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Experimental and numerical investigation of flame speed retardation by water mist

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ABSTRACT

Water mist has been recognized as an alternative of halogenated hydrocarbon fire suppressants due to its high thermal and chemical effects on the flame speeds. In the present study, the effects of fine water mist on laminar flame speeds of propane-air mixtures are investigated both experimentally and numerically. In experiments, the laminar flame speeds are measured using a single jet-plate configuration for the cases with and without water mist. The numerical simulation is also performed using the PREMIX and OPPDIF codes in CHEMKIN package. To include the phase change with evaporation, the evaporation process is assumed as a chemical reaction of which rate constant follows the Arrhenius law. The laminar flame speeds without water mist increase with stretch rate for all the equivalence ratios tested and are in fairly good agreement with the previous experiments. When the water mist is added, the numerical simulation predicts the positive dependence of flame speed on stretch rate similar to the case without water mist, whereas in the experiments the flame speeds decrease with stretch rate. In the stagnation flow field, the large radial acceleration of the flow induces the mist droplet accumulation around the stagnation stream line, leading to the negative dependence of flame speed on stretch rate. Numerical simulation reveals the thermal, dilution and chemical effects of water mist on laminar flame speed, and the chemical effect is found to be small but cannot be neglected. The water mist reduces the rates of chemical reactions involving the radicals such as O, H and OH, which have the positive sensitivity of flame speed. Furthermore, three-body chain terminating reactions involving H_2O are enhanced. These reactions have large negative sensitivities of flame speed due to high chaperon efficiency of H_2O.

1. Introduction

Water mist is a favorable substitute for typical halogenated hydrocarbon fire suppressants, e.g. Halon 1301 (CF_3Br) and Halon 1211 (CF_2ClBr), because water mist is ubiquitous, inexpensive, non-electrically conductive and environmentally acceptable and also is fairly effective to suppress fires and to mitigate explosions [1–4]. Adding water mist in a reactive mixture is known to cause significant changes in flame properties by three following mechanisms; (a) thermal effect due to the absorption of the heat, (b) dilution effect caused by the reduction in reactants concentration, (c) chemical effect owing to the activity of water vapor that may alter some reaction paths. Fine water mist enhances these effects due to significant increase in surface area available for heat absorption and evaporation. Those three mechanisms are concomitant and closely linked with each other. In addition, the flame stretch also affects the flame properties and extinguishment process. However, few studies exist in the literature relating to the effect of water mist on stretched flame from the point of view of fire suppression and explosion mitigation.

The effectiveness of gaseous water vapor as a fire suppressant has also been long recognized. The influences of gaseous water vapor on the laminar flame speed of methane flames were investigated [5], and the numerically predicted reduction in flame speed was in good agreement with the experiments. In addition, the chemical effect of water vapor on the combustion reactions of H_2–CH_4–Air mixtures was found to be small but not negligible [6]. Effects of elevated temperatures and pressures on the laminar flame speed of H_2–O_2–water vapor system were studied both experimentally and computationally [7], and a significant reduction of the flame speed was found by addition of water vapor.

Liquid water has a more favorable thermal property for fire suppression, because it has a high latent heat of evaporation and can absorb a significant quantity of heat from flames. Therefore, water mist should be more effective in reducing the flame speed of

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methane-air flames than other gaseous thermal agents (N_2 and CF_4) or chemical agents (CF_3Br), and also more effective than the same mass of gaseous water vapor [8]. Furthermore, the flame speeds of propane-air premixed flame stabilized in the stagnation flowfield and influenced by water mist were measured [9] and the dependence of flame speed on stretch rate was found to change from positive to negative by addition of water mist. In the diverging flow field, the mist droplets accumulate around the stagnation stream line due to the Stokes number effect acting on mist droplets.

Laminar flame speed is a fundamental property of a flammable gaseous mixture describing the overall reaction rate, heat release and heat and mass transport in the flame and as such many efforts have been devoted to measure or predict the precise laminar flame speeds of various kinds of fuels. For the flame speed measurement, the counterflow, opposed-jet technique was well documented [10–15], and has been traditionally implemented with the use of twin-opposed-nozzle or single jet-plate configurations. In a twin-flame or single-flame configuration, the velocity minimum is identified in the velocity profile as a reference upstream flame speed S_L and the velocity gradient a ahead of the minimum point is identified as the stretch rate K (= a for an axisymmetric flame) experienced by the flame. The unstretched laminar flame speed S_L^0 is obtained by systematically determining the dependence of the reference flame speed S_L on the stretch rate K and extrapolating S_L to zero K.

