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Extinguishment of hydrogen diffusion flames by ultrafine water mist in a cup burner apparatus – A numerical study

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ABSTRACT

Transient simulations with full hydrogen chemistry were performed to reveal the flame structure and extinguishment process of co-flow hydrogen diffusion flame suppressed by ultrafine water mist (UFM). As UFM was added incrementally to the oxidizer stream, the flame experienced a series of destabilization process, i.e., detachment, drifting and blow-off. The simulations predicted that the critical mass flow rate of 10-μm UFM was 6 g/min, which is in agreement with the value calculated by a perfectly stirred reactor model and the value measured by the experiments. The critical mass flow rate exhibited a plateau region as the diameter increased from 5 μm to 20 μm. The optimal diameter for UFM was ≈ 10 μm. A scrutiny on the extinguishing mechanisms reveals that both the chemical kinetic effect and latent heat play important roles in determining the optimal diameter in this configuration. For the chemical kinetic effect, water molecule inhibits the flame through 1) enhancing the chain-terminating reaction $H + O_2 (+M) = HO_2 (+M)$ and 2) subsequently scavenging free radicals in the flame. An energy equation was used to investigate the relative importance of extinguishing mechanisms for UFM. It shows that the thermal cooling outweighs the chemical kinetic effect in terms of contributions to flame inhibition although the chemical kinetic effect is obviously enhanced compared with N_2.

Introduction

Ultrafine water mist (UFM) is an emerging fire extinguisher with merits of good diffusivity, small water damage, and high evaporation rate [1]. Hydrogen is a promising clean energy, but is dangerous for its low-energy ignition and wide flammability range. Previous studies [2,3] have showed that UFM has superior ability to mitigate gas explosion and many efforts [4–6] have been paid recently to investigate the effects of UFM in suppressing hydrogen-air explosion. The recognized effects include: 1) decreasing the burning velocity of hydrogen over a wide range of equivalence ratios [4]; 2) reducing both the initial rate of pressure rise and maximum overpressure [5–7]; 3) narrowing the total extent of the flammable region [8]. Compared with premixed gas explosion, hydrogen diffusion flames may be encountered when hydrogen leakage occurs. The extinguishing efficiency and mechanisms of the diffusion

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flame differ from its premixed counterpart because of different burning velocities and flame structures. However, few studies have been reported on UFM's abilities to suppress these flames and its inherent extinguishing mechanisms. The scope of the present study is restricted to the interaction of UFM and hydrogen diffusion flame in a cup burner apparatus at normal pressure. This arrangement is based on the following reasons besides of hydrogen safety. Firstly, Cup-burner Method is a widely accepted way to measure extinguishers' minimum extinguishing concentration (MEC), which serves as a reference for the design of fire protection systems. Although this method is designed for gas extinguishers, it is applicable for the two-phase UFM flow due to the excellent following features of UFM [9]. Secondly, the pool-fire-like cup-burner flame is more stable than real fires so that investigations on extinguishing mechanisms are readily performed. Finally, the hydrogen-air reaction mechanism is fundamentally important for sophisticated hydrocarbon fuels. The obtained results might be useful for interpreting the interaction process of UFM and hydrocarbon flames.

