Optimal Droplet Diameter and Relative Sprinkler Location in Fire-Sprinkler Interaction

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ABSTRACT

A one/two-dimensional, quasi-steady heat-and-mass transfer model is presented to describe gas-sprinkler interaction. The spray droplet dynamics in gas flow is accounted for in heat transfer by introducing the droplet residential time into droplet number density. The model is capable, therefore, of simulating gas cooling effects in terms of sprinkler locations relative to fire source, initial droplet angles, velocities and droplet diameters. It is also capable of estimating the droplet evaporation rate and influence of gas flow parameters, such as velocity direction and magnitude, temperature and initial relative humidity. With combination of droplet dynamics and heat-mass transfer, an optimal droplet diameter is defined in gas cooling. The sensitivity of the spray model to the initial droplet angle, number of droplet trajectories to represent the sprinkler spray, droplet diameter distribution and relative fire-sprinkler locations, has been demonstrated. Finally, a one-trajectory, single-size droplet model is adopted. Gas cooling rates calculated with this model and penetration predictions are compared with experimental data and other simulations from the literature.

KEYWORDS: Spray model, relative fire-sprinkler locations, optimal diameter, residential time.

INTRODUCTION

As it is classified by Pepi [1], there are three possible sprinkler performance objectives: fire suppression, i.e. sharp reduction in the rate of heat release with no re-growth; extinguishment, i.e. complete suppression of a fire with no burning combustibles; and, control, i.e. limiting the fire growth by controlling gas temperature. The most important mechanism by which water sprays are believed to act to suppress a fire is heat extraction. Other mechanisms in fire-sprinkler interaction are oxygen displacement by steam, direct impingement and wetting and cooling of the combustibles. In a number of cases reported in the literature, fire suppression or extinguishment was under-predicted. In other words, computational time of suppression was much shorter than achieved experimentally [2]. There are also cases where sprinklers were unable to suppress fire, even though they complied with sprinkler performance requirements. Unsuccessful use of steam for fire protection on marine vessels at the beginning of the century was also reported [1]. All these cases indicate that there is no uniform answer yet on how sprinklers act in different situations, and how the different mechanisms of suppression contribute to the overall result. However, the main factors that affect fire-sprinkler interaction are known [3, 4, 5] as the following: the discharge rate of water, mean droplet diameter, fire size, relative location of the fuel and ventilation conditions. The present study is an attempt to explain how and why these factors act, and how sensitive the total cooling is to each of these factors.

MODEL DESCRIPTION

In order to obtain the droplet trajectories and velocities in two-dimensional gas-droplet flow, the equations of motion were integrated over the droplet path. The solution is based on a Langrangian approach, and the forth order Runge-Kutta scheme is used for integration. The model allowed any gas velocity profile to be included, as well as droplet initial size and velocity distribution. Since experimental data on droplet trajectories is not available, the comparison has been made and agreement obtained with numerical results of different authors [6, 7].

The heat transfer equation for completely mixing, isothermal droplets [8, 9] can be written as follows:

$$\delta Q_d = \delta Q_{conv} + \delta Q_{ev} + \delta Q_{rad} \qquad (1)$$

where δQ_{conv}, δQ_{ev}, δQ_{rad} are the heat transfer rates to droplets transferred by convection, evaporation and Stefan-Boltzmann radiation [8], respectively. The assumption of isothermal droplets with low thermal resistance is reasonable for the values of Biot number (Bi) less than unity [10]. For the range of the investigated sprinkler-gas parameters, Bi was calculated to be less than 10^{-2}.

The fraction of radiation in Equation (1) was estimated for the highest values of the gas temperature in hot layer at the moment of sprinkler activation (250-300°C), and it was found not to exceed few percent of the total heat transferred.

As summarized in Reference11 where the spray behaviour in gas flow is studied, the main properties of the droplet liquid phase that affect droplet behavior and spray thermal performance are: 1) droplet size; 2) droplet velocity; 3) droplet location and 4) number of droplets in a given control volume (or droplet number density).

