NISTIR 6046

A Note on Improving Corridor Flow Predictions in a Zone Fire Model

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Abstract

Presently, the Consolidated Fire and Smoke Transport (CFAST) zone fire model assumes that smoke travels instantly from one side of a compartment to another. As a result, upper layers start forming in compartments connected at the end of long corridors much sooner than expected. This report documents a procedure for estimating ceiling jet travel times so that initial layer formation may be predicted more accurately in compartments connected to long corridors. Standard correlations are not suitable for predicting ceiling jet velocities and temperatures in corridors because ceiling jet arrival time at a distance r is proportional to r^2 in 'normal' rooms (rooms with length to height ratios near one) and proportional to r in corridors (rooms with large length to height ratios). Correlations are derived by performing numerical experiments to estimate ceiling jet arrival times, temperature fall off rates and depths for cases with various inlet ceiling jet temperatures and depths. These correlations are used to improve predictions of corridor smoke flow in the CFAST zone fire model.

1 Introduction

A standard assumption in zone fire modeling is that once hot smoke enters a compartment, a well defined upper layer forms instantly throughout the compartment. This assumption breaks down in large compartments and long corridors due to the time required to fill these spaces. This note proposes a simple procedure for accounting for the formation delay of an upper layer in a long corridor by using correlations developed from numerical experiments generated with the three dimensional Large Eddy Simulation (LES3D) field model[1]. Two parameters related to corridor flow are then estimated, the time, t_c, required for a ceiling jet to travel in a corridor and the temperature distribution down the corridor. These estimates will then be used in the zone fire model, CFAST, by delaying flow into adjacent compartments until the ceiling jet has passed the compartment.

2 Theory

This section outlines a procedure for estimating a ceiling jet's temperature decay, depth, velocity and hence arrival time at each vent in a corridor. A field model, LES3D, is used to estimate these parameters by running a number of cases for various inlet layer depths and temperatures. The vent flow algorithm in CFAST then uses this information to compute mass and enthalpy flow between the corridor and adjacent compartments. This is accomplished by presenting the vent algorithm with a one layer environment (the lower layer) before the ceiling jet reaches the vent and a two layer environment afterwards. Estimated ceiling jet temperatures and depths are used to define upper layer properties.

The problem is to estimate the ceiling jet temperature and depth as a function of time until it reaches the end of the corridor. Two solution procedures were considered for solving this problem. The first involves the use of the horizontal momentum equation to model ceiling jet flow. Simpson[2] gives a practical treatment of gravity currents found in nature. He does not consider heat transfer. Matsushita and Klote[3] derive a one dimensional horizontal momentum equation, integrated over the vertical dimension, for tracking smoke flow in a corridor. Rehm *et al* in [4, 5] observes that a three dimensional model is necessary for capturing the behavior induced by heat transfer between the ceiling jet and the walls. Either approach is expensive computationally compared to the time required to compute other components of a zone fire model.

A second approach, the approach described in this note, is to run a field model as a pre-processing step and to summarize the results as correlations describing the ceiling jet's temperatures and velocities. An outline of this process is given by

1. Model corridor flow for a range of inlet ceiling jet temperatures and depths. Inlet velocities are derived from the inlet temperatures and depths.

2. For each model run calculate average ceiling jet temperature and velocity as a function of distance down the corridor.

3. Correlate the temperature and velocity distribution down the hall.

The zone fire model then uses these correlations to estimate conditions in the corridor. An outline of the steps involved is given by

1. Estimate the inlet temperature, depth and velocity of the ceiling jet. If the corridor is the fire room then use a standard correlation. If the source of the ceiling jet is another room then calculate the inlet ceiling jet flow using Bernoulli's law for the vent connecting the source room and the corridor.

2. Use correlations in 3. above to estimate the ceiling jet arrival time at each vent.

3. For each vent in the corridor use lower layer properties to compute vent flow before the ceiling jet arrives at the vent and lower/upper layer properties afterwards.

2.1 Assumptions

The assumptions made in order to develop the correlations described in this note are:

- The time scale of interest is the time required for a ceiling jet to traverse the length of the corridor. For example, for a 100 m corridor with 1 m/s flow, the characteristic time period would be 100 seconds.

- Cooling of the ceiling jet due to mixing with adjacent cool air is large compared to cooling due to heat loss to walls. Equivalently, we assume that walls are adiabatic. This assumption is conservative. An adiabatic corridor model predicts more severe conditions downstream in a corridor than a model that accounts for heat transfer to walls, since cooler ceiling jets travel slower and not as far.

- We do not account for the fact that ceiling jets that are sufficiently cooled will stagnate. Similar to the previous assumption, this assumption is conservative and results in over predictions of conditions in compartments connected to corridors (since the model predicts that a ceiling jet may arrive at a compartment when in fact it may have stagnated before reaching it).

- Ceiling jet flow is buoyancy driven and behaves like a gravity current. The inlet velocity of the ceiling jet is related to its temperature and depth.

- Ceiling jet flow lost to compartments adjacent to the corridor is not considered when estimating ceiling jet temperatures and depths. Similarly, a ceiling jet in a corridor is assumed to have only one source.

- The temperature and velocity at the corridor inlet is constant in time.

- The corridor height and width do not effect a ceiling jet's characteristics. Two ceiling jets with the same inlet temperature, depth and velocity behave the same when flowing in corridors with different widths or heights as long as the inlet widths are the same fraction of the corridor width.

- Flow entering the corridor enters at or near the ceiling. The inlet ceiling jet velocity is reduced from the vent inlet velocity by a factor of w_{vent}/w_{room} where w_{vent} and w_{room} are the width of the vent and room respectively.

2.2 Ceiling Jet Characteristics

2.2.1 Compartments with Length Height Ratios Near One - Normal Rooms

In a normal compartment where the length to height ratio is near one, ceiling jet velocities can be estimated from correlations such as ones found in [6] or [7]., or by solving the horizontal momentum equation in addition to the mass and energy conservation equations.

Smoke flow in a normal room is qualitatively different from smoke flow in a corridor in one important respect. Corridor smoke spreads in only one dimension, along the length of the corridor. Smoke spreads in a normal room on the other hand in two dimensions. In addition, assuming no friction or heat transfer to boundaries, ceiling velocities in corridors will be essentially constant while ceiling jet velocities in normal rooms will be approximately proportional to $(1/r)$[1] As a result, these correlations are not valid for estimating ceiling jet velocities in corridors.

If the length to height ratio of the room of fire origin is near one then ceiling jet traversal times may be estimated using the velocity correlation for a steady state fire,

$$u(r) = \begin{cases} 0.96 \left(\frac{Q}{H}\right)^{1/3} & r/H < 0.15 \\ 0.198 \frac{(Q/H)^{1/3}}{(r/H)^{5/6}} & r/H \geq 0.15 \end{cases}, \quad (1)$$

found in [6] where H is the ceiling height (m), Q is the total energy release rate of the fire (W) and r is the distance from the plume centerline (m). The constants, 0.96 and 0.195 each have units of $(\mathrm{m}^{4/3}/(W^{1/3}s)$. CFAST [8] estimates ceiling jet temperatures and velocities using a correlation derived by Cooper, given in [7].

