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A CLOSED-FORM ESTIMATE OF FIRE-INDUCED VENTILATION THROUGH SINGLE RECTANGULAR WALL OPENINGS

by

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SUMMARY

A closed-form method is developed for estimating quasi-steady mass flow rates in room fires ventilated only through a single rectangular wall opening. This method uses linearized forms of the vent flow and plume entrainment equations. Two forms of plume entrainment equations are considered: axisymmetric plumes and line fires located against walls. Mass flow rates calculated by this method are compared with mass flow rates measured in a series of room fire experiments.

INTRODUCTION

Enclosures with single rectangular wall openings are commonly used for room fire experiments. They also are commonly involved in real fire scenarios, where a single door or window opening serves as the only path for fire-induced natural ventilation to the enclosure. Typically, the hot gas layer that forms in compartment fires descends within the opening until a quasi-steady balance is struck between the rate of mass inflow to the layer and the rate of outflow from the layer. This scenario is depicted in Figure 1.

A complete solution for the mass flow rate in this scenario typically requires equating and solving three nonlinear equations describing the vent flow rate and the plume entrainment rate as functions of the layer interface height and the neutral plane height. An iterative approach is normally employed where the layer interface height is guessed, the rates of mass inflow and outflow are calculated based on this guessed height, and improved guesses are made until the mass balance converges to solution. Numerical techniques such as the Newton-Raphson method handle this type of iteration efficiently. Nonetheless, a simple closed-form method for estimating the mass balance is desirable because it permits hand calculations to be made as a preliminary step in the hazard analysis process. This precludes the need for computer-based numerical solutions.

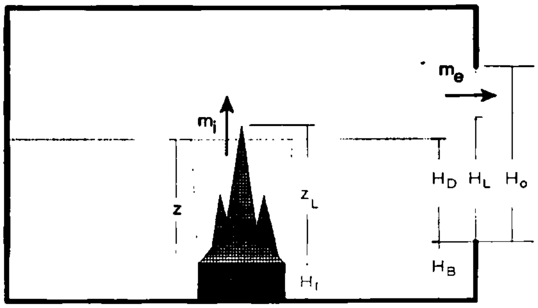

Figure 1. The naturally ventilated room fire geometry.

A simple method to evaluate the mass flow balance in naturally ventilated fire scenarios has been developed. This method uses linearized forms of the vent flow and plume entrainment equations to permit development of a closed-form estimate of the mass flow rate. Two forms of the entrainment equation are considered, one for axisymmetric plumes and one for line fires located against walls.

VENT FLOW RATE

Based on application of Bernoulli's Equation, the mass efflux rate through a vertical rectangular opening can be expressed as[1]:

$$\dot{m}_e = \frac{2}{3} C_d W_o \rho_f \sqrt{2 g \left(\frac{\rho_o}{\rho_f} - 1\right)} \left(H_o - H_L\right)^{3/2} \quad (1)$$

where

C_d = Orifice flow coefficient
W_o = Opening width (m)
ρ = gas density (ambient and fire) (kg/m^3)
H_o = Opening height (m)
H_L = Height of layer above bottom of opening (m)

The flow coefficient, C_d accounts for differences between theoretical and actual flows due to friction and flow contraction at an orifice. A value of 0.7 is representative for flows through rectangular wall openings[2,3]. Equation 1 appears to depend strongly on the smoke layer temperature, but this dependence is weak over the temperature range typically of interest (> ~ 200°C) for hazardous room fires. This weak dependence exists because as the temperature goes up, the density goes down. This causes a greater pressure difference across the opening, which in turn causes the gas velocity to increase. The decreased density and increased gas velocity tend to offset each other, resulting in a fairly constant mass flux. Consequently, for hot gas layer temperatures above approximately 200°C, Equation 1 can be simplified to[4]:

$$\dot{m}_e = 1.20\, A_o \sqrt{H_o} \left(1 - \frac{H_L}{H_o}\right)^{3/2} (kg/s) \qquad (2)$$

Values used for this simplification are: C_d = 0.7, ρ_o = 1.20 kg/m^3 (T_o = 20°C) and ρ_f = 0.45 kg/m^3 (T_f = 250°C). But other values for T_o near 20°C (e.g., ± 20°C) and for T_f in the range of approximately 200° to 600°C work equally well.