Sensitivity Analysis

The total droplet number, N, is proportional to droplet residential time, τ_d, and droplet mass fraction, f_d: $N \propto \Sigma f_d \tau_d d^{-3}$, where d is the droplet diameter. The surface area of a single droplet is proportional to d^2. Therefore, for the mono-disperse sprays with equal discharge rates, a comparative study can be based on $\tau_d d^{-1}$. The objectives of this section are to analyze the results of modelling under different initial conditions and to understand the sensitivity of the model to the input parameters, before conclusions are made about sprinkler thermal performance.

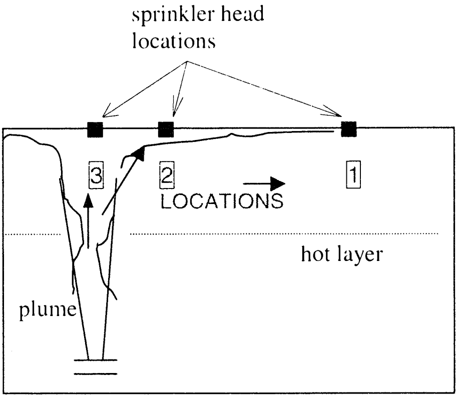

FIGURE 1. Relative fire-sprinkler locations. Gas velocity vector is shown by filled arrow heads.

In this study, gas flow is represented by three parameters: the gas temperature, specific humidity, and uniform velocity. Three cases of gas movement are discussed: horizontally moving hot layer (Location 1), plume turning point where gas velocity vector has equal horizontal and upward vertical components (Location 2), and uprising fire plume (Location 3). The ceiling jet is not included at this stage. Locations 1 to 3 are illustrated in Figure 1.

For the sensitivity analysis, the heat-and-mass transfer model was simplified to a one-dimensional one-step model. The time step is the time interval over which a droplet interacts with gas flow. Depending on the control volume size, the time step can be either the total droplet residential time, or a reasonable fraction of it for convergence. The total droplet residential time is obtained from the solution of the two-dimensional equations of droplet motion within a given control volume for each representative droplet in the spray [6, 7]. Friction drag and gravity forces are taken into account. The droplet residential time is limited either by the hot layer depth (Location 1), or by the natural boundaries, such as ceiling or wall (Locations 2 and 3). Based on the droplet residential times, the number of droplets and total spray interface can be calculated, and subsequently, the heat transfer equations can be solved. The gas mass flow rate through the sprinkler spray is taken as the product of gas velocity and spray radial cross-section, similar to the approach given by Cooper [12].

Droplet residential times and number density. As discussed previously, the droplet residential time appears in heat-transfer equations to calculate the total number of droplets. The droplet residential time is the common parameter between droplet dynamics and heat transfer, which joins these two sets of calculations. A summary is given in Table 1 of the residential times of different diameter droplets discharged at the three locations mentioned above. Sprays are represented by a single trajectory with an initial angle of 68°. The magnitude of gas velocity is 2m/s in all cases.

TABLE 1. Residential times (s) for 0.8m distance (or until droplets hit the ceiling) for different droplet diameters, initial droplet velocity of 5m/s, droplet initial angle of 68° and total water mass flow rate of 1.84 kg/s. Gas velocity is 2m/s.

d (mm)	**LOC 1** τ_d **(sec)**	**LOC 1** $\tau_d d^{-1}$ **(s m^{-1})**	**LOC 2** τ_d **(sec)**	**LOC 2** $\tau_d d^{-1}$ **(s m^{-1})**	**LOC 3** τ_d **(sec)**	**LOC 3** $\tau_d d^{-1}$ **(s m^{-1})**
0.2	0.77	3.85e3	0.27	1.35e3	0.12	0.6e3
0.3	0.66	2.2e3	0.78	2.6e3	0.31	1.03e3
0.5	0.41	0.82e3	1.21	2.42e3	3.4	6.8e3
0.7	0.34	0.48e3	0.54	0.77e3	0.82	1.17e3
1	0.3	0.3e3	0.37	0.37e3	0.43	0.43e3
1.5	0.27	0.18e3	0.31	0.2e3	0.33	0.22e3