The time, $t(r)$, required for the jet to travel a distance r from the source can then be obtained from the velocity by integrating the quantity $dr/u(r)$. Using the correlation given in [6] we obtain

$$\begin{aligned} t(r) &= \int_0^r \frac{dr}{u(r)} \\ &= \begin{cases} \int_0^r \frac{dr}{0.96\left(\frac{Q}{H}\right)^{1/3}} & r/H < 0.15 \\ \int_0^{0.15H} \frac{dr}{0.96\left(\frac{Q}{H}\right)^{1/3}} + \int_{0.15h}^r \frac{r^{5/6}}{0.195Q^{1/3}H^{1/2}} dr & r/H \geq 0.15 \end{cases} \\ &= \begin{cases} \frac{r}{0.96\left(\frac{Q}{H}\right)^{1/3}} & r/H < 0.15 \\ \frac{0.15H}{0.96\left(\frac{Q}{H}\right)^{1/3}} + \frac{6}{11 \times 0.195Q^{1/3}H^{1/2}} \left(r^{11/6} - (0.15H)^{11/6}\right) & r/H \geq 0.15 \end{cases} \\ &= \begin{cases} \frac{\hat{r}}{6.4\hat{Q}} & \hat{r} < 1 \\ \frac{1}{6.4\hat{Q}} + \frac{1}{11.6\hat{Q}} \left(\hat{r}^{11/6} - 1\right) & \hat{r} \geq 1 \end{cases} \end{aligned} \quad (2)$$

[1]Since the surface area at the exterior boundary is proportional to r then the velocity must be proportional to $1/r$ so that the mass flow out remains equal to the mass flow in.

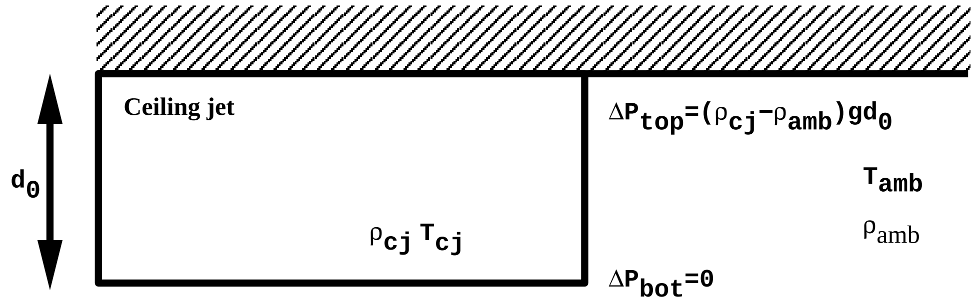


Figure 1: Schematic of a gravity current defining terms used to estimate its inlet velocity.

where $\hat{r} = r/(.15H)$ and $\hat{Q} = (Q/H)^{1/3}/H$. The time $t(r)$ corresponding to Cooper's velocity correlation must be integrated numerically.[2] The arrival time is approximately proportional to r^2, the distance squared. It will be shown later empirically that in a corridor the arrival time is proportional to r, the distance.

2.2.2 Compartments with Large Length Height Ratios - Corridors

The correlations defined by (1) and (2) are not appropriate in corridors. Ceiling jet flow in a corridor can be characterized as a one dimensional gravity current. To a first approximation, the velocity of the current depends on the difference of the density of the gas located at the leading edge of the current and the gas in the adjacent ambient air. The velocity also depends on the depth of the current below the ceiling. A simple formula for the gravity current velocity may be derived by equating the potential energy of the current, $mgd_0/2$, measured at the half-height $d_0/2$ with its kinetic energy, $mU^2/2$ to obtain

$$U = \sqrt{gd_0} \tag{3}$$

where m is mass, g is the acceleration of gravity, H is the height of the gravity current and U is the velocity. When the density difference, $\Delta\rho = \rho_{amb} - \rho_{cj}$, between the current and the ambient fluid is small, the velocity U is proportional to $\sqrt{gd_0\frac{\Delta\rho}{\rho_{cj}}} = \sqrt{gd_0\frac{\Delta T}{T_{amb}}}$ where ρ_{amb}, T_{amb} are the ambient density and temperature, ρ_{cj}, T_{cj} are the density and temperature of the ceiling jet, $\Delta T = T_{cj} - T_{amb}$ is the temperature difference. Here use has been made of the ideal gas law, $\rho_{amb}T_{amb} \approx \rho_{cj}T_{cj}$.

This can be shown using terms defined in Figure 1 by using an integrated form of Bernoulli's law noting that the pressure drop at the bottom of the ceiling jet is $P_b = 0$, the pressure drop at the top is $P_t = gd_0(\rho_{cj} - \rho_{amb})$ and using a vent coefficient $c_{vent} = 0.74$,

[2]There is no analytic formula for $t(r)$ since the calculation depends on a correlation that is obtained numerically.

to obtain

$$\begin{aligned}
U_0 &= c_{vent}\frac{\sqrt{8}}{3}\frac{1}{\sqrt{\rho_{cj}}}\frac{P_t+\sqrt{P_tP_b}+P_b}{\sqrt{P_t}+\sqrt{P_b}} \\
&= c_{vent}\frac{\sqrt{8}}{3}\sqrt{P_t/\rho_{cj}} \\
&= c_{vent}\frac{\sqrt{8}}{3}\sqrt{gd_0\frac{\rho_{amb}-\rho_{cj}}{\rho_{cj}}} \\
&\approx 0.7\sqrt{gd_0\frac{\Delta T}{T_{amb}}}\ . \qquad (4)
\end{aligned}$$

Formulas of the form of equation (4) lead one to conclude that a ceiling jet's characteristics in a corridor depend on on its depth, d_0, and relative temperature difference, $\Delta T/T_{amb}$. Therefore, as the jet cools, it slows down, due to the factor $\Delta T/T_{amb}$. If no heat transfer occurs between the ceiling jet and the surrounding walls, then the only mechanism for cooling is mixing with surrounding cool air.

2.3 Numerical Experiments

2.3.1 The Parameter Study

In order to better understand the effects of the inlet ceiling jet temperature and depth on its characteristics downstream in a corridor, a number of numerical experiments were performed using the field model LES3D[1]. Twenty cases were run with five different inlet depths and four different inlet temperatures.

Boundary Conditions - corridor flow entrance The inlet ceiling jet temperature rise, ΔT_0, and depth, d_0, were used to define an inlet velocity, U_0 using $U_0 = 0.7\sqrt{gd_0\Delta T_0/T_{amb}}$. This formula is derived from Bernoulli's law for flow through a vent.

The inlet ceiling jet depths, d_0, used in the parameter study are 0.15 m, 0.30 m, 0.45 m, 0.60 m and 0.75 m. The inlet ceiling jet temperature rises, ΔT_0, used in the parameter study are 100 °C, 200 °C, 300 °C and 400 °C. Velocities using equation (4) corresponding to these inlet depths and temperature rises are given in Table 1.

Boundary Conditions - all other surfaces For each case, a non-slip velocity boundary condition was imposed at all solid boundaries. Adiabatic thermal boundary conditions were imposed at the walls to simulate no heat transfer to wall surfaces. A vertical symmetry plane along the centerline of the corridor was used to reduce the number of grids, thereby improving the resolution. An open boundary condition was imposed at the far end of the corridor.

Table 1: Inlet Velocity as a function of Inlet Temperature and Depth

	Temperature Excess (°C)			
Depth (m)	+100	+200	+300	+400
0.15	0.50	0.71	0.87	1.00
0.30	0.71	1.00	1.22	1.41
0.45	0.87	1.22	1.50	1.73
0.60	1.00	1.41	1.73	2.00
0.75	1.12	1.58	1.94	2.24

Geometry The simulated corridor had dimensions of 10 m $\times$ 2.4 m $\times$ 2.4 m. Each grid cell had dimensions of approximately 10 cm $\times$ 5 cm $\times$ 2.5 cm (4.0 in $\times$ 2.0 in $\times$ 1.0 in) where the longest grid dimension occurred along the length of the corridor. Approximately 220,000 grid cells were used to model the corridor; 24 across the width of the corridor and 96 along both the height and length of the corridor. For most cases, a Reynold's number of 9200 (approximately 96^2) was used to resolve the small scale flow features.

