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Zone Model Plume Algorithm Performance

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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 were the over-fire region dominates the plume flow is discussed.

Key words

Room fires, plumes, zone fire models

Introduction

It is appropriate, in a seminar honoring Prof. Kawagoe, to take up the subject of room fire modeling, a field in which he 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) - their modification displaces downward the point source [15]; (2) an un-displaced M-T-T point source plume (Pt), (3) the McCaffrey plume (McC)[16], and (4) the Cetegen-Kubota-Zukoski plume (C-K-Z)[17]. 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 [18] has not been included in this study because the author was unsure of some details of the procedure.

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 alpha 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 alpha represents the plume entrainment expected in a "normally noisy" room environment.

McCaffrey conducted his tests with a square gas burner "... 0.75 m above the floor and under a passive hood in a large laboratory."[19] 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 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 0.05 cm 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 ...".[17] 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.[20] 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.[21] 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 [17] 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 argumentation.[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 "intermittent" 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 Lim, Zukoski and Kubota [22] and from Quintiere et. al.[23] who 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.[21] 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 x 2.8 x 2.18 m high room [2], Figure 1; a two room version of much the same experiment [24], 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 (0.02 m above actually) and centered on the room floor (A location) and the "6/6" door (0.74 wide by 1.83 m 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 door. (3) A set of 11 tests with the flush, centered burner operating at fixed output but with varying width doors. (4) Comparisons with the 28 tests of [24]. (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 cases, input for the simulations was made as much alike as

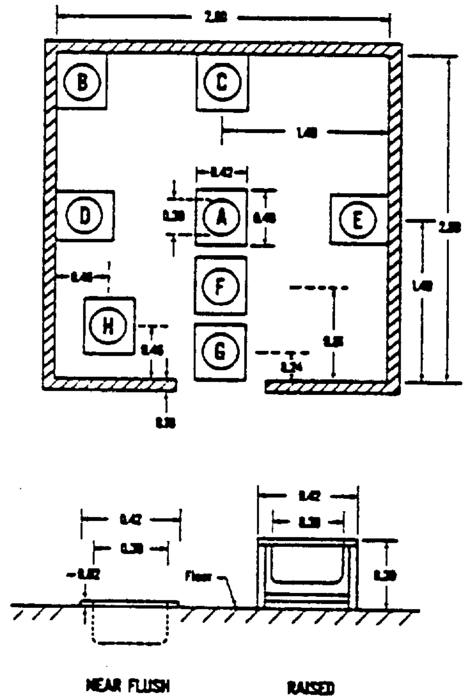

Figure 1: Steckler room: plan, burner locations, and burner arrangement.

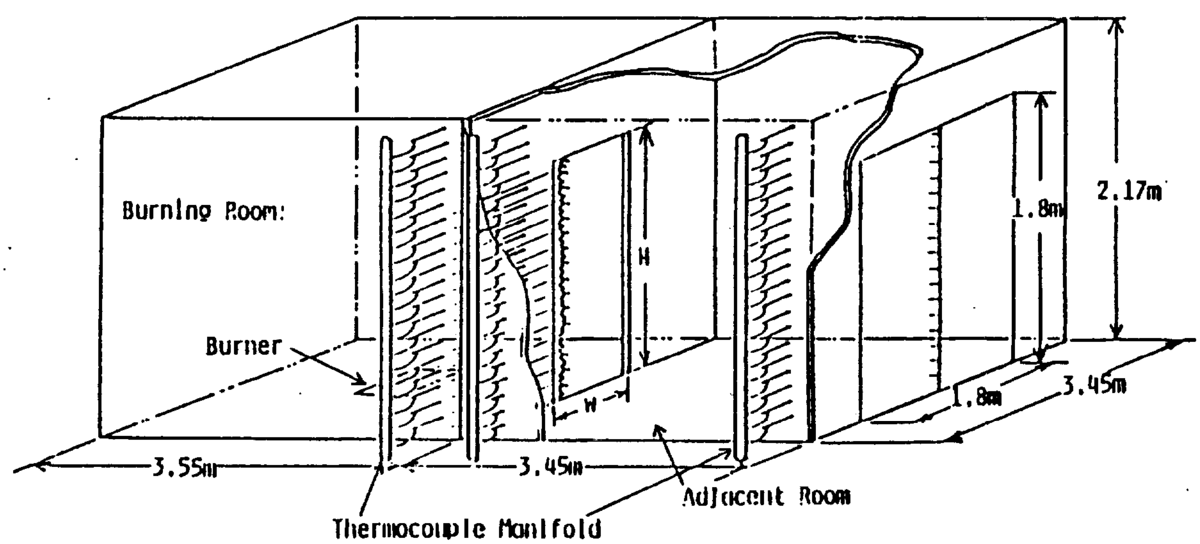

Figure 2: Nakaya et. Al. 2 room facility and instrument placement.