At Location 3, droplets of 0.5 mm diameter are nearly suspended in a 2m/s updraft gas flow, and the drag and gravity forces on each droplet balance each other. In this case, droplets move very slowly, and residential time is very high. In fact, the residential time would go to infinity, if there is no connection between droplet evaporation and droplet motion. This phenomenon was mentioned by Gardiner [9] when the author referred to the ballistic calculations of Lapple and Shepherd [13]. For small droplets (0.2-0.3 mm), the residential times and the product ($\tau_d d^{-1}$) are much smaller when they are discharged in updraft gas flow (Location 3) in comparison with horizontal gas flow (Location 1). If droplets move in horizontal gas flow, the product ($\tau_d d^{-1}$) decreases as the diameter increases. If the droplets are discharged against gas flow (Location 3), then value of ($\tau_d d^{-1}$) sharply increases as the diameter decreases down to a critical value, which depends on the magnitude of upward gas velocity. For example, for 2m/s of upward plume velocity, the critical diameter is about 0.5 mm; whereas for 1m/s, it is about 0.3 mm. Thus, a critical diameter divides the droplet discharge to two parts. Larger droplets are capable of penetrating the vertically moving plume. Smaller droplets are diverted, and they fail to penetrate the fire. Hence, under certain conditions, fine sprays can be less effective in comparison with large droplet sprays due to lower values of ($\tau_d d^{-1}$). This result agrees with the experimental observation [14] that water droplets of average diameter 0.3 mm could not penetrate to a fire base.

Droplet initial angles. The representation of sprinkler by one trajectory should be based on a reasonable value of the initial angle. There is no uniform answer in the literature on how real sprinklers have to be represented, as well as how the number of trajectories affect the results. Some authors represent sprinklers by one initial angle [15, 16] (usually, either 45° or 90°), and one diameter [15, 17], others use from few [9] to few hundreds of discrete trajectories [18] with discrete initial angles and with either one droplet diameter or a diameter distribution. A review of different sprinkler representations is given in Reference19. In most calculations, the total flow rate is assumed to be uniformly distributed among the discrete number of initial angles.

In the present study, the results of heat and mass transfer calculations based on spray representations from 1 to 30 discrete trajectories have been compared for discharge angles between –90° and 90°. The sensitivity to the number of trajectories was found to be higher at Location 3, since at this location the residential times and trajectories are affected more by the initial droplet angles. However, it has been concluded that at Locations 1 and 3, a total of 7-19 trajectories is sufficient. In fact, one trajectory with an initial angle of 45° can be used to represent a spray in a horizontal gas flow, if the droplet diameter distribution consists of 0.5 mm, 0.7 mm and 1 mm droplets of mass fractions 25% -50%-25% of the total, respectively. For Location 3 (upward moving plume), the spray can be represented by a single trajectory of 30°. The division to hundreds of trajectories for heat transfer calculations is not necessary, especially if a coarse spray is being considered.

The sensitivity of the droplet residential times to the initial angles has also been investigated based on droplet dynamics. Subsequently, the influence of the droplet initial angles on sprinkler thermal performance has been evaluated. In Table 2, the convective cooling rate of a water spray is given in terms of the different initial discharge angles. The results are listed for two different locations. In each case, the spray is represented by one droplet diameter (as discussed in the next section) and one initial angle (one trajectory spray). The values of initial gas temperature, 99.5°, hot layer depth, 0.8m, and water mass flow rate, 1.84 kg/s, correspond to the experimental values of Gardiner [9] (p.165). The gas velocity is 2m/s. One experimental result from Reference 9 is also included in the last column of Table 2 for comparison. Although this comparison is complicated by the lack of experimental input parameters and details of measurements, the experimental convective cooling rate is within the same order of magnitude as the calculated values.

