THERMALLY DRIVEN BUOYANCY WITHIN A HOT LAYER DUE TO SPRINKLER OPERATION

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ABSTRACT

A two-dimensional zone-like model is developed to predict the interaction between hot gas layer and water droplets after sprinkler activation. The model combines the motion equations for each droplet with heat and mass transfer between the gas and water. The results indicate that negative buoyancy in the hot layer can only be obtained if the initial temperature profile is uniform. If an experimental profile is used instead, positive buoyancy results. This conclusion has been confirmed with experimental data.

INTRODUCTION

The criterion to examine the layer logging phenomenon, the instability in a buoyant hot gas layer due to heat transfer to a sprinkler spray, was first suggested by Bullen [1]. If the ratio of the drag force due to the spray to hot gas buoyancy force, D/B ratio, is greater than unity, the smoke layer will "collapse", and it will be pushed down towards the floor. Bullen's criterion is used both in CFD modelling [2] and zone modelling [3,4,5].

Although both two-phase heat transfer and fire zone modelling have developed separately, there have been few works that have combined these two aspects to analyse gas cooling and logging phenomenon in detail. Two such works are those of Morgan [3] and Gardiner [4]. Both authors used Bullen's criterion for gas logging, *the average drag to buoyancy ratio*, and they utilised the basic equations of droplet motion and heat transfer to calculate this criterion. Morgan used averaged uniform temperatures within a hot layer, and he simplified the heat transfer equations to the convective component only. Gardiner used both uniform and non-uniform temperature profiles before sprinkler interaction. The gas temperatures calculated after interaction were averaged across the width and depth of the layer to obtain an average value of drag to buoyancy ratio to characterise smoke instability, similar to Morgan.

Results given by both Morgan and Gardiner included the effects of water discharge rate, initial gas temperature and ventilation rate on the average drag to buoyancy ratio. The effect of droplet diameter was also given through results for different types of commercial sprinklers [4]. Gardiner's results contained other characteristics, such as residential times and initial velocity distribution.

The heat transfer equations developed for two-phase direct contact spray heat-exchangers by Crowe et al. [6] are combined here with zone modelling of hot gas flow. The effects of different variables, such as inlet gas temperature profiles, droplet size, initial velocity and distribution on gas cooling are investigated in order to explain the logging phenomenon. One possible explanation is developed in terms of the local temperature gradient due to non-uniform cooling of the hot layer within the spray volume. Comparison is provided between the predicted hot layer temperature distribution and experimental data from a full-scale fire experiment.

