A NUMERICAL MODEL FOR WATER MIST SUPPRESSION OF A SOLID PLATE IN BOUNDARY LAYER FLOW

Ramagopal Ananth (rananth@castor.nrl.navy.mil, 202-767-3197),
Navy Technology Center for Safety & Survivability, Chemistry Division
Naval Research Laboratory, Washington, DC 20375
Chuka C. Ndubizu
Geo-Centers Inc., Lahnam, MD
Fredrick W. Williams
Navy Technology Center for Safety & Survivability, Chemistry Division
Naval Research Laboratory, Washington, DC 20375

ABSTRACT

Solid materials, bulkheads and ceilings, often form boundary layer flames, where in wind aids the burning process. The wind aided burning is one of the most hazardous conditions in practice and is also least understood. Simulation of water mist suppression of wind aided combustion can play a fundamental role in extending water mist technology to various parts of a surface ship. We have generalized the transient solutions of full Navier-Stokes equations for combustion of a PMMA plate to include suppression effects due to water droplets, which were varied in size, concentration, and velocity. Simulations were performed for both traditional water mist and fog like ultra fine mist, which has relatively small momentum and droplet size (1-10 microns). As the droplets are introduced, the leading edge of a stable boundary layer flame advances downstream establishing a quench distance. At increased droplet concentrations, the flame detaches from the surface and is transported off the computational domain, and the flame is extinguished. We present the effects of droplet size and concentrations on flame temperature and local pyrolysis rate profiles for the fine mist and regular mist, and show comparisons with experimental data.

INTRODUCTION

Water mist is being tested as a replacement to halon 1301 and as a main fire suppression agent on Navy ships. In the total flooding scenario, very small water droplets are suspended in the air for a significant length of time so that they are carried by the air currants near a burning bulkhead. Ultra fine mist (1-10 microns) is also being evaluated for suppression of cable fires in small electronic spaces in sub floor geometries, where water damage to operation of electrical circuits is of a concern. The fog like ultra fine mist is generated by piezoelectric method at ambient pressure rather than the traditional high pressure nozzles, which impart large momentum to the droplets. The objective of this work is to develop an understanding of the suppression characteristics of both the traditional and ultra fine water mist on burning solid plates.

Boundary layer flames often form naturally due to the buoyancy driven flow past solid materials, such as bulkheads and ceilings of a surface ship. To gain insights, buoyancy driven flow is often replaced by well defined forced convection past a flat surface in the laboratory. This enables us to vary the air velocity, which has crucial effect on the rate of burning, as an independent parameter. Emmons [1] provided the theoretical basis by deriving classical boundary layer solutions, which predict that the dimensionless burning rate decreases as inverse square root of the Reynolds number. Recently, Ananth et al. [2] obtained solutions of full Navier-Stokes (NS) equations along with iterative solutions for the surface temperature and pyrolysis rate distributions along the surface of a PMMA (Poly-methylmethacrylate) plate. The predicted pyrolysis rate and temperature distributions were compared with our experiments by Ndubizu et al. [3] for boundary layer combustion of thermally thick PMMA plates. At short distances from the leading edge of the PMMA plate, it is found that the NS solutions for pyrolysis rates agree with the experiments at short burn times. As the burn time increases the measured pyrolysis rate decreases due to moving boundary effects in the experiments. At long distances from the leading edge of the PMMA plate, however, the NS solutions agree with the experiments at long burn times. At short burn times, the pyrolysis rates increase with time due to transient thermal conduction into the solid phase.

Numerous studies were performed on fire suppression by water droplets as reviewed by Tatem et al [4]. Recently a few studies have considered the effects of fine water mist. Lentati and Chelliah [5] studied suppression and extinction of a diffusion flame formed between two opposing jets of methane and air (counter-flow). Prasad et al. studied water mist suppression of diffusion flames formed between two parallel jets of methane and air (co-flow) [6]. The water mist was introduced with the air flow at different concentrations and size distributions. Prasad et al. [7] also simulated water mist suppression of methanol pool combustion. Schwer et al. [8] studied the effects of fine mist and particles on detonations in a tube.