The reduction in laminar flame speed is frequently used as an indicator of the fire suppression effectiveness of an inhibiting agent [16–18]. The impact of gaseous water vapor or liquid water mist on stretched laminar flame has been the subject of a relatively limited number of studies. In the present study, the effects of water mist on the laminar flame speeds of propane-air mixtures are investigated both experimentally and numerically. In the experiments, stretched laminar premixed flames are established in the stagnation flow field produced by a mixture flow emerging from a nozzle impinging on a flat plate. The unstretched laminar flame speed S_L^0 is obtained by a linear or nonlinear extrapolation to zero stretch. The effect of water mist on flame structure and flame speed is also simulated numerically by using PREMIX and OPPDIF codes in CHEMKIN package, modified to include the evaporation process, which is assumed to be a chemical reaction.

2. Experiments

2.1. Experimental apparatus

Hitherto, a twin flame [10–14] or a single flame [15] has been used for the determination of laminar flame speeds and stretch rates at extinguishment of H_2 and C_1–C_3 hydrocarbon fuels. In the present study, experiments were performed for atmospheric propane/air flames at different equivalence ratios in the single jet-plate configuration with and without water mist in the mixture. The details of experimental apparatus have been described in Ref. 9. In brief, the single jet-plate configuration included impingement of mixture flow from a contoured nozzle on a stainless steel stagnation plate. The inside diameter of the nozzle exit was 45 mm. The mixture flow was surrounded by a shroud flow of air to protect from the disturbances caused by the entrainment of surrounding air. Propane was used as a fuel throughout. Water mist diameters and their distributions were measured by a phase Doppler particle analyzer (PDPA) and the flow velocity by a laser Doppler velocimeter (LDV). For PDPA and LDV measurements, the mixture flow should be seeded with light scattering particles. For the case without water mist, the mixture flow was seeded with aluminum oxide (Al_2O_3) particles of a nominal diameter of 1 μm, generated by a fan-stirred particle generator. When the water mist was added to the mixture flow, the water mist itself played a role of light scattering particles. To generate fine water mist, 6 piezoelectric atomizers were used, which could be operated separately. The number mean diameter of water mist droplets D_{10} was 11.5 μm and the Sauter mean diameter D_{32} was 18.4 μm with a wide range of size distribution ranging from 1 μm to 60 μm.

The fidelity of the water mist droplet to the flowfield change may be determined by the Stokes number defined as

$$St = \left(\frac{\rho_w D_0^2}{18\mu}\right)\left(\frac{du}{dz}\right)$$

where ρ_w and D_0 are density and diameter of droplet and μ viscosity of air, u is the velocity of mixture, z the distance from the stagnation plate. Therefore, the traceability of the droplets depends not only on diameter but also on local velocity gradient. At the velocity minimum where the flame speeds were determined, the flow deceleration changes to acceleration and there exists a neutral point where the velocity gradient vanishes and droplets of all sizes move following the flowfield. This condition was really achieved in our previous study [19], in which the droplet velocity of each size was measured near the velocity minimum in the stagnation flowfield by PDPA and all the droplets with varying diameter from 1 μm to 60 μm had a same velocity even the global velocity gradient estimated using far-field quantities of approaching flow was as large as 300 s^{-1}.

The most crucial experimental uncertainties in the present study could be associated with the reactant flow rates, i.e. equivalence ratio ϕ, of which reproducibility was within 5%. Other experimental uncertainties such as diagnostic equipment, flow velocity measuring approach, data analysis, and finally data interpretation, based on 2σ, where σ is the standard deviation, can be lower than 5%.

2.2. Unstretched laminar flame speeds without water mist, S_L^0

The present experimental conditions were limited within the range of equivalence ratio, $0.8 < \phi < 1.3$, because, when $\phi > 1.4$, the cellular instability appeared at small velocity gradient a for large separation distance L and small flow velocity u, and when $\phi < 0.7$, the flame was deformed significantly and was not stationary at small a.

The velocity profile along the stagnation stream line can be considered to be the superposition of the effects of the flame and the stagnation flow field. When approaching the flame zone, the velocity decreases almost linearly with the distance from the stagnation plate z. The velocity gradient $a = du/dz$ was obtained from the velocity profile along the stagnation stream line. Then, the flame stretch rate $K = a$ was determined. The velocity abruptly increases in the flame zone due to thermal expansion, and then decreases again toward the stagnation plate. The velocity at the point of initial temperature rise is the point where the curve starts to depart from the descending line due to thermal expansion, and the minimum point was defined as a reference upstream flame speed of a stretched flame S_L, similarly to previous investigations by Law and co-workers [10–15]. The unstretched laminar flame speed S_L^0 can be subsequently determined by systematically extrapolating S_L to zero K. By increasing the nozzle exit velocities or decreasing the separation distance, K increases, the flames are pushed toward the stagnation plate, and extinguishment is eventually occurred when a critical value K_{ext} is reached.

3. Numerical simulations

The PREMIX and OPPDIF codes in the CHEMKIN package were utilized to simulate the flame structure and the flame speed of stretched, adiabatic, laminar propane-air premixed flames stabilized in the stagnation flow field. The flame speeds estimated by CHEMKIN depend on the reaction mechanism adopted. The present