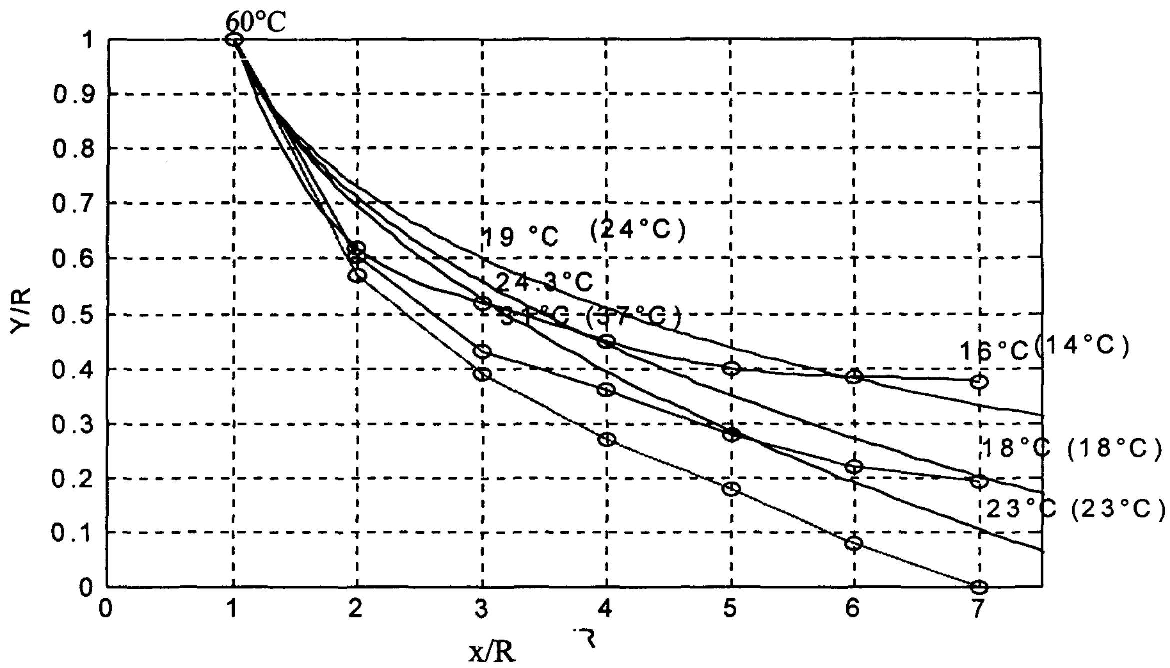


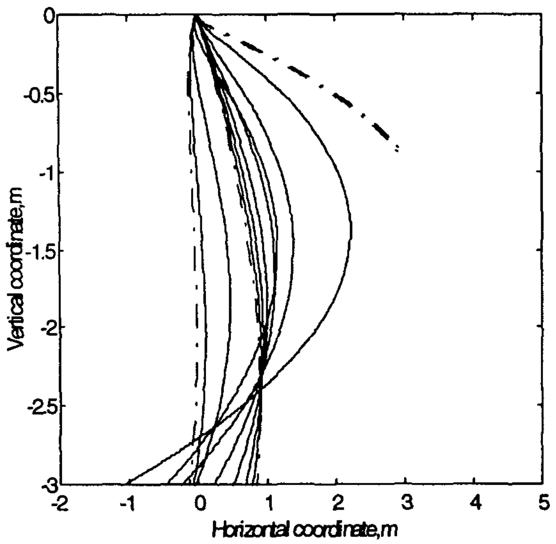
Fig. 1 Comparison between Crowe et al's results [6] (⊕, temperatures in parantheses) and present calculations (solid lines). In both cases, the water spray is characterised by three droplet diameters: 0.74 mm (25%), 1 mm (50%) and 1.38 mm (25%). The initial droplet velocity and the gas velocity are both 2 m/s. The initial droplet angle is 25°. The horizontal and vertical coordinates are non-dimensionalised with the cavity radius, where the droplets are released.

TWO-PHASE HEAT TRANSFER MODEL

In this study, the heat transfer to droplets falling through a hot layer has been calculated based on the two-phase heat exchanger model of Crowe et al. [6]. Although the model had been developed for CFD simulations, it was simplified to the equations for droplet motion and heat transfer. A two-phase flow model was hence developed based on energy balance and momentum equations [7].

A comparison is given in Figure 1 of the droplet trajectories and temperatures obtained with the present simplified model and Crowe et al's results. For this comparison, a gas flow with uniform initial temperature and velocity was used. The momentum exchange between water droplets and hot gas, and gas internal turbulence were not modelled in obtaining the present results. This comparison indicates that the present simplified model is acceptable.

The simplified model was then used to calculate hot layer-sprinkler interaction in zone modelling sense. Zone modelling allows treatment of fire environment as two gas layers, upper, hot, and lower, cold layers. These layers are usually described by temperature and velocity step functions, with a uniform distribution across each layer. The gas mass flow rate is given as a function of either fire heat release rate or the maximum excess flame temperature [8].



