ZONE MODEL PLUME ALGORITHM PERFORMANCE

Dr. John A. Rockett

Fire Modeling & Analysis

Washington, D.C 20016-2041, U.S.A

(Received September 26, 1995, Accepted November 27)

ABSTRACT

Four plume algorithms used by three zone type building fire simulators are evaluated against experiential data of Steckler and Nakaya. Significant differences in the room flow predictions are found with even the best performing plume algorithms predicting flows well below the measured values. Differences in plume behavior is attributed to (1) the background noise (turbulence) present when the data used in formulating the algorithms was collected, and (2) the inability of the plume algorithms to easily simulate the effect of plume blowing.

The behavior of the McCaffrey plume in situations where the over-fire region dominates the plume flow is discussed.

KEY WORDS

Room fires, fire plumes, zone fire models

INTRODUCTION

This paper is dedicated to Prof. T. Handa, a generous friend and stimulating colleague, and to Prof. K. Kawagoe, friend and thoughtful counselor. Room fire modeling is a field to which Prof. Kawagoe made pioneering and major contributions.

Some years ago the author coded into Harvard V/NIST FIRST six of the then published plume algorithms.[1,10] Their performance was compared with data from Steckler [2] and used to assess the probable behavior of a proposed Fire Fighter Training Facility for the U.S. Navy. [3] This and additional experience in using some of these plume algorithms suggested at least three problems: (1) their behavior in tall buildings where the over-fire part of the plume was dominant, [4] (2) their ability to predict behavior of plumes from large fires, [3] and (3) their capability to express the behavior of plumes subject to a cross wind—for example, a door jet.[5] An additional problem associated with door jets—the behavior of the plume when the fire straddled the edge of the door jet—was encountered.[6] This situation can result in considerable swirl in

the plume as studied by Emmons and Ying.[7] Recently the effect of background turbulence on plume entrainment, noted by Zukoski, [8] has appeared.

A major ISO program to assess and calibrate fire models has recently started.[9] The first test description has been circulated to participants who must now return simulations for comparison with undisclosed test data. This first test is a single room, not unlike that used by Steckler.[2] The ISO program again raises questions about the capability of the available plume algorithms. It has stimulated a revisit to the Steckler room data, this time with several zone-type fire simulators. The simulators used were FIRST[10], CFAST20 [11], and BRI2 version VR, a modification of the BRI release version V[12,13,14]. The VR version of BRI2 is not documented at this writing although an English language user's guide is in preparation.

Plume algorithms

The current FIRST includes the same six plume algorithms used earlier, but two of these—the Delichatsios and Hasemi/Tokunaga plumes—did not operate reliably in the current version of FIRST with the Steckler room as input and are not included in this study. The algorithms used

are (1) the Thomas/Hinkley modification (M-T-H) of the Morton, Turner and Taylor plume (M-T-T)[15]-their modification displaces downward the point source [16]; (2) an un-displaced M-T-T point source plume (Pt)[15]; (3) the McCaffrey plume (McC)[17], and (4) the Cetegen-Kubota-Zukoski plume (C-K-Z)[18]. BRI2VR includes both the Zukoski plume, standard in recent Building Research Institute release versions, and also the McCaffrey plume, transcribed from BRI1. CFAST uses a modified version of the McCaffrey plume. The modification is not so much to the plume algorithm as to the way in which it is imbedded in the overall simulation.[11]

Zukoski's recent re-correlation of the Cal Tech data[19] has not been included in this study because the author was not sufficiently knowledgeable about some details of the procedure to generate an algorithm.

Effect of ambient turbulence

FIRST allows, as a user input option, adjustment of the plume entrainment coefficient used in the M-T-H and Pt plume algorithms.[10] The default value, $\alpha=0.1$, is the result of studies early in the development of the Harvard single room simulator in which the M-T-H plume was used and α was varied. The present default value was the one found to give the best overall agreement with the three FM bed-room tests and a number of allied tests in which urethane foam mats (simulated mattresses) were burned in a room. Thus the default α represents the plume entrainment expected in a "normally noisy" room environment.

McCaffrey conducted his tests with a square gas burner "... 0.75m above the floor and under a passive hood in a large laboratory." [20] There were no screens around the burner. Thus his plume measurements were made, again, in a "normally noisy" room environment.

The McCaffrey and Thomas/Hinkley plumes often give similar results where the over-fire region is not important.

Cetegen's data was collected using a steel

box placed inside a larger forced flow hood. "Two layers of 16x18 mesh screens made of 0.05cm diameter wire were hung from the bottom rims of the hood and allowed to fall around the floor, the floor-screen arrangement was used to reduce the strength of the disturbances present in the laboratory ..." [18] Thus the C-K-Z plume data was collected in a relatively noise free environment.

It will be seen that the C-K-Z plume entrains noticeably less than the M-T-H and McC plumes under similar conditions.

The Delichatsios plume model entered in FIRST is based on FM measurements made in an enclosing tank.[21] Air was fed from a settling chamber below the gas burner, up through screens and a pebble bed. Exhaust was sucked from the top of a conical, converging section of the tank well above the measuring station. Thus the FM data probably represents entrainment from a very low noise level environment. Although the Delichatsios plume model has not been used here, it has been found to entrain somewhat less than the others.[1]

Plume blowing

Quintiere, using the Steckler room, measured the angle of tilt of plumes in a cross wind and estimated the increased entrainment resulting. [22] Their data is for small fires relative to the room size.

