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Experimental Study of a Downward Directed Water Mist suppressing a Diffusion Flame

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Experimental Study of a Downward Directed Water Mist suppressing a Diffusion Flame

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ABSTRACT

Interaction of fires with water have been a focus of study for human kind from the times immemorial. With the recent advances in water-based suppression, and restrictions put on halon usage, sprinklers and water-mist based fire suppression systems have become popular for industrial usage. Of this water mist is an interesting candidate, for it has advantages and to name a few would be less water requirement, non-wetting nature, gas phase action on fire. Water mist, as an effective fire suppressant, works on the principle of oxygen dilution and flame cooling.

In this work, we are studying the action of water mist on a diffusion flame. The water mist was generated from a Delavan nozzle, fed with high pressure water, which is then directed downward into the raising flame. A circular burner fed with Methane in a controlled manner generated the diffusion flame. The reason to prefer a gas burner is to have a control over heat release rate which will help in simulating various fuel sources of different burning rate. A glass cubicle was used to isolate the experiments from ambient disturbances. A Digital SLR camera was used to record the flame and subsequently the images were processed to obtain flame height. Particle Image Velocimetry was used to study the effect of the flame on the water mist., by imaging the Mie scattered laser light from the droplets. Parameters that were varied were the injection pressure and flow rate of the Methane into the burner.

Visual imaging from the camera indicated that there were occasional flame tip flattening during the suppression mechanism. The flame luminosity is diminished and the diffusion flame height is reduced due to the action of the water mist. Moreover, this effect is more pronounced for smaller flame than larger flame, indicating the role of the buoyancy in fire suppression effectiveness. The PIV results show that the droplets are slowed down very close to the nozzle due to the flame. Also, a recirculation zone is observed at the periphery of the spray cone, very close to the nozzle. It is a toroidal vortex that is generated due to the interaction, and the droplets thrown away from the spray cone gets trapped into this flow. The flow structure is present in a highly turbulent region and is identified in the mean field. Another finding is that close to the burner, fine droplets that could make it to the base, gets entrained into the flame. It is expected that the droplets tend to be entrained into the larger flame, as the entrainment is stronger for large flame, compared to the smaller flame. But the PIV results indicate otherwise, which is attributed to the larger size of droplets making its way close to the burner.

We believe that these results will enlarge our understanding of the suppression mechanism of water mist and could form a basis for validating various simulation models.

KEYWORDS:

Water mist; fire suppression; PIV; Flame height; Image Processing

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INTRODUCTION

Water mist is the name given to a water spray in which all droplets are of the diameter less than 1000µm [1]. Water has been a firefighting material since time immemorial. But water in the form of mist has been studied for fires fighting only in the last few decades. There have been tests carried out to assess the effectiveness of water mist in the late 50s and 60s [2]. But the momentum for scaling the technology died out due to various reasons, mainly due to the prevalence of Halon. A renewed interest in the water mist has been observed lately. There has been a lot of factors that fuelled this. The Montreal protocol banned Halons, which called for a swift identification of a suitable substitute, and water mist has been a top contender.

The mechanism of fire suppression by water droplets has been well studied. The droplets in the water mist enter the fire and evaporate which cools the fire as well as dilutes the ambient of Oxygen due to rapid phase change from liquid to gas. There have been speculations on the degree of the role played by water mist in the kinetics of the flame suppression but this is yet to be fully studied [3]. In the past, few studies on fire suppression have been carried out by loading the co-flow with water mist that enters the flame [4][5]. This case is not very representative of real fires as entrainment occurs from the stagnant ambient air. Also, the water mist may not enter perfectly from the entrainment. Studies have been carried out where the water mist was generated from high-pressure nozzle systems. For practical purposes, the convenient mounting and orientation of mist injection would be from the ceiling, in continuance with sprinkler system. This motivated few studies where the mist was directed downward into the flame [6]**.** Few pool fire suppression studies using the same orientation has also been undertaken [7][8]**.**

Some experiments that have been carried in the past shows the use water mist consisting droplets of diameter ranging from 5μm [9] **to** few hundreds of microns. The parameters that were studied in large extent were loading fraction, temperature and species. Many of them were intrusive and there is a paucity of non-intrusive diagnosis. Piezoelectric discs have been employed to generate ultra-fine mists, which has been commercialized too. But there is quite an uncertainty as to what is the exact loading, diameter and velocity that will quench or suppress the fire [10]. Droplets with large momentum might penetrate the flame front without cooling the flame, while droplets with less momentum might evaporate before reaching the flame front. A lot of work has gone into the numerical simulation too [11], that have attempted to validate the results.