A coarser grid with dimensions 10 cm $\times$ 5 cm $\times$ 5 cm was used initially. It was found that the vertical grid dimension, 5 cm was not sufficiently small to resolve the thin, 0.15m ceiling jet cases.

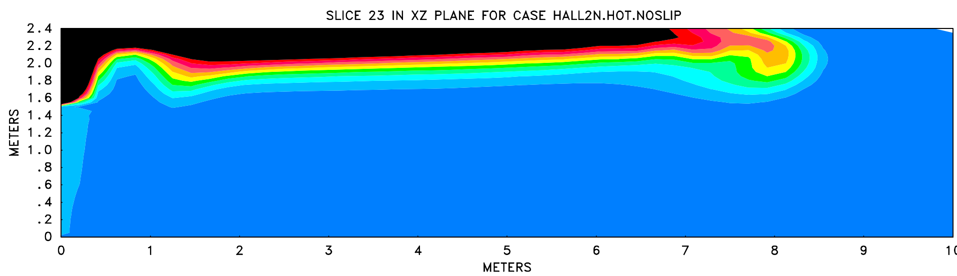
Qualitative numerical corridor flow experiments Figures 2 through 7 are presented to illustrate how various boundary conditions (adiabatic walls, cold walls *etc*) affect qualitative ceiling jet characteristics. These simulations were performed using LES3D[1]. Next a parameter study was performed in order to study the quantitative behavior of the ceiling jet by varying the inlet ceiling jet depth and temperature rise.

As can be seen from Figures 2 and 3 a ceiling jet modeled in an enclosure with adiabatic walls travels farther and faster than a ceiling jet modeled with cold walls.

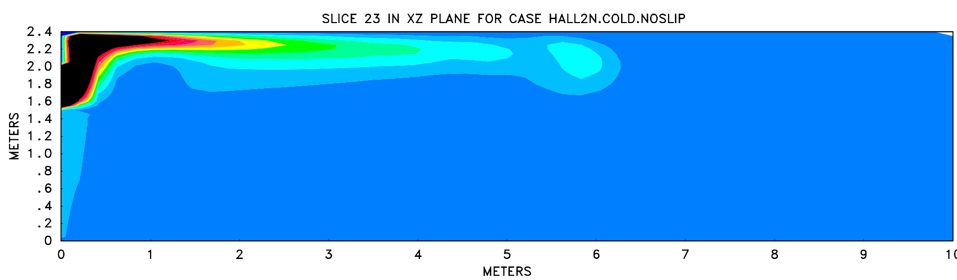
Figure 4 shows shaded temperature contours in a vertical plane along the centerline of a 10 m corridor at 10 and 20 seconds. The temperature distribution at these two times is about the same. Even though an individual portion of smoke has moved up to 10 m, the peak temperature (edge of darkest contour) has only shifted by about one meter, from 5 m to 4 m.

Similarly, Figure 5 shows shaded velocity contours in a vertical plane along the centerline of a 10 m corridor at 20 and 40 seconds. The velocity distribution does not change much between the two times. Because of this, we assume that the walls do not heat up and that the temperature and velocity distributions quickly reach steady state.

Figure 6 shows shaded velocity contours in a vertical plane along the centerline of a 10



(a) adiabatic walls



(b) cold walls

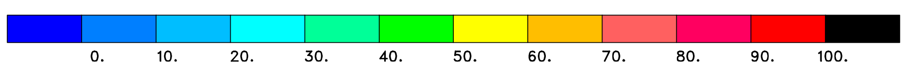
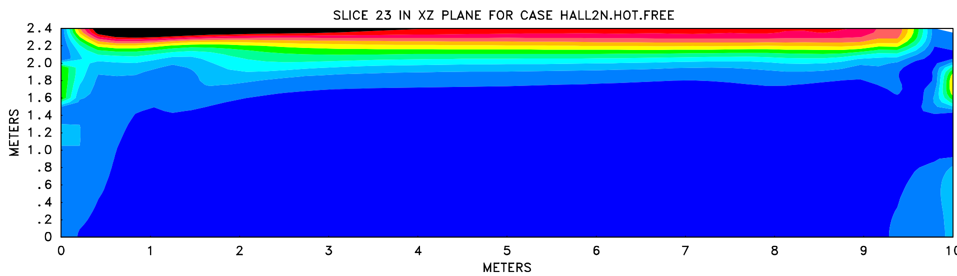
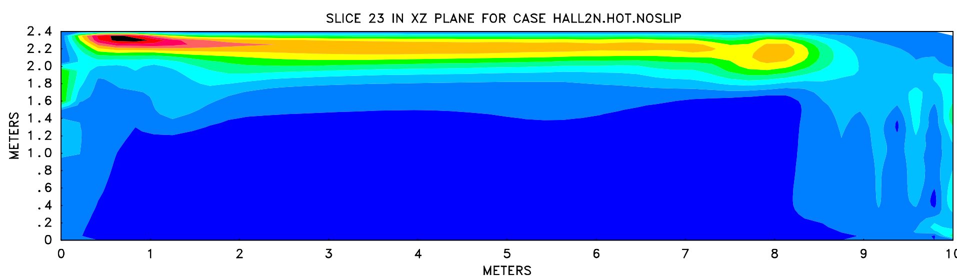


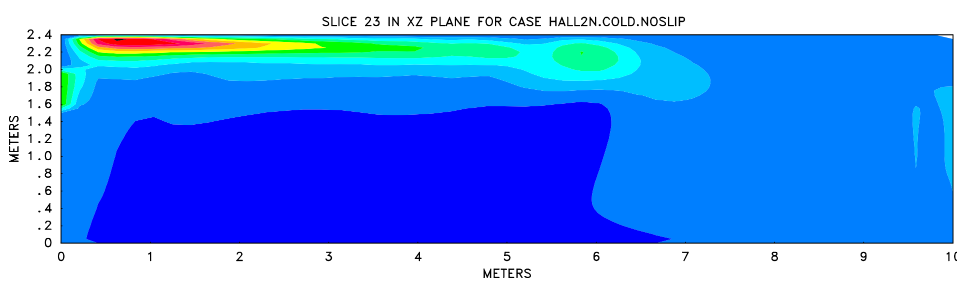
Figure 2: Shaded temperature contours along the corridor centerline for three temperature boundary conditions. The inlet flow has a depth of 0.6 m (2 ft), a velocity of 1.0 m/s and a temperature rise of 300 °C above ambient. A no-slip boundary condition is imposed at all wall surfaces.



(a) free-slip, adiabatic

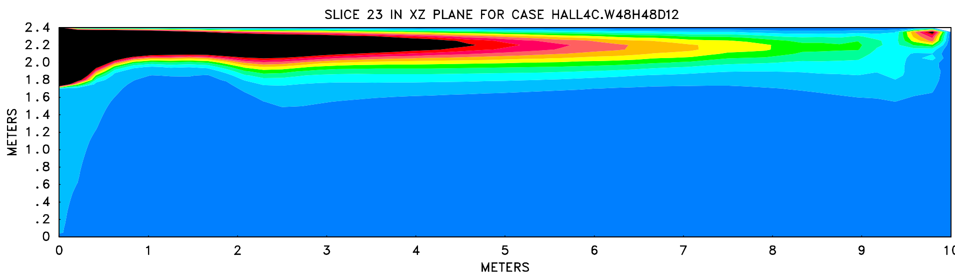


(b) no-slip, adiabatic

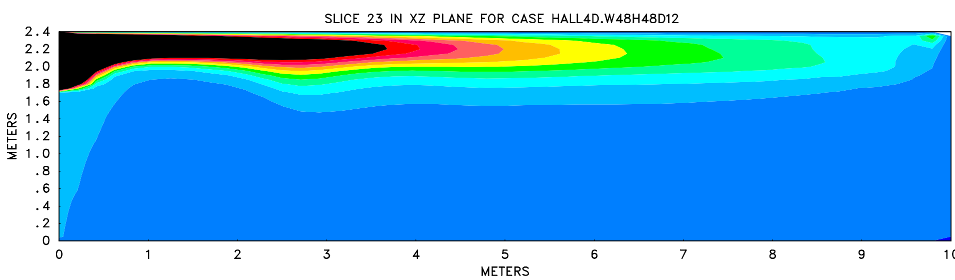


(c) no-slip, cold walls

Figure 3: Shaded U velocity contours along the corridor centerline for three different boundary conditions. The inlet flow has a depth of 0.6 m (2 ft), a velocity of 1.0 m/s and a temperature rise of 300 °C above ambient.