In compartments with single rectangular openings in one wall, the single opening serves both for air inflow to and for smoke outflow from the enclosure. The maximum rate of mass exchange is limited by the opening size and shape and can be estimated, in units of kg/s, as:

$$\dot{m}_{max} = 0.5\, A_o \sqrt{H_o} \qquad (3)$$

where A_o is the opening area in m^2 and H_o is the opening height (m). This is the well known ventilation limit of air flow first deduced by Kawagoe[5].

Equations 2 and 3 can be equated to estimate the relative height of the layer in the opening when the ventilation limit is reached:

$$\left(\frac{H_L}{H_o}\right)_{@\ V.L.} \approx 0.44 \qquad (4)$$

This suggests that the ventilation limit of air flow is achieved when the hot gas layer descends to fill the upper 56% of the opening. Rockett[1] has shown that the exact value of H_L/H_o at the ventilation limit is a function of the ratio of the absolute gas temperature to the absolute ambient temperature, but this dependency is weak, and a value of H_L/H_o = 0.44 at the ventilation limit is a reasonable approximation. As a consequence, Equation 2 only applies over the range $0.44 < H_L/H_o < 1$. Over this range, Equation 2 can be linearized as:

$$\left(1 - \frac{H_L}{H_o}\right)^{3/2} \approx 0.9\left(0.9 - \frac{H_L}{H_o}\right) \qquad (5)$$

This linear fit is accurate to within 10 percent of the maximum mass flux over the range $0.44 < H_L/H_o < 0.9$, as shown in Figure 2. Between $0.9 < H_L/H_o < 1.0$, this linear fit would predict a negative mass flow. In this range, the mass efflux prediction can be set to zero to minimize the difference from the analytical solution. Figure 2 also shows a least squares linear fit of the left hand side of Equation 5 over the range $0.44 < H_L/H_o < 1.0$. The linear fit expressed by Equation 5 is considered to be more appropriate than the least squares fit for the present purposes. The selected linear fit demonstrates the correct limit behavior at H_L/H_o = 0.44 and

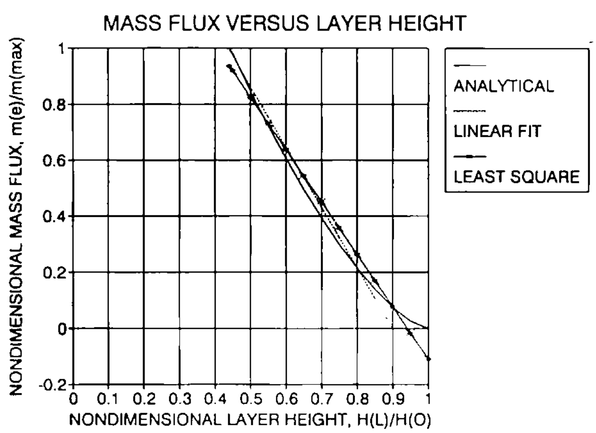

Figure 2. Comparison of exact and approximate mass flux rates as a function of the nondimensional layer height.

exhibits an accuracy similar to the least squares fit over the entire range of interest.

With the simplification expressed by Equation 5, the mass efflux term can be expressed as a linear function of the hot gas layer height above the bottom of the opening:

$$\dot{m}_e = A_o \sqrt{H_o}\left(0.97 - 1.08\frac{H_L}{H_o}\right) \quad (6)$$

Equation 6 can be nondimensionalized by dividing by the maximum vent flow rate expressed by Equation 3:

$$\frac{\dot{m}_e}{\dot{m}_{max}} = 2\left(0.97 - 1.08\frac{H_L}{H_o}\right) \quad (7)$$

Under quasi-steady conditions, the mass efflux term must be balanced with the plume entrainment rate to evaluate the location of the hot gas layer interface and the mass flow rate.

Plume Entrainment Rate

Entrainment is considered in terms of two types of plumes: axisymmetric and line fire.

