Effects of Thermal Radiation on the Fluid Dynamics of Compartment Fires

S. KUMAR
Fire Research Station
Borehamwood, Herts WD6 2BL, UK

A. K. GUPTA
Central Building Research Institute
Roorkee 247667, India

G. COX
Fire Research Station
Borehamwood, Herts WD6 2BL, UK

ABSTRACT

This paper describes the application of a numerical field model to the problem of fire induced flows in rooms. Particular attention is paid to the effect on air entrainment of fire location, and of thermal radiation. The comprehensive set of full scale room fire experiments reported by Steckler et al has been used for comparison with predictions.

It is shown for corner fires that in addition to the jet of hot combustion products leaving under the top of a doorway opening, there is, below it, a significant outflow of heated air apparently resulting from the redistribution of energy between hot and cool layers by thermal radiation. A comparison of the predicted doorway flow rates with measurements is shown to be in good agreement.

KEYWORDS: Mathematical Model, Field Model, Compartment Fires

INTRODUCTION

The gross features of domestic-sized room fires can often be reasonably well represented by a two layer, zonal approximation [1]. This is based on the assumption that the products of combustion fill the upper regions of the room in the manner of a bathtub filling with water. A one dimensional, stagnant and well mixed hot gas layer grows at the expense of a cool air layer beneath it.

However, this greatly simplifies a very complex process. For a greater understanding of the many interactions taking place, it is essential that the important mechanisms involved in transferring mass between lower and upper gas layers are realistically represented. Most zonal methods simply utilise an axisymmetric plume entrainment equation to describe this mass transfer process.

There are a variety of such expressions in common use, ranging from that for a classical axisymmetric thermal plume, reported by Morton et al [2], to fire-specific expressions such as those recommended by, for example, Zukoski et al [3].

Such treatments can be overly simplistic. Quintiere et al [4] drew attention to the significant enhancement of entrainment that can occur if the flame is deflected by the cool doorway inflow air jet. For fires close to or touching a wall, further modification is also required to account for asymmetries in entrainment caused by the presence of boundaries. Another mechanism, not routinely incorporated, is the extra mass entrained by thermal plumes rising from the floor, or lower portions of walls, heated by thermal radiation. Jaluria [5] has recently attempted to quantify this effect, but it is difficult to see how it can be incorporated into the simple models in any general way.

All of these phenomena are, however, naturally accounted for by models of the 'field' type using the techniques of computational fluid dynamics. By solving, numerically, the full partial differential equation set describing local conservation of mass, momentum, energy and species, subject to the particular boundary conditions of the problem, empirical assumptions concerning air entrainment are unnecessary.

Whilst models of this type are applied routinely in many combustion applications, their widespread use in fire research has been limited. Much work, until comparatively recently, has concentrated on validating their methodology [6] (numerical methods and turbulence modelling) rather than on elucidating the complex interactions involved in fire.

This paper describes a theoretical study, using the field model JASMINE [7,8], of the room fire experiments reported by Steckler et al [9], with the objective of focusing on the effects on entrainment of fire position and thermal radiation. The importance of thermal radiation on the fluid dynamics is examined with a six-flux model of radiation. Special attention is paid to fire in the corner of the room. The effect of the draught caused by the air inflow on the fire plume is shown for the central fire.

An earlier study by Cox [10] of some of these experiments, using a less sophisticated version of the model used here, represented one of the earliest validations of three dimensional field modelling methodology applied to fires.

MODEL DESCRIPTION

The mathematical basis of JASMINE has been described elsewhere [7,8,11] and will not be repeated here. Suffice it to say that it is a three-dimensional, transient, 'field' model which describes the fluid dynamics of an enclosure fire in terms of the three Cartesian velocity components, the pressure, enthalpy, kinetic energy of turbulence and its rate of energy dissipation. The turbulence model is adapted to incorporate the effect of buoyancy, which gives rise to unstable stratification in the rising fire plume, and stable stratification in the hot ceiling layer [11]. Combustion is simulated by a one-step chemical reaction, where complete oxidation of fuel is assumed when sufficient oxygen is available, and the local reaction rate is calculated from a modified version of the well known eddy break up model (see for example

Refs 7 and 8). A simple six-flux model [12] is used here to describe radiative heat transfer inside the enclosure. Since the transport equations for all the characteristic flow parameters are solved simultaneously, the radiation-convection coupling in the fluid, as well as at the boundaries, is accounted for. A detailed description of the flow-boundary treatment is given in Ref.12.