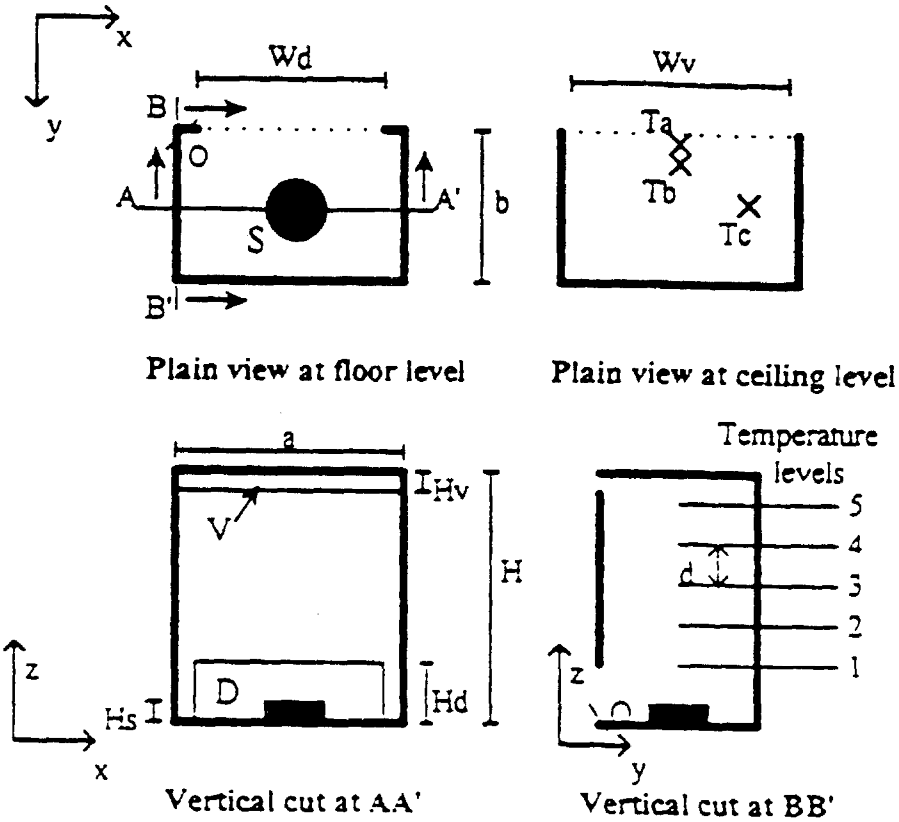

Figure 1. Basic scenario A.

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.

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, [24], lists fuel flow rates in [l/min]. These were converted to [kg/s] using a propane density, from [25], 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 [26] for the higher heat of combustion and 46,600 based on 13.1 [MJ/kg-O_2] used. Lewis and von Elbe [27] list a value which, after units conversion, is 50,374 [kJ/kg] and NFPA [28] a similar number - 49,982 [kJ/kg]. Figure 6 of [24] suggests their estimate of heat release rate for 100 [l/min] to be about 170 [kW] (implied 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 Propane was used with all three simulators. The results for a given set of room conditions depend weakly on rate of heat release; 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 0.02 m above the floor; the "6/6" door was used. Figure 4a compares BRI2VR simulations for (1) the Cetegen-Kubota-Zukoski plume [17], (2) the McCaffrey plume [16] 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 McCaffrey 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 [24] with the test data. Only flow through the burn room to foyer door is considered. BRI2VR simulations with the McC plume were very

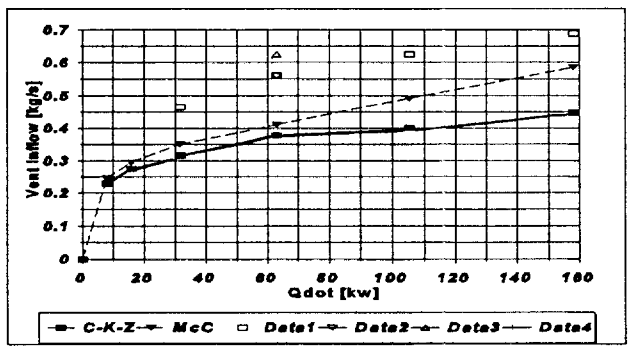

Figure 4a: Steckler room, A location, 6/6 door; data and BRI2VR simulations.