TABLE 2. Convective heat absorption rate, kW, of the sprays, represented by one diameter (0.7mm) and one initial angle taken to the vertical. The residential times are calculated for Locations 1 and 3. Water mass flow rate, gas velocity and initial temperature are the same as in Table 1.

		Initial droplet angle to vertical (°)				**Experimental [9]**
		0°	**45°**	**68°**	**90°**	
Convective heat absorbed (kW)	**Location 3**	78	122	158	223	
	Location 1	60	77	94	125	**157**

Within the same location, the spray heat absorption rate is sensitive to the discharge angle, since the residential times are sensitive to it. The sensitivity to discharge angle, in practice means that different shape of spray cones, (hollow or filled, narrow or broad, etc.) affect sprinkler thermal effectiveness. Therefore, spray cone shape needs consideration in sprinkler design.

Mean droplet diameter. The effect of droplet diameter distribution, f_d, on total surface area was studied based on a comparison of a 0.7 mm-diameter droplet spray, and a spray consisting of 0.5 mm, 0.7 mm and 1 mm droplets of mass fractions 25% -50%-25% of the total, respectively. For this case, the total droplet surface area was approximately the same for both the single diameter spray and the 3-droplet diameter one. A similar conclusion was reached by Novozhilov *et al* 20 regarding "reasonable insensitivity" of the CFD predictions to the type of droplet diameter distribution, especially for coarse sprays.

Consequently, a spray represented by one mean droplet diameter and one trajectory is used to study the important role of droplet size in sprinkler thermal performance. The lack of experimental measurements of heat absorption does not allow direct comparison with experiment. However, the comparison with heat transfer calculations in terms of spray cooling rates [21], gas and water temperatures [22] have shown reasonable qualitative agreement [6, 7]

Prediction of Optimal Droplet Diameter

The spray characteristic that is usually varied in practice to achieve sprinkler performance objectives, is the water discharge rate. To illustrate the effect of this parameter in combination with different mean droplet diameters, the results of heat transfer calculations at Location 3 are shown in Figures 2 and 3. The values of discharge rates are taken from Gardiner's work [9]. Location 3 (the updraft gas velocity) is chosen as the most critical, where small droplets can be blown away and contribute little to heat transfer. In Figure 2, the discrete calculated points are joined by straight lines, showing a peak value of cooling rate for 0.5 mm diameter. As shown in this figure, the sprinkler effectiveness can be achieved by changing either the water discharge rate or the droplet diameter, when they are treated as independent parameters. The gas cooling rate by large droplets is relatively low and insensitive to the droplet diameter. Therefore, large-droplet sprinklers are not effective in gas cooling, but they can be used for fuel wetting and cooling. In the range of 0.4-0.7 mm droplet diameters, the gas cooling rate is much more sensitive to droplet diameter than to sprinkler discharge rate. In this range, effective cooling can be achieved by choosing the appropriate droplet diameter with a minimal flow rate of water. This result is also confirmed in Figure 3 that clearly shows the existence of an optimal combination of mean droplet diameter and water flow rate. In this figure, the flow rate needed to absorb 100 kW and 300 kW is plotted against mean droplet diameter. The minimum of the curves in Figure 3, correspond to the same range of optimum droplet diameters as given for the maximum cooling rates in Figure 2. The closer the diameters to the critical value, the less flow rate is needed to provide the same cooling rate, due to high droplet residential times. If the diameters are too small and their residential times are too short, more water is needed to provide the same heat absorption rate. The type of relationship plotted in Figure 3 is a conventional way of describing sprinkler performance for thermal effectiveness. Most of the works in fire-sprinkler interaction try to predict or measure the minimal discharge rate needed for extinguishment [3, 5, 23] and qualitatively look like the right half of the two curves given in Figure 3. It is difficult to provide quantitative comparison with these data, since the clear criteria of extinguishment usually are not given.