(a) 10 seconds



(b) 20 seconds

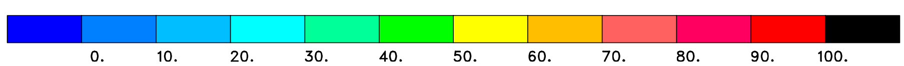
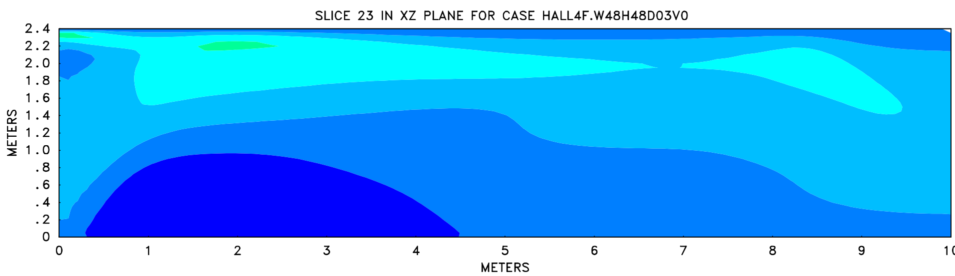
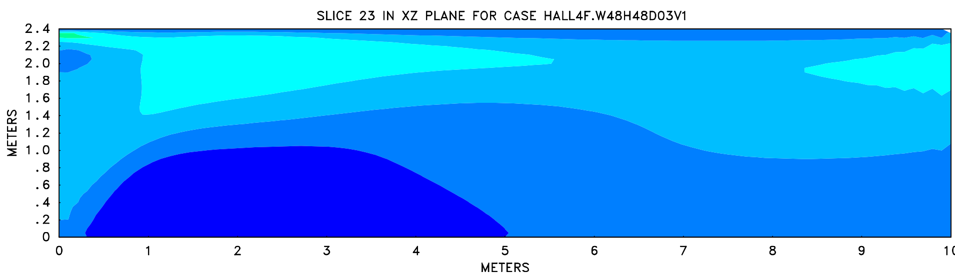


Figure 4: Shaded temperature contours along the corridor centerline at two different times during the simulation. The inlet flow has a depth of 0.6 m (2 ft), a velocity of 1.0 m/s and a temperature rise of 300 °C above ambient.



(a) 20 seconds



(b) 40 seconds

Figure 5: Shaded U velocity contours along the corridor centerline at two different times during the simulation. The inlet flow has a depth of 0.6 m (2 ft), a velocity of 1.0 m/s and a temperature rise of 312 °C above ambient.

m corridor for three inlet ceiling jet depths. The inlet velocity in each case is 1.0 m/s. Note that the ceiling jet velocity increases as the inlet depth increases.

Figure 7 shows shaded velocity contours in a vertical plane along the centerline of a 10 m corridor for three inlet ceiling jet temperatures. Note that the ceiling jet velocity increases as the inlet temperature increases.

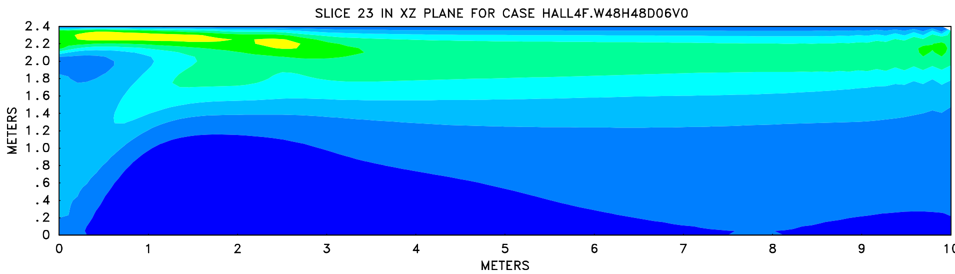
2.3.2 Reducing the Data

Estimating Zone Fire Modeling Quantities from Field Modeling Results The computational fluid dynamic or field model, LES3D, calculates temperatures, pressures and velocities at many points in a 3-D rectangular grid. The zone fire model, CFAST, on the other hand calculates pressure at the floor, temperatures in the lower and upper layer and a layer interface height. In this section, a procedure is presented for reducing the data from a field model to a form consistent with a zone fire model. For each vertical plane along the length of a corridor, a layer interface height is estimated by using the distance above the floor where the temperature gradient is greatest. An upper layer temperature is calculated by averaging all temperatures in the slice above the estimated layer height.

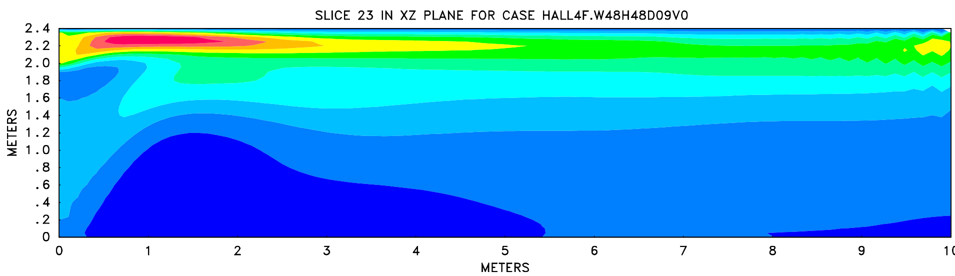
The simulation of these cases resulted in an extensive set of velocity, temperature and pressure predictions. This data is reduced to a more manageable size by noting that the inlet high-temperature ceiling jet flow stratifies the corridor gases into two regions; an upper region of hot, fast flowing air and a lower region of relatively cool quiescent air. An average upper layer temperature and layer height is estimated for each vertical slice along the length of the corridor. To estimate the upper layer temperature, $T_{avg}(i)$, and interface height, $y_{lay}(i)$ for each vertical slice, i, downstream in a corridor, perform the following calculations.