If the fire is large enough, relative to the room in which it is found, the plume will penetrate the hot-cool interface while still within its "initial" or "continuous flame" region. In this case, if the C-K-Z plume flow correlation [18] is used, a correction for blowing can be made. Entrainment for the C-K-Z correlation applicable to the flame base depends directly on fire diameter; the correction is to artificially increase the fire diameter by the estimated amount of plume entrainment augmentation.[5] This "fix" will not work for situations where the hot-cool interface is higher because the correlation depends differently on fire diameter for the "inter-

mittent" and "over-fire" regions.

The Thomas/Hinkley plume can be "adjusted" to simulate blown plumes by artificially increasing the fire diameter. The relation between the fire diameter increase and entrainment increase is not linear as is the case with the C-K-Z plume. As mentioned, the Harvard single room simulator includes, as an input item, the plume entrainment coefficient. To correct the M-T-H plume for blowing, rather than adjusting the fire diameter, it appears preferable to increase the default entrainment coefficient.

Vent mixing

All three fire simulators used here include mixing at the vents. Very little data is available against which to test their mixing algorithms. As far as the author knows, the only direct, quantitative measurement of vent mixing is from experiments of Zukoski.[23] Quintiere et. al.[24] provide experimental evidence of mixing for fires in a small room. Data from fire experiments can be used to infer mixing based on layer temperatures.[22]

However, conclusions about mixing algorithms based on layer temperatures are clouded by the wall/floor heating algorithms used, gas emissivity estimates, modeling of radiation exchange, and convective heat transfer assumptions.

Simulation Procedure

Three room configurations were modeled: Steckler's $2.8 \times 2.8 \times 2.18$ m high room[2], Figure 1; a two room version of much the same experiment[25], Figure 2, and the CIB W14 Scenario A[9], Figure 3. The Steckler report lists 55 room/fire configurations that were tested. Comparisons presented here are for (1) a set of seven tests with four fire sizes with the gas burner fire flush with (0.02m above actually) and centered on the room floor (A location) and the "6/6" door (0.74 wide by 1.83m high). (2) A set of four tests with the raised burner in four locations (AR, FR, GR and HR), with a 62.9 kW fire and the 6/6

Figure 1 Steckler room: plan, burner locations, and burner arrangement.

door. (3) A set of 11 tests with the flush, centered burner operating at fixed, 62.9 kW output but with varying width doors. (4) Comparisons with the 28 tests of [25]. (5) A brief look at the variation among predictions that might be made for the ISO-W14 fire[9].

It is not possible to strictly model the identical fire with the three simulators chosen for this study. Each models the fire somewhat differently. In addition, although the McCaffrey plume algorithm is available and nominally the same for all three models, its use differs in detail. FIRST and BRI2VR include several user selectable plume algorithms. Four from FIRST and the two of BRI2VR were used. CFAST20.[11] uses only a modified version of the McCaffrey plume. In all

Figure 2 Nakaya et. al. 2 room facility and instrument placement.

Figure 1. Basic scenario A.

Table 2. Properties of the different wall types in scenario A.

Wall name	Thickness (mm)	Conductivity (W/m.K)	Specific heat (J/kg.K)	Density (kg/m ³)	Surface emissivity
Wall1	10	0.16	900	790	0.9
Wall2	220	0.8	1000	1600	0.94
Wall3	560	0.8	1000	1600	0.94
Wall4	10	0.036	795	105	0.9

Figure 3 ISO W14 scenario A, test room.

cases, input for the simulations was made as much alike as possible. It is believed that the results presented here reflect primarily differences in the plume algorithms and the way in which they are used.

The two-room simulation report, [25], lists fuel flow rates in [l/min]. These were converted to [kg/s] using a propane density, from [26], of 2.014 [g/l] at 0 C. Thus a flow of 100 [l/min] at 20 C converted to 0.003054 [kg/s]. This flow rate yielded slightly different rates of heat release for BRI2V (129.28 [kW]) and CFAST20 (140.0 [kW])¹, although both used the same heat of combustion 46,450 [kJ/kg]—the value provided for Propane in the BRI2V data base,. This value is close to the 46,343 [kJ/kg] in [27] for the higher heat of combustion and 46,600 based on 13.1 [MJ/kg-02] used. Lewis and von Elbe [28] list a value which, after units conversion, is 50,374 [kJ/kg] and NFPA [29] a similar number – 49,982 [kJ/kg]. Figure 6 of [25] suggests their estimate of heat release rate to have been based on a heat of combustion 55,700 [kJ/kg]. Data is presented here based on fuel flow rate, rather than heat release rate. The 46,450 [kJ/kg] value for

¹CFAST20 rounds the fuel flow from 0.0030524 (entered) to 0.0031. This accounts for only a small part of the difference.

Propane was used with all three simulators. The results for a given set of room conditions depend weakly enough on rate of heat release that conclusions drawn here should not change if fires from each simulator released the same heat.