In this study, a set of experiments were carried out to understand more about the interaction of downward directed fine water droplets of the mist with flame. In line with real fires, a diffusion flame is set up with no co-flow. A circular burner fed with Methane was used for this. Also, being gas fed gives the advantage to control the heat release rate and the scale of the fire with which the water mist is interacting to suppress it. Water mist was generated from a simplex nozzle and they spray was directed downward into the flame. Particle Image Velocimetry was used to deduce the velocity field within the spray cone. A Digital SLR camera was used to study the effect of water mist on the flame.

The height between the water mist injection point and the flame was fixed at a height of 900mm. The injection pressure of water into the nozzle was varied between **7bar** and **10bar**. The flow rate of gas into the burner was adjusted to provide an equivalent heat release rate of 5kW (10 slpm of CH4), and 10kW (20 slpm of CH4). The hear release rate is estimated by making use of CH_4's heat of combustion.

We believe that the results from these experiments will facilitate as a baseline for validating and comparing simulation results.

METHODOLOGY

Experimental setup

The schematics of the experimental setup is shown in Fig.1. A Delavan nozzle of the model CT-1.5–30 B was used to generate the water mist. The nozzle generated a solid cone spray with a spray angle of 30°. The flow rate at 7bar(100psi) gauge pressure was around 0.084 LPM(1.5GPH). The nozzle was mounted on a 600mm X 600 mm Aluminium plate, which houses a machined nozzle holder. A stainless-steel water pressure tank was pressurised in the range of 7-10bar which was connected to the nozzle. Compressed N2 was used for pressurising the water tank.

A 50mm internal diameter burner of height 200mm forms a diffusion flame. CH4 was fed through Alicat MFC into the burner to set a controlled flame. CH4 flows through a set of four meshes with progressively reducing wire and mesh sizes, which sets up a uniform profile at the outlet at the burner mouth. A gas fed diffusion flame burner is the closest analogy to a real-life fire encountered in fire accidents.

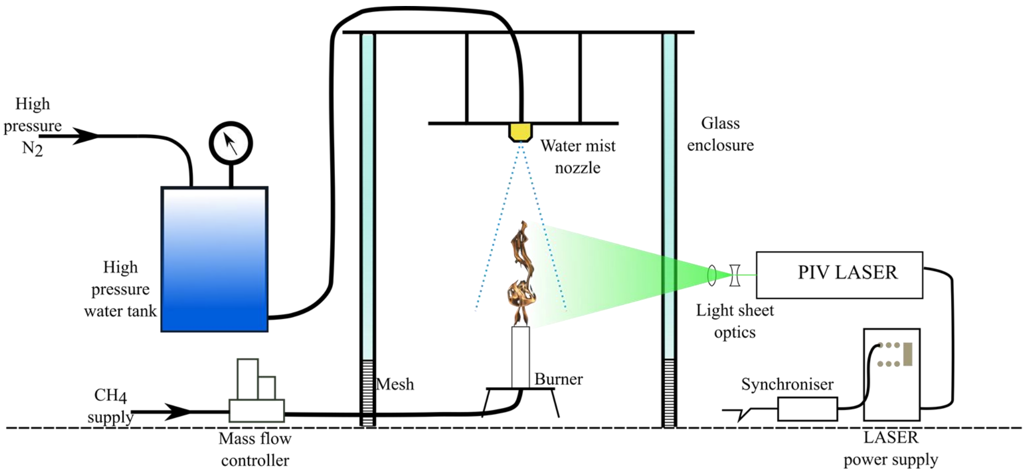


Fig.1.Schematic of the experiment; the sketch is not to scale.

An enclosure made of 6mm tempered glass contained the nozzle and the burner at its centre and all experiments are conducted within it. The motive was to avoid any disturbances from entering the experimental region and hence provide good control over the ambient flow conditions. This enclosure is of size 2m X 2m X 2m. A 400mm opening is provided at the base, all around the enclosure for entrainment of ambient air required for combustion of the flame set up by the burner. A fine mesh is installed all around it to help a draught proof entrainment, hence the effect of the ambient flow disturbances is reduced inside the enclosure. An active hood of 150 cubic feet per minute flow rate, is present at the top of the enclosure.