A fixed mean absorption coefficient for the gas of 1 m^{-1} together with a wall emissivity of 0.9 was used in most of the work described here. Radiative scattering was considered negligible. This simplified approximation of the actual fire environment in the compartment was used initially. Later, this was improved by exploiting Modak's model ABSORB [13] to provide local predictions of absorption coefficient based on predicted concentrations of CO_2 and H_2O, together with an elementary treatment for soot.

EXPERIMENTS CONSIDERED

A systematic experimental compartment fire programme was reported by Steckler et al [6]. Many steady-state experiments were conducted in the compartment, with a variety of door and window openings. A gas burner was used to provide simulations of fire of various rates of heat release. A selection of these experiments was chosen for the current study and is summarised in Fig 1.

The figure shows the plan of the compartment and the burner locations. The compartment was 2.8 m x 2.8 m in plan and 2.18 m in height. The burner was flush with the floor for locations A, B and C and raised by 0.3 m for locations D and G. The walls and ceiling were covered with a ceramic fibre insulation board, to establish near steady conditions within 30 minutes of ignition of the 0.3 m diameter porous plate diffusion burner. The fire was produced by burning commercial grade methane at a fixed rate. For all the experiments chosen here, only one fire strength, of theoretical heat release rate 62.9 kW, and one door size opening (0.74 m wide and 1.83 m high) were considered. Vertical columns of thermocouples and bi-directional velocity probes were provided within the doorway opening. A fixed column of aspirated thermocouples in the front corner (location O) of the compartment was also provided.

DETAILS OF THE NUMERICAL SIMULATIONS

Two sets of numerical simulations were performed for each of the fire locations shown in Fig 1. Initially, radiation exchange in the gas phase was ignored and a lumped heat transfer coefficient (LHTC) model [1,7,8] was used to account for the effect of radiation and convection exchange between near wall grid cells and the solid boundaries. For the second set, the six-flux radiation model was used to allow radiation exchange within the gas phase, in addition to exchange with the boundaries. The convective heat losses to the boundaries were calculated by standard wall laws (see eg Ref.12). For all fire locations, except the one in the corner, steady-state converged solutions were obtained directly. For the corner fire, 'B', a converged solution for the steady state could only be obtained through transient simulations.

For each of the numerical simulations, a moderately fine grid was used to ensure accurate detailed comparison of the temperature and velocity profiles. For all the cases, the computation domain was extended outside the door by 5 metres (represented by 5 grid cells) to where a fixed pressure boundary condition was prescribed. A similar condition was prescribed on an 'extended' ceiling. The extension was necessary to simulate realistic flow conditions at the door opening [11]. The total number of grid cells used to represent the actual compartment and the extended domain outside the door opening for fire location B were 4845 and 1425 respectively; slight variations in the grid were allowed for to accommodate other fire locations.

RESULTS AND DISCUSSIONS

The fire in the corner, at location B, being the most interesting but most difficult to simulate numerically, is discussed here. The predictions of doorway centreline velocities and temperatures as a function of height are compared with measurements in Fig 2. It can be seen that the LHTC model predictions show reasonable overall agreement with the measurements, but miss out a 'foot' observed at the hot-cold layer interface both in the velocity and temperature profile. The six-flux radiation model captures this experimental observation very well and improves the prediction throughout. This 'foot' has interesting characteristics. It can be seen from Fig 3 that it contains mainly heated air with a relatively low concentration of combustion products. This appears to be caused by radiant heating of the slightly contaminated but cooler gases situated beneath the hot layer. This is supported by Fig 4 where enhancement in velocity vectors at the interface can be seen with the six-flux model. Results obtained using Modak's model agreed fairly closely with those obtained with the fixed absorption coefficient. In the hot layer, Modak's model predicted an absorption coefficient in the range 0.3-0.5 m^{-1}. The associated increase in the predicted mass flow rate through the doorway in this fire, due to the foot, was found, with the constant absorption coefficient, to be more than 25% as can be seen in Table I and around 22% with Modak's model.