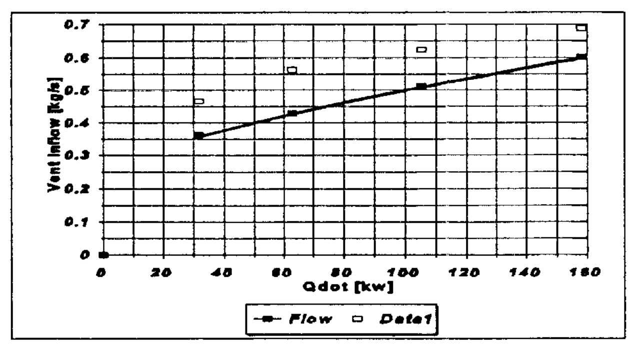

Figure 4b: Steckler room, A location, 6/6 door; data and CFAST20 simulations.

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

close to the CFAST20 results and are not shown in figure 5a. 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, 0.29 m, and the widest, 0.89 m. The C-K-Z plume gave generally similar flows to the McC plume and the data for the narrowest door, but was well below the data and below the McC results for the widest door.

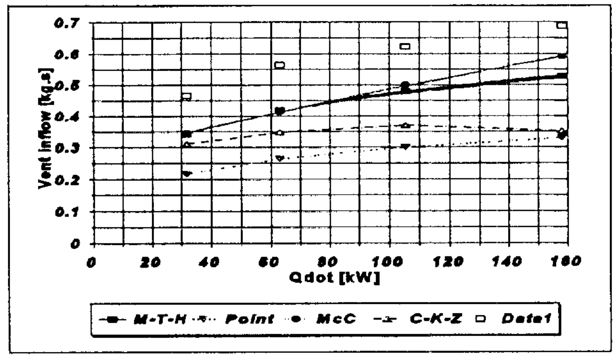

Figure 4c: Steckler room, A location, 6/6 door; data and FIRST simulations.

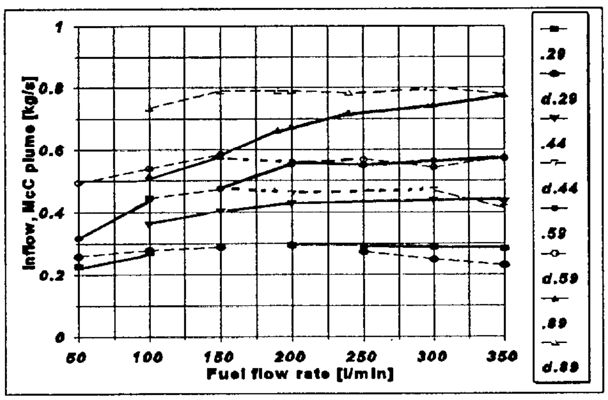

Figure 5a: Nakaya et. al. 2 room test; rm 1 data and CFAST20 simulations.

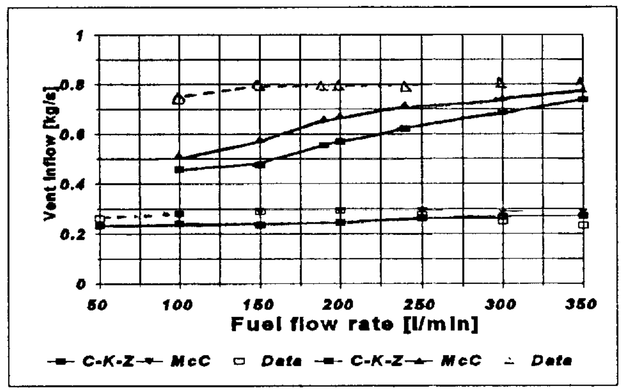

Figure 5b: Nakaya et. al. 2 room test; rm 1 data and BRI2VR simulations.