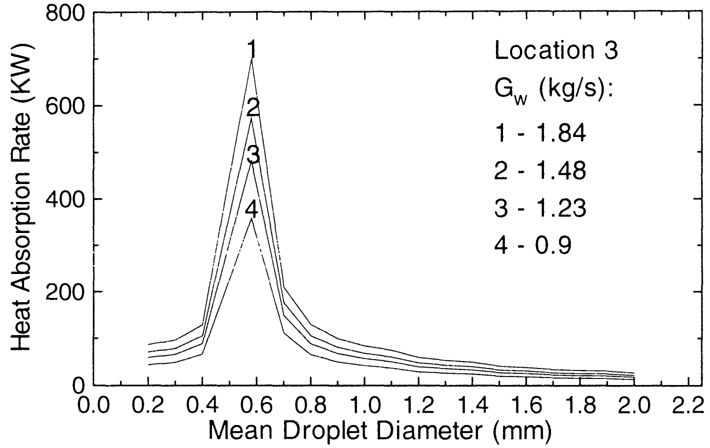

FIGURE 2. Effect of spray diameter and discharge flow rate on convective heat absorption rate. The uniform vertical gas velocity is 2m/s. The sprinkler discharge rates are listed as numbered. Location 3 is chosen as the most critical.

The figures based on calculations with a clear minimum and two branches similar to those plotted in Figure 3 were first published by Ball and Pietrzak [4] in 1978. One of the figures taken from Pietrzak and Johanson [5] is reproduced in Figure 4 for comparison. In this figure, the successful combination is given of water delivered density and mean droplet diameter in controlling fire. The curve for 0% fuel exposure to water, which involves only gas cooling, has a clear minimum in water flow rate corresponding to the optimal droplet diameter, in agreement with the present results. Of the three curves given in Figure 4, only this one can be compared with the present gas cooling results. Because of the lack of gas and sprinkler input parameters, the results given by Pietrzak and Johanson [5] can not be compared quantitatively with the present calculations for Location 3. Although the curve for 50% exposure in Figure 4 also has a minimum, the optimal diameter is not as obvious. The 100% fuel exposure curve has no minimum, and it is insensitive to droplet diameters of 0.4 mm and larger. Hence, the larger the diameter, more likely it is for the spray or the fraction of spray to reach and cover the fuel, providing suppression regardless the droplet diameter. These conclusions do not contradict the present results, but only highlight that fuel coverage and surface cooling mechanisms should also be studied. The unique results given by Pietrzak *et al.* [4, 5] do not contain quantitative comparison with experimental results, but only a general discussion is provided. Similar to the present work, a fire was represented in Reference 5 by a uniform updraft gas velocity, and qualitative agreement with experimental data of water mist is reported. The zone model developed, Fire Demand (FD), is for the manual extinguishment of post-flashover fires.

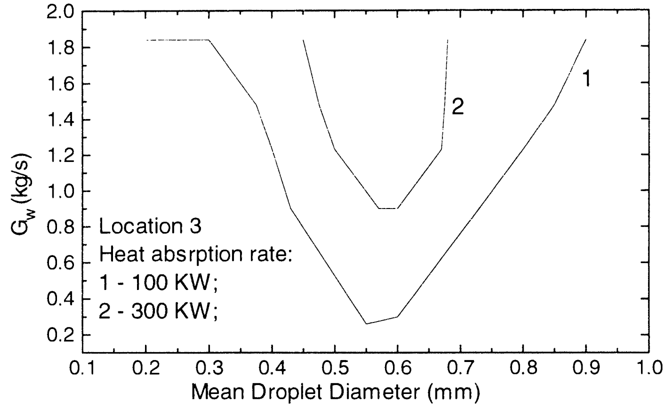

FIGURE 3. Variation of the sprinkler discharge rate with the spray mean droplet diameter for two convective heat transfer rates: 100 kW (curve 1) and 300 kW (curve 2). The environmental conditions and spray characteristics are the same as in Figure 2.