In this work, we consider a boundary layer flame formed over a PMMA plate by forced convection of air at a specified velocity. The solutions for this base case and the effects of increased air velocity have already described in detail by Ananth et al. [2] in a previous paper. Water droplets are then introduced into the air stream at prespecified concentration and at air velocity. We consider both mono dispersed droplets with a specified size and poly dispersed droplets with a specified size distribution measured in the experiments, which are described in a separate paper presented by Ndubizu et al. at this conference. The droplets are grouped in to five sections. Each section contains droplets of prespecified size range, with a characteristic droplet velocity and a characteristic droplet concentration. As the droplets approach the flame front they begin to follow the stream lines to the degree permitted by their drag and inertia. The droplets also begin to evaporate, they reduce size and transfer mass, energy, and momentum to other sections. Thus, the sections of droplets interact with one another while interacting with the flame. Transient solutions to the NS equations are obtained for each section of the droplet phase and for the gas phase. The results presented here focus mainly on the effects of droplets on flame temperature and pyrolysis rates.

APPROACH

We consider air flow past a flat solid surface, which consists of a leading inert plate (1.7 cm), followed by a PMMA plate (6.5 cm), and followed by another inert plate (8 cm) as shown in

Figure 1. The solid surface is assumed to remain flat during combustion. Gases are ignited along the entire PMMA surface by adding external energy for a short period of time. Forced convection is assumed to dominate the buoyancy effects especially for a short distance from the leading edge, where the most burning occurs. The NS equations include radiation losses from the hot gases to the ambient following Stefan-Boltzman law. Methyl methacrylate monomer vapor is assumed to undergo stoichiometric combustion to form water vapor and carbon dioxide. A single-step, second-order, PMMA combustion kinetics given by Krishnamurthy and Williams [9] is used (E = 43 Kcal/gmole, ΔH = 2530 KJ/gmole). The solid polymer is assumed to undergo zeroth-order, single step pyrolysis at the surface to form the monomer vapor as shown by Arisawa and Brill [10] (E = 66000 cal/gmole, A = $8x10^{17}$ gm/cm^2sec). The NS equations are solved by using Barely Implicit Correction to Flux Corrected Transport (BIC-FCT) algorithms [2] with time-step splitting. The equations are discretized using 192 x 144 finite volume cells, with the smallest cells (0.2 mm x 0.2 mm) placed near the leading edge of the fuel plate. The cells are stretched at a low rate in both x and y directions from the leading edge. An iterative scheme is used to impose interfacial balances at the solid gas interface and to obtain distributions at the surface.

Once a steady state boundary layer flame is established, water droplets are introduced into the air stream. We use sectional approach described originally by Tabor et al. [11]. This approach was applied successfully by Prasad et al. [6,7] to water mist suppression of co-flow diffusion flames and by Schwer et al. [8] to effects of on detonations. In this approach droplets are divided into different sections. Each section contains a prespeciifed range of droplet sizes. The droplets in a given section travel at an integrated average velocity, temperature, and concentration. The mass density and momentum for each section are obtained from conservation equations written separately for each section. These balance equations, which are a form of Boltzman spray equation [12] are solved by FCT (Flux Corrected Transport) algorithms. The mass and momentum equations for each section of the droplets are coupled to the NS equations for the gas phase via coupling terms, which include, drag, inertia, and evaporation effects. Therefore, the conservation equations for the five sections of the droplet phase and the NS equations for the gas phase are solved together at each time step. The time marching scheme is continued until a new steady state flame is formed or the flame is extinguished. The simulations are carried out for different values of the concentration and size distribution for each section of droplets in the inlet air. The velocity of all droplets at inlet is set to be that of the air stream.

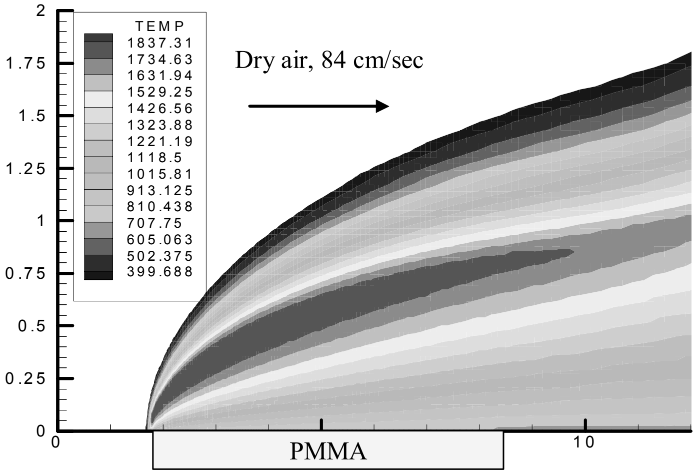

Figure 1. Temperature contours without water mist (base case)