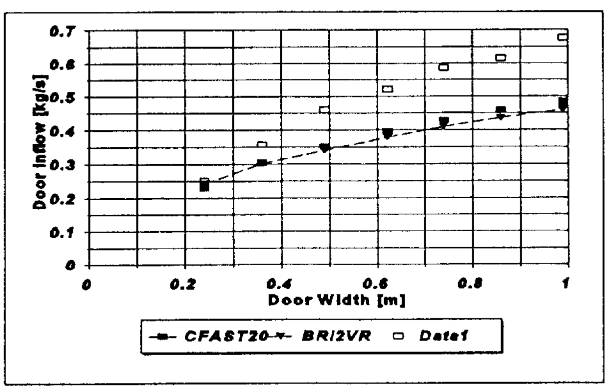

Figure 6: Steckler room, A location, 62.9 kW fire; vent inflow as a function of door width, CFAST 20 and BRI2VR, McC plume.

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. BRI2V 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 ceiling were covered with a ceramic fiber insulation board..." The floor is not described but was "Marinite" over plywood on wood joists. Marinite is a low density mineral board.[29, p12]; Kaowool is less conductive than Marinite. 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 the ceiling and upper walls, another for the lower walls and floor. Figure 7b shows lower layer temperature comparisons with

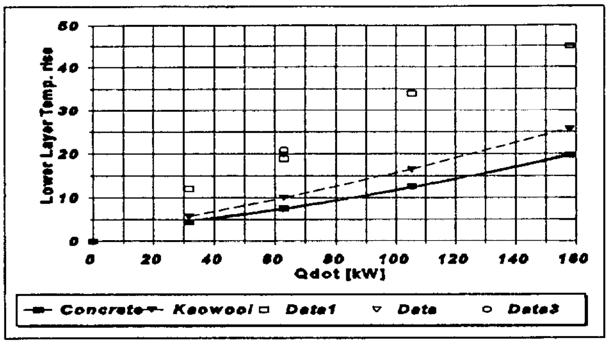

Figure 7a: Steckler room, A location, 6/6 door; lower layer gas temperature for two floor materials, CFAST simulations.

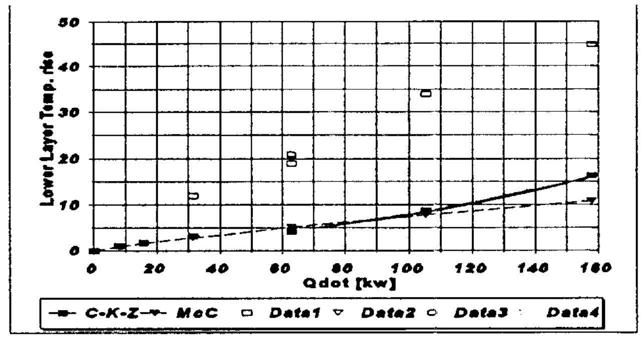

Figure 7b: Steckler room, A location, 6/6 door; lower layer gas temperature for two plume algorithms, BRI2VR simulations.

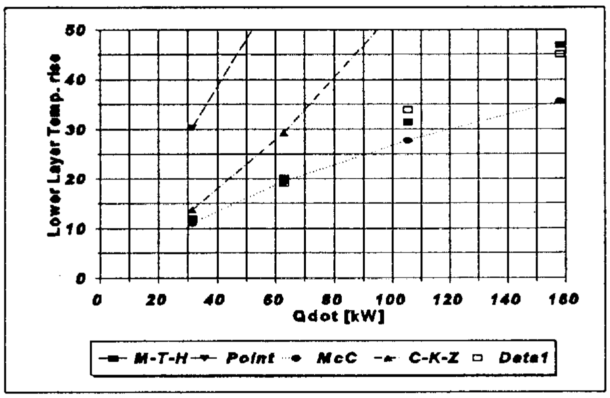

Figure 7c: Steckler room, A location, 6/6 door; lower layer gas temperature for four plume algorithms, FIRST simulations.

BRI2VR and Figure 7c for FIRST. It is seen that the CFAST20 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. Due to a lack of data, similar plots can not be made for the runs of [24].

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 0.30 m 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 the predictions with data for 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.