The terms, ibar, jbar and kbar refer to the number of grid cells in the i, j and k directions respectively. The i direction is down the longest side of the corridor, the j direction is across the corridor and the k direction is along the vertical direction. Let $T(i,j,k)$ be the temperature of the grid cell (i,j,k). Consider the i'th vertical slice. For each vertical elevation k in the i'th slice, define an average temperature T_{avg}, a temperature gradient, ΔT_{avg} (ratio of the difference between adjacent average temperatures in the vertical direction and the grid spacing). Finally define a maximum temperature gradient ΔT_{max}. Calculate these terms using

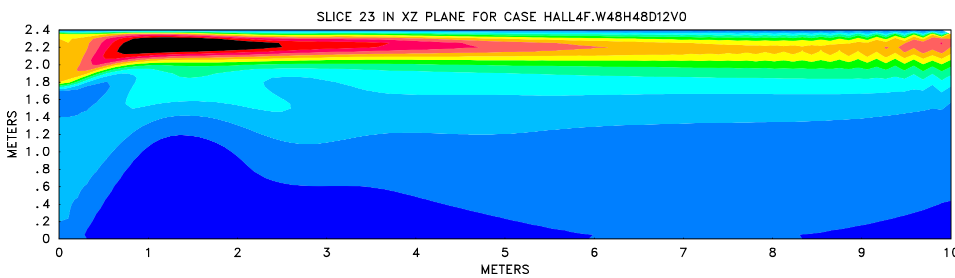
$$\begin{aligned} T_{avg}(i,k) &= \frac{1}{\text{jbar}} \sum_{j=1}^{\text{jbar}} T(i,j,k) \qquad (5) \\ \Delta T_{avg}(i,k) &= T_{avg}(i,k+1) - T_{avg}(i,k) \\ \Delta T_{max}(i) &= \max_{1 \le k \le \text{kbar}} \Delta T_{max}(i,k) \end{aligned}$$



(a) depth = 0.30 m

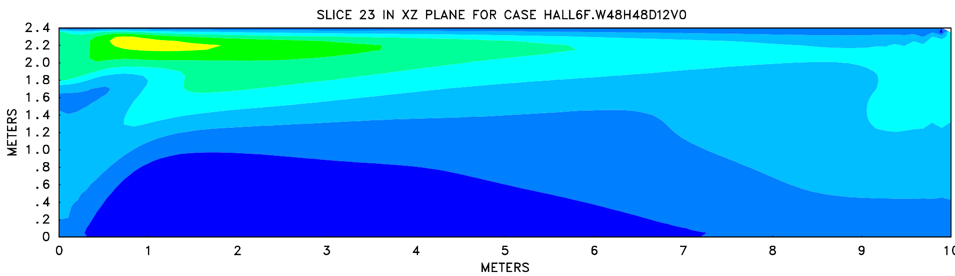


(b) depth = 0.45 m

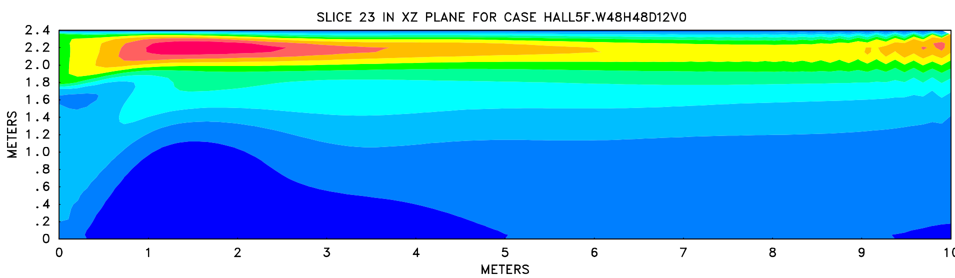


(c) depth = 0.60 m

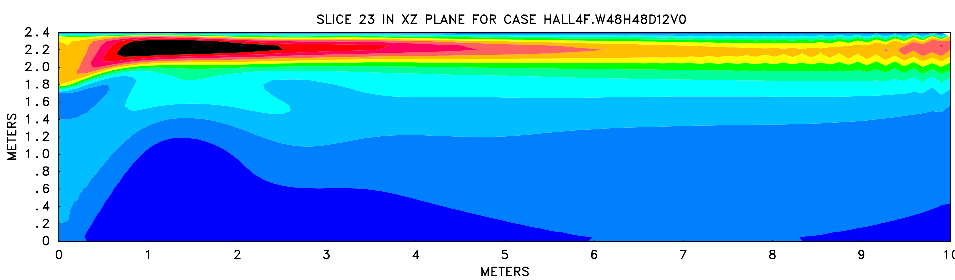
Figure 6: Shaded U velocity contours along the corridor centerline for three different inlet ceiling jet depths. The inlet flow has a velocity of 1.0 m/s a temperature rise of 312 °C above ambient and a depth of 0.30 m, 0.45 m or 0.60 m



(a) $\Delta T_0 = 62°\mathrm{C}$



(b) $\Delta T_0 = 162°\mathrm{C}$



(c) $\Delta T_0 = 312°\mathrm{C}$

Figure 7: Shaded U velocity contours along the corridor centerline for three different inlet ceiling jet temperature rises, ΔT_0. The inlet flow has a depth of 0.60 m and a velocity of 1.0 m/s .

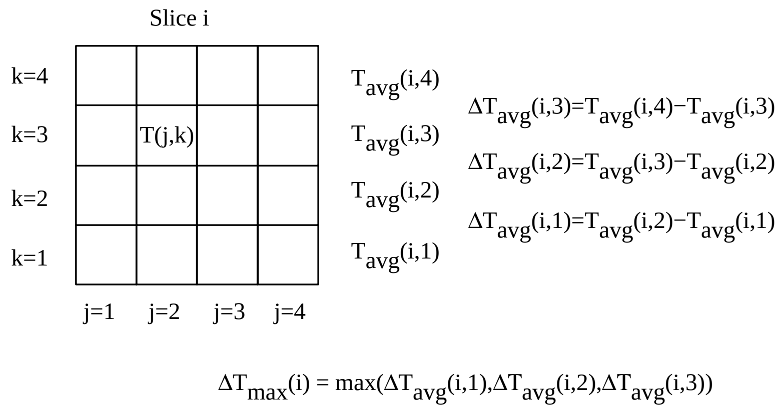


Figure 8: Illustration of an average temperature calculation for one 4×4 vertical slice. The estimated layer interface is the row where the greatest temperature change occurs.

The layer height is then the index k_{max} that corresponds to the maximum temperature change given by ΔT_{max}. In other words, the height above the floor where the temperature changes from a cool lower layer to a warm upper layer. The average upper layer temperature for slice i is then given by

$$\begin{aligned} T_U(i) &= \frac{1}{\text{jbar}\ (\text{kbar}\ +1-k_{max})} \sum_{j=1}^{\text{jbar}} \sum_{k=k_{max}}^{\text{kbar}} T(i,j,k) \\ &= \frac{1}{\text{kbar}\ +1-k_{max}} \sum_{k=k_{max}}^{\text{kbar}} T_{avg}(i,k)\ . \end{aligned}$$

Figure 8 gives an example of this calculation for $JBAR = KBAR = 4$.

The temperature rise above ambient for each slice i is given by $\Delta T(i) = T_U(i) - T_{amb}$. These temperature rises are scaled by the inlet temperature rise, ΔT_0, and transformed using $\log(\Delta T/\Delta T_0)$. The resulting data are presented in Figure 9. Note that each plot is nearly linear and that all plots (except for the $d_0 = 0.15m$ group) lie within a single group. This implies that the relative temperature falloff is independent of the inlet temperature rise and depth (assuming that the inlet depth is sufficiently thick).

The temperature curves presented in Figure 9 were approximated by straight lines using a linear least squares curve fitting procedure.

2.3.3 Summary of Results

Ceiling Jet Temperatures The line that fits the temperature fall off data in a least squares sense is given for the plots in Figure 9. This fit is given in the form of

$$\log\left(\frac{\Delta T}{\Delta T_0}\right) = a + bx \tag{6}$$

This is equivalent to

$$\frac{\Delta T}{\Delta T_0} = C_1 10^{bx} \tag{7}$$

$$= C_1 \left(\frac{1}{2}\right)^{x/h_{1/2}} . \tag{8}$$

where $C_1 = 10^a$ and $h_{1/2} = -\log(2)/b$. The parameter $h_{1/2}$ in equation (8) has a physical interpretation. It is the distance down the corridor where the temperature rise ΔT, falls off to 50 per cent of its original value or equivalently, $\Delta T(x + h_{0.5}) = 0.5\Delta T(x)$. Equation (7) and (8) are equivalent mathematically. Equation (8) is more intuitive however, because the coefficient, $h_{1/2}$ has a physical interpretation.

