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Experimental and numerical investigation of the influence of laterally sprayed water mist on a methane-air jet flame

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HIGHLIGHTS

- Experimentally investigated impact of laterally sprayed water on methane jet flame.
- Studied impact on flame shape, temperature, radiation intensity, and extinguishment.
- Developed relationship between the mean flame tilt angle and Froude number.
- 3D numerical simulation showed sound agreement with experimental data.

ARTICLE INFO

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ABSTRACT

This paper investigates the impact of a laterally sprayed water mist on a methane-air jet flame. An experimental apparatus for suppressing a flame using laterally sprayed water mist was developed and used to investigate the effect of the mist on the flame shape, temperature field, velocity field, radiation intensity, and extinguishment. A 3D numerical simulation was then performed to reveal the underlying mechanisms observed in the experiments, with the simulations showing reasonable agreement with the experimental data. Increasing the pressure of the water mist decreased the flame height and increased its tilt angle. For a given water mist pressure, lower–velocity flames exhibited larger tilt angles, because they were more strongly affected by the transverse shear forces exerted by the water mist; additionally, they were more likely to be extinguished by the mist. A relationship between the mean flame tilt angle, and the Froude number was deduced. Water mist was also discovered to substantially decrease the radiation intensity of the flame. Moreover, the influence of gas velocity and water mist pressure on the turbulence intensity, radiation temperature, and velocity field were discussed numerically. This can theoretically help interpret the suppressing effect of water mist on a methane-air jet flame.

1. Introduction

The rapid advancement of human society and progress of modern industries have made natural gas a major energy source for powering cities and suburbs. However, this wide usage has also increased the risk of fires and explosions [1]. The gas pipelines used in the transportation and production of natural gas typically have large diameters and are under high pressure, making them liable to leakages and bursting [2]. Such events can have considerable human, environmental, and societal economic impacts because, once leaked, the flammable and explosive gases can mix with air to initiate jet fires, flash fires, and even vapor cloud explosions. Jet fires are the most frequent and complex accidents because of their low stability and unclear cause. Therefore, research into jet flame suppression continues to be a critical issue [3].

The technology used to suppress natural gas jet fires requires a swift response mechanism that is efficient at extinguishing the flame while also protecting the local environment. Numerous experimental and theoretical studies have been performed to investigate means of suppressing gas jet flames, including those considering liquid carbon dioxide [4], inert gases [5,6], phosphorous-based aerosols [7],

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halogenated alkanes [8–11], sodium bicarbonate particles [12], semi-aromatic polyamide [13], exfoliated clay nanocomposites [14], and halon replacements [15]. One study discovered that the suppression efficiency of water mist was approximately 3.5-times greater than that of N_2, CF_4, and CF_3Br, while also bearing in mind that many non-water suppressants exhibit inevitable drawbacks [16]. Indeed, water mist has become a promising replacement for halon for the extinguishing and control of fires. Several studies have demonstrated that the relatively high heat capacity and latent heat of vaporization of water mist mean that the mist's vaporization not only substantially decreases the local oxygen concentration, but also effectively extracts thermal energy from the fire [17–19].

Numerous experimental attempts have focused on using water mist to suppress jet flames. Some have investigated the physical suppression mechanism [20–23], whereas others have studied the suppression efficiency of water mist. For example, Mesli, etc. and Thomas compared the suppression effect of the structure of water mist by focusing on the droplet size and mass fraction of the condensed phase, mean strain rate, equivalence ratio, and degree of turbulence. They reported that extinguishing the richer flames with water mist is a complex phenomenon unless the concentration of the mist is trivially increased [24,25]. Similarly, Liu and Liao discussed the influence of the droplet size and mass fraction of the condensed phase on the temperature distribution of a methane-air flame and discovered that a mist consisting of 10–100 μm water droplets was an effective suppressant for a co-flow cup-burner flame [26]. Zhang et al. proposed a model of a flame heat-balance model that predicts the minimum concentration of different fire-extinguishing options for a methane-air diffusion flame in a cup-burner by testing ultrasonic- and air-atomized water mists containing various additives. The observations revealed that the presence of additives could change the fire extinguishing efficiency of pure water in comparison to the counterparts and the efficacy is ranked as $KCl > KH_2PO_4 > NH_4H_2PO_4$ [27]. Mazas et al. investigated the effect of increasing steam density on the laminar burning velocity of a premixed, oxygen-enriched methane flame, and concluded that the chemical impact on the flame speed was prominent and regarded as an inert diluent for highly oxygen-enriched flames [28]. Yoshida et al. analyzed the effect of mass loss and droplet velocity on the suppression of a counter flow, diffusion, methane-air flame; their results showed that an appropriate combination of stretch rate and water mist mass fraction could counterbalance the intensity of fire [29,30]. Huang considered whether a water suppressant was feasible by analyzing the ratio of water mist momentum to flame momentum. The author observed that the radiation flux of flame was closely related to fuel flow and diameter of jet nozzle and solely a function of pressure of water mist [31]. Yao et al. examined the interaction between water mist and a diffusion flame and found that the diffusion of oxygen in a confined space was particularly crucial for suppression using water mists. Furthermore, their results revealed that the effect on the smoldering using water mists was less than that of the flaming fires, and more smoke was produced [32,33]. Sasongko discussed the effect of polydisperse water droplet size distribution on the burning behavior and extinction condition of counterflow spray diffusion flame. The results indicated that for fuel droplet size higher than 48 μm, the optimum of water droplet size for suppressing counterflow spray diffusion flame was smaller than gaseous flame [34]. Richard conducted a phenomenological study and investigated the chemical and physical effects of water vapor addition on diffusion flames; results showed that that adding water vapor affects both physical phenomena and chemical reactions, and inhibits the soot formation and shifts CO to CO_2 [35]. These experimental studies revealed the burning behavior and suppression effect by varying the physical parameters or appendage content in various situations.

