Superdrop Modelling of a Sprinkler Spray in a Two-phase CFD-particle Tracking Model

S. KUMAR
Fire Research Station
Garston, Watford, WD2 7JR, UK

G.M. HEYWOOD and S.K. LIEW
W.S. Atkins, Woodcote Grove, Surrey KT18 5BW, UK

ABSTRACT

This paper introduces a 'superdrop' concept for the characterisation of a sprinkler spray, where the statistical characteristics of each 'superdrop' have been determined from the experimental data of a Wormald 'A' cu/p sprinkler in the pendant position.

The computational fluid dynamics (CFD) model JASMINE has been adapted to incorporate a particle tracking formulation based on the Particle-Source-In-Cell method and a sprinkler sub-model based on the 'superdrop' concept. The enhanced JASMINE sprinkler model has been verified against a full scale experiment examining the influence of the water spray on hot combustion products due to a fire in an enclosure. The predicted gas temperatures and the velocities are shown to be in qualitative agreement with the measurements. Further improvements in the model predictions can be obtained by improving the heat loss treatment to the boundaries and suitable optimisation of the 'superdrops'.

KEY WORDS: CFD model JASMINE, Sprinkler model, Superdrop concept

INTRODUCTION

Because of the current trends in Building Regulations from prescriptive to functional based building codes, CFD fire models (e.g. Kumar and Cox [1-3]) are increasingly being used for the design and assessment of fire safety in buildings. They can be used to examine the interactions between smoke venting, sprinklers, compartment geometry, visibility, travel distances and egress times, enabling the fire practitioners to make better decisions on the trade-off between compartment size and presence of sprinklers.

Two distinct approaches exist for simulating the two phase (liquid-gas) flow problem posed by the interactions of sprinkler sprays with the hot gases generated due to a fire. An Eulerian, or fixed frame, approach has been used by Hoffmann et al [4] for modelling fire spray systems. The approach is not appropriate for the treatment of the liquid phase in situations where a range of drop sizes need to be considered. The Lagrangian approach, also known as the particle tracking approach, will therefore be considered in this paper.

For over the last couple of decades the particle tracking approach, differing mainly in the formulation of drop trajectories, has been used quite extensively [eg Refs 5 and 6]. Crowe et al [5] have solved analytically the equations of motion for falling drops by treating them as spheres. On the other hand, Moffat and Pericleous [6] have favoured a numerical approach for the solution of these equations so as to allow, where necessary, for non-spherical drops.

This paper presents a simplified 'superdrop' modelling approach for the characterisation of a sprinkler so as to incorporate real sprinkler characteristics in a particle tracking formulation. The following section describes a sprinkler sub-model based on the 'superdrop' concept and its implementation in the JASMINE particle tracking model based on the Particle-Source-In-Cell method of Crowe et al [5], where each 'superdrop' is a statistical representation of a number of real drops of the sprinkler spray. A full scale experiment designed to measure the influence of the water spray on the gas temperature and velocity field close to ceiling will then be used to verify the model.

MODEL DESCRIPTION

Modelling of gas phase - CFD model JASMINE

A detailed description of JASMINE has been given elsewhere [e.g., Ref. 1] and will not be repeated here. Suffice it to say that it is a three-dimensional, transient computational fluid dynamics (CFD) model which describes the fluid dynamics of an enclosure fire in terms of the three Cartesian velocity components, pressure, enthalpy, kinetic energy of turbulence (k) and its rate of energy dissipation (ϵ). The k-ϵ turbulence model is adapted to incorporate the effect of buoyancy so as to account for the unstable stratification in the rising plume and stable stratification in the hot ceiling layer. Combustion is simulated by a one-step chemical reaction, where complete oxidation is assumed when sufficient oxygen is available. The local rate of reaction is calculated from a modified version of the well known eddy break up model (see for example Refs [1-2]). The modelling of the radiation-convection coupling in the gas phase is not considered in this paper. However, a lumped heat transfer coefficient approach [2] is used to account for the effect of radiation and convection exchange between the near wall grid cells and the solid boundaries of an enclosure.