Axisymmetric Plumes

Heskestad[6] suggests that the rate of entrainment into axisymmetric fire plumes can be treated as a linear function of the height, z, in a region near the fire source, where $z < z_L$:

$$\dot{m}_i = k_e\, \dot{Q}_c \frac{z}{z_L} \quad (8)$$

k_e is an appropriate entrainment coefficient in the flame region. Heskestad suggests a value of 0.0054 kg/kJ for this parameter. The effective flame height, z_L, is given as:

$$z_L = z_o + 0.166\, \dot{Q}_c^{2/5} \quad (9)$$

z_o is a virtual origin offset, given as:

$$z_o = -1.02\, D + 0.083\, \dot{Q}^{2/5} \quad (10)$$

where

D = Effective fire diameter (m)
= $(4\, A_f/\pi)^{1/2}$ for noncircular sources
$\dot{Q}$ = Total heat release rate (kW)
$\dot{Q}_c$ = Convective heat release rate (kW)

For fires along walls and in corners, the method of reflection is used to estimate the effect on entrainment[7]. This method suggests that a fire burning along a wall can be treated as a fire burning with twice the actual intensity that entrains air around only one-half its perimeter. A fire burning in a corner is treated as a fire with four times the intensity of the actual fire that entrains air around only one-quarter of its perimeter. Consequently Equations 8 through 10 can be rewritten to treat fires along walls and in corners as:

$$\dot{m}_i = k_e \frac{\left(k_{LF}\, \dot{Q}_c\right)}{k_{LF}} \frac{z}{z_L} \quad (11)$$

$$z_L = z_o + 0.166\left(k_{LF}\, \dot{Q}_c\right)^{2/5} \quad (12)$$

$$z_o = -1.02\, D\sqrt{k_{LF}} + 0.083\left(k_{LF}\, \dot{Q}\right)^{2/5} \quad (13)$$

k_{LF} is an appropriate location factor coefficient. Equation 11 is identical to Equation 8. Equation 12 and 13 can be used in place of Equations 9 and 10 by using $k_{LF} = 1$ for fires in the center of rooms, $k_{LF} = 2$ for fires located along walls, and $k_{LF} = 4$ for fires in corners.

Assuming that the convective heat release rate, $\dot{Q}_c$, is approximately 70 percent of the total heat release rate, $\dot{Q}$, the plume entrainment in the near fire region can be expressed as:

$$\dot{m}_i = \frac{k_f\, \dot{Q}_c\, z}{-1.02\, D\sqrt{k_{LF}} + 0.262\left(k_{LF}\, \dot{Q}_c\right)^{2/5}} \quad (14)$$

where $z = H_D + H_B - H_f$. H_D is the height of the thermal discontinuity above the bottom of the opening, H_f is the fire source height relative to the floor level and H_B is the distance from the floor to the bottom of the opening. Until the ventilation limit is reached, the difference between the thermal discontinuity height, H_D, and the layer interface height, H_L, is not generally significant. This distinction is neglected here, and it is assumed that $H_D \approx H_L$ before the ventilation limit is reached.

If the virtual origin offset is neglected, the expression for entrainment in the near field becomes:

$$\dot{m}_i = \frac{6.0\, k_e\, \dot{Q}^{3/5}\, z}{k_{LF}^{2/5}} \approx \frac{4.8\, k_e\, \dot{Q}_c^{3/5}\, z}{k_{LF}^{2/5}} \quad (15)$$

For regions far above the fire source ($z > z_L$), Heskestad[6] and other investigators[8,9] suggest the entrainment rate will follow the form suggested by classical plume theory[10]:

$$\dot{m}_i = k_e \dot{Q}^{1/3} z^{5/3} \quad (16)$$

Here k_e is an appropriate entrainment coefficient in the plume region, with units of kg/s–kW$^{1/3}$–m$^{5/3}$. The plume entrainment coefficient should not be confused with the flame region entrainment coefficient. In the plume region, the mass balance results in a nonlinear equation requiring iterative solution.

Line Fire Plumes

Grella and Faeth[11] developed an expression for plume entrainment for the situation of a line fire burning along an adiabatic wall. This relationship can be expressed in terms of the pyrolysis rate per unit length of burner as:

$$\dot{m}_p = E_o F_m^{2/3} \rho_o \left[\frac{g \dot{Q}'}{c_p T_o}\right]^{1/3} z \quad (17)$$

According to Grella and Faeth, appropriate values are E_o = 0.067 and F_m = 5.71. The total mass entrainment rate can be expressed as:

$$\dot{m}_i = k_e \dot{Q}^{1/3} L^{2/3} (H_L + H_b - H_f) \quad (18)$$

Here k_e is an appropriate entrainment coefficient for a line fire, with units of kg/s–kW$^{1/3}$–m$^{5/3}$. k_e = 0.083 for the coefficients suggested by Grella and Faeth, with the other parameters evaluated at an ambient temperature of 293 K. L is the length of the line burner.