The half-distance, $h_{1/2}$, can be approximated by $h_{1/2} = \log(2)/0.018 \approx 16.7$ where $b = -0.018$ is given in Figure 9. Similarly, the coefficients C_1 is approximated by $C_1 = 10^a = 10^{-0.003} \approx 1$ where a is also given in Figure 9. Therefore the temperature rise, ΔT, may be approximated by

$$\Delta T = \Delta T_0 \left(\frac{1}{2}\right)^{\frac{x}{15}} \tag{9}$$

Ceiling Jet Arrival Times Numerical thermocouples were placed 0.15 m (6 in) below the ceiling every 0.5 m along the center line of the corridor for all cases except for the $d_0 = 0.15$m cases where they were placed 0.075 m below the ceiling. Ceiling jet arrival times were recorded by noting when the temperatures rose $1°$C. The arrival time for each case was scaled by the ceiling jet velocity, U_0, at the left entry vent. These reduced data are displayed in Figure 10. Relative temperature fall off data for all ceiling jets are displayed in Figure 9. Note that most arrival time curves lie within approximately the same region. A group of curves, corresponding to the inlet depth of $d_0 = 0.15$m, are separate from the main group. This is because the 0.15m ceiling jets are weaker than the rest. They lose their driving potential resulting in lower velocities and hence greater arrival times. The arrival time of the ceiling jet head may be approximated by $t = x/U_0$ for all d_0 except for $d_0 = 0.15$m. As stated before, the $d_0 = 0.15$m ceiling jets are not strong enough to sustain a well defined flow for the length of the corridor.

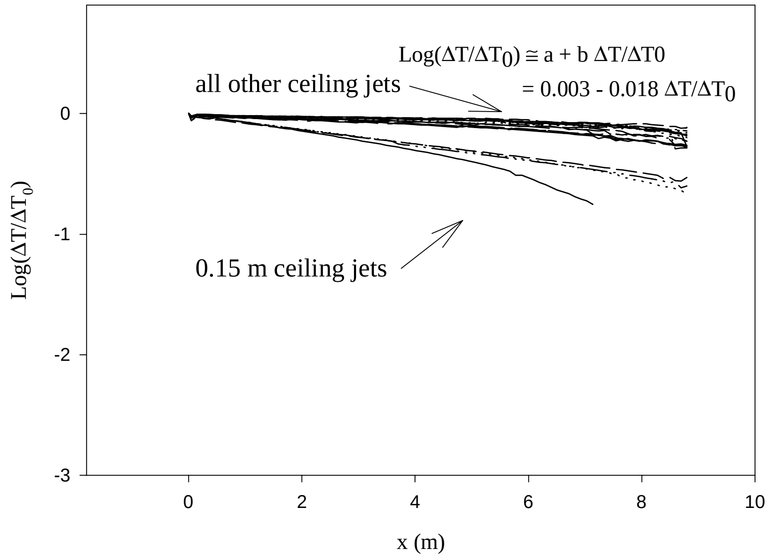


Figure 9: Common log of relative temperature excess downstream in a corridor using an adiabatic temperature boundary conditions for several inlet depths and inlet temperature rises. The inlet velocity, U_0, is given by equation (4)

3 Summary and Conclusions

A procedure for estimating ceiling jet travel times using correlations has been described. The procedure allows initial layer formation to be predicted more accurately in compartments connected to long corridors. These correlations were derived by performing numerical experiments using the computational field model LES3D to estimate ceiling jet arrival times, temperature fall off rates and ceiling jet depths for cases with various specified inlet ceiling jet temperatures and depths. These correlations were then used to improve predictions of corridor smoke flow in the zone fire model, CFAST

The numerical experiments with LES3D demonstrated that for the cases simulated, ceiling jet characteristics depend on the relative inlet temperature rise and not the inlet depth. Flow in long corridors (greater than 10 m) need to be better characterized due to the flow stagnation which may occur because of the ceiling jet's temperature decay. Even though the use of LES3D served as a good tool to design a corridor flow sub-model, comparisons still need to be made between real-scale experiments and the zone fire model predictions. Such comparisons will allow us to assess the validity of the modeling assumptions, to determine the accuracy of the predictions and to gain better confidence in the use of this model.

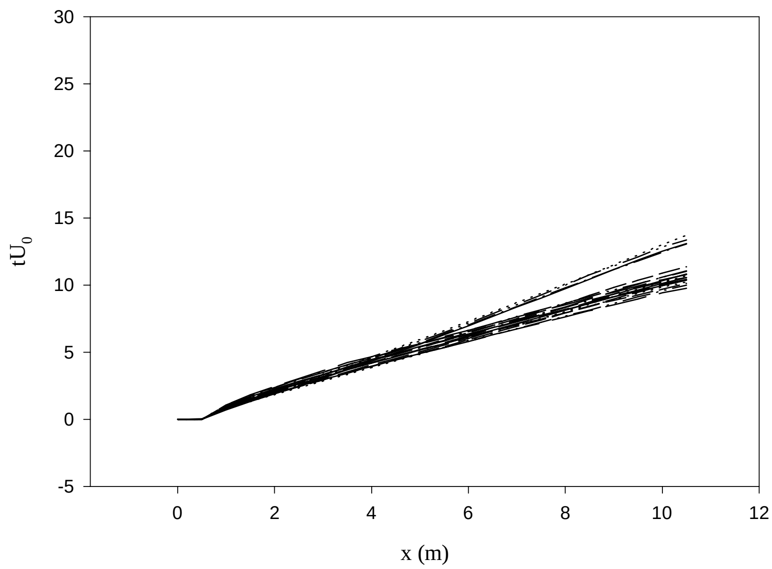


Figure 10: Ceiling jet arrival time as a function of distance down the corridor scaled by the initial ceiling jet velocity, U_0 for several initial inlet depths, d_0, and temperature rises, ΔT_0. The walls are adiabatic. The inlet velocity, U_0, is given by equation (4). The ceiling jet's arrival time is measured by noting when its temperature rises 1 °C above ambient at a given distance downstream from the inlet.

A Implementation

A.1 Data Structures

Several new variables have been introduced to record the status of the corridor model. IZHALL indicates whether a room is a hall and whether user defined velocities and depths should be used. IZVENT records distance information for vents connected to halls. ZZHALL records times, velocities and depths ceiling jets in each corridor. More details are given below.

HALLDIST(I,J,K,L) First note that the triple (I,J,K) defines a unique vent in CFAST. HALLDIST(I,J,K,1) is then the distance between vent (I,J,K) and a reference point in room I. It doesn't matter where this point is as long as each vent connected to ROOM I uses the same reference point. HALLDIST(I,J,K,2) is the distance between vent (I,J,K) and a reference point in room J. Similarly, the reference point for ROOM J must be the same for all vents connected to ROOM J. This variable is set in NPUTQ.

IZHALL(IROOM,index) This array records integer information about a hall in room IROOM. The parameter, index may be one of IHDEPTHFLAG, IHHALLFLAG, IHMODE, IHROOM, IHVELFLAG, IHVENTNUM or IHXY which are defined below.

IHDEPTHFLAG If IZHALL(I,IHDEPTHFLAG)=1 then use the depth specified on the HALL command line for the ceiling jet depth. This variable is set in NPUTQ.

IHHALFFLAG If IZHALL(I,IHHALFFLAG) is non-zero then use the temperature decay parameter specified on the HALL command line. This variable is set in NPUTQ.

IHMODE The variable IZHALL(I,IHMODE) can have a value of IHBEFORE, IHDURING or IHAFTER. If IHBEFORE, then flow has not started in corridor I. If IHDURING, then flow has started but has not reached the end of the corridor. If IHAFTER, then flow has reached the end of the corridor. This variable is set in SETHALL, INITMM and NPUTQ.