All simulations were run to 3600 simulation seconds although essentially steady state was achieved at about 1800 seconds.

Simulation Comparisons

1) Variation of vent flow as a function of fire rate-of-heat-release for fixed fire location and vent geometry

The fire chosen was at Steckler's location A: centered in the room, its surface 0.02m above the floor; the "6/6" door was used. Figure 4a compares BRI2VR simulations for (1) the Cetegen-Kubota-Zukoski plume (C-K-Z)[18], (2) the McCaffrey plume (McC)[17] and (3) the Steckler data [2]. Figure 4b is a similar comparison for CFAST20, and Figure 4c for four plume algorithms from FIRST. For these simulations, the C-K-Z plume entrains less than the McC plume resulting in a thinner, hotter upper layer and lower door flow (layer temperature data not shown here).

All the plume models predict lower entrainment than the data suggests.

Figures 5a and b compare two-room simulations of the tests of [25] with the test data. Only

Figure 4a Steckler room, A location, 6/6 door; data and BRI2VR simulations.

Figure 4b Steckler room, A location, 6/6 door; data and CFAST20 simulations.

Figure 4c Steckler room, A location, 6/6 door; data and FIRST simulations.

Figure 5a Nakaya 2 room test; rm1 data and CFAST20 simulations.

Figure 5b Naskaya 2 room test; rm1 data and BRI2VR simulations.

flow through the burn room to foyer door is considered. BRI2VR simulations with the McC plume were very close to the CFAST20 results and are not shown separately. The predicted flows are generally less than the experimental values over rates of heat release similar to those of Steckler. At higher heat release rates the predicted flows approach and sometimes slightly exceed the measured values. The figure includes simulations and data for all the reported Nakaya runs – the effect of heat release rate and of door width are presented on a single plot. Figure 5b compares the McC and C-K-Z plume (BRI2VR) for two door widths – the narrowest, 0.29m, and the widest, 0.89m. The C-K-Z plume gave generally similar flows to the McC plume and the data or the narrowest door, but was well below the data and below the McC results for the widest door.

Figure 6 shows the variation of door inflow as the door width was varied. The fire was centered in the room (Location A) and the fire fixed at 62.9 kW. BRI2VR and CFAST results, using the same plume are very similar. A similar comparison may be inferred from the data of figure 5.

Figure 7a compares CFAST lower layer temperatures with the Steckler data. Simulations are presented for Kaowool and concrete.[2] describes the room as: “The lightweight walls and

Figure 6 Steckler room, A location, 62.9 kW fire; vent inflow versus door width, data, CFAST20 and BRI2VR simulations, McC plume.

Figure 7a Steckler room, A location, 6/6 door; lower layer gas temperature data and CFAST20 simulations for two floor materials.

ceiling were covered with a ceramic fiber insulation board...” The floor is not described but was “Marinite” over plywood on wood joists. Marmite is a low density mineral board.[30, pl2]; Kaowool is less conductive than Marinite. The figure shows the small effect of floor material on lower layer gas temperature. CFAST was used to compare the effect of the floor material as it allows definition of the ceiling, walls, and floor separately. FIRST uses the same material for all the room surfaces; BRI2 uses one material for

Figure 7b Steckler room, A location, 6/6 door; lower layer gas temperature data and BRI2VR simulations for C-K-Z and McC plume algorithms.

Figure 7c Steckler room, A location, 6/6 door; lower layer gas temperature data and FIRST simulations for four plume algorithms.

the ceiling and upper walls, another for the lower walls and floor.

Figure 7b shows lower layer temperature comparisons with BRI2VR and Figure 7c for

FIRST. It is seen that the CFAST20² and BRI2VR predictions are all well below the data. FIRST, which uses a data based vent mixing algorithm, does well with the M-T-H and McC plumes but over predicts lower layer temperatures for the other two.

Not shown are comparisons of upper layer temperature and layer thickness. The lower plume flows resulted in hotter, thinner layers.

A correction for wall flows was made in [1]. This was small and would not change any of the above results.

2) Steckler room: Variation of fire location for fixed fire size and vent

The Steckler tests and these simulations used the "raised fire": burner surface 0.30m above the floor and a 62.9 kW fire. Fire locations AR, FR, GR, and HR were examined with the 6/6 door. Figure 8 compares predictions with data for the four fire locations. BRI2VR treats all fire locations alike. FIRST and CFAST20 request fire location as part of the input. However, for these simulations, it was found that FIRST and CFAST gave identical results for the four fire locations considered, hence only one entry is made for each model. It is seen that all the simulated flows are well below the data. Since no correction was made for blowing, this is not surprising for the AR, FR and GR locations. The HR location is close to, but away from the walls in a location where it should not have been blown by the door jet nor was it close enough to the jet edge to have induced swirl.² Nevertheless, this fire location resulted in a significantly larger door flow than the models predicted.