Figure 5 compares the predicted and measured temperature profiles in the front corner (O) of the compartment for the corner fire B. Both LHTC and six flux models correctly capture the stratified layer interface. As expected, radiation redistributes the thermal energy and reduces the temperature stratification. The temperature profile predicted by the six-flux radiation model agrees fairly well with the measurements. The figure does show why the fire environment inside the compartment can often be approximated by two layers, although here the lower layer is not at external ambient temperature but is heated.

It is evident from Figs 2 to 5 that inclusion of thermal radiation is important for the realistic description of the fluid dynamics inside enclosures of this size. Therefore, only predictions using the six-flux model will be shown for further comparison with the measurements.

Figure 6 compares the predicted horizontal velocity profiles with measurements for Fire B across the doorway width in the hot and cold door jets (at heights 1.311 m and 0.399 m from the floor). The predictions show a maximum velocity in the centre and a minimum at the edges of the door whereas the measured profiles show the opposite behaviour.

Steckler et al [14] have discussed this and argue that the experimental profile, with peak velocities at the edges, is to be expected from potential flow theory, if it can be assumed that the bulk

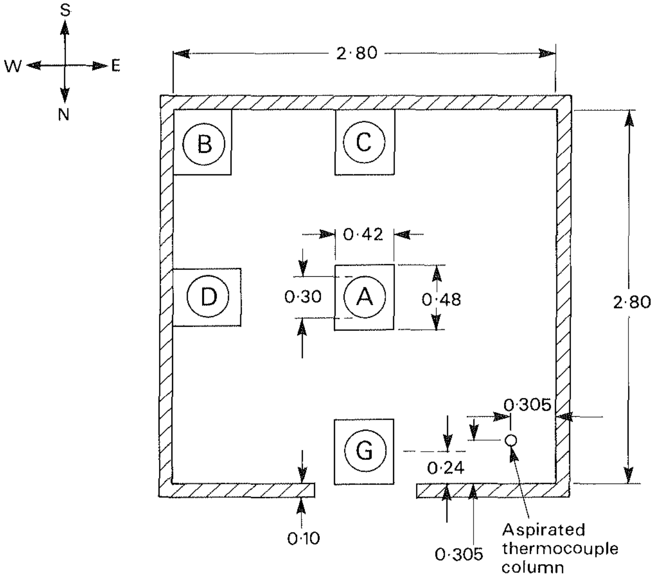


Figure 1. Plan of compartment with gas burner locations

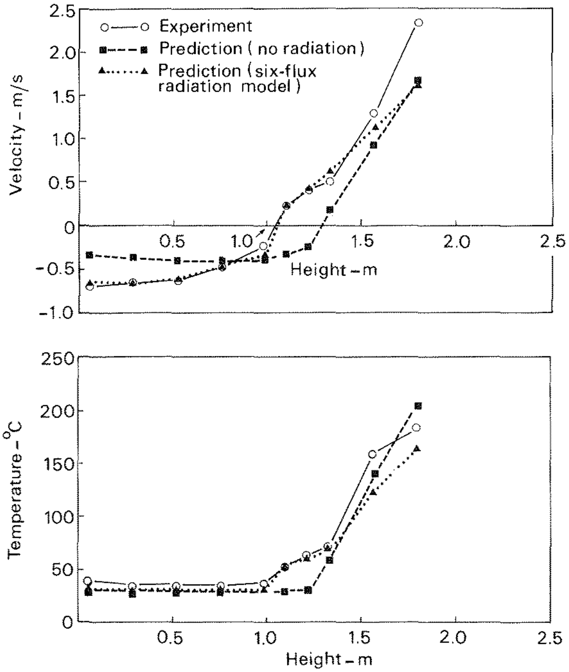
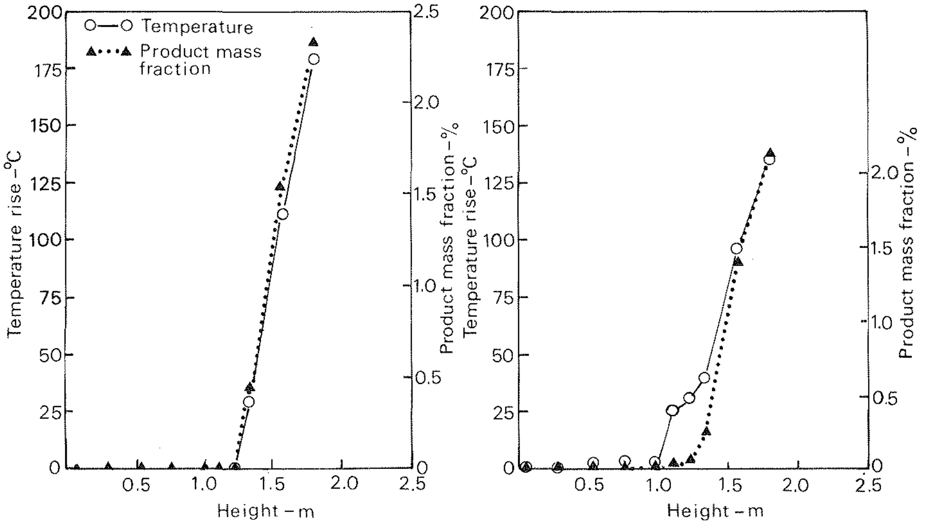
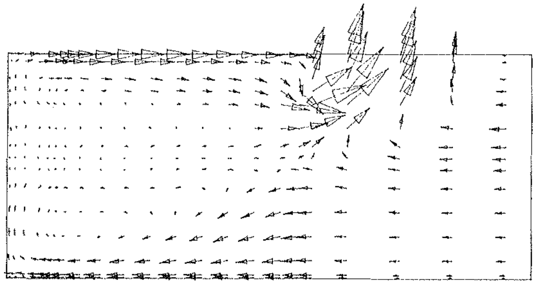


Figure 2. Doorway centreline velocities and temperatures as a function of height for fire B

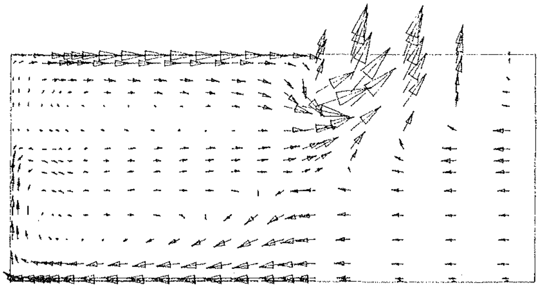


(a) No radiation model (b) Six-flux radiation model

Figure 3. Predicted doorway centreline temperatures and product mass fractions for fire B



(a) No radiation model



(b) Six-flux radiation model

Figure 4. Velocity vectors on the vertical plane midway through the door for fire B

