eff}=2ml/min (GLR=6.96). The water mist is the most efficient in configuration 2 compared to the other two configurations. One explanation may be related to the strong cooling effect of the water mist in this configuration : the hot products are cooled by droplet evaporation which reduces the heat transferred to the fresh mixture and therefore reduces the flame propagation velocity and the robustness of the flame. Furthermore, the heat sinks generated by droplet evaporation within the hot gases create local temperature heterogeneities and possibly local gradients contributing to increase the total strain affecting the flame. In configuration 3, the main flame extinction mechanism seems to be the dilution effect, which is obviously less efficient than the hot gases cooling effect. This difference between the two extinction mechanisms is interesting as it is observed for the same droplet mass fraction for the two configurations, as shown on **Figure 18**.

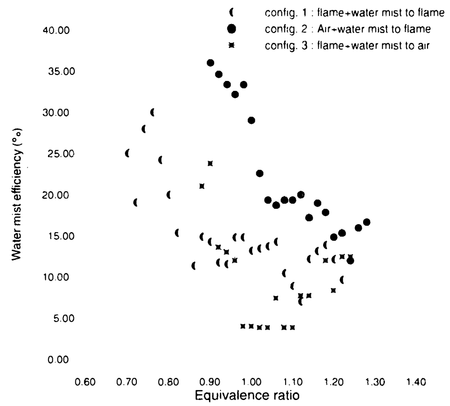

FIGURE 17 Water mist efficiency for different flame configuration as a function of equivalence ratio for q_{eff}=2ml/min (GLR=6.96)

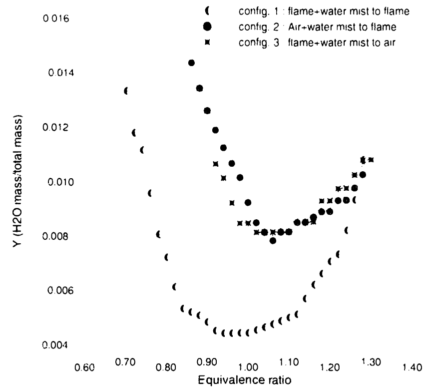

FIGURE 18 Droplet mass fraction as a function of equivalence ratio for q_{eff}=2ml/min (GLR=6.96) and different flame configuration

CONCLUDING REMARKS AND FUTURE WORK

The experimental set up used for the study of water mist extinction of opposed jet turbulent premixed methane/air flames is described. An existing opposed jet turbulent premixed flame experimental set-up is modified to include a water mist production system. An air assisted atomizer is developed to produce and control the water mist. The structure of the water mist is characterized by a Phase Doppler Anemometer. Typical water mist mean droplet diameters (D_{10}) range in this study around 4 μm. The effect of several parameters including the mass fraction of condensed phase, the mean strain rate and the equivalence ratio have been studied for different flame configurations. A parameter characterizing the water mist efficiency is introduced and used to compare the interaction regimes between water mist and the explored flame configurations. The main conclusions of the work indicate (i) that richer flames are more difficult to extinguish with water mist; (ii) increasing water mist concentration facilitates flame extinction; (iii) hot gases cooling effect is found much more efficient than the dilution effect for turbulent premixed flame extinction. This observation gives some useful insight for the water mist application procedures to fire situations. Future work will concentrate on the effects of turbulence on water mist efficiency in extinguishing opposed jet premixed flames, on the one hand, and on the optimization of the amount of water used, on the other hand.

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