²The author never witnessed a test with the fire in the HR location. At that time, Rinkinen had a small, table top model room-ceiling and walls with door opening placed over a fixed burner set into a large "floor". The room box could be moved relative to the burner. When the box was positioned so that the plume was entirely within the door jet it was blown back toward the rear of the room. When the room was moved so that the plume approached the edge of the door jet it began to swirl vigorously. Still further movement toward the side of the room brought the plume into relatively still air. It was quiet but leaned slightly toward the corner of the room without actually touching the corner. It is understood that the AH burner location was found by trial, the burner being moved toward the side wall until it became quiet. A slight movement back toward the door jet would produce intermittent swirl. The AH position avoided this. Nevertheless, the plume must have been in a region with considerable secondary flows.

Figure 8 Steckler room, door inflow versus fire location; data, BRI2VR, CFAST, and FIRST simulations.

The ratio of the highest predicted flow (Figure 8, CFAST) to the measured HR flow is 3:4.

The increase of entrained flow as the fire was moved toward the door, AR-→ AF-→ AG, suggests the effect of plume blowing. Quintiere et. al.[22], provide a way of estimating the enhanced entrainment due to a cross wind, in this case the door jet. Their paper is based on data obtained using the Steckler room. Substituting numbers in their formula gives an estimated maximum dimensionless cross wind, $V = v/u^* = 0.309$ for the 62.9 kW fire. This would decrease as the location of interest moved into the room since v , the average gas velocity, would decrease toward 0 at the rear wall. The associated decreased blowing is clear from the GR-→ FR-→ AR data. One estimate of the entrainment argumentation is to compare the blown plumes to the sheltered one (HR location). The ratio of the AR to HR flows is 1.08 and for the GR to HR, 1.19.

3) Simulations with FIRST and the M-T-H plume and variable plume entrainment coefficient, alpha

Figure 9 shows the effect on the Steckler room, 62.9 kW fire, 6/6 door inflow as the M-T-H plume entrainment coefficient, alpha, is varied. The two curves are for the fire at the A (flush) and AR(raised) locations. To bring the

Figure 9 Steckler room, A location, 6/6 door, M-T-H plume; variation of inflow as plume entrainment coefficient is varied.

predicted A location door flow up to the average of four tests, 0.588[kg/s], alpha had to be increased from 0.1 to 0.275. To obtain agreement between prediction and test data for the AR location required an increase from 0.1 to 0.250. In order to make the prediction agree, with test for the GR location, alpha had to be made 0.415, for the FR location, 0.295 and, for the HR location, 0.195. These increases would include the effect of blowing only if it is assumed that the noise level in the absence of blowing has already been subsumed in the Harvard/FM selected default, 0.1. Table 1 lists other calculated values and their experimental measurements for several inputs and alphas.

ISO, scenario A

The prescribed input for this is 90[kW] from time 0 to 10 s, 180[kW] 10-30 s and 90[kW] 30-300 s. The room has two vents, a low, wide door, 3.4x1[m] high open throughout and a window just under the ceiling, 3.6x0.2[m] high open after 120 s. During the first 30 s the flow is dominated by heat addition(gas expansion). Later the effect of the plume algorithm choice is seen. It is clearest during the steady burning period after the window opening transient has been passed, after about 150 s. The dimensionless cross wind, V

$=v/u^*=0.20$, was found from preliminary simulation results which included no correction for plume blowing. If the plume entrainment were increased, v and V would increase. Thus similar plume blowing to that for the Steckler room might be anticipated. From the above, one could surmise that the zone models will under-predict the flow through the room, over predict upper layer temperature and under predict the upper layer thickness, unless a plume blowing correction is made.

Discussion

Blown plumes in noisy spaces

Above it was suggested that varying alpha for the M-T-H plume might be used to correct the entrainment for blowing and noise. From figure 9 it is seen that this is both a substantial and very non-linear correction. Changing alpha with the M-T-H plume changes the basic entrainment in direct proportion. Thus a change from $\alpha=0.1$ to 0.25 should produce 2.5 times the flow at any given height. However, in a room, the stronger entrainment causes the layer to move down so that entrainment occurs over a shorter length of plume. Hence the diminishing

return as alpha is increased and the shape of the curve in figure 9. It has been argued above that the M-T-H plume with $\alpha=0.1$ has been corrected for typical laboratory noise except possibly for the HR location. For the A location the blowing effect would be the difference between $0.434[\text{kg/s}]$ (Table 1 and figure 4c) and 0.588 (average of 4 tests). These flows are in the ratio of 1:1.4. From figure 9 it is seen that increasing alpha from .1 to .14 did not yield the desired flow. An increase to about $\alpha=0.25$ was needed. A factor of 2.5 increased flow due to blowing is within the expected range for a V of about 0.3.[22] Table 1 shows that when the calculated and measured flows have been made to agree, the calculated layer interface is too low and the upper layer temperature too low. Changing the wall thermal properties changes the predicted response of the room. The wall values used and the default heat transfer coefficients of FIRST apparently do not reproduce the test conditions; too much heat was lost to the walls. With less wall heat loss the alpha correction to yield equal vent inflow would be somewhat smaller than those of Table 1. Upper layer temperature and thickness would be improved.