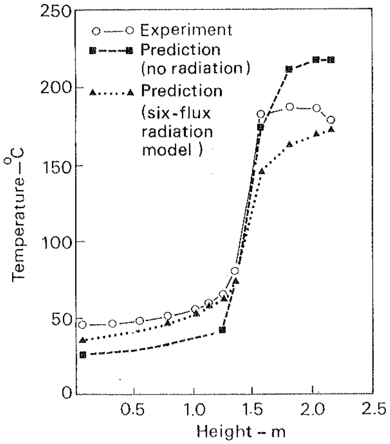
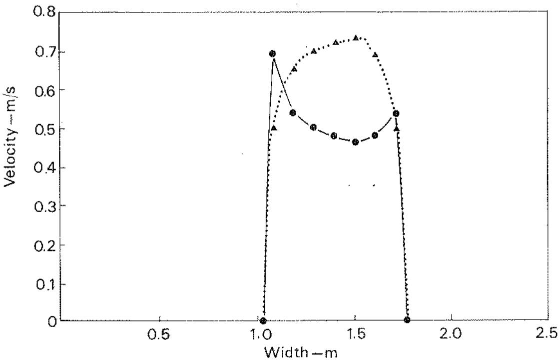
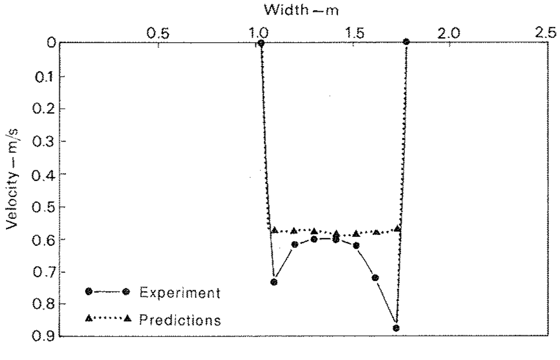


Figure 5 Vertical temperature profile in corner of compartment for fire B



(a) Upper hot layer (1.311m from floor)



(b) Lower cold layer (0.399m from floor)

Figure 6 Variation of velocities across width of doorway at heights of 1.311m and 0.399m from floor for fire B

TABLE 1. Comparison of predicted and measured mass flow rates (kg/s) through door

Fire Location	Flow Direction	Prediction		Experiment
		LHTC$^+$ model	Six-flux* model	
A	Inflow	0.510	0.497	0.553
	Outflow	0.511	0.498	0.567
B	Inflow	0.303	0.423 0.401**	0.440
	Outflow	0.304	0.424 0.402**	0.439
C	Inflow	0.345	0.448	0.474
	Outflow	0.346	0.449	0.476
D	Inflow	0.370	0.510	0.470
	Outflow	0.371	0.511	0.485
G	Inflow	0.631	0.630	0.550
	Outflow	0.632	0.632	0.601

$^+$ LHTC = Lumped Heat Transfer Coefficient
* Constant absorption coefficient
** Absorption coefficients estimated from Modak's model.

flow can be treated as irrotational and inviscid. Clearly JASMINE appears not to predict this detail correctly. If this explanation is accepted then an overprediction of turbulent viscosity, due either to excessive numerical diffusion or to the turbulence model itself, would appear to be the cause of this discrepancy.

Fortunately, the shape of the horizontal velocity profile across the doorway width does not seem important to the overall dynamics of the fire. This is clear since all the important characteristic features of the compartment fires, such as the interface height, detailed vertical profiles and mass flow rates through the doorway opening, are correctly predicted and agree well with the measurements.

It is worth mentioning here that the six-flux model has simulated, realistically, the radiative heating of the floor and, as a consequence, the convective heating of the cooler air flowing over it. However, it does not simulate accurately the effect of wall plumes. For this the discrete transfer method, recently applied to fires by Lockwood and Malalesekera [15], which allows heat transfer at angles oblique to the Cartesian grid, would be more suitable.

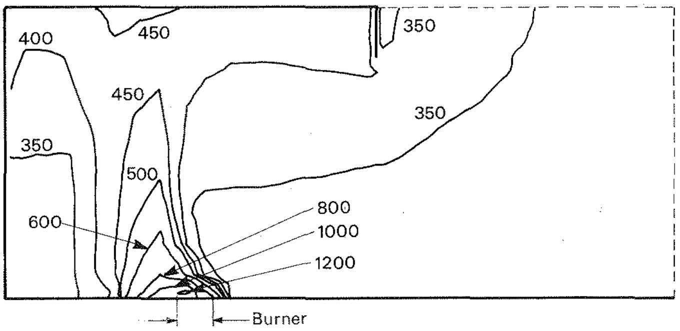


Figure 7 Contours of temperatures (K) on the vertical central plane through fire A

For fire locations A, C, D and G, the predicted velocity and temperature profiles were found to be in reasonable agreement with the measurements. For brevity, only the mass flow rates through the doorway opening are given here for comparison. These are summarised in Table 1.