For visual imaging of the flame, Nikon D5200 DSLR was used, fitted with an 18-55mm Nikon lens. Videos were recorded using the DSLR at 60 frames per second with a frame size resolution of 1920px X 1080px. A Litron twin cavity Nd: YAG laser is used for Particle Image Velocimetry studies. The 532nm laser beams were pulsed at a repetition rate of 12Hz and the beams passed through a set of sheet optics to create a thin sheet. Mie scattering from the droplets was imaged directly to measure the velocity field. LaVision's HighSpeedStar camera was used to image the scattered light, which is fitted with a Sigma 70-300mm Lens and a 532nm(±3nm) narrow bandpass filter to cut out on ambient light. To Synchronize the camera and laser pulse, a simple Arduino was used, to ensure the two pulses straddles between the frames. All the above systems were set out of the enclosure to not affect the experiments as well as to protect these systems from the dispersing fine mist.

Data processing techniques

The DSLR videos were read using Matlab and each frame was thresholded to obtain a binary image which isolated the flame from the dark background region. The binary images were ensemble averaged and the flame height was estimated as the vertically the farthest point on a contour line corresponding to the value of 0.5. This method of obtaining flame height has been reported in works of Zukoski and Cetegenzu [12]. These binary images were also used in further processing to obtain.

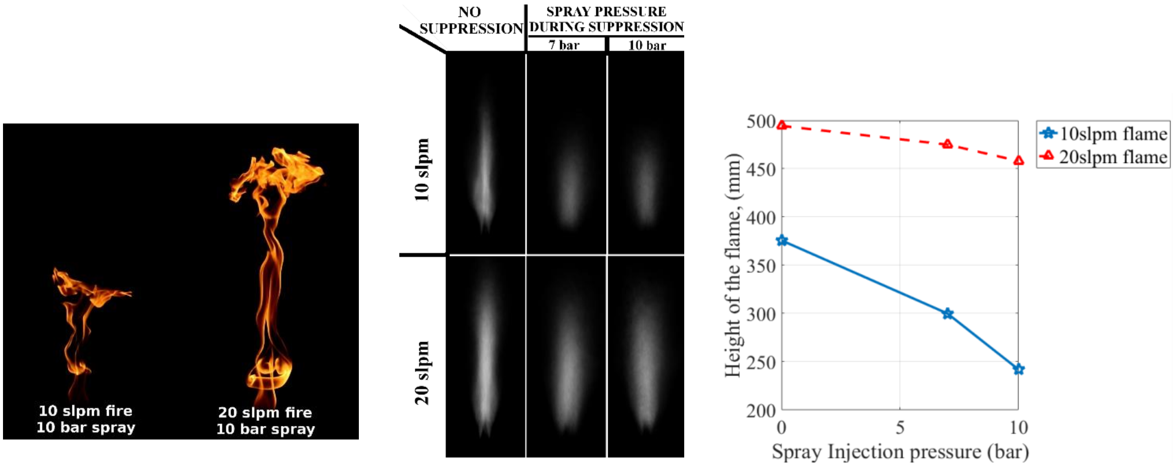
The high-speed camera captures the Mie scattered light from the spray and while the spray interacted with flame. These images were later processed for obtaining data on the velocity field. A window close to the nozzle and another close to the burner were chosen for PIV. The camera was moved to each of these regions of interest by means of a traverse. The window size was large in those regions where the droplet concentrations are less, say close to the burner, and the window size was small in regions where concentrations are high. Also, the delay between the two-laser pulse was adjusted according to the window size and average velocity expected in that region [13].

The images acquired were 1024px X 1024px with bit-depth of 12-bit per pixel. These images were scaled to 16-bit images and were processed using LaVision’s Davis software for obtaining PIV results. A multi-pass scheme was used from the cross-correlation with an initial interrogation window size of 128px X 128px to a final 32px X 32px. The last pass had 50% overlap of windows. A 3X3 smoothening operation was performed before the PIV processing, as this will help in increasing the efficiency of correlation. For this work, the parameter of interest in the mean velocity field, hence the results are averaged and is presented here.

RESULTS AND DISCUSSIONS

Flame Height variation

The flame height was calculated for the flame with and without mist suppression. The experiments were repeated three times on two occasions, recreating the same conditions. Instantaneous image from the video revealed occasional flame tip flattening, during suppression, which is shown in Fig.2a. Also, the flame luminosity was significantly diminished during the process of suppression. This is shown in Fig.2b obtained from ensembled average of images extracted from 60fps video recorded over 30 seconds. Furthermore, flame heights were calculated as described in the above section. The trend of the flame height is depicted in Fig.2c. The weaker flame tends to get suppressed a lot faster than the stronger flame. This could be attributed to the hot and large momentum of the buoyant plume present in the 20 slpm flame, which carries away and evaporates a lot of the mist droplets, while the droplets could reach well into the smaller 10slpm flame and suppress it.