Modelling of Sprinkler - 'Superdrop' Concept

The specification of initial drop characteristics (diameter, position, trajectory and velocity components) of a sprinkler spray (after it has been atomised) is crucial for the accurate prediction of heat, mass and momentum transfer between the water drops and fire gases. The mechanisms involved in the atomization of a sprinkler spray and subsequent water break-up are quite complex and are not yet fully understood. It has been found experimentally [7,8] that the atomization of a sprinkler spray does not take place at its head emission point but at some distance from the spray head (i.e., at the spray envelope of some finite radius). Following Jackman [8], the break-up zone has a relatively high momentum and the large drops and ligament volumes present a relatively low surface area. Consequently, the heat and momentum transfer in this region can be considered small.

In the present study, the initial drop characteristics of a sprinkler spray will be obtained from its measured values after it has been fully atomised at a fixed radius from the sprinkler emission head. The modelling of initial water break-up is not considered here.

The atomization of a typical sprinkler spray produces of the order of 10^8 water droplets in the air at any one time. Current computing resources do not allow any computer program to store the position, velocity, temperature and diameter of each of these droplets and to recalculate them at each time step. The capability to perform transient analyses requires the tracking of individual droplets between time steps, rather than simply the calculations of trajectories.

To overcome this problem, Alpert [9] simulated a polydisperse water spray by a line (two-dimensional) spray with droplet injection characteristics similar to those expected for real spray nozzles. The line spray was represented by five discrete droplet sizes, each having 20 per cent of the total water flow with radii characterised by a Rosin -Rammler distribution. The droplets were assumed to be isothermal and were injected from the line source along six uniformly distributed trajectories such that water mass flow per unit angle of the initial spray is constant. Recently Bill [10] and Nam [11] have used this method for predicting "Actual Delivered Densities" (ADD) of fast response sprinklers, where a total of 250 to 275 droplet trajectories were used to get reasonable agreement with the measured data. Bill [10] used five discrete drop sizes and 50 drop trajectories for each drop size and Nam [11] used 10 discrete drop sizes and 25 trajectories for each drop size, and additional 25 trajectories close to the axis. It should be noted that the method assumes uniform discharge speed of the drops in a spray but the discharge angles of the trajectories change continuously so as to yield a reasonable match between the predicted and measured water flux distributions and spray momenta at different distances below the sprinkler.

In contrast, the concept of 'superdrops' is introduced for the characterisation of a sprinkler spray in the JASMINE particle tracking model. The concept is based on the assumption that each 'superdrop' represents a number of real droplets within the sprinkler spray, and its characteristics are determined according to statistical distributions of real droplets. The sprinkler will be modelled by a number of these 'superdrops', each covering a specified range of azimuthal angles.

The 'superdrop' concept was developed by using the measurements [7] of water frequency distribution map or 'splash pattern' and intensive property data on initial drop diameters and their velocities and trajectories at several horizontal and vertical positions around the sprinkler head. Splash patterns were examined experimentally by Jackman [7] for a range of sprinklers. Each tested sprinkler was found to produce a unique splash pattern, where angular variations could be related to structural features of the sprinkler spray head (yoke arms and striker plate). The effects of these features become more pronounced at increasing flow rates. The study indicated that drops of different sizes are expected to fall at different positions on the floor and follow a unique path (in space and time) from the sprinkler head, thus resulting in unique splash pattern for a particular type of sprinkler. A measured splash pattern at floor for the Wormald 'A' conventional (cu/p, K-80) sprinkler in a pendant position is shown in figure 1. The splash pattern clearly shows symmetry along and normal to the yoke arm. It has pronounced lobes at 45° and 75° and a continuous peak from 75° through to 105°.

Figure 2 shows a schematic representation of a typical splash pattern on the floor of a compartment and horizontal data sampling locations. It should be noted that only a quadrant of the sprinkler was considered by Jackman [7,8] for horizontal data sampling because of the symmetry observed in the splash water distribution on the floor. The sprinkler data was sampled for the Wormald sprinkler at five horizontal and four vertical angles, totalling 20 locations. The original drop data set for this sprinkler contained 1800 drops and the revised set 1690 drops, where the difference between the drops accounted for those travelling back towards the sprinkler and thus removed from the set. The initial droplet diameter and velocity characteristics of the sprinkler were determined from the data of Jackman et al [7]. A log-normal distribution was fitted to the drop diameter data and a normal distribution to the horizontal and vertical velocity components data.