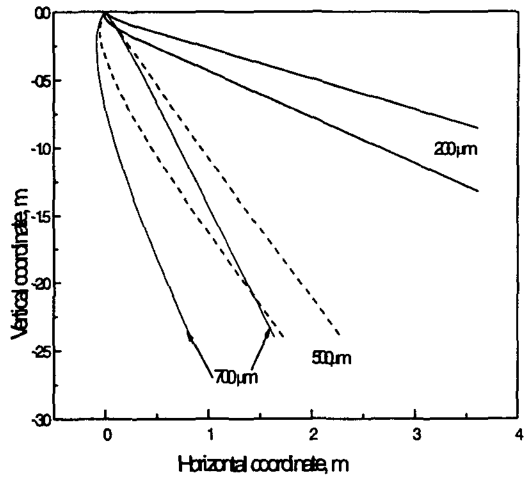


Fig. 2 Droplet (150 - 800µm) trajectories in linearly varying gas velocity. $U_g=U_{gmax}+(U_{gmax})z/LD)$, where LD is layer depth and z is the vertical distance across the layer. The initial trajectory angles are ± 45°

Fig. 3 Droplet trajectories in uniform 2 m/s gas velocity. The initial trajectory angles are ± 45°.

DROPLET TRAJECTORIES AND RESIDENTIAL TIME

Prior to heat and mass transfer calculations, droplet trajectories in different gas velocity profiles were investigated. The equation of motion for each droplet was integrated using a 4th order Runge-Kutta scheme. The program was written in FORTRAN, and it allowed to include any gas velocity distribution, as well as droplet initial size and velocity distribution, or randomisation of these parameters.

In Figure 2, the gas velocity is taken to vary linearly with distance from the ceiling at z = 0 m. In Figure 3, the gas velocity is uniform at 2 m/s. Droplet diameters of 150- 800 µm are considered in generating the data for these figures. The initial trajectory angles were ± 45°. The initial droplet velocity was 2 m/s for both.

The most important dynamic parameter that affects droplets' heat and mass transfer characteristics has been observed to be the droplet residential time in a given gas flow. In Figure 4, the vertical distance from the sprinkler head is given as a function of time for different droplet diameters and initial angles in uniform gas velocity. In Figure 4, the grid lines conditionally divide the hot gas layer into cells. The residential time changes from cell to cell as droplets traverse control volumes. The residential time depends on droplets' size. The initial angle is also effective for large droplets of 500µm diameter or more.

The downward droplet velocity was calculated to be constant for both heavy (700µm) and light (150 µm) droplets. The heavy droplets accelerate, and the light droplets decelerate at the very beginning of their flight, and then, they move with constant velocities. This fact corresponds to the case of zero momentum exchange between the phases, when a droplet moves only under gravity and drag force, as discussed by Alessandri et al. [9].

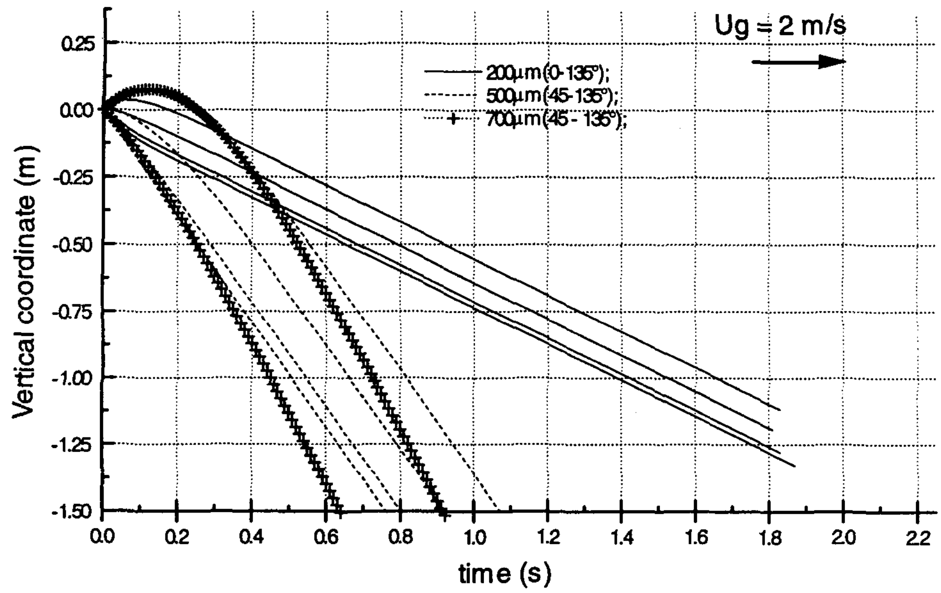


Fig 4 Droplet vertical distance from the sprinkler head versus time of flight. The initial angle variation is given in parentheses for each diameter.