Table 1

Comparison of predicted and measured values for various alpha

Location	Calculation FIRST M-T-H plume					Steckler data			
	alpha	flow	del Tul	Layer	del Tll	flow	del Tul	Layer	del Tll
A	.1	0.434	128.23	1.196	20.21				
	.25	0.581	93.92	0.833	16.77	0.588	100.	0.985	20.3
AR	.1	0.363	155.22	1.325	28.91				
	.25	0.521	105.74	1.010	15.82	0.522	130.	1.26	15.
FR	.3	0.543	101.09	0.950	15.70	0.541	122.	1.14	17.
GR	.4	0.572	95.54	0.861	16.30	0.575	110.	1.09	21.
HR	.2	0.490	113.00	1.088	16.69	0.483	143.	1.26	12.

To match the experimental flow at the HR location, an alpha of about 0.2 was needed. Considering that the default 0.1 presumably accounts for normal noise levels for room experiments where the room is in an open laboratory, this

seems a large correction. The HR plume location would appear from the simulations done here to have either been subjected to an abnormally noisy background or not to have been completely free of swirl.

A weakness of the M-T-H plume is its lack of detail. The McC and C-K-Z plumes distinguish between the flame and over-fire regions. With the M-T-H plume there is only one region.³ For many applications this may not matter. However, what is needed is usable data correlations that separately distinguish the effect of background noise and of blowing. Appropriate input parameters should be available to the user to allow recognition of these evidently important effects. Presumably the added mixing associated with high noise levels and/or blowing would change the plume region boundaries, thus there appears no simple "correction" that can be used in general. If, as mentioned above, the interface will always be low enough to expose only the lowest plume region, a simple area correction can be used with the C-K-Z plume. It must correct for both noise and blowing, since the correlation is based on a relatively quiet surround. The author's experience with this correction has not been uniformly successful.

In reconstructing actual fires, it is the exception, rather than the rule to find the fire directly in the unobstructed door jet of a room. Furniture may be between the door and the fire, or the location of the fire may place it out of the jet's direct path. In the case of obstructions, the noise level at the fire may be unusually high. In the case of fires away from the door, it may be difficult to estimate the local blowing velocity. To a limited extent Quintiere[22] looked at this problem. The effect of both doors and windows were examined, but only fires flush with the floor were included. They did not measure local velocity near the fire; an upper limit estimate for blowing velocity was provided. Local turbulence levels were not measured nor were fires away from the room center or out of the direct path of the jet included.

The modeler has several options: the fire may be modeled using several plumes (for example, C-K-Z and McC) to bracket the effect of "normal" noise. This approach introduces other problems because of the different functional behavior between the two plume models. Similarly, blowing may be bracketed by estimating the maximum and minimum blowing velocities and varying alpha, with the M-T-H plume, to cover this range. If the noise and blowing effects are small, this may be sufficient. However, it has been seen in the case of the Steckler room that blowing may increase plume entrainment by a factor of about three over still air. In the case of the RH fire location, presumably local noise increased room inflow in the ratio of 0.35 : 0.48 or about 37% (equivalent alpha double the normal noise value).

Data is clearly needed to provide the fire simulators with documented plume algorithms able to represent the various entrainment regimes of the fire plume and, in addition, allow input parameters such that they are capable of expressing the effect of local noise and blowing. Additional tests to document local blowing and turbulence levels in realistic fire situations would be very useful. Such a research project's goal should be correlations the modeler could use to estimate these effects for his fire situation.

Plumes in tall spaces

A major problem with the McCaffrey plume is its behavior in the over-fire region. The Morton-Taylor-Turner theory[15], and much experimental data suggests that the plume entrainment in the over-fire region should depend on height raised to the 5/3rds power. The McCaffrey correlation uses the 1.895 power.[17] This may be related to his plume width assumption. It results in what appears to be a severe over-prediction of plume flows far above the fire. The

³The theory of [1] extended the Fang variation of Steward's analysis.[31] This analysis included burning over the lower part of the plume. The flame length was close to the experimental values without artificial increasing it as Steward had done. The plume necked in strongly near its base as did the Steward and Fan models. The model depends on entrainment coefficient, alpha, similarly to the M-T-T plume so could be used to estimate blowing.

Figure 10 Descent of hot layer, 36.6m high room, floor level door, 140m³/s exhaust at ceiling; three plumes, FIRST simulations.

author found theoretical support for the McCaffrey's correlation in the immediate over-fire region but the flow prediction changed rapidly with height, resulting in a shift to the 5/3 power.[1]

The original BRI simulator [32] used the McC plume but, with BRI2, a shift was made to the C-K-Z algorithm. Justification for this change may be found in[12], pp 98-100. Here experimental data from three fire tests in a 23.7m high, domed Sumo Hall are compared with BRI2 calculations. The experimental and calculated values for the descent of the hot layer and of its temperature as functions of time are presented. Satisfactory agreement was found. The calculations used only the C-K-Z plume.

Figure 10 shows FIRST simulations of the main concourse of New York's Grand Central Terminal. This is a 93.6×61.3×36.6m high room ventilated by doors at floor level and forced exhaust just below the ceiling. The simulations were for a 5MW fire on the floor and 140m³/s forced exhaust. It is seen that the McC plume results in a much lower hot-cool interface than the M-T-H or C-K-Z plumes. To bring the McC predicted interface up to the level of the other two required almost 350m³/s exhaust. The cost differential between fans of 350 versus 140m³/s capacity for this building alone would probably cover the cost of an experimental program to

Figure 11 Log-log plot, three plume models, flow unrestricted, Nakaya 350 l/min burner fire; plume flow versus height.

settle the issue of which algorithm(if any)is correct.