The cup burner flame is a laminar co-flow diffusion flame anchored upon a cup fuel source inside a quartz chimney [10]. Recent studies on the cup-burner flame have focused on two aspects: 1) setting up simplified models to accurately predict the MECs of gas agents for the purpose of harmonizing MEC data in standards, and 2) simulating the flame-suppressant interaction to further understand the extinguishing mechanisms. Senecal [11] developed an explicit relations for predicting MECs of inert gas agents in terms of heat capacity and fuel properties. The model worked well for inert gases but failed for chemical suppressants due to the neglect of detailed chemical reactions. Zhang et al. [12] and Liu et al. [13] proposed their simplified models based on a perfectly-stirred reactor (PSR). Their models incorporated detailed chemistry so that its scope was extended to chemical gas suppressants. However, the applicability of the above models to UFM has not been testified because UFM is a two-phase suppressant instead of a gas agent. Both experiments and simulations revealed that the base of the cup burner flame oscillated at a specific frequency due to the vortex evolution, fuel-air mixing and flame base propagation [14]. As the suppressant concentration was increased, the extinction occurred via a blowoff process rather than the global chemical extinction typical of counter-flow flames [15,16]. The flame-UFM interaction was a complex process that involved thermal cooling, dilution, chemical inhibition and radiation attenuation [17–19]. The first two factors were the dominant extinguishing mechanisms for water mist [17]. However, when the droplet diameter was reduced to ultrafine level, the chemical kinetic effect might play an important role in flame suppression [20,21]. The optimal diameter of monodisperse water mist was dependent on configurations and fuel types [22,23]. Numerical simulations showed that 32 μm was the optimal diameter for suppressing methane co-flow flame [22] but experimental investigations on laminar, freely propagating hydrogen-air premixed flames suggested that 5 μm was close to the small-droplet limit [23]. For hydrogen diffusion flames, the optimal diameter has rarely been reported. Hydrogen is distinguished from ordinary gas fuels with wide flammability range, high flame speed and reactivity. Besides, the fact that its combustion product is water indicates the potential capability of UFM in terms of fire suppression. These features might render different flame-UFM dynamics and extinguishing mechanisms.

In this study, hydrogen co-flow diffusion flames are simulated with full chemistry and their interactions with monodisperse UFM are investigated. The simulated critical mass flow rates of UFM ($\dot{m}_{c,\,UFM}$) are compared with the results of experiments and simplified models respectively. Besides, the optimal droplet diameter is obtained and the underlying reasons for this phenomenon are analyzed qualitatively. Finally, the relative importance of the extinguishing mechanisms is revealed by using an energy balance equation. The objective of this work is to understand the features concerning the interaction of UFM and hydrogen cup-burner flames with an emphasis on extinguishment limit and extinguishing mechanisms. Besides, the modified PSR model is expected to provide a quick method to estimate for other cup-burner flames.

The experiment and CFD modeling

The physical model setup

A sketch of the cup burner is shown in Fig. 1(a). The cup burner has a cylindrical stainless steel cup and a cylindrical quartz chimney. Gas flow rates are measured by calibrated mass flow meters and their uncertainty is 1% of the indicated flow. The fuel gas is H_2 and the suppressants are N_2 and UFM. UFM is supplied by an apparatus similar to that in Refs. [9,24], which consists of an auxiliary reservoir and a container for accommodating four ultrasonic mist generators. The mist generation rate (MGR) is controlled by adjusting the voltage applied on the mist generators. MGR is indirectly determined by measuring the mass loss rate of the container. The deposited UFM on the walls during each experiment is collected and subtracted from the MGR. The UFM is characterized by a Particle Master IMI produced by Lavision Co. [25] prior to the extinguishment tests. To determine the extinguishment limit, the agent is gradually added to the air stream at a fixed fuel and air flow rate until the flame temperature suddenly drops.

The parameters of the physical model are set according to the experimental conditions. Hydrogen is injected from the fuel inlet with initial temperature of 298 K and velocity of 6.5 cm/s in order to achieve a laminar flame with a visible flame height between 75 mm and 85 mm [10]. The temperature of the inlet oxidizer stream is 298 K and its velocity is fixed at 13.6 cm/s under 1 atm. The temperature of the chimney and cup wall is set at 298 K except the 600-K cup wall within 1 mm from the top cup brim [22]. No slip condition is applied to the walls. The normal thermal emittances of the hot cup wall and cool cup wall are 0.24 and 0.22 respectively [25]; the hemisphere integrated radiant emittance is 0.93 for the chimney wall. Four types of oxidizer stream are considered in the simulations, i.e., dry air, dry air with nitrogen, dry air with water vapor, and saturated air with monodisperse UFM (5 μm, 10 μm, 15 μm and 20 μm). The outflow pressure equals to 1 atm and the backflow is dry air. The time-dependent calculation is run for separate cases in which the