HOT LAYER TEMPERATURE PROFILE CALCULATIONS

In order to obtain 2-D temperature distributions, the hot gas layer in an enclosure of given size, is subdivided into a L rows and M columns [4]. For convenience, the number of rows, L, was chosen to be the same as the number thermocouples across the hot layer during full-scale fire experiments (these experiments are mentioned in detail in the next section). The number of columns, M determines a time or length increment. Averaging of parameters means an arithmetic average taken over either M or L elements. To simplify the heat and mass transfer calculations further, the sublayers are assumed to be independent with no heat exchange or turbulent mixing between them. The layer depth was assumed to be constant in calculations [3,4,5]. The sprinkler spray is represented either by one representative droplet diameter or by a distribution of droplet diameters. For the monodisperse cases, a representative trajectory (or residential time) was used for an average initial angle, say 45°. For polydisperse cases, the trajectory is calculated for each diameter, and its fraction in total spectrum is taken into account. Comparisons are made below between the results for monodisperse (Figures 5 and 6) and polydisperse distributions (Figure 7).

Heat and mass transfer equations are solved along each droplet trajectory within horizontal sublayers. Each sublayer is divided into horizontal cells of length increment $\Delta y = R/M$, where R is the distance of maximum spray radius in a given compartment. A time increment is calculated corresponding to $\Delta\tau = \Delta y/u$, where u is the horizontal velocity component. Only the horizontal velocity component was taken into account [3]. After a droplet crosses the boundary between two sublayers, the calculation along the horizontal direction continues along the uninterrupted droplet trajectory. This approach lead to realistic non-uniform gas layer cooling both across the length and height of the hot layer. Towards the bottom of the hot layer, the higher droplet temperatures were obtained leading to reduced effective cooling. The differences in droplet residential times within each sublayer also lead to variation in gas temperature as it passed the water spray.

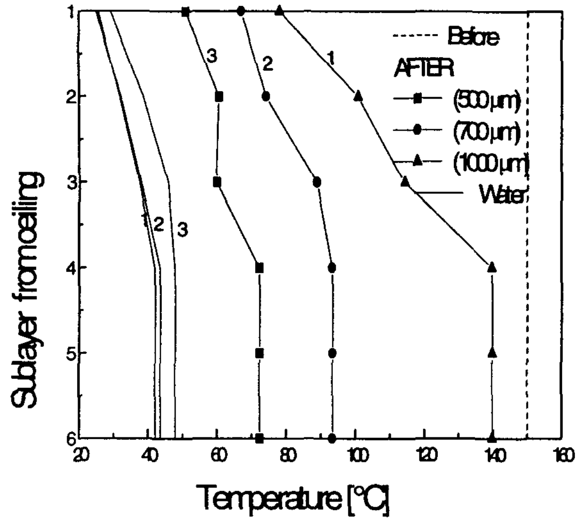


Fig.5 Temperature profiles of water (solid lines) and hot layer (•,▪,▲) before and after sprinkler interaction; water to gas mass flow ratio:0.35. Each sublayer number corresponds to a height of 25 mm.