For the input of figure 10, the M-T-H plume yields layer interface heights close to, but consistently above those for the C-K-Z plume. Although, in principal, the entrained flow for the M-T-H plume follows the 5/3rds power of height, as does its parent the M-T-T plume[15], the flow is from a downward displaced point source(5/3rds power) minus the flow entrained between the point source and the fuel surface (constant). As a result the overall entrained flow always increases slightly more slowly than the 5/3rds power would imply.

Three of the plume models discussed here are shown in figure 11. The plume simulations were for an unconfined fire in still air. The fire was the Nakaya 350 l/min fire(452.5 kW), area 0.36m², $Q_d^* = 1.080$. For this the McC continuous-to-intermittent flame boundary is at 0.923m and the intermittent flame-to-plume boundary at 2.308m; for the C-K-Z plume the mean flame height (50% intermittency) was at 2.304m and the maximum flame height 3.043m. The over-fire part of the C-K-Z plume follows the 5/3rds law, the McC plume, as mentioned, the 1.895 power, and the M-T-H plume, while approach-

ing the 5/3rds power, even at 15m still has a noticeably lower slope.

For this fire, for heights up to about 2m, the C-K-Z plume entrains noticeably less than the other two. In its initial region, the C-K-Z plume flow increases with the 3/4 power of height. The nearly square-root(0.566 power) behavior of the McC plume is apparent at low heights. The M-T-H plume lies between the other two, but comes close to the McC plume well before the C-K-Z plume makes its transition to the turbulent flame zone and "catches up". The disagreement between the McC and C-K-Z maximum flame height may reflect the background noise levels in the two sets of experiments.

The very different shapes of the three entrainment curves for heights within the continuous flame region(up to about 1.2m for this example) makes it hard to decide which of these is the best.

A layer mass balance shows that, even where the various plume algorithms may give similar door inflows, "they get there by different routes". One striking case of this is shown in Table 2 where BRI2VR results for the C-K-Z and McC plumes are compared.

Although the simulations were run to 3600s, the temperatures were still slowly increasing. As a result there is an excess gas flow out shown by the mass balances. For both plumes, the mass penetrating the layer is less than that found for the same height above the fire for the free plumes (figure 11). BRI2 assumes that the plume flow is axi-symmetric with Gaussian radial velocity and temperature distributions.[13] It is further assumed that only the core of the plume will be able to penetrate the upper gas layer. The outer part of the Gaussian distribution is too cool to maintain a positive buoyancy in the upper layer and fails to penetrate. In the above example, because of the high upper layer temperature,

only about 60% of the mass flow of the C-K-Z plume approaching the layer interface is able to penetrate it. Almost all the McC plume flow penetrates.⁴

For the McC plume, all the flow entering the door is entrained by the plume. The burn room-to-foyer door neutral plane is above the burn room hot-cool interface. For the C-K-Z plume, there is a much larger inflow than is entrained by the plume. The excess, 66% of the inflow, returns to the foyer as lower layer to lower layer(AA)flow. The neutral plane at the burn room-to-foyer door is well below the hot-cool interface in the burn room. The fact that, for this particular case, the hot-cool interface happens to be at the same height in both rooms is purely accidental. The flow associated with the C-K-Z plume is strongly influenced by the high average temperature of the burn room(rml)relative to the foyer(rm2). We know from Kawagoe[33] that such a temperature difference will produce a flow through the room independent of a fire plume.

Conclusions

The McCaffrey plume and Thomas/Hinkley modification of the Morton, Turner and Taylor plume (M-T-H) give the best agreement with both the Steckler and Nakaya data. The M-T-H plume has two advantages over the McC plume: (1) its behavior in the over-fire region seems to accord better with tests of fires in high rooms, and (2) it can be "adjusted" for plume blowing by using an entrainment coefficient increased over the preferred value for normally noisy, still air. The C-K-Z plume gives lower entrainment for fires of the size and QD* range of the Steckler room but better results for the larger fires and the QD* ranges of the Nakaya tests. It may be preferable to the McC plume, based on high-bay tests where the over-fire region dominated.

⁴In the BRI2 standard output listing for each time step, the "K-VALUE" entered immediately below the "MASS FLOW RATE PENETRATING LAYER INTERFACE" is not the fraction of the total plume flow approaching the interface that penetrates.