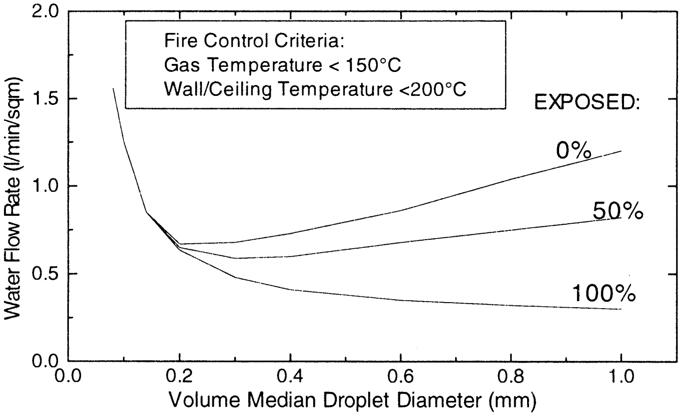

FIGURE 4. Successful combinations in controlling fire of mean droplet diameter and water delivered density (Figure 3 of Pietrzak and Johanson [5]). 0% exposure curve corresponds to the present results given in Figure 3.

Based on the results obtained, an explanation is also possible of some of the experimental results in the well-known work of Kung [23] in the extinguishment of a room fire by sprinkler sprays. The results obtained by Kung showed high sensitivity of fire extinguishment to the sprinkler activation time. For example, a sprinkler with the same water discharge rate (0.448 kg/s) and mean droplet diameter (0.155 mm) led to extinguishment if it was activated in 60s, and failed to extinguish fire if it was activated in 75s. This result can be explained as follows. Since heat release rate (HRR) of fire before sprinkler activation is reported to be about 1.5 times greater in the latter case in comparison with the earlier activation, the gas velocity which is proportional to $HRR^{1/3}$, must have been also higher. As a result, the droplets could not reach the fire base. In Figure 2, the later activation would have the effect of shifting the peak of heat absorption curves to the right due to the higher gas velocity.

In order to have the global picture reflecting the history of fire-sprinkler interaction including fire suppression and extinguishment, the developed spray cooling model has been combined [24] as a sub-model with the NRCC-VUT (National Research Council, Canada – Victoria University of Technology) one-zone model [25]. The zone model allows the inclusion of relative sprinkler location, and its effect can be estimated. It also allows gas cooling, oxygen replacement and fuel cooling and coverage to be calculated.

Stability of Hot Layer after Sprinkler Activation

From a momentum conservation point of view, a group of decelerating droplets can have a significant effect on the gas flow causing it to accelerate if their momentum drop is significant [22]. If the droplets' momentum does not change, they still affect gas flow due to the non-slip condition and resultant drag force [26]. The criterion of layer stability suggested by Bullen [15] is based on the Drag-to-Buoyancy Ratio, D/B. D equals to the vertical component of the drag force experienced by moving droplets. B is proportional to the ratio of the gas temperature rise above the ambient to ambient temperature and to the gas volume contained in the spray cone: $D/B = 0.5\Sigma\{C_D A V_{rel}^2\}/[(T_{max}-T_{ref})g\ vol\ /T_{ref}]$, where C_D is the friction drag coefficient [22]; A is the droplet projected area; *vol* is the gas volume confined within the spray; V_{rel} is the relative velocity between each droplet and gas; T_{max} and T_{amb} are the maximum temperature within the control volume (e.g. the hot layer temperature before sprinkler activation) and reference ambient temperature, respectively. The summation is over all droplets within the control volume. In the present study, by dividing the horizontally moving hot layer into five conditional sublayers, the Drag-to-Buoyancy Ratio distribution across the layer was calculated for each sublayer. The control volume was taken as the volume of a cylinder with height equal to the sublayer depth, and diameter of spray cone at the given height. The time interval corresponded to the droplet residential time in each sublayer. Along the droplet trajectory, gas temperature was calculated based on new residential times in each sublayer. The D/B ratio distributions across the hot gas layer for three one-size droplet sprays are plotted in Figure 5. The droplet diameters of 0.5, 0.7 and 1.5 mm were investigated. The trend of the curves is similar for different diameters: the closer the distance to the sprinkler head, the higher is the D/B ratio. A similar pattern was mentioned by Lam [27] in his CFD study of fire-sprinkler interaction. For the same water flow rate, the D/B ratio is much higher for the small droplets, especially at the beginning, in comparison with large droplets. The reason is that smaller the diameter, greater the droplet concentration within a given gas volume, and consequently, larger is the total drag force. The D/B ratio for the three sprays is much higher than unity at the two sublayers closer to the sprinkler head. Further away, D/B falls below unity. These results confirm the suggestion of Lam [27] that the usual calculation of the D/B ratio for the entire hot layer is not appropriate to characterize the layer stability. The stability of hot layer can be disturbed at a certain distance below the sprinkler head, and downward movement can initiate. This distance depends on droplet diameter and gas excessive temperature, and it is a result of the balance between two forces – droplet drag force and gas buoyancy confined into spray cone. A similar conclusions can be found in Reference 12. As it was shown earlier by the authors [7], a stability of hot layer may also be disturbed by the negative buoyancy phenomenon, which is caused by a non-uniform gas cooling within the hot layer by sprinkler spray.