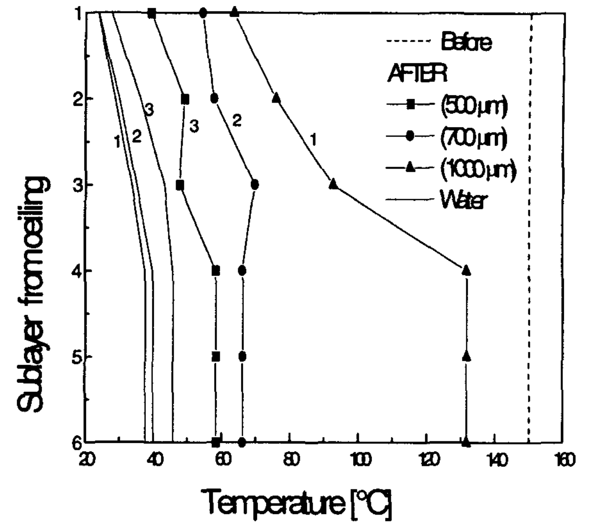


Fig. 6 Temperature profiles of water (solid lines) and hot layer (•,▪,▲) before and after sprinkler interaction; water to gas mass flow ratio: 0.5.

HOT LAYER TEMPERATURE PROFILES

The temperature profiles of an initially constant temperature hot gas layer are given in Figures 5 and 6 for two different mass flow rate ratios of water to gas of 0.35 and 0.5, respectively. The resulting temperature profiles in Figures 5 and 6 show that the sublayers closer to the ceiling are cooled better and have much lower temperatures in comparison with lower sublayers. This non-uniform cooling indicates *negative buoyancy* or gas lowering.

To evaluate sprinkler cooling effectiveness, different water to gas mass flow rate ratios were investigated. This ratio is found to be a determining parameter in total gas cooling rather then recommended sprinkler delivered density.

The effect on sprinkler performance of representation by one mean droplet diameter or by a droplet size distribution was also investigated. In Figure 7, one such comparison is given between a uniform droplet size distribution of 700 μm and a variable distribution of 500 μm (25%), 700 μm (50%) and 1000 μm (25%). The comparison shows the relative insensitivity of the resulting hot layer temperature distribution.

As a more realistic case, the effect of a non-uniform hot layer temperature profile was investigated before the sprinkler interaction. In the present study, the temperature profile was taken from a full-scale fire experiment with real furniture in a burn room of 3.6m x5.4m x2.4 m. The fuel load was 30 kg/m^2 of wood crib equivalent. The full-scale tests were carried out at the Centre for Environmental Safety and Risk Engineering (CESARE) of Victoria University of Technology. In Figure 8, the temperature histories are given within the hot layer as obtained from a thermocouple rack. Two sprinkler heads were placed 0.5 m away from the thermocouple rack in opposite directions at 85 mm below the ceiling. Both sprinklers were charged: the first at 270 seconds, and the second sprinkler at 381 seconds from ignition.

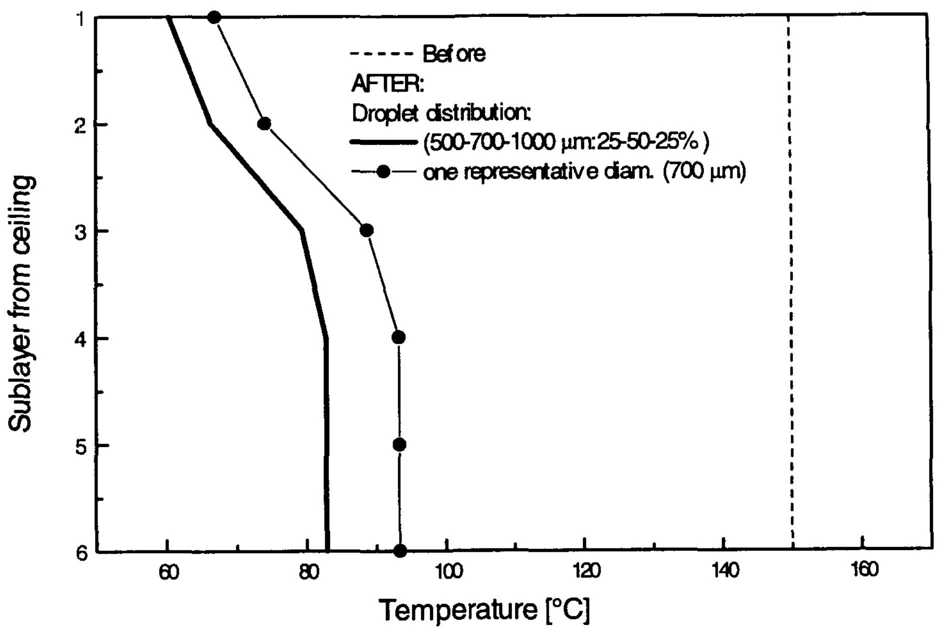


Fig. 7 Temperature profiles before and after sprinkler interaction for the uniform and variable droplet size distribution ($G_w/G_g = 0.35$)