Modelling of Gas-Drop Interaction - JASMINE Particle Tracking Model

The two phase capability developed within the CFD model JASMINE uses the Particle-Source-In-Cell (PSI-Cell) method developed by Crowe et al [5]. The capability, which will hereafter be referred to as the JASMINE particle tracking model, is intended primarily to examine the interaction of sprinkler sprays with fire and its hot combustion products. Some salient features of the particle tracking approach are outlined below. It allows full transient analyses for gas phase combustion products and liquid phase sprinkler droplets, and full coupling of mass, momentum and heat transfer between the two phases.

Various processes involved in the gas-drop interactions are illustrated in figure 3. The motion of the drop is determined by the downward force of gravity and the upward drag force exerted by the hot gas flow field. The heat transferred from the hot gas flow field to the cold drop reduces the temperature and density of the gas flow field which in turn may change the trajectory of the drop. A schematic of the PSI-Cell method is illustrated in figure 4. As a drop (indicated by solid circles) travels through the gas flow field (indicated by vectors), the changes in its mass, momentum and heat are calculated and treated as sources or sinks (indicated by crosses) in the gas phase equations.

The main assumptions made in this study are as follows:

- Drops are spherical in shape. The consequence of this assumption is that mutual collisions, shape deformations and coalescence of droplets are ignored.
- Drops interact only with mean gas motion and follow their deterministic trajectories.
- Turbulence effects on dispersion of drops and the interphase transport are ignored.
- The liquid drop phase volume is less than the gas phase volume.
- Drop evaporation has little influence on drag coefficient and heat transfer.
- The Lewis number is equal to unity.

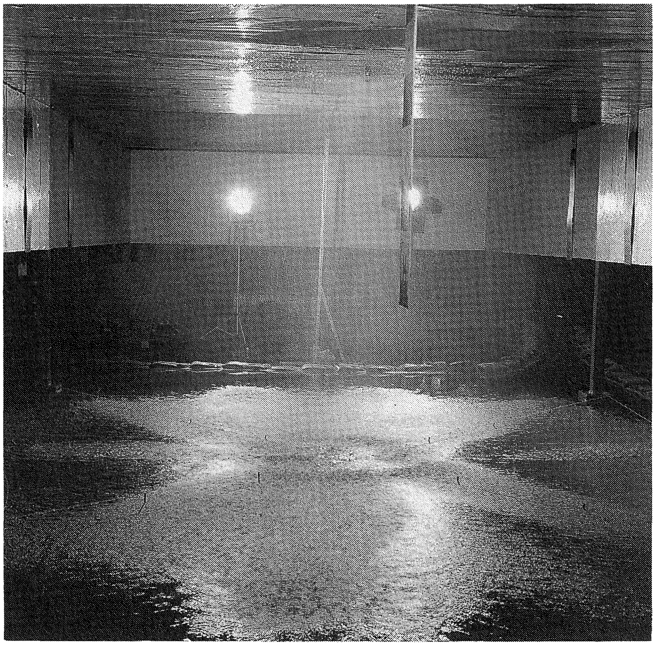
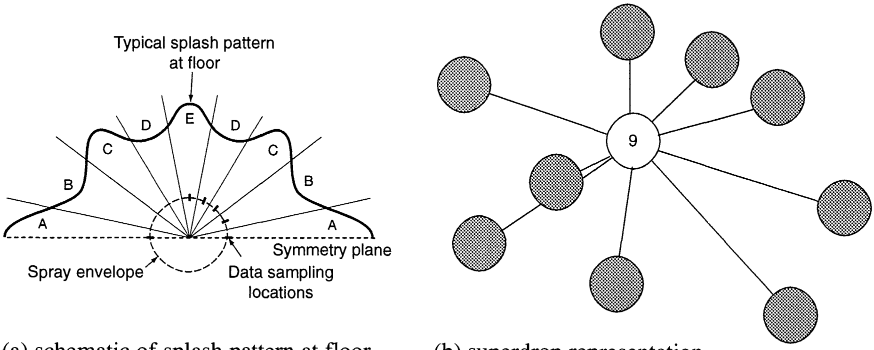