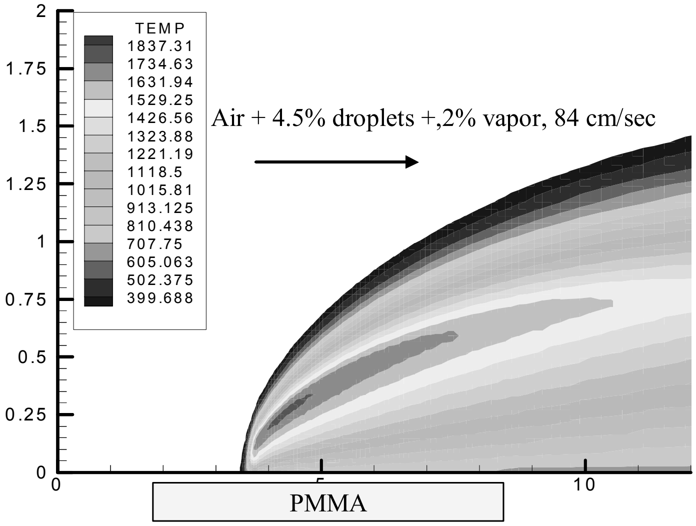

Figure 2. Temperature contours with ultra fine mist, which contains a mixture of water droplets and vapor

RESULTS AND DISCUSSION

In the simulations for the ultra fine mist, which is a mixture of water vapor and droplets. The inlet air stream is saturated with water vapor, since the droplets undergo evaporation near room temperatures atthese extremely small droplet sizes. When the concentration of the droplets is higher than the air saturation (about 2.0 mass %), the liquid droplets travel with air towards the flame over the PMMA plate. This is consistent with the observations made in the experiments by Ndubizu et al. (presented in an accompanying paper at this conference), who show that the fog like mist travels as a cloud above the flame. Ndubizu et al. measured the droplet size distributions and the concentrations in the bulk.

Simulations are performed for the poly dispersed ultra fine mist. Figure 1 shows flame temperature contours for the base case before the water droplets are introduced. Figure 2 shows the temperatures after ultra fine mist is introduced into the air stream and a new steady state is established. In addition to saturating the bulk air with water vapor, the mist contains 4.5% water as liquid droplets at the inlet. As the vapor and droplet mixture approach the flame they begin to evaporate and cool the surrounding hot gases. They also produce water vapor, which dilutes the oxygen. This reduces the rates of reaction and heat release near the leading edge of the flame. Due to the reduced heat release rate it takes a longer distance for the gases to rise to combustion temperature. Therefore, the leading edge of the flame moves downstream and attaches at a distance (quench distance) from the leading edge of PMMA plate. Furthermore, the temperatures are clearly much smaller with mist in Figure 2 than without. The flame length is also much shorter in the presence of the ultra fine mist.

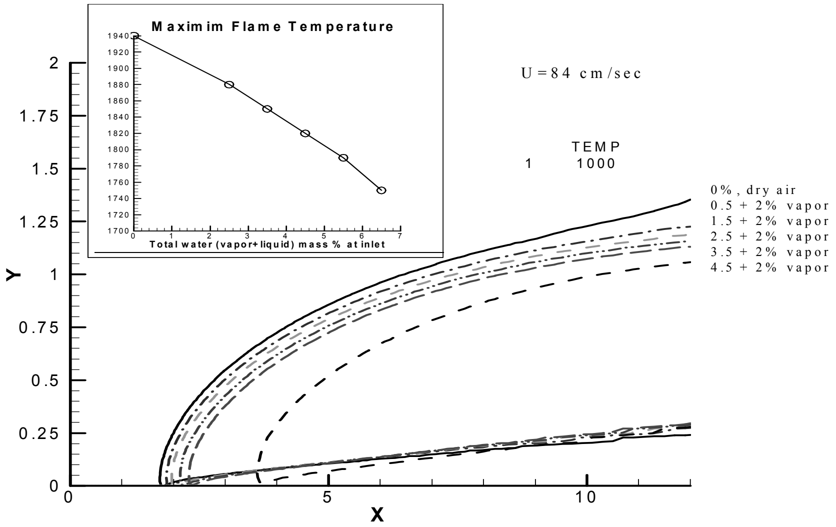

Figure 3. Temeprature contours (1000 K) at different values of ultra fine mist concentrations