It can be seen that the inclusion of radiant heat transfer generally increases the predicted doorway mass flow rates for those fires situated around the compartment periphery (B, C, D). This pattern is not repeated for the fires A and G, situated away from the walls and closer to the open doorway. It would appear, then, that this enhancement is most pronounced where the opportunities for large scale recirculation are greatest.

For the central fire A, Figure 7 displays the contours of predicted gas temperatures on the vertical plane through the centre of the fire. The deflection of the fire plume, as discussed by Quintiere et al [4] and due to the draught of air 'blowing' through the doorway opening, is clearly evident.

CONCLUSIONS

The 'field' model has clearly illustrated the qualitative effects of thermal radiation on room fire air entrainment. It has also naturally included any entrainment enhancement due to plume deflections.

The model, has provided reasonably accurate predictions of measured doorway flow rates despite detailed differences in the shapes of the doorway horizontal velocity profiles.

The presence of a jet of warm air leaving the doorway beneath the primary flow of hot products is particularly striking. In the case of the corner fire this constitutes around 25% of the total outflow.

It is acknowledged that the radiation model employed is deficient in its treatment of radiant heat transfer along directions oblique to the Cartesian grid employed. A more general treatment based on the discrete transfer method (eg Ref.15) coupled with an emissive power model [13], can rectify these deficiencies and should simulate the upward wall flows more accurately than the six flux model.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution of Peter Cumber in modifying JASMINE to incorporate ABSORB.

One of the authors (AKG) wishes to acknowledge the support of the British Council for the duration of his stay at the Fire Research Station.

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

REFERENCES

1. Emmons H W, Mitler H E and Trefethen L N. Computer Fire Code III, Home Fire Project Technical Report No.25, Harvard University, 1978.
2. Morton B R, Taylor G I and Turner, J S. Proc. Roy. Soc. A234, 1, (1956).
3. Zukoski E E, Kubota T and Cetegen G. Fire Safety J., 3, 107 (1981).
4. Quintiere J G, Rinkinen W J and Jones W W. Comb. Sci. Tech. 26, 193 (1981).
5. Jaluria Y. Handbook of Fire Protection Engineering, First Edition, p 1-116, Society of Fire Protection Engineers, 1988.
6. Cox G, Kumar S and Markatos N C. Proc of First Intl Symp on Fire Safety Science, p 159, Hemisphere, 1986.
7. Kumar S and Cox G. Fifth International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels, paper B1, 61 (1985).
8. Cox G and Kumar S. Comb. Sci. Tech. 52, 7 (1987).
9. Steckler K D, Quintiere J G and Rinkinen W J. Flow Induced by Fire in a Compartment, NBSIR82-2520, National Bureau of Standards, Washington, DC, (1984).
10. Cox G. Proc. CSNI Specialists Meeting on Fire and Explosion in Nuclear Facilities, 0199 Los Alamos Report LA 9911C (1983).
11. Markatos N C, Malin M R and Cox G. Int. J. Heat Mass Transf. 25, 63 (1982).
12. Kumar S and Cox G. Proc. Second International Symposium on Fire Safety Science, p 851 Hemisphere, (1989).
13. Modak A T. Fire Research 1, 339 (1979).
14. Steckler K D, Baum H R and Quintiere J G. Twentieth Symposium (International) on Combustion, p 1591, The Combustion Institute 1984.
15. Lockwood F C and Malalesekera W M G. Twenty-Second Symposium (International) on Combustion, p 1319 The Combustion Institute, 1988.