The Mass Balance

The mass balance is evaluated by equating the appropriate plume equation (Equations 14, 15 or 18) with the linearized vent flow equation (Equation 6). This results in the following equation for the relative layer height:

$$\frac{H_L}{H_o} = \frac{0.97 A_o \sqrt{H_o} + \beta(H_f - H_b)}{1.08 A_o \sqrt{H_o} + \beta H_o} \quad (19)$$

For the case of the axisymmetric plume with the virtual origin offset considered:

$$\beta = \frac{k_e \dot{Q}_c}{-1.02 D \sqrt{k_{LF} + 0.262 \left(k_{LF} \dot{Q}_c\right)^{2/5}}} \quad (20)$$

For the case of the axisymmetric plume with the virtual origin offset neglected:

$$\beta = \frac{6.0\, k_e \dot{Q}^{3/5}}{k_{LF}^{2/5}} \approx \frac{4.8\, k_e \dot{Q}_c^{3/5}}{k_{LF}^{2/5}} \quad (21)$$

For the case of the line fire plume:

$$\beta = k_e \dot{Q}_c^{1/3} L^{2/3} \quad (22)$$

Once the layer height is calculated from Equation 19 using the appropriate value for β, the quasi-steady mass flow rate for naturally ventilated enclosure fires can be expressed as:

$$\dot{m} = A_o \sqrt{H_o} \times MIN\left[0.5, 0.97 - 1.08 \frac{H_L}{H_o}\right] \quad (23)$$

The *MIN* function in Equation 23 prevents the calculated mass flow rate from exceeding the ventilation limit. If Equation 23 evaluates to a negative number, it implies that $H_L/H_o > 0.9$. This situation cannot arise for the present analysis because H_L/H_o is evaluated by equating the mass influx and the mass efflux terms. Consequently, H_L/H_o will always have a calculated value of less than 0.9 with this method.

Comparisons With Experimental Data

Mass flow rates calculated by the methods presented above are compared with mass flow rates measured in a series of steady-state experiments conducted by Steckler, *et al.*[3]. These experiments were designed to determine the effects of room-opening geometry, fire strength and fire location on the flows through openings and on the opening coefficients.

These experiments were conducted in a 2.8 m x 2.8 m x 2.18 m high compartment with a single rectangular ventilation opening in one of the walls. The walls and ceiling were covered with a ceramic fiber insulation board to permit the room to reach quasi-steady conditions within approximately one-half hour.

The size of the ventilation opening was varied between experiments to represent different door and window configurations. Door opening heights were maintained at 1.83 m while six different widths were used, ranging from 0.24 m to

0.99 m wide. Three different window sizes were used. All window openings were maintained with a width of 0.74 m and with the top of the opening 1.83 m above the floor. The three opening heights included 0.46 m, 0.92 m and 1.38 m.

A 0.3 m diameter diffusion gas burner served as the primary fire source for these experiments. The circular burner was centered in a square lip 0.42 m on a side. For most experiments, the face of the burner was located 0.02 m above the floor; for some experiments the face of the burner was located 0.3 m above the floor. The burner was positioned in three primary locations: at the center of the room, in the back left corner and along the center of the rear wall relative to the wall with the opening. Other locations were also examined.

Commercial grade methane was supplied to the burner to yield fire strengths between 31.6 and 158 kW. The fire strength was constant for each experiment. A line burner was used for eight of the experiments reported by Steckler, *et al.* The line burner was located along the base of the rear wall. The length of the line burner was either 0.46 m or 1.83 m. The fire strength was 30 kW when the 0.46 m burner was used and 120 kW for the 1.83 m burner.

These experiments represent one of the few series where careful vent flow measurements were made. For this reason, they are valuable for comparison with models of mass flow in naturally ventilated enclosure fires. But their value for the present comparisons is diminished by the relatively low intensity fires used in the experiments. These low intensity fires resulted in flame lengths that did not generally penetrate the hot gas layer and in hot gas layer temperatures that were generally less than the 200°C threshold suggested for use of Equation 2. Despite these shortcomings, these experiments are useful for evaluation of the mass balance estimate developed here.

Comparisons of the calculated and measured mass flow rates for the experiments of Steckler, *et al.*, are shown in Figures 3a to 3e.

Figure 3a shows the comparison for the fire located at the floor in the center of the room.