Figure 3 shows 1000 K temperature contour for the base case and for different concentrations of the droplets in the saturated (sat.) vapor liquid mixture (ultra fine mist) in the inlet air at steady sate. The contours are curved like a parabola on the air side and become straight line on fuel side above PMMA surface (Y=0). As the droplet concentration increases, the flame front advances downstream with a biggest jump occurring at 4.5 mass %. A further increase in droplet mass % to 6.5 resulted an unsteady flame, in which the flame continues to advance downstream with time, without reaching a steady sate. As time progresses, the flame eventually blows off the computational domain and is extinguished. The inset in Figure 3 shows the effect of increased droplet concentration on maximum flame temperature. The first point at 2.5% total water contains 0.5% in droplet form and 2% in vapor form. The maximum flame temperature drops below 1750 K before flame extinction occurs.

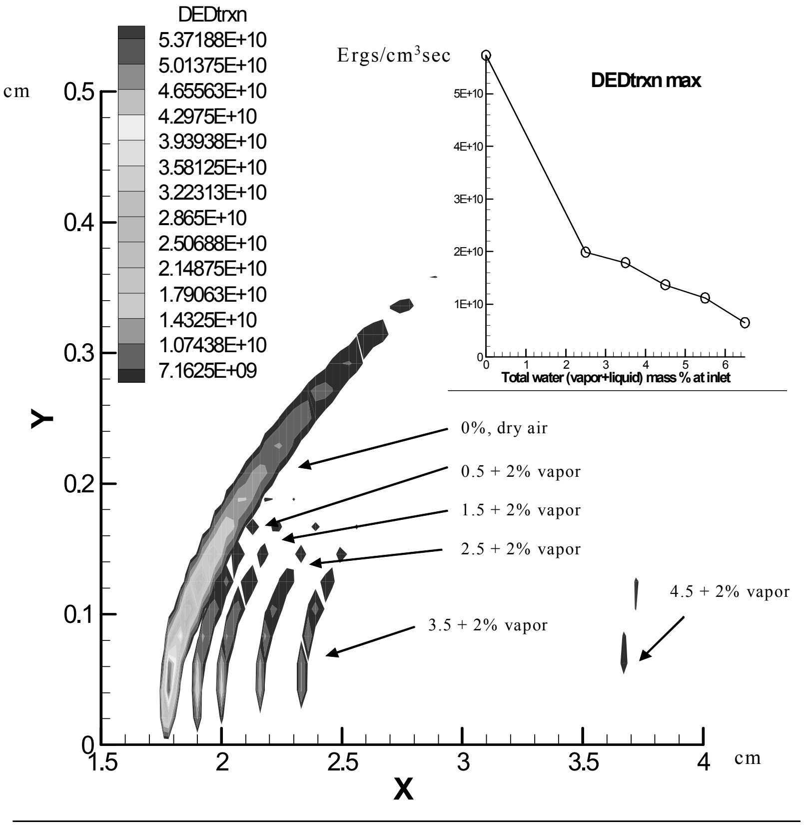

Figure 4. Effect of ultra fine mist concentration on heat release rate DEDtrxn for U=84 cm/sec

As the droplets and vapor mixture lower the temperature and dilute the oxygen of in the gases near the leading edge of the flame, the combustion reaction rates are reduced significantly as shown in Figure 4. Figure 4 shows the heat release rate contours at different concentrations of droplets in the droplet and vapor mixture of the ultra fine mist. Clearly, the contours decrease both in size and in intensity as droplet concentration is increased. At 4.5 mass%, the hrr contour is very small. The discontinuous nature of the contours is artificial to plotting. The combustion reaction and the associated heat release are the highest near the leading edge of the flame, where fresh fuel vapor meets fresh air. The inset in Figure 4 shows quantitatively that the maximum heat release rate (ergs/cm^{3}sec) decreases by a factor of 10 as the droplet concentration increases to 4.5 mass%. Indeed most change in hrr appears to occur due to the introduction of the saturated air (2% water vapor) as indicated by the first point at 2.5% total water in the inset to Figure 4. Clearly, dilution effect plays a major role in the effectiveness of the ultra fine mist.