Figure 1 Experimentally observed water splash pattern at floor for Wormald 'A' cu/p sprinkler – pendant position, 15mm bore, flow rate of 1 litre/s



(a) schematic of splash pattern at floor and data sampling locations

(b) superdrop representation

Figure 2 Modelling of sprinkler – 'superdrop' concept

The position and velocity of a drop, describing its trajectory, are obtained from the equation of motion:

$$m_d \frac{d\vec{v}_d}{dt} = -C_D \rho (\vec{u} - \vec{v}_d) \, |\vec{u} - \vec{v}_d| \frac{A_d}{2} + m_d g \tag{1}$$

$$C_D = \frac{24}{Re} (1 + 0.15 \, Re^{0.687}) \; ; \; Re \equiv \rho \, |\vec{u} - \vec{v}_d| \, \frac{d}{\mu} \tag{2}$$

$$X_d = X_{d0} + (v_d + v_{d0}) \, t/2 \tag{3}$$

where u denotes gas velocity, m_d the mass of the drop, v_d its velocity and X_d its position, and C_D is the drag coefficient. The equation is solved numerically by using a fourth order Runge-Kutta method.

The drop diameter history is obtained from the mass conservation equation (i.e. rate of decrease of mass due to evaporation):

$$\frac{dm_d}{dt} = -\frac{h_m}{RT} (p_v - p_\infty) (\pi d) \tag{4}$$

$$\Rightarrow \frac{d(d)}{dt} = -\frac{h}{c_p \rho R T} (p_v - p_\infty) \frac{2}{\rho_d d} \; ; (Le = 1) \tag{5}$$

where h_m is a mass transfer coefficient, ρ and T are respectively the density and temperature of the water vapour, T_d is the temperature of a droplet, and p_v and p_∞ are the partial vapour pressures at T_d and in the free stream respectively.

The temperature history of the drop is obtained from the heat balance equation:

$$m_d c_{p,d} \frac{dT_d}{dt} = \dot{q}_d + L \frac{dm_d}{dt} \tag{6}$$

$$\dot{q}_d = h (T_g - T_d) \, \pi d^2 \tag{7}$$

where $\dot{q}_d$ is the rate of heat transfer to the droplet, L the latent heat of vaporisation of the droplet, $c_{p,d}$ the specific heat of the droplet, T_g the gas temperature and T_d the droplet temperature.

The generic gas phase equation, adapted for drop source terms, is of the form:

$$\frac{\partial (\rho \phi)}{\partial t} + \vec{u}.\vec{\nabla}(\rho \phi) = \vec{\nabla}.(\Gamma_\phi \vec{\nabla} \phi) + S_{\phi,g} + S_{\phi,d,cell} \tag{8}$$

$$S_{\phi,d,cell} = \sum_i \pi \rho_d \eta_j(d_i) \frac{\phi_{d,exit} d_{i,exit}^3 - \phi_{d,entry} d_{i,entry}^3}{6} \tag{9}$$