(a) (b) (c)

Fig. 2a Instantaneous Flame tip flattening, Fig.2b Changes to the flame luminosity, Fig.2c Flame height trend

Heskestad's work [14] on flame height indicate a direct correlation between heat release rate and flame height. In future, calorific studies will be carried out to quantify the relation between the flame height under suppression and the associated reduction in heat release rate.

Velocity field

The origin of the coordinate system coincided with the centre of the nozzle exit. The mean velocity was estimated by averaging the results spanning 50-60s. The presence of the flame affected the spray significantly close to the nozzle. The flow rapidly slows down along the vertical direction and increases radial velocity. This is clearly seen from Fig 3. Also, the light bands that pad about the central solid lines are the standard deviation values. Clearly, the flame increases the fluctuations and hence the turbulence in the spray field.

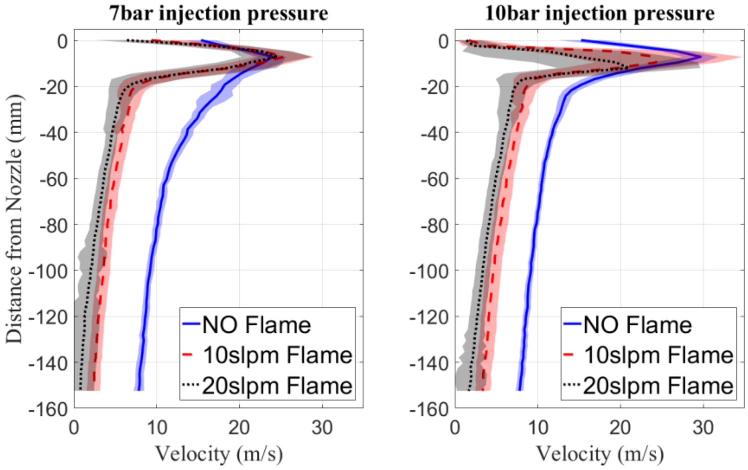
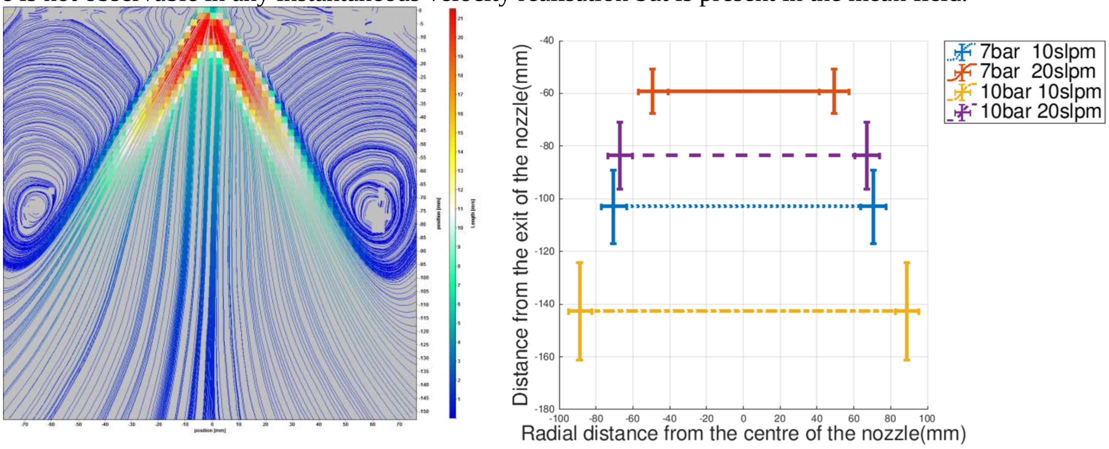


Fig. 3. Centreline velocity magnitude profile of the spray, with and without flame.

Another effect of the flame on the spray is that the droplets are thrown away from the spray cone. Due to the strong entrainment of ambient into the spray cone, the dispersed droplets partly re-enter the spray region, close to the nozzle. This causes a re-circulation zone in a shape of a toroidal vortex to be formed very close to the nozzle and on the periphery of the spray cone. Again, for representative purposes, the flow close to the nozzle is depicted in Fig.4(a), with streamlines false coloured according to the velocity magnitude. A clear vortex is noticeable and the shape is supposedly toroidal, due to circular symmetry. The size and location of this re-circulation zone are related to the injection pressure and the flame strength. The variation of the location and size (diameter of the toroid's axis) is depicted in Fig 4(b). The bars indicate the root-mean-squared values of the position, which was obtained by performing a moving average over successive 10 seconds of PIV results. The spread indicates that the structures are not stationary with time and are turbulent in nature. This vortical structure is not observable in any instantaneous velocity realisation but is present in the mean field.