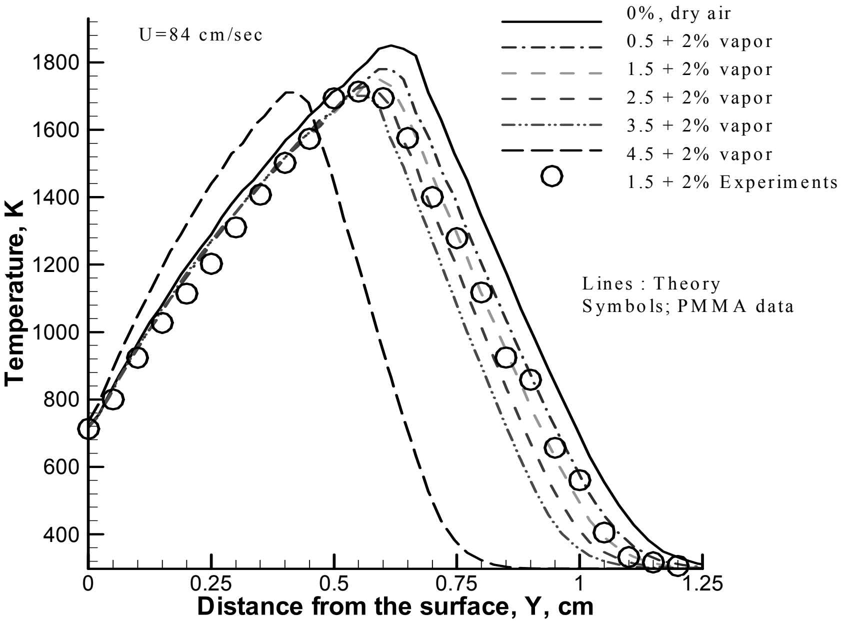

Figure 5. Comparison of theory with PMMA data for temperature profile across the flame at xl=3.7 cm from the leading edge of the plate.

Figure 5 compares the NS solutions with our experimental data (Ndubizu et al.) for the temperature profiles across the flame measured at xl=38 mm from the leading edge of the PMMA plate. It shows good agreement between the experiments with the ultra fine mist and the computations. Comparisons were also made at different distances from the leading edge, xl. They show that the NS solutions over predict the data near the surface at small values of xl. This is partly due to the fact that surface regresses significantly at small values of xl, and the vertical distance from the surface, Y, shown in Figure 5 is measured from the original unburnt surface. At large values of xl, however, the surface regression is relatively small, and the theory is in good agreement with the data.

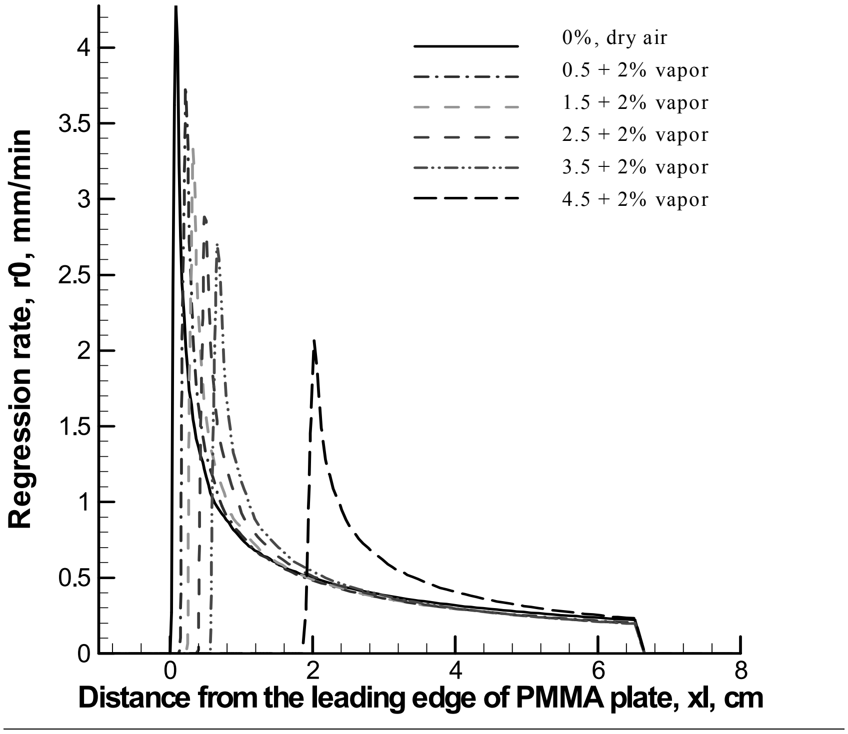

Figure 6. Effect of ultra fine mist on the regression rate of PMMA for U=84 cm/sec