IHROOM If IZHALL(I,IHROOM)=1 then room I is a hall. This variable is set in NPUTQ.

IHVELFLAG — If IZHALL(I,IHVELFLAG)=1 then use the velocity specified on the HALL command line for the ceiling jet velocity. This variable is set in NPUTQ.

IHVENTNUM — If IZHALL(I,IHVENTNUM) is non-zero then it contains the number of the vent that initiated flow into the hall. This variable is set in NPUTQ.

IHXY — If IZHALL(I,IHXY) is one, then the X direction corresponds to the longest dimension of hall I. If this value is two then the Y direction corresponds to the longest dimension of hall I. This variable is set in INITAMB.

IZVENT(IV,4) — If IZVENT(IV,4)=1 then the 'from' room is a hall. The from room is the first room specified on the HVENT command line. This variable is set in DATACOPY.

IZVENT(IV,5) — If IZVENT(IV,5)=1 then the 'to' room is a hall. The 'to' room is the second room specified on the HVENT command line. This variable is set in DATACOPY.

UPDATEHALL — If UPDATEHALL is TRUE then the hall flow velocity, temperature and depth is updated in the subroutine HFLOW. The variable UPDATEHALL is set in the subroutine SOLVE after RESID is called.

ZZHALL(I,index) — This array records floating point information about a hall in room IROOM. The parameter, index, may be one of IHDEPTH, IHDIST, IHHALF, IHMAXLEN, IHORG, IHTEMP IHTIME0 or IHVEL, which are defined below.

IHDEPTH — If IZHALL(I,IHDEPTHFLAG) is not zero, then the variable ZZHALL(I,IHDEPTH) contains the corridor flow depth specified on the HALL command line for room I. If IZHALL(I,IHDEPTHFLAG) is zero, then ZZHALL(IHDEPTH) contains the corridor flow depth calculated by the hybrid model.

IHDIST — The variable, ZZHALL(I,IHDIST), contains the distance that the ceiling jet has traveled down the hall. This variable is set in SETHALL.

IHHALF — If IZHALL(I,IHHALFFLAG) is not zero then ZZHALL(I,IHHALF) contains the distance where the ceiling jet flow temperature is reduced 50 per cent. If IZHALL(I,IHHALFFLAG) is zero then the variable ZZHALL(I,IHHALF) contains the 50 per cent distance parameter specified on the HALL command for room I. This variable is set in NPUTQ and HALLTRV.

IHMAXLEN — This variable contains the maximum length that flow can travel in room I before it encounters the end of the corridor. This variable is set in SETHALL.

IHORG — The variable, ZZ(I,IHORG), contains the distance down the hall where flow starts. This dimension corresponds to either a vent opening or a fire location. where corridor flow originates. Note that the variables ZZHALL(I,IHORG) and ZZHALL(I,IHMAXLEN) always sum to the length of the corridor. This variable is set in SETHALL.

IHTEMP — The variable ZZHALL(I,IHTEMP) contains the initial temperature of the ceiling jet flow in room I. This variable is set in SETHALL.

IHTIME0 — If ZZHALL(I,IHTIME0)$>$0 then this variable contains the time when smoke started flowing into hall I. This variable is set in SETHALL.

IHVEL — If IZHALL(I,IHVELFLAG) is not zero, then ZZHALL(IHVEL) contains the corridor flow velocity specified on the HALL command line for room I. If IZHALL(I,IHVELFLAG) is, then ZZHALL(IHVEL) contains the corridor flow velocity calculated by the hybrid model. This variable is set in NPUTQ and SETHALL.

ZZVENTDIST(I,J) — The variable ZZVENTDIST(I,J) (if greater than zero) contains the distance between vent J and the vent where smoke started entering HALL I. Note that vent J must be connected to room I. This variable is set in SETHALL.

A.2 Routines

Three new routines have been created to update hall data structures and to calculate correlations for ceiling properties in halls.

HALLHT — This routine computes the temperature and velocity of the ceiling jet at each detector location in a corridor. The routine CEILHT performs the same function for rooms that are not corridors. The correlations are used only while the ceiling jet is traveling down the corridor.

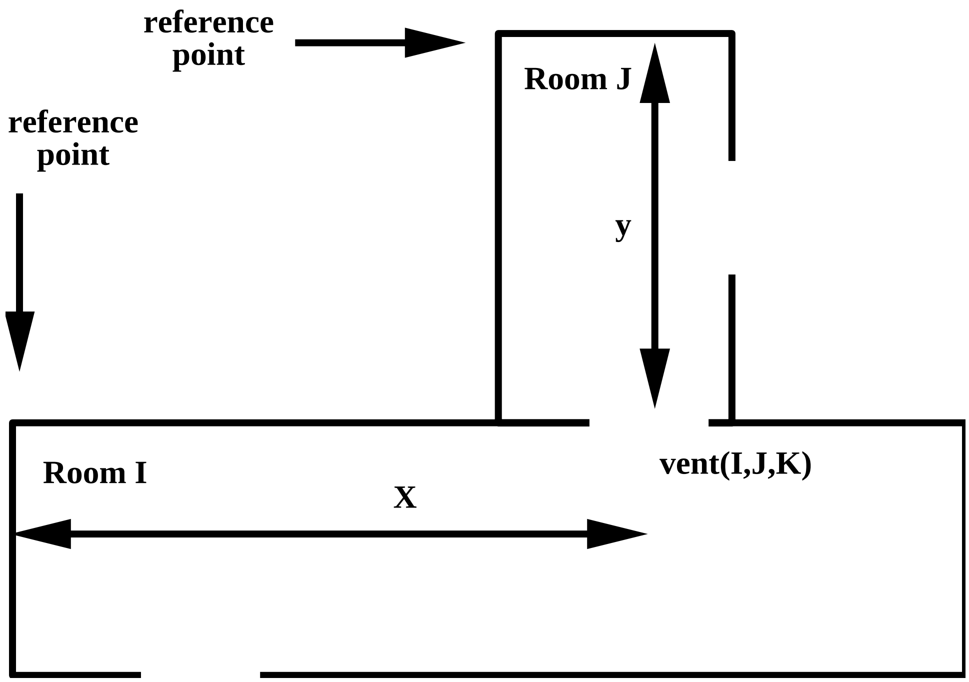


Figure 11: Diagram for the HALLDIST command

HALLTRV — This routine computes the ceiling temperature, density and velocity at a given distance from where smoke enters the corridor. The routine HALLHT calls HALLTRV for each detector location.

SETHALL — This routine updates the hall data structures, ZZHALL and IZHALL each time control is returned from DASSL. In particular, it re-calculates ceiling jet velocities, temperatures and determines whether the ceiling jet has reached the end of the corridor.

A.3 Algorithms

This section presents an outline of the calculations that were performed to implement the hybrid model by relating the equations and correlations developed in previous sections with FORTRAN code used to perform the calculations.

1. Initialize various components of ZZHALL and IZHALL in the subroutine INITMM.

2. Read in the HALL and HVENT commands to define which rooms are corridors and where vents are located in the hall.

3. Update the hall data structures. Hall data structures are updated after DASSL completes a time step. In SOLVE, the logical variable UPDATEHALL is set allowing SETHALL to be called from both the subroutines, FIRES and HFLOW (a ceiling jet in a hall may start due to a fire in the hall or flow through a vent from an adjacent room).

   (a) In FIRES, determine whether the room containing the main fire is a hall. If it is a hall, then use the ceiling jet routine CEILHT, to estimate initial ceiling jet temperature, velocity and depth.