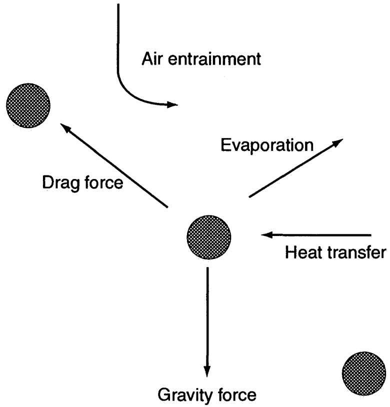


Figure 3 Gas-drop interactions in a two phase system

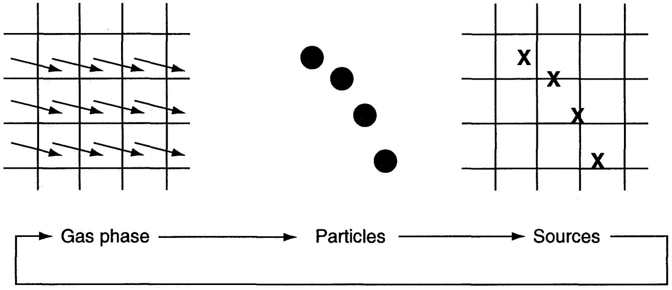


Figure 4 Schematic representation of particle-source-in-cell method

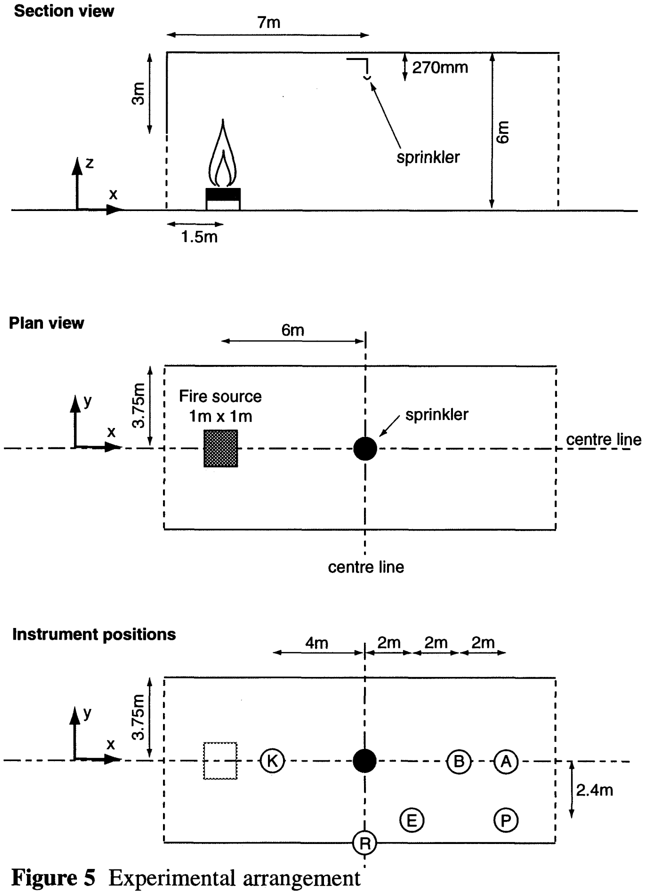


Figure 5 Experimental arrangement

where ϕ_d is equal to 1 (continuity equation), v_d (momentum equation), h_d (heat equation); $h_d = h_v - L$, η_j (d_i) denotes the number flow rate of droplets traversing a given cell along trajectory i and in sector j ; h_v is the enthalpy of the vapour.

DETAILS OF EXPERIMENT AND NUMERICAL SIMULATIONS

A full scale experiment conducted by Ingason and Olsson [12]was used to verify the enhanced JASMINE particle tracking model. The main objective of the experiment was to measure the influence of the water spray on the gas temperature and velocity field close to ceiling. The experimental arrangement, illustrated in figure 5, consists of a short length of corridor which is open at both ends. The fire source was located 1.5m from one of the openings, which was fitted with a 3m deep soffit. Measurements were made at eleven stations, six of which were used for comparison with the model predictions. The tests involving a heat output of 1 MW both with and without the sprinkler activated, using water flow rate of 1 litre/s, were used for the verification of the model. A Wormald 'A' cu/p, K-80 sprinkler in the pendant position with the deflector plate 270mm below the ceiling was located centrally in the compartment.

Due to symmetry, the sprinkler was characterised by nine 'superdrops', each superdrop being described by the mean and standard deviation of the diameter and of the horizontal and vertical velocity components associated with all drops in a particular azimuthal angular section. The superdrops and the associated azimuthal angular sectors are illustrated in figure 2 and are given in Table 1. A log-normal distribution was fitted to the drop diameter data and a normal distribution to the horizontal and vertical velocities data of Jackman et al [7].