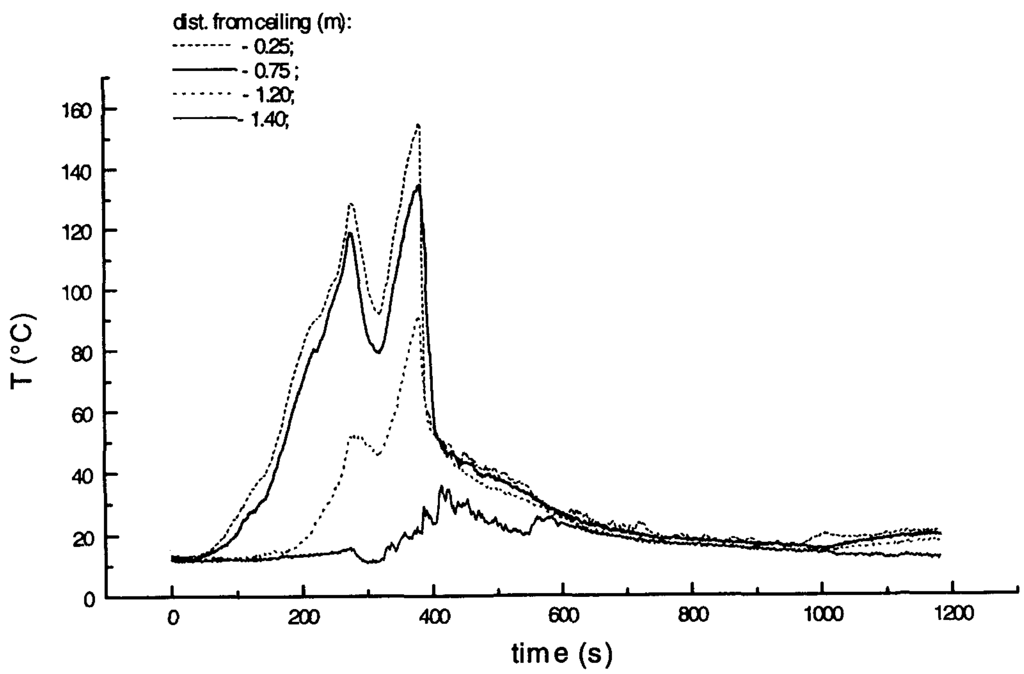


Fig 8 Temperature histories within the hot layer of a burn room taken at distances 0.25, 0.75, 1.25 and 1.4 m below the ceiling. The first sprinkler activation time is 270 seconds, and the second one 381 seconds from ignition.