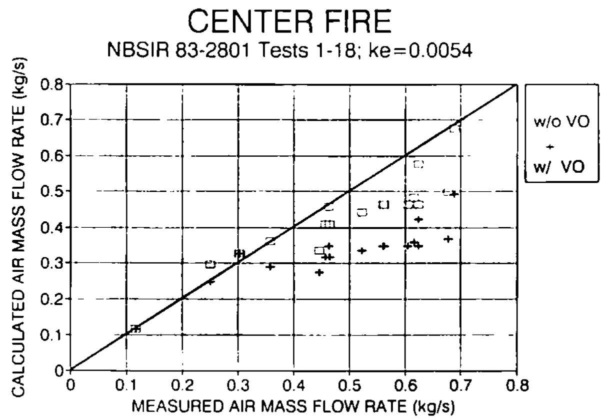

Figure 3a. Calculated and measured air mass flow rates for center fires. k_e = 0.0054. (w/VO means with virtual origin; w/o VO means without virtual origin).

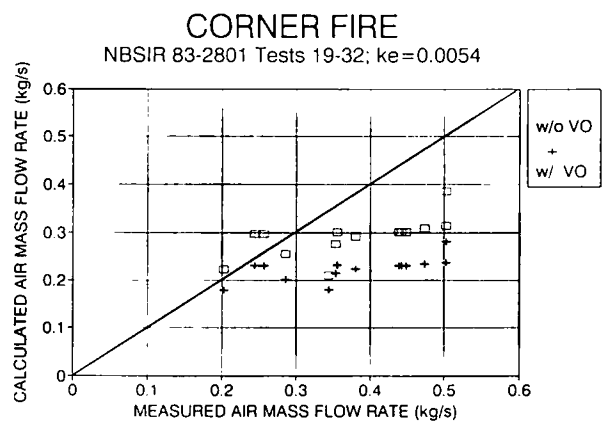

Figure 3b. Calculated and measured air mass flow rates for corner fires. k_e = 0.0054. (w/VO means with virtual origin; w/o VO means without virtual origin).

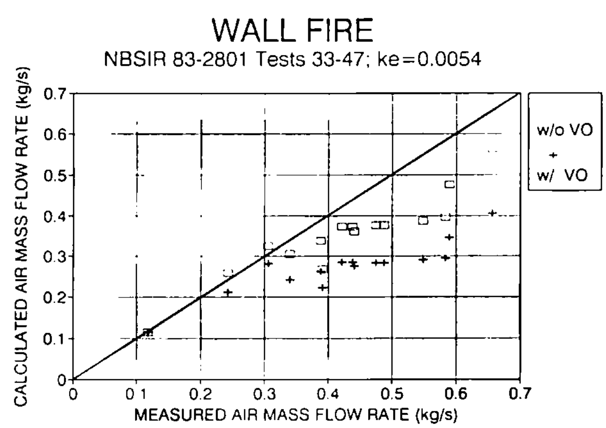

Figure 3c. Calculated and measured air mass flow rates for wall fires. k_e = 0.0054. (w/VO means with virtual origin; w/o VO means without virtual origin).

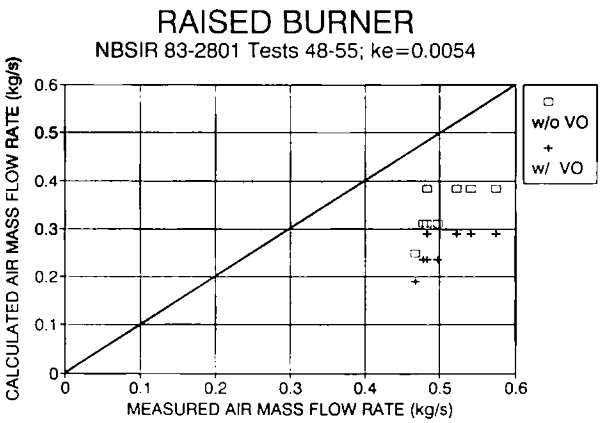

Figure 3d. Calculated and measured air mass flow rates for raised fires. k_e = 0.0054. (w/VO means with virtual origin; w/o VO means without virtual origin).