In recent decades, numerical research has investigated premixed and non-premixed flame-water mist interactions to better understand the influence of lateral spray water mists on methane-air jet flames and the mechanism involved in their suppression. For example, Prasad et al. quantified the relative contribution of various mist-suppression mechanisms and the effect of spray-injection-density, spray velocity, and droplet diameter on water-mist entrainment into a flame and flame suppression; their results indicated that smaller droplets exhibit smaller characteristic time for decrease in relative velocity and entrain most rapidly into the diffusion flame [36]. By using the PREMIX and OPPDIF codes in the CHEMKIN package, Arias et al. numerically investigated the effects of fine water–mist on laminar and turbulent flames, and revealed the thermal, dilution, and chemical effects of water mist on laminar flame speed. The authors observed a little chemical effect but not negligible, and water mist reduces the rates of chemical reactions involving the radicals that have the positive influence on the flame speed [37,38]. Teresa et al. conducted a numerical simulation to appraise the chemistry and behaviors of water and gas during the propagation of a premixed flame in a confined domain when the flame interacted with water mist. The authors presented the chemical structure and fluid pattern flow of non-perturbed and perturbed flames and concluded that the droplet break-up is due to the pressure wave, whereas the smaller droplets tend to acquire heat and vaporize rapidly, leading to greater effectiveness in flame quenching [39]. Shimizu et al. evaluated the gas-liquid two-phase problem by applying the Eulerian equation and established a numerical model of suppression of a methane-air jet flame by a water suppression; the numerical results showed remarkable flame quenching and observed the same with experimental results [40]. Yang et al. used a computational model to describe the thermal and chemical interactions between a freely propagating premixed flame and two phases of fine droplets; the numerical results indicated that both the droplet size and density had a significant influence on burning velocity and extinction conditions, and the results were delineated with the published theoretical analyses [41]. The numerical investigations were mainly focused on the influence of velocity, diameter of water mist on the chemical, physical, and burning properties on a vertical flame. However, current research on gas jet flames suppressed by water mist has mainly concentrated on the water mist jet source displayed above or below the flame [42]. Furthermore, experience suggests that unmitigated jet fires caused by gas leakage can have wide-ranging negative and localized effects. From a technical point of view, lateral water spraying can more readily alleviate the harm caused by fire [43]. However, the mechanism through which lateral sprays operate and their overall impact on a jet flame have not been fully documented yet.

Thus, this paper presented a novel experimental technique for suppressing a methane-air jet flame through lateral spraying with water mist. The mist's influence on the flame was evaluated to determine the combustion characteristics, such as the heat release rate, flame structure, radiation intensity, and extinguishing time. In addition, a three-dimensional (3D) numerical simulation was employed to model the experimental conditions. The reported findings are anticipated to enhance the understanding of such processes and will be useful in developing water mist fire-suppression systems, improving the efficiency and widening the field of application of fire-suppression systems and fire-control systems more generally.

2. Experimental

2.1. Experimental apparatus

The experimental set-up was composed of a jet burner, a water mist sprayer, and a data measurement and acquisition system, as illustrated in Fig. 1. Bottled methane was used as the fuel; the purity of methane was up to 95%. A decompressor (the mode is 190H-80) was mounted on the gas cylinder to ensure uniform and stable pressure of flowmeter. A rotator flowmeter (LZB-3WD) was used to control the flux of fuel. The range and precision grade of the rotator flowmeter were 0–10 L/min and 2.5 LZB, respectively. The external and internal diameters of the jet tube were 28 and 5 mm, respectively.