(a) (b)

Fig.4. Representation of the re-circulation zone for 7bar spray suppressing a 20slpm flame and the location-size statistics of the vortex.

We also would like to predict that the presence of this vortex, however minimal, should to some degree, enhance fire suppression as the re-entering combustion products tend to be inert and lacking in Oxygen. Detailed studies will be carried out in future to decipher the degree of this spray vortical structure's effect on flame suppression.

Similarly, studying the radial velocity component of the droplet field, close to the burner as shown in Fig.5., one can observe that there is a strong tendency for the droplets to move towards the burner. This is caused by the entraining ambient fresh air into the flame. The fine water droplets are easily affected by a weak entrainment flow of air into diffusion flame. It is expected that with an increase in strength of the flame, the stronger the entrainment and hence larger the tendency of the droplets to move towards the flame. These entraining droplets too will suppress the fire. But the observation is contrary to the prediction, with droplets moving slowly towards the flame when the flame is stronger. This might be because small droplets could have been carried away by the strong plume and only large drops make it to the base of the burner mouth. Droplet size measurement will be carried out in future to validate this. Also, one can observe, the radial velocities are larger for higher injection pressure indicating that when droplets are with larger momentum, they can reach the burner mouth. The large peaks present at the centre of the profile are due to the soot scattering from the flame.

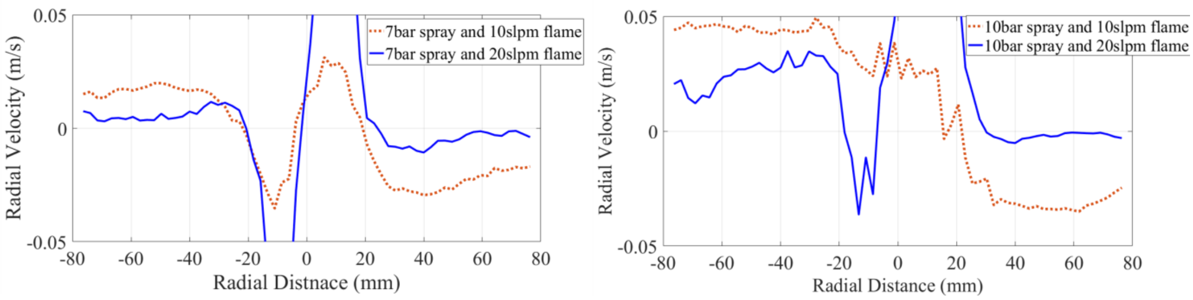


Fig.5.Radial profile of the Radial velocity component, 80mm above the burner.

SUMMARY AND CONCLUSION

To understand the action of the water mist on diffusion fires, plain imaging and PIV experiments were carried out to understand the flame behaviour and to measure the velocity field of the water droplets, respectively. Commercially available Delavan nozzle was used at two different pressures (7bar and 10bar) to generate fine, atomized water mist. A circular burner of 50mm diameter generated a buoyant diffusion flame which was fed using Methane. The intensity of the flame was controlled by altering the flow rate of Methane. Two flow rates, 10 and 20 slpm of Methane were used in this study. The mist from the nozzle was directed downward into the rising flame. Visual imaging of the flame by means of DSLR aided in estimating the flame heights. By means of PIV, selected regions of the spray cone were studied. The Mie scattered light from the droplets was captured and was processed using LaVision's Davis software.

Flame tip flattening and flame height reduction were observed when the videos were analysed. The flame height of the weaker flame(10slpm) is significantly reduced in comparison to the stronger flame(20slpm), which could be because of the strong buoyant plume carrying away the droplets, rendering the suppression to be ineffective. Results from the velocity field indicate the development of a toroidal vortex at the other edge of the spray cone, close to the nozzle, in the presence of the flame. The strength and the injection pressure dictates the size and location of the vortex. Owing to large turbulence in both the flow field, the vortex's location and size keep on changing. Also, fine droplets which made it close to the burner gets caught up by the slow-moving entrainment flow and these droplets enter the flame at the burner mouth. Despite a stronger entrainment for the larger flame, the droplet's radial velocities were small compared to a smaller flame, possibly indicating that only larger droplets make it to the base of the flame

To take this work further, studies could include the statistics of the droplet sizes which will indicate the droplet evaporation, multiphase PIV, high-speed PIV to investigate the turbulence, temperature measurement of the flame field, etc. Subsequently, the results from these future work, will add to the already existing body of knowledge of fire suppression and further refine our understanding of the action of water mist on fire.

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