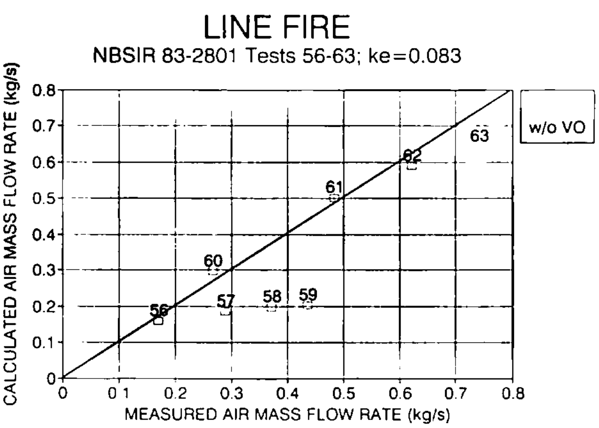

Figure 3e. Calculated and measured air mass flow rates for line fires. k_e = 0.083. (w/o VO means without virtual origin).

Figure 3b shows results for the corner fire experiments and Figure 3c for the wall fire experiments. Figure 3d shows results for the raised burner experiments and Figure 3e for the line fire experiments. For Figures 3a to 3d, the axisymmetric plume correlation of Heskestad is used, with an entrainment coefficient of k_e = 0.0054. For Figure 3e, the line plume correlation of Grella and Faeth is used, with an entrainment coefficient of k_e = 0.083. Units for the entrainment coefficients are described previously.

The mass flow rates calculated for the fire experiments with an axisymmetric source generally underpredict the measured mass flow rates in those experiments, as illustrated in Figures 3a to 3d. A plausible reason for this underprediction has been discussed by Quintiere, *et al*,[12], in terms of the fire plume tilt caused by the directed air inflow through the wall opening. This tilt effectively acts to increase the entrainment length, resulting in greater entrainment than for an undisturbed axisymmetric plume. To compensate for the plume tilt effect, the calculations were performed a second time, using an entrainment coefficient of k_e = 0.0081, a value 50 percent higher than the value suggested by Heskestad. Results using this entrainment coefficient are illustrated in Figures 4a to 4d, for the center, corner, wall and raised fire locations, respectively. Use of this higher entrainment coefficient produces calculated mass flow rates much more consistent with the measured mass flow rates.

Flame tilt caused by blowing in a door jet offers a plausible explanation for increased entrainment for cases where the burner is located in the center of the room, particularly near the doorway. It would not appear to be a good reason for wall and corner fires, where the walls prevent the flame from being blown over. However, for the experiments conducted by Steckler, the burner had a lip on it, which caused the base of the flame to be offset a small distance from the walls. This would permit some blowing of the flame to occur. As noted by Williamson, *et al*.[13], small separation distances from a corner result in large differences in entrainment.

The results of the line burner experiments, illustrated in Figure 3e, show two trends. These trends are consistent with the experimental conditions. Experiments 56 through 59 were conducted with a heat release rate of approximately 30 kW and a burner length of 0.46 m. Experiments 60 through 63 were conducted with a heat release rate of approximately 120 kW and a burner length of 1.83 m.

The calculated mass flow rates for Experiments 56 through 59 do not track the measured flow rates very well for these low intensity fires. Experiment 56 shows reasonable agreement between calculated and measured flow rates,

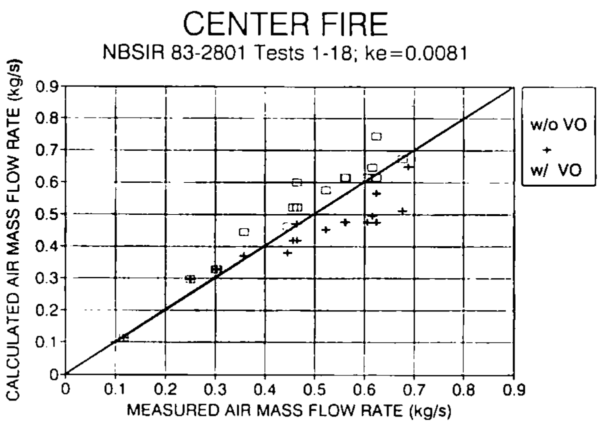

Figure 4a. Calculated and measured air mass flow rates for center fires. k_e = 0.0081. (w/VO means with virtual origin; w/o VO means without virtual origin).