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

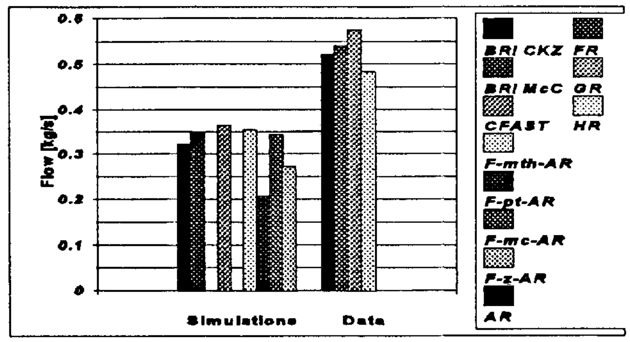

Figure 8: Steckler room, door inflow versus fire location; BRI2VR, CFAST, FIRST, data.

The increase of entrained flow as the fire was moved toward the door, AR->FR->GR, suggests the effect of plume blowing. Quintiere et. al. [21], 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

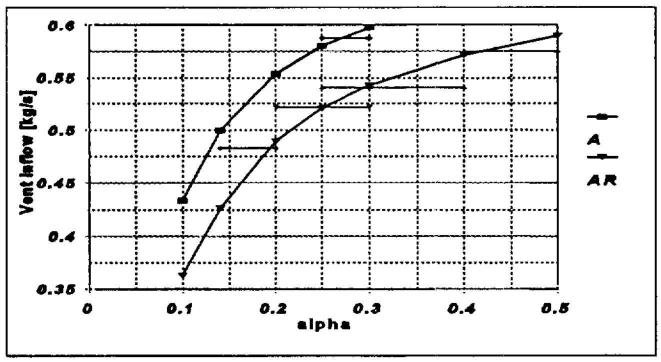

Figure 9: Steckler room, A location, 6/6 door, M-T-H plume; variation of inflow as plume entrainment coefficient, alpha, is varied.

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 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 only the effect of blowing 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.

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[2] The 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.

Table 1

Comparison of predicted and measured values for various alpha

	Calculation FIRST M-T-H plume					Steckler data			
Location	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	.588	100.	.985	20.3
AR	.1	0.363	155.22	1.325	28.91				
	.25	0.521	105.74	1.010	15.82	.522	130.	1.26	15.
FR	.3	0.543	101.09	0.950	15.70	.541	122.	1.14	17.
GR	.4	0.572	95.54	0.861	16.30	.575	110.	1.09	21.
HR	.2	0.490	113.00	1.088	16.69	.483	143.	1.26	12.

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. 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 noise except possibly for the HR location. For the A location the blowing effect would be the difference between 0.434 [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.[21] 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. Apparently, 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.

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 rather a large correction. The HR plume location would appear from the simulations done here to have been 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 algorithms 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 with appropriate input parameters 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 for 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 [21] 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 M-T-H) to bracket the effect of "normal" noise. 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 HR 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.

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[3] The theory of [1] extended the Fang variation of Steward's analysis.[30] 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.

Plumes in tall spaces

A major problem with the McCaffrey plume is its behavior in the over-fire region. The Morton-Taylor-Turner theory, and much experimental data suggests that the plume entrainment in the over-fire region should depend on height raised to the 5/3 power. The McCaffrey correlation uses the 1.895 power.[16] 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 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[31] 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 23.7 m 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 x 61.3 x 36.6 m high room ventilated by doors at floor level and forced exhaust just below the ceiling. The simulations were for a 5 MW fire on the floor and 140 m^3/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 350 m^3/s exhaust. The cost differential between fans of 350 versus 140 m^3/s capacity for this building alone would probably cover the cost of an experimental program to settle the issue of which algorithm (if any) is correct.

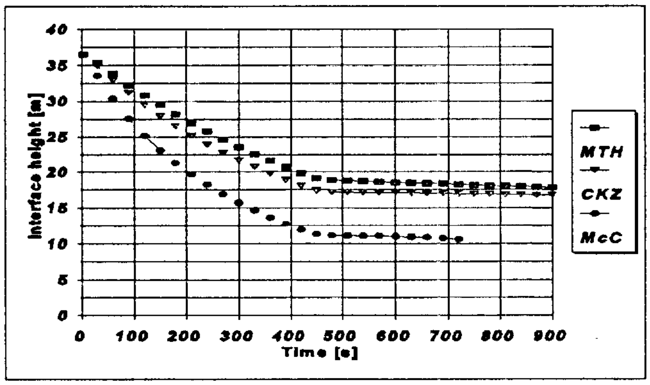

Figure 10: Descent of the hot layer, 36.6 m high room, 140 m^3/s exhaust at ceiling; three plumes, FIRST simulations.