Figure 6 shows the pyrolysis rates of PMMA at different values of the ultra fine mist droplet concentrations. As the mist concentration is increased, the maximum regression rate of the PMMA surface predicted by the theory decreases. The maximum regression or pyrolysis rate occurs at the flame attachment point, where the heat feed back to the surface by conduction and convection are highest. The flame attaches larger distances downstream of the leading edge of the PMMA plate as the mist concentration is increased. A further increase is mist concentration from 4.5 to 6.5% droplets causes flame extinction by blow-off. Figure 6 also seems to show, that the addition of mist has very small effect on the regression rate at large distances (>30 mm) from the leading edge of the PMMA plate until one reaches 4.5% droplet addition. This is consistent with Figure 5, which shows that the slope of the temperature profile at the surface (Y=0) does not change significantly as the droplets are added for xl=38 mm.

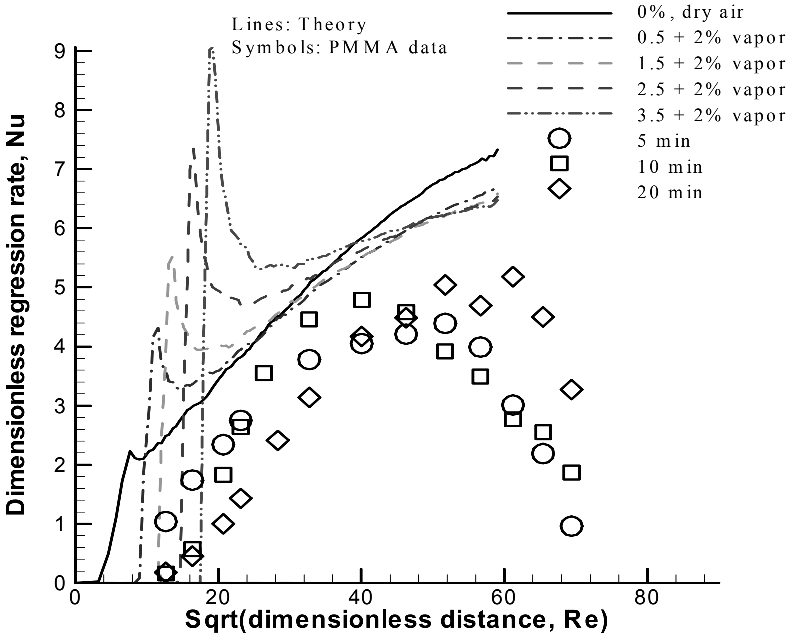

Figure 7. Effect of ultra fine mist on dimensionless regression and comparisons with PMMA data

Figure 7 compares the steady state regression rate,Nu, predictions with the experimental data, which are inherently transient due to the moving boundary and solid phase conduction effects discussed by Ananth et al [2]. Nusselt number, Nu, is the dimensionless regression rate and Reynolds number, Re, is the dimension less distance from leading edge of the PMMA plate. The main point of Figure 7 is that the experimental data approach the theoretical solutions for large values of xl or Re as time progresses. Figure 7 shows that the measured regression rates decrease with time at small values of xl or Re due to the moving boundary, and increase with time at large values of xl or Re due to transient solid phase conduction. As the time progresses, the solid phase conduction approaches steady state and regression rates approach the steady state theoretical predictions. Higher the air velocity, the faster this occurs. This was seen clearly for the base case at air velocity of 169 cm/sec as shown by Ananth et al [2]. At air velocity of 84 cm/sec, however, the transient effects still persist both in the base case and for the mist cases. However, it can be seen clearly from Figure 7, that that the regression rate, Nu, increases towards the theoretical predictions.

CONCLUSIONS

Water mist suppression of a burning PMMA plate has been studied theoretically and experimentally to show the effects of ultra fine mist and traditional mist on flame temperature, heat release rate, pyrolysis rate, and extinction. Computations were performed at different air velocities, droplet diameters, and concentrations. However, we focused mainly on the ultra fine mist, which is a mixture of poly dispersed droplets and water vapor, and presented results for different droplet concentrations. The results provide new insights into the dilution effects at these very low droplet sizes.

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