Table 1. 'Superdrop' characterisation for Wormald 'A' cu/p, K-80 sprinkler

Superdrop Number	Azimuthal Angular sectors (degrees)	Data Subset (see figure 2)
1	0-10	A
2	10-30	B
3	30-50	C
4	50-70	D
5	70-110	E
6	110-130	D
7	130-150	C
8	150-170	B
9	170-180	A

As an illustration, the mean values and standard deviations of the fitted (dotted line) and measured (solid line) distributions for subsets B and E are shown in figure 6.

A total of 28x13x19 grid cells were used to simulate half the corridor shaped compartment where a symmetry boundary was used on the vertical mid plane through the fire and along the corridor. Two sets of numerical simulations were performed, using the 'superdrop' data

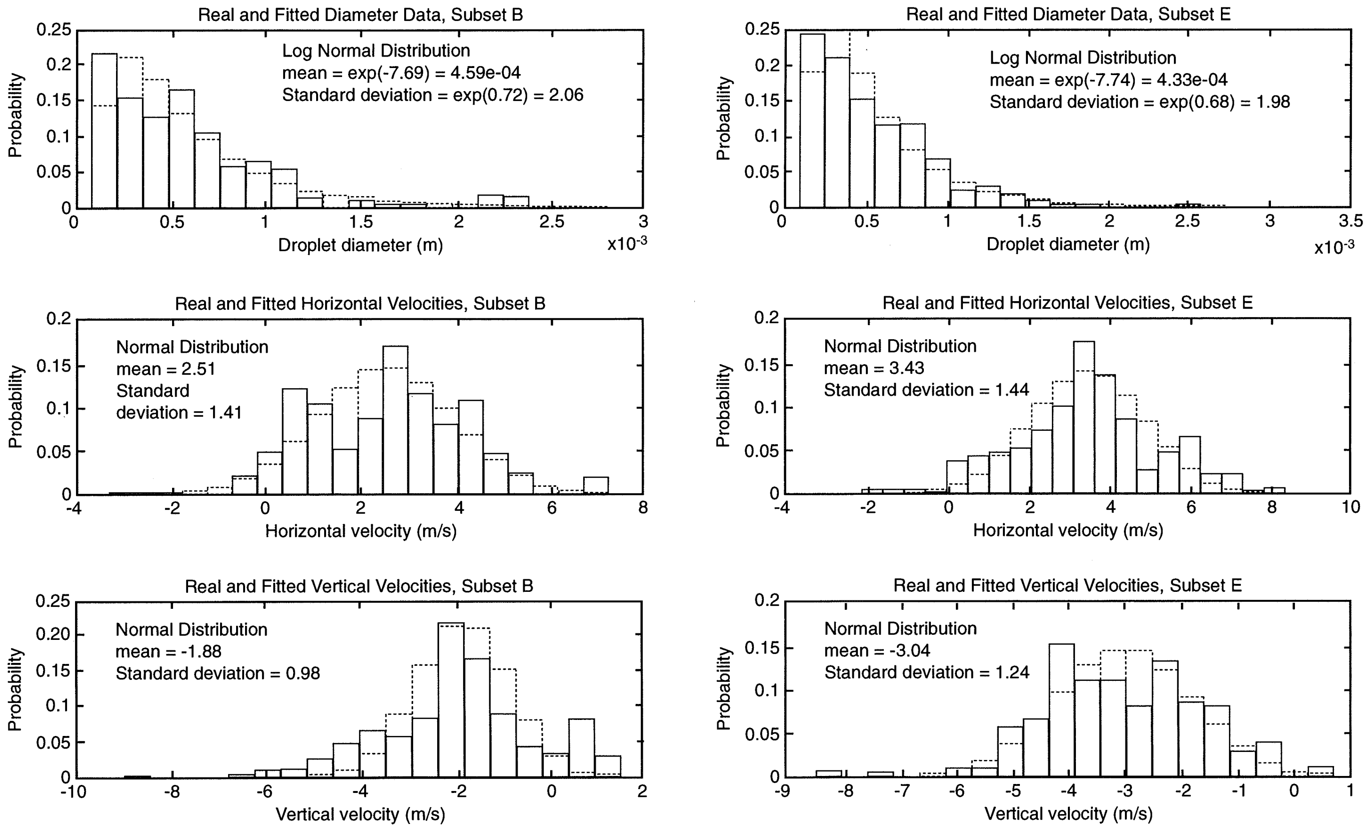


Figure 6 Comparison of fitted and measured distributions for Wormald 'A' cu/p sprinkler