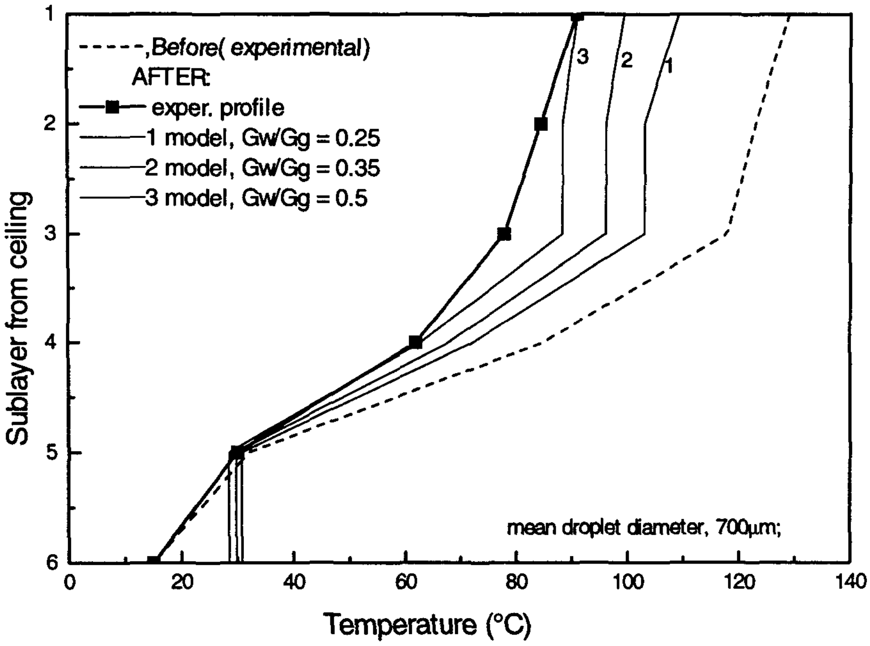


Fig. 9 Experimental and predicted temperature profiles before and after sprinkler interaction for different water to gas mass flow rate ratios :G_w/G_g = 0.25; 0.35; 0.5.

In Figure 9, the dashed line is the experimentally measured hot layer temperature profile before sprinkler interaction corresponding to the first peak values in Figure 8. The experimental hot layer temperature profile after interaction is given by the square symbols, and these temperatures are the values after the first sprinkler activation in Figure 8. In Figure 9, three sets of calculated hot layer temperature profiles are also given each corresponding to a different water to gas mass flow rate ratio. The spray is represented by one mean droplet diameter of 700µm. In the experiment, the first sprinkler discharge was about 0.8 kg/s (3/8" BSP at 70 kPa) and air ventilation rate was of about 1300 l/s. From the comparison in Figure 9 with the experimental values after interaction, a mass flow rate ratio of 0.5 appears reasonable. If the hot layer results after interaction given in Figure 9 are compared with those in Figures 5 to 7, it can be observed that when a non-uniform hot layer temperature is used before interaction, negative buoyancy disappears.

The results given in Figures 5 to 7 and 9 can be viewed in terms of buoyancy. The temperature difference across the hot layer is, $\Delta T_{lr} = (T_{up}-T_{low})$, where T_{up} and T_{low} are the temperatures of the upper and lower sublayers, respectively Buoyancy is normally defined as proportional to the temperature difference between the maximum hot layer temperature at a certain distance from the fire origin and ambient temperature, B ~ $(T_{max} - T_{amb})$ [5]. A new buoyancy caused by non-uniform layer cooling, B', can be defined as B'~ ΔT_{lr}. This new buoyancy appears as an addition to the average buoyancy term. The sign of the ΔT_{lr} is negative only in Figures 5 to 7, indicating negative buoyancy, and positive in Figure 9, meaning positive or normal buoyancy. The term B', taken with its sign can be used to express the overall drag to buoyancy ratio, as D/(B+B') or $D/((\Delta T_{maxr}+\Delta T_{lr}) / T_{max}) \times \rho \times g \times Vol)$, where . $\rho \times g \times Vol$ is the mass of air contained within the sprinkler spray.

CONCLUSIONS

Hot layer-sprinkler interaction has been simulated with a simple two-phase zone-like model. The following conclusions are reached with this model.

1. For an initially uniform hot layer temperature profile, the gas temperature after sprinkler interaction increases with increasing distance from the ceiling. Such a gradient causes negative buoyancy and gas lowering effect.
2. If a realistic non-uniform hot layer temperature profile is used before sprinkler interaction, no negative buoyancy exists after interaction. This results has been confirmed with experimental data.
3. These results indicate the importance of having a real gas temperature distribution in the study of smoke layer logging phenomenon.
4. Gas cooling is strongly affected by the sprinkler mean droplet diameter. The coarser the spray, the less effective is cooling, and gas logging effect due to negative buoyancy is more.
5. Gas temperature and velocity variations within the hot layer are important in obtaining realistic results.

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