Table 2 continued

Room 2, layer height 1.30 m		Room 2, layer height: 1.25	
Lower layer, T: 34.41 C		Lower layer, T: 33.38 C	
Inflow [kg/s]		Inflow [kg/s]	
Door AA	0.98335	Door AA	1.00890
Mixing from ul	0.00003	From rm 1 SA	<u>0.39246</u>
From rm 1, AA	<u>0.48858</u>		
Total	1.47196	Total	1.40136
Outflow [kg/s]		Outflow [kg/s]	
To outside AA	0.14889	To outside AA	0.08419
To rm 1 AA	0.73904	To rm 1 AA	0.66797
Mixing to ul	<u>0.58422</u>	To rm 1AS	0.11104
		Mixing to ul	<u>0.53828</u>
Total	1.47215	Total	1.40148
Excess out	0.00019	Excess out	0.00012
Upper layer, T: 323.08 C		Upper layer, T: 350.23 C	
Inflow		Inflow	
From rm1 SS	0.26170	From rm 1 SS	0.39755
Mixing from ll	0.58422	Mixing from ll	<u>0.53828</u>
From rm 1AS	<u>0.00003</u>	Total	<u>0.84595</u>
Total	0.93583		
Outflow		Outflow	
To outside SA	0.84594	To outside SA	<u>0.93595</u>
Mixing to ll	<u>0.00003</u>		
Total	0.84597		
Excess out	0.00002	Excess out	0.00012

Upper and lower layer mass balances, Nakaya 2 room test, .89 door, 350 l/min fire.

C-K-Z, Rm 1 door inflow: 0.73904		McC, Rm 1 door inflow: 0.66797	
Room 1, layer: 1.30 m		Room 1, layer 0.57 m	
Lower layer, T: 218.59 C		Lower layer, T: 82.87 C	
Inflow [kg/s]		Inflow [kg/s]	
Door AA	0.73904	Door AA	0.66797
Fuel flow	<u>0.01068</u>	Fuel flow	0.01068
		Mixing from ul	<u>0.12305</u>
Total	0.74972	Total	0.80170
Outflow [kg/s]		Outflow [kg/s]	
Penetrating interface	0.26158	Penetrating interface	<u>0.80188</u>
Door AS	0.00003		
Door AA	<u>0.48858</u>		
Total	0.75019		
Excess out	0.00047	Excess out	0.00018
Upper layer, T: 788.57 C		Upper layer, T: 490.98 C	
Inflow [kg/s]		Inflow [kg/s]	
Penetrating interface	<u>0.26158</u>	Penetrating layer	0.80188
		Door AS	<u>0.11104</u>
Total	0.26158	Total	0.91292
Outflow [kg/s]		Outflow [kg/s]	
Door SS	0.26170	Door SS	0.39755
		Door SA	0.39246
		Mixing to ll	<u>0.12305</u>
		Total	0.91306
Excess out	0.00012	Excess out	0.00014

All the plumes studied, if uncorrected for blowing, gave generally lower entrainments than the data. This may be partly because they are based on experimental data obtained under relatively quiet conditions as compared with actual room-fire test conditions. At present there is insufficient data available to make a quantitative assessment of the effect of background turbulence level on plume entrainment.

An experimental program is needed to document the local blowing velocity and turbulence levels in a wider range of room fire situations than has been tested. From these tests, correlations which will assist the modeler in assessing the local environment of his particular fire should be developed.

An experimental and theoretical program is needed leading to well documented plume models which can (1) represent the various entrainment/burning regimes of the fire, (2) capture the effects of blowing and local turbulence levels, and (3) cover fire sizes (heat release rates) larger than previous tests. They should be structured to allow a user to input local turbulence and blowing conditions.

An experimental and theoretical program is needed to document the inter-layer gas mixing at vents between rooms of a multi-room building. The present algorithms are plausible, but insufficiently supported by experimental data and appear to be inaccurate. Logically based correlations should be developed from the experimental data and reduced to algorithms usable in present zone building fire models.

References

- 1] Rockett, J.A., "A Comparison of Plume Entrainment Models", unpublished. Some of the material from this paper appears in Section 7 of Rockett, J.A., "Using the Harvard/NIST Mark VI Fire Simulation", NISTIR 4464, U.S. National Bureau of Standards, Gaithersburg, MD 20899, November 1990
- 2] Steckler, K.D., Quintiere, J.G. and Rinkinen, W.J., "Flow Induced by Fire in a Compartment", NBSIR 82-2520, U.S. National Bureau of Standards, Gaithersburg, MD 20899, September 1982
- 3] McCaffrey, B.J., Rockett, J.A. and Levine, R.S., "Naval Fire Fighting Trainers - Effect of Ventilation on Fire Environment (Model Calculations for 19F3 FFT)", NBSIR 85-3238, U.S. National Bureau of Standards, Gaithersburg, MD 20899, December 1985
- 4] Rockett, J.A., Howe, J.M. and Hanbury, W.D., "Modeling Fire Safety in Multi-use Domed Stadia", *J. of Fire Prot. Eng.* 6(1), 1994, pp 11-22
- 5] Rockett, J.A., Keski-Rahkonen, O. and Heikkila, Liisa, "HDR reactor containment fire modeling with BRI2", VTT Publications 113, VTT, Technical Research Centre of Finland, Espoo, 1992
- 6] Rockett, J.A., "Park Service Room Fire Test Simulations Using the Harvard Level 5.2 Computer Fire Model", NBSIR 83-2085, U.S. National Bureau of Standards, Gaithersburg, MD 20899, June 1984
- 7] Emmons, H.W. and Ying, S-J, "The Fire Whirl", Eleventh Symposium on Combustion, International. The Combustion Institute, Pittsburgh PA 1967, pp 475-488
- 8] Zukoski, E.E. (personal communication): In early plume entrainment tests the door to the large laboratory room was often open and no screens were placed around the plume apparatus. To reduce scatter in the data, for subsequent tests, the laboratory door was kept closed and turbulence suppressing screens surrounded the apparatus. Data scatter was much reduced, but the flows recorded appeared to be 28-30% less than in the "noisy" room.
- 9] Keski-Rahkonen, O. and Hostikka, S., "CIB W14 Round Robin of Code Assessment; Design Report of Scenario A", VTT Building Technology, VTT, Technical Research Centre of Finland, Espoo, 1995
- 10] Mitler, H.E. and Rockett, J.A., "User's Guide to FIRST, A Comprehensive Single-room Fire