given in Table 1 and figure 6. In the first set of simulations, referred to as 'Model 1', the heat transfer to compartment walls and ceiling were ignored. The second set of simulations, referred to as 'Model 2', were performed by allowing heat losses to the compartment boundaries, using a quasi-steady one dimensional heat transfer analysis.

RESULTS AND DISCUSSION

The fitted log-normal distribution for the drop diameter data and normal distribution to the horizontal and vertical velocities data of Jackman et al [7] were compared with the measurements for each of the five data subsets. As an illustration, the fitted (dotted line) and measured (solid line) distributions for subsets B and E are compared in figure 6. It can be seen that the log-normal distribution provides a reasonably good fit to the drop diameter data. The differences between the normally fitted and measured distributions are more pronounced for the horizontal and vertical velocity components; however, the agreement can still be considered satisfactory.

The effect of heat losses to the boundaries and the influence of the sprinkler spray on the gas phase temperature and velocity predictions were examined by the comparing 'Model 1' and 'Model 2' predictions with the data for all the six measurement locations. (see figure 5).

Comparison of the model predictions with measurements at locations B and K is shown in figure 7. The 'Model 1' predictions are denoted by shaded symbol, 'Model 2' predictions by solid symbols and the measurements by open symbols. The results for the sprinkler-off case are denoted by square symbols and for the sprinkler-on case by diamond symbols. It can be seen that the model has reproduced sprinkler cooling of the hot gases, as is indicated by the lower predicted gas temperatures for the sprinkler-on case. In contrast, the increase in gas velocity at station B for the sprinkler-on case can possibly be attributed to the recirculation generated by the sprinkler, and this is supported by the velocity vector plots shown in figure 8. However, this needs to be checked by refining the grid in the vicinity of the sprinkler.

Figure 7 shows that by allowing heat losses to the compartment boundaries the 'Model 2' predictions are in better agreement with the measurements than 'Model 1' predictions. The significant differences in predictions and measurements in the sprinkler-off case (square symbols) suggest that a better heat transfer model would be necessary. Further improvements could be made by optimising the number of 'superdrops' in the sprinkler sub-model.

CONCLUSIONS

A sprinkler sub-model based on a 'superdrop' concept has been developed for the characterisation of a conventional sprinkler in the pendant position. The analysis of the sprinkler emission data suggests that each 'superdrop' can be modelled by a log-normal distribution to characterise its diameter and a normal distribution to characterise its horizontal and vertical velocity components.

The potential of the JASMINE particle tracking model, enhanced with the 'superdrop' sprinkler sub-model, in simulating realistically the sprinkler-fire gas interactions has been