   (b) In HFLOW, determine whether smoke has started flowing from an adjacent room to a hall. If it has, then record the start time and vent number into the ZZHALL and IZHALL data structures. HALL is flowing into the

A.4 New Input Command

In order to specify CFAST cases involving corridor flow a new input command HALL was created and the command HVENT was modified. The command used to define a room as a hall is

HALL iroom[, vel, depth, tdecay]

where iroom is the room number, and vel, depth and tdecay are optional parameters used to specify the ceiling jet velocity, depth and distance where the temperature falls off by 50 per cent. The HVENT input command was modified to allow the user to enter further dimensional data about a vent.

The new HVENT command is given by

HVENT I, J, K, W, H, L, VWCOS, HI, HJ

The parameters I, J, K, W, H, L and VWCOS are defined as before (I is the from room, J is the to room, K is the vent number from 1 to 4, W is the width of the vent, H is the soffit or top of the vent, L is the sill or bottom of the vent and VWCOS is the wind velocity direction cosine ranging from 1 to -1). The new parameter HI is the distance between this vent and the reference point in room I. Similarly, HJ is the distance between this vent and the reference point in room J.

A.5 Examples

Figure 12 illustrates a scenario involving a fire room, a corridor and two side rooms. Room 1 contains a constant 100 kW fire. The vents connecting the corridor (room 2) to rooms 1, 4, 5 and 3 (room 5 is designated as the outside) are located at 0 m, 1 m, 9 m and 10 m respectively. These are specified as open doors using the vent commands

```
HVENT 1 2 1 .79 2.34 0.0 0.0  0.0 0.0
```

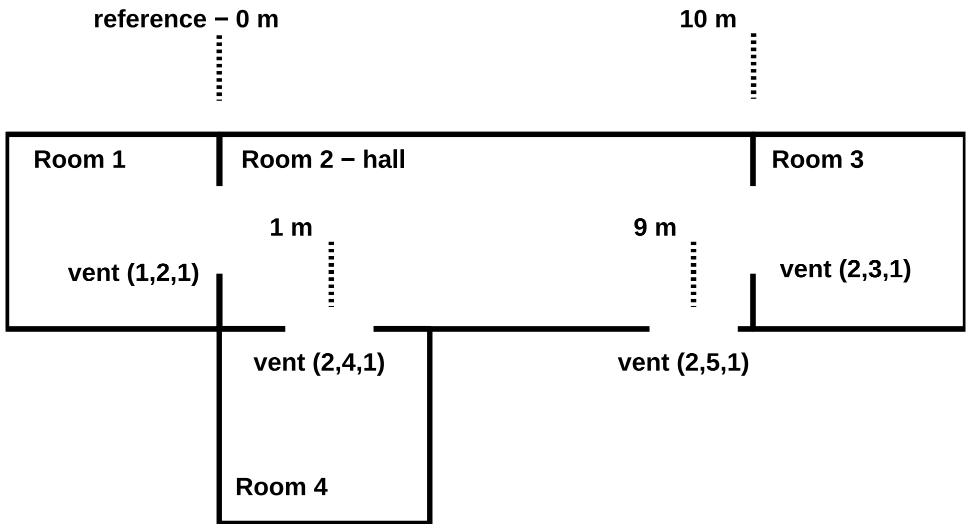
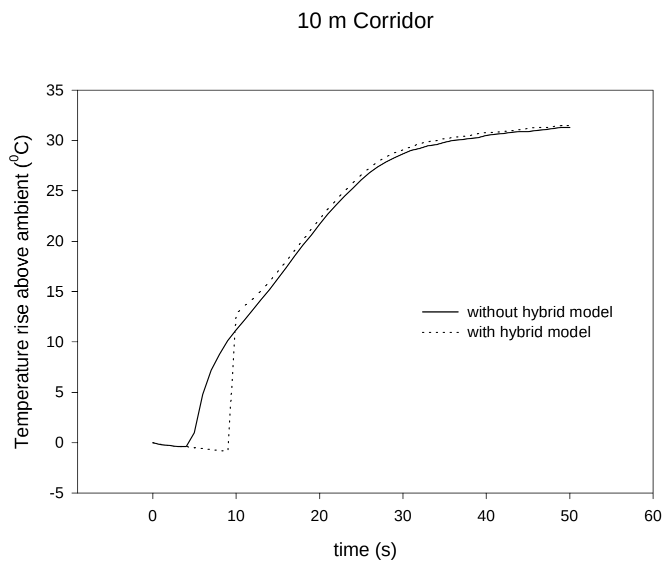


Figure 12: Diagram of a CFAST scenario involving a 10 m corridor and three side rooms.

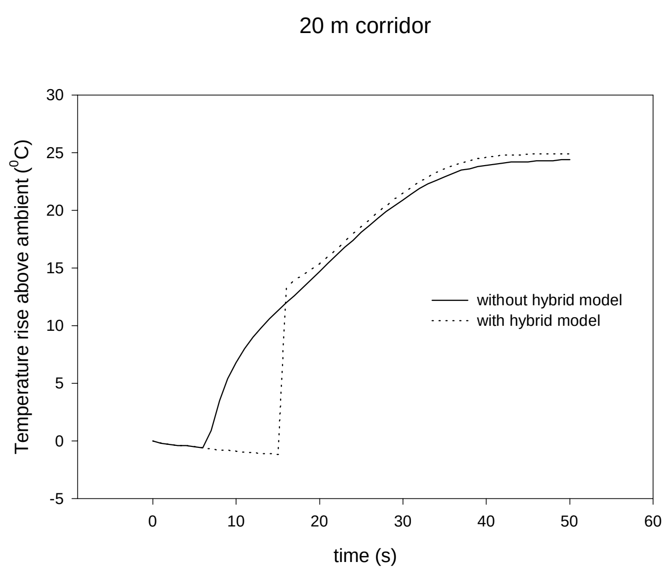
```
HVENT 2 4 1 .79 2.34 0.0 0.0  1.0 0.0
HVENT 2 5 1 .79 2.34 0.0 0.0  9.0 0.0
HVENT 2 3 1 .79 2.34 0.0 0.0 10.0 0.0
```

The (i,j,k) vent coordinate is defined in Figure 12. Each vent extends from the floor (first 0.0) to the ceiling (2.34) and is 0.79 m wide. The wind at the vent is 0.0 m/s (second 0.0 on the command line). Since room 2 is a hall, the vent distance is the 9'th parameter for the first HVENT command and the 8'th parameter for all other HVENT commands.

This scenario is simulated for 30 seconds. A second scenario, the same as the first except that the corridor is 20 m instead of 10 m is also simulated. Upper layer temperatures for room 3 are presented in Figure 13 along with simulations for the same scenario modeled without the hybrid option. The delay enforced by the hybrid option causes the delay in temperature rise for room 3 in the two cases.



(a) 10 m corridor



(b) 20 m corridor

Figure 13: Plot of temperature excess (°C) vs. time for corridors of length 10 m and 20 m.

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Presently, the Consolidated Fire and Smoke Transport Model zone fire model (CFAST) assumes that smoke travels instantly from one side of a compartment to another. As a result, upper layers start forming in compartments connected to the end of long corridor much sooner than expected. This report documents a procedure for estimating ceiling jet travel times so that initial layer formation may be predicted more accurately in compartments connected to long corridors. Standard correlations are not suitable for predicting ceiling jet velocities and temperatures in corridors because ceiling jet time arrival at a distance r is proportional to r**2 in normal rooms (rooms with length to height ratio's near one) and proportional to r in corridors (rooms with large length to height ratios). Correlations are derived by performing numerical experiments to estimate ceiling jet arrival times, temperature fall off rates and depths for cases with various initial ceiling jet temperatures and depths. These correlations are used to improve predictions of corridor smoke flow in the CFAST zone fire model.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

correlation; corridors; fire research; fire simulation

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