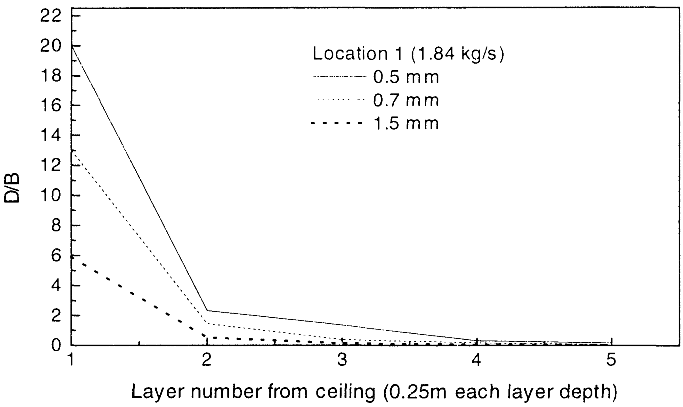

FIGURE 5. The Drag-to-Buoyancy ratio distribution across the hot gas layer. Initial gas temperature is 99.5°C. Water mass flow rate is 1.84 kgs^{-1}. Three droplet diameters are considered, as indicated. Location 1 is where hot layer lowering can be observed.

CONCLUSIONS

The conclusions of this study can be summarized as follows:

1. The ratio of droplet residential time to droplet diameter, ($\tau_d d^{-1}$), defines spray cooling effectiveness. This governing parameter also links droplet dynamics and heat transfer.
2. The relative location of fire source and sprinkler head plays an important role in heat transfer. There are three main pendant sprinkler locations relative to fire which coincide with the three zones in a fire environment: upward moving fire plume, turning region and horizontal hot gas layer.
3. There is an optimal diameter in gas cooling by water spray, which provides the same cooling effect with minimum quantity of water. This diameter, discharged at Location 3 (just above the plume) corresponds to the balance of gravity and drag forces, which results in a significant residential time and considerable heat transfer.
4. The major contribution to fire-sprinkler interaction comes from convective heat transfer, and this mode is responsible for gas cooling. Under standard sprinkler activation conditions, radiation heat exchange rate between gas and droplets does not exceed few percent of the total heat transfer rate.
5. The effect of discharge angle on heat transfer effectiveness was found to be significant, especially under certain circumstances. If a sprinkler is discharged above the fire (Location

3), a narrow spray angle is preferred for fine sprays. A broader spray angle is more effective for coarse sprays.

6. The stability of the hot layer after sprinkler activation is analyzed in terms of drag-to-buoyancy (D/B) ratio distribution across the layer rather than on one value for the entire layer.

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