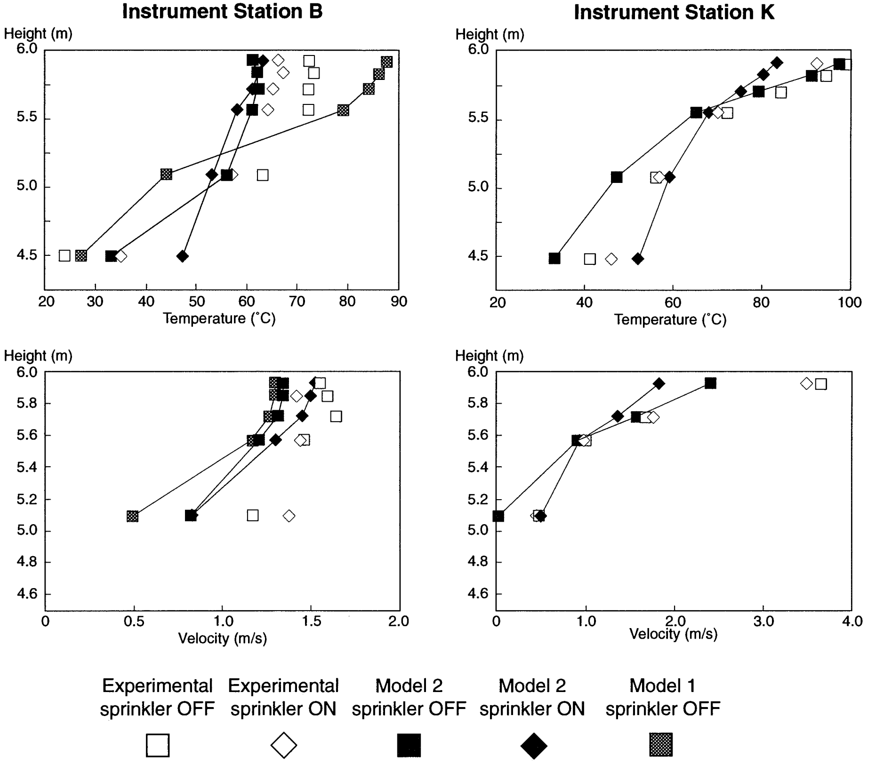
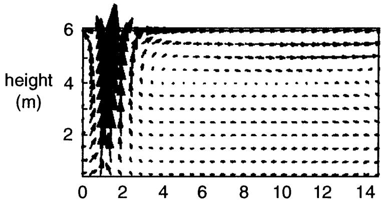
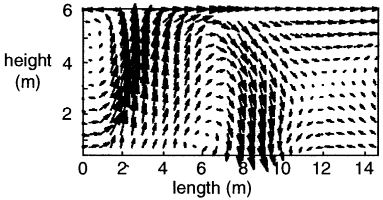


Figure 7 Comparison of model predictions with measurements



(a) Sprinkler off



(b) Sprinkler on

Figure 8 Velocity vectors in the steady state on the vertical plane midway through the fire and sprinkler demonstrated. The extension of the 'superdrop' sub-model for other types of sprinklers will be the subject of further study.

The performance of the enhanced JASMINE particle tracking model can be improved by refining the treatment of heat losses to the boundaries in the CFD model and optimisation of the 'superdrops' in the sprinkler sub-model. Optimisation will ensure that each 'superdrop' is a more realistic statistical representation of a number of real drops and hence provide improved coupling between the gas phase and the individual droplets.

ACKNOWLEDGEMENTS

The paper forms part of the work of the Fire Research Station, Building Research Establishments, Department of the Environment, UK. It is contributed by permission of the Chief Executive of the Building Research Establishment.

REFERENCES

1. Cox G and Kumar S. Combus. Sci. Technol., 52, 7, 1987.
2. Kumar S and Cox G. In Proc 5th Intl. Conf. on Aerodynamics and Ventilation of Vehicle Tunnels, Lille, France, p 61, 1985.
3. Kumar S, Gupta A K and Cox G. In Proc. 3rd Intl. Symp. on Fire Safety Science, Edinburgh, Scotland, p 345, 1991.
4. Hoffmann N, Galea E R and Markatos N C. Appl. Math. Modelling, 13, 298, 1989.
5. Crowe C T, Sharma M P, Stock D E, Trans ASME J Fluid Engng. p 325 , 1977.
6. Moffat J and Pericleous K. In Proc. 3rd Intl. PHOENICS User Conf., 1989.
7. Jackman L A. Sprinkler spray model with fire gases interaction, Ph. D. Thesis, South Bank University, London, UK, 1992.
8. Jackman L A. In Proc. 1st Intl. Conf. Fire Suppression Research, 5-8 May, Stockholm, 1992.
9. Alpert R L. Journal of Heat Transfer, 106, 310, 1984.
10. Bill R G, Jr. Fire Safety Journal, 20, 227, 1993.
11. Nam S. Fire Safety Journal, 26, 1, 1996.
12. Ingason H and Olsson S, SP-Report 1992:11, Fire Technology, Boras, 1992.