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 Q^* range of the Steckler room but better results for the larger fires and Q^* ranges of the Nakaya tests. It may be preferable to the McC plume, based on high-bay tests where the over-fire region dominated. All the plumes studied, if uncorrected for blowing, gave generally lower entraiments than the data. This may be 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 and (2) capture the effects of blowing and local turbulence levels (3) be documented for a wider range of fire sizes (i.e.: larger) than present models. 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 interlayer 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.

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Table 1

Comparison of predicted and measured values for various alpha

	Calculation FIRST M-T-H plume					Steckler data			
Location	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.

Table 2

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
Room 1, layer: 1.30 m

Lower layer, T: 218.59 C	
Inflow [kg/s]	
Door AA	0.73904
Fuel flow	0.01068
Total	0.74972
Outflow [kg/s]	
Penetrating interface	0.26158
Door AS	0.00003
Door AA	0.48858
Total	0.75019
Excess out	0.00047

Upper layer, T: 788.57 C	
Inflow [kg/s]	
Penetrating interface	0.26158
Total	0.26158
Outflow [kg/s]	
Door SS	0.26170
Excess out	0.00012

McC, Rm 1 door inflow: 0.66797
Room 1, layer 0.57 m

Lower layer, T: 82.87 C	
Inflow [kg/s]	
Door AA	0.66797
Fuel flow	0.01068
Mixing from ul	0.12305
Total	0.80170
Outflow [kg/s]	
Penetrating interface	0.80188
Excess out	0.00018

Upper layer, T: 490.98 C	
Inflow [kg/s]	
Penetrating layer	0.80188
Door AS	0.11104
Total	0.91292
Outflow [kg/s]	
Door SS	0.39755
Door SA	0.39246
Mixing to ll	0.12305
Total	0.91306
Excess out	0.00014

Table 2 continued

Room 2, layer height 1.30 m	
Lower layer, T: 34.41 C	
Inflow [kg/s]	
Door AA	0.98335
Mixing from ul	0.00003
From rm 1, AA	0.48858
Total	1.47196
Outflow [kg/s]	
To outside AA	0.14889
To rm 1 AA	0.73904
Mixing to ul	0.58422
Total	1.47215
Excess out	0.00019
Upper layer, T: 323.08 C	
Inflow	
From rm1 SS	0.26170
Mixing from ll	0.58422
From rm 1AS	0.00003
Total	0.93583
Outflow	
To outside SA	0.84594
Mixing to ll	0.00003
Total	0.84597
Excess out	0.00002

Room 2, layer height: 1.25	
Lower layer, T: 33.38 C	
Inflow [kg/s]	
Door AA	1.00890
From rm 1 SA	0.39246
Total	1.40136
Outflow [kg/s]	
To outside AA	0.08419
To rm 1 AA	0.66797
To rm 1AS	0.11104
Mixing to ul	0.53828
Total	1.40148
Excess out	0.00012
Upper layer, T: 350.23 C	
Inflow	
From rm 1 SS	0.39755
Mixing from ll	0.53828
Total	0.84595
Outflow	
To outside SA	0.93595
Excess out	0.00012

Discussion

Edward Zukoski: I have a couple of comments. The first one is that I think we do not distinguish well enough between the flaming region and the far field plume. The data we have are not well digested, but they certainly show that there is a marked difference between the near field where the fire is visible and the far field where the heat addition is virtually zero. We also have to worry about Q* or something like Q*. In that Factory Mutual data that John talked about, the flames were very long, skinny flames, almost jet-like flames, whereas most fires are about not much more than times two of the burning area height. The second comment is that we need a lot more data. We have good data for 20 cm and 50 cm burners; and if you're going to use an offset, you can't get there from here. McCaffrey's data is based on a single sized burner and the larger fires that Phil Thomas and Hinkley analyzed many years ago and more recently showed unambiguously that the diameter was an important parameter. Thank you.