- Model", NBSIR 87-3595, U.S. National Bureau of Standards, Gaithersburg, MD 20899, September 1987
- 11] Peacock, R.D., Forney, G.P., Reneke, P., Portier, R. and Jones, W.W., "CFAST, the Consolidated Model of Fire Growth and Smoke Transport", NIST Tech. Note 1299, U.S. National Bureau of Standards, Gaithersburg, MD 20899, February 1993
 - 12] Tanaka, T. and Nakamura, K., "A Model for Predicting Smoke Transport in Buildings", Report of the Building Research Institute, No 123, Ministry of Construction, Tokyo Japan, October 1989 (in Japanese)
 - 13] Tanaka, T and Nakamura, K, "Predicting Capability of a Multiroom Fire Model", Fire Safety Science, Proceedings of the second international symposium, Hemisphere, 1989
 - 14] Yamada, S. and Tanaka, T., "A model for predicting concentrations of carbon monoxide in building fires", Fire Safety Science, Proceedings of the fourth international symposium, IAFSS 1995
 - 15] Morton, B.R., Taylor, G.I. and Turner, J.S., "Turbulent gravitational convection from maintained and instantaneous sources", Proc. Royal Soc. Series A., 24 Jan. 1956, pp 1-23
 - 16] Thomas, P.H. and Hinkley, P.L., "Design of roof-venting systems for single-story buildings", Fire Res. Tech. Paper No 10, Her Majesty's Stationary Office, London, 1964
 - 17] McCaffrey, B.J., "Momentum Implication for Buoyant Diffusion Flames", Comb. and Flame, 52, No 2, pp 149-167, Sept. 1983
 - 18] Cetegen, B.M., Zukoski, E.E. and Kubota, T., "Entrainment and flame geometry of fire plumes", Cal. Inst. of Tech., Daniel and Florence Guggenheim Jet Propulsion Center, Pasadena, CA, August 1982
 - 19] Zukoski, E.E., "Mass Flux in Fire Plumes", Fire Safety Science-Proceedings of the Fourth International Symposium, IAFSS, 1994, pp 13
 - 20] McCaffrey, B.J., "Purely buoyant diffusion flames:some experimental results", NBSIR 79-1910, U.S.Nat. Bureau of Stds, Gaithersburg MD 20899, October 1979
 - 21] Delichatsios, M.A., "Air entrainment into buoyant jet flames and open pool fires", FMRC, Norwood MA02062, August 1985
 - 22] Quintiere, J.G., Rinkinen, W.J. and Jones, W.W., "The effect of room openings on fire plume entrainment", Comb. Sc. and Tech., 18, pp 1-19
 - 23] Lim, C.S., Zukoski, E.E. and Kubota, T., "Mixing in Doorway Flows and Entrainment in Fire Plumes", Cal. Inst. of Tech., Pasadena, CA, June 1984
 - 24] Quintiere, J.G., McCaffrey, B.J. and Harkleroad, M., "The Burning of Wood and Plastic Cribs", Products Research Committee, December 1979
 - 25] Nakaya, I., Tanaka, T. and Yoshida, M., "Doorway Flow Induced by a Propane Fire", Fire Safety Journal, 10(1986)185-195
 - 26] Hodgman, C.D., "Handbook of Chemistry and Physics", Chemical Rubber Publishing Co., 1943
 - 27] "Fuel Flue Gases, 1941 ed", Am. Gas Assoc.
 - 28] Lewis, B. and von Elbe, G., "Combustion, Flames and Explosions of Gases", 2nd ed, Academic Pres 24. 1961
 - 29] "Fire Protection Handbook, 14th Ed.", Nat. Fire Prot. Assoc., Boston, 1976
 - 30] Gross, D., "Data Sources for Parameters Used in Predictive Modeling of Fire Growth and Smoke Spread", NBSIR 85-3223, U.S. National Bureau of Standards, Gaithersburg, MD 20899, September 1985
 - 31] Fang, J.B., "Analysis of the behavior of a freely burning fire in a quiescent atmosphere", NBSIR 73-115, Nat. Bur. of Stds, Washington D.C., 20234, February 1973
 - 32] Tanaka, T., "A model of multi room fire spread", NBSIR 83-2718, U.S. Nat. Bur. of Stds., Gaithersburg, MD 20899, August 1983
 - 33] Kawagoe, K., "Fire behavior in rooms", Building Research Institute Report No.27, 1958, Ministry of Construction, Tokyo, Japan