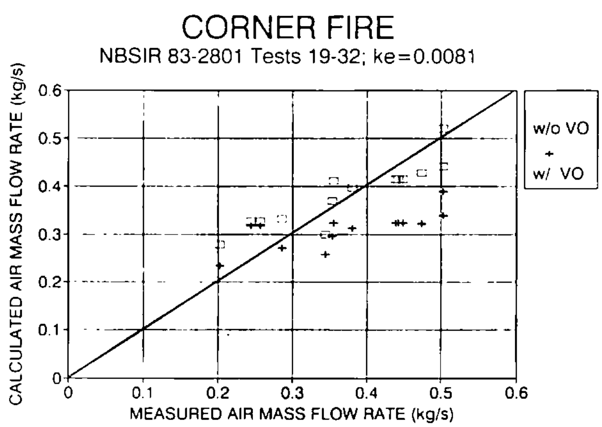

Figure 4b. Calculated and measured air mass flow rates for corner fires. k_e = 0.0081. (w/VO means with virtual origin; w/o VO means without virtual origin).

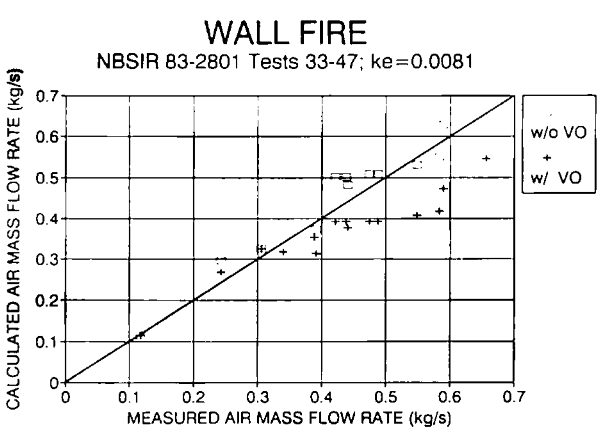

Figure 4c. Calculated and measured air mass flow rates for wall fires. k_e = 0.0081. (w/VO means with virtual origin; w/o VO means without virtual origin).

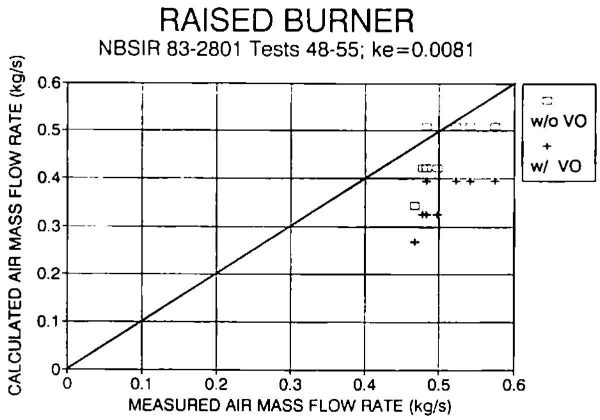

Figure 4d. Calculated and measured air mass flow rates for raised fires. k_c = 0.0081. (w/VO means with virtual origin; w/o VO means without virtual origin).

but this is most likely due to the approach of ventilation limited flow conditions for this case. It is suspected that the relatively short length of the burner may have an effect, because greater entrainment can be expected near the ends of the burner, where the flow field is two-dimensional, than in the middle of the burner, where the flow is more likely to be one-dimensional. Another factor, the gas temperature, also is likely to have a significant effect for these low intensity fires. This effect is discussed below.

The calculated and measured mass flow rates become much closer to each other for Experiments 60 to 63. This is most likely due to the higher gas temperatures achieved in these experiments and to the longer length of the burner, which would minimize end effects.

Gas temperature plays a role in the accuracy of these calculations. Equation 2 is based on the assumption that the hot gas layer temperature will be near or above 200°C. Many of the experiments compared here had average upper gas layer temperatures closer to 150°C than to 200°C. As illustrated in Figures 5a and 5b, there seems to be a general trend between the temperature ratio (gas temperature/ambient temperature) and the mass flow ratio (calculated flow rate/measured flow rate), with the mass flow ratio approaching unity as the temperature ratio increases.

Two final observations are in order. First, it is worth noting that calculations using virtual origin corrections tended to produce less accurate calculated mass flows than did calculations without virtual origin offsets. The significance of this has not been established, but at least for the mass flow estimates developed here for these experiments, use of a virtual origin correction seems inadvisable.

The second observation relates to entrainment models. The Heskestad entrainment model[6] was used for these comparisons. Heskestad developed this model based