Fire Safety Journal 71 (2015) 217–225

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Inhibition of counterflow methane/air diffusion flame by water mist with varying mist diameter

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ARTICLE INFO

Article history:
Received 15 March 2014
Received in revised form
29 September 2014
Accepted 30 November 2014
Available online 12 December 2014

Keywords:
Fire suppression
Water mist
Extinguishment
Counterflow diffusion flame
Surface area parameter

ABSTRACT

In the present study, the effect of fine water mist on extinguishment of a methane–air counterflow diffusion flame was investigated to understand the underlying physics of fire extinguishment of highly stretched diffusion flame by water mist. Twin-fluid atomizers were used to generate polydisperse water mist of which Sauter mean diameters were 10, 20, 40, and 60 μm. When water mist is not added, the critical stretch rate at extinguishment is 439 s^{-1} as compared to the theoretical value of 460 s^{-1}. For the case with water mist addition, when the stretch rate is small enough, almost all the water mist evaporates within the flame zone. On the other hand, for high stretch rate case, large mist droplets pass through the flame zone and can reach the stagnation plane. However, no oscillatory motion was found around the stagnation plane. Critical stretch rate at extinguishment decreases monotonously with the mass fraction of water mist independently of the mist diameter within the range of D_{32} from 10 μm to 60 μm. On the other hand, with increase in the surface area parameter, the critical stretch rate at extinguishment decreases rapidly and becomes less sensitive at large surface area parameter, of which tendency is qualitatively in good agreement with theoretical predictions. For a constant surface area parameter, the critical stretch rate decreases with mist diameter because the mass fraction of water mist should increase in proportion to the mist diameter to keep the surface area parameter constant. When the water mist evaporates completely in the flame zone as in the present study, the mass fraction of the water mist is the dominant factor for fire extinguishment, rather than the surface area parameter. Therefore, an appropriate combination of stretch rate and water mist mass fraction should be provided to suppress effectively a given fire with a small amount of water mist.

1. Introduction

Halon 1301 (trifluoroboromomethane, CF_3Br) was a typical fire suppressant among halogenated hydrocarbons and used world widely [1]. However, the production of fire suppressants containing bromine was banned by Montreal protocol in 1987 because of their depletion potential of stratospheric ozone [2]. Then the feasibility of alternative fire suppressants has been investigated to establish their effectiveness and to understand their fire suppression mechanisms. The new agents include halogenated hydrocarbons other than Halon 1301 [3–13], metal compounds [14,15], phosphorus compounds [16,17] and inert gases [18–20]. One of the most effective fire suppression agents is fine water mist because water mist is inexpensive, ubiquitous, non-electrically conductive and nontoxic [21–23]. Additionally, water mist imposes no environmental problems. Furthermore, it can be expected that various kinds of fires should be suppressed by water mist with water quantities much less than sprinklers and hence collateral damages should be reduced.

Water has favorable physical properties for fire suppression. A significant quantity of heat is absorbed due to large latent heat of evaporation of water and high heat capacity of water vapor (2239 kJ/kg and 2.018 kJ/kg K, respectively at 100 kPa and 383.15 K). Water expands 1400 times in volume when it evaporates to vapor under above conditions, which results in the dilution of the surrounding oxygen concentration. Fine water mist leads to a significant increase in the surface area of water that is available for heat absorption and evaporation, and its effectiveness in fire suppression should be increased with decrease of mist diameter due to large surface to volume ratio. In addition, the evaporated vapor acts as a third body in the three-body chain terminating reactions, removing a certain amount of chain carrying or branching radicals. Therefore, water mist should have a

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http://dx.doi.org/10.1016/j.firesaf.2014.11.030
0379-7112/

chemical suppression effect which was investigated based on the detailed chemical reactions [24].

Even though stretch-free flames were assumed in most computational analyses for premixed flames [24,25], the flame in a given fire is in general subjected to flow stretching which affects significantly the extinguishment of the flame. For the cup burner, provided by NFPA standards [2], the flame is stretched at the base region where the flame is stabilized. However, the stretch effect on fire extinguishment has not been studied. The primary mechanisms of extinguishment should be due to heat extraction and oxygen displacement, which interact significantly with flame stretch [26]. Additionally, the flame stretch effect is coupled with other physical processes such as air entrainment and buoyancy. The air flow induced by buoyancy is 3-dimentional and time-varying. In addition, injected water mist entrains surrounding air, and when the water mist is delivered downwards to fire, the air flow induced by water mist injection impinges on the buoyancy-induced air flow. Therefore, the flow field in which the flame is generated is extremely complex. Consequently, the fire extinguishment by fine water mist is fairly complicated process. Indeed, the optimal design of the mist system has not been identified, including mist size, velocity, orientation and mass fraction.

Using coflowing diffusion flames to simulate the effect of air entrainment, the relative contribution of thermal cooling and oxygen depletion to fire extinguishment has been studied and extinguishment was found to depend on the water mist mass loading, velocity and orientation of injection [27]. Actually the flames in practical fires are stretched to some extent, and the highly stretched flame should be more easily extinguished. For coflowing jets or cup burners, it was found that the flame extinguishment is controlled by the behavior of the premixed flame, formed at the flame attachment point in the base of diffusion flame [28]. Blow off mechanism of a coflowing jet diffusion flame differs from a typical counterflow diffusion flame extinguishment, which is caused by an imbalance between the rates of chemical reaction and diffusion [29,30].

In general, the coflowing diffusion flame is stabilized by the premixed reaction kernel at the flame base, by which the extinguishment of diffusion flame is controlled. On the other hand, the counterflow diffusion flame is established in the forward stagnation region of a porous cylinder placed perpendicular to the air flow or between two opposed jets from circular tubes, and no premixed reaction kernel exists. Therefore, the importance of the counterflow diffusion flames has been long recognized for the fundamental understanding of flame processes such as the interaction of transport and chemical processes leading to extinguishment [31–33]. For a long time, the critical stretch rates beyond which the flame cannot be stabilized have been studied experimentally [34,35] and theoretically [36–42]. The counterflow configuration can provide a convenient experimental configuration to understand the interactions between mist droplets dynamics with flames, including flame extinguishment.

In the simulation, movements of gas and droplet were described separately based on a hybrid Eulerian–Lagrangian formulation, and the analysis of droplet dynamics and effects of water mist in extinguishing diffusion flames was performed. Results showed that the thermal effects, mainly through the latent heat of evaporation, influence significantly the flame extinguishment [43–46]. The effect of thermal cooling and oxygen depletion on fire suppression was investigated using large scale pool fires [47,48].

In the counterflow configuration, the mist droplets within a certain diameter range pass through the flame zone and remain in the liquid state. These mist droplets are then forced back by the opposing flow thus exhibiting an oscillatory motion in the vicinity of the stagnation plane [11,43]. Mist droplets with initial diameters smaller than the oscillatory threshold usually undergo complete evaporation upon entering the flame zone. However, the effectiveness of flame extinguishment is deteriorated by increasing droplet diameters larger than the threshold due to incomplete evaporation. It has been also shown that there exists an optimal mist droplet diameter, beyond which the stretch rate at extinguishment decreases linearly with increase in the specific surface area of water mist. As the mist droplets approach an optimal diameter, the linear correlation fails, suggesting an interaction between thermal and finite-rate reaction effects [49]. The mist droplets of optimal size should evaporate in the oxygen consumption layer of the flame zone, which leads to the radical deactivation as well as thermal cooling.

Using a counterflow propane–air flame, the behavior of droplets in the vicinity of the flame zone was investigated experimentally and it was found that 30 μm is the threshold size of droplets above which droplets cannot evaporate completely within the flame zone [50]. The behavior of the droplets near the flame zone is rather complicated. Large droplets do not follow the gas phase flow with high stretch rate. In addition, the droplet threshold diameter is also affected by stretch rate imposed by the flow field, although it seems no systematic investigation on this effect has been carried out except for Ref. [50].

Optimal use of water mist systems requires detailed knowledge of the behavior and suppression effectiveness of water mist in the vicinity of the flame zone in terms of mist droplet diameter as well as the flow field parameters, such as velocity and velocity gradient. Within the limited range of mass loading and mist diameter, the behavior of water mist in flames and the mechanism of extinguishment were investigated, using counterflow diffusion flame [26,51,52], and the critical stretch rate at extinguishment depends strongly on the droplet surface area parameter. To understand the underlying physics of the extinguishment of highly stretched diffusion flame by water mist, more experimental data are required, including measurement of the stretch rate at extinguishment with various mist diameters. In the present study, polydisperse water mist is used, because polydispersion is essential for the practical water mist generated by atomizers [46–48,50]. If all the mist droplets are small enough, they can evaporate in the flame zone and the diameter distribution should have only a secondary influence on the extinguishing behavior. However, if the diameter distribution includes some large droplets, they can go through the flame zone [46,47,49,50]. The current experiments are extensions of previous studies [26,51,52] and in the present study the experiments are conducted over a wider range of water mist diameters. The present investigation would advance the fundamental understanding of fire suppression by water mist from a scientific perspective and will be included in the design of water mist system.

2. Experimental apparatus

The experimental setup and measuring system are shown in Fig. 1. Air is supplied from a blower to the combustion wind tunnel, which consists of a diffuser, a settling chamber and a converging nozzle of a contraction ratio of 17.4. The combustion chamber was mounted vertically on the converging nozzle. The air stream entering the combustion chamber has a uniform velocity profile. The turbulence intensity was less than 2%. The cross section of the rectangular combustion chamber is 30 mm × 120 mm. Water mist was supplied by twin-fluid atomizers installed in the settling chamber and mixed with air stream and a uniformly dispersed mist-laden air stream was produced.

In the combustion chamber, an uncooled porous cylinder of 30 mm in diameter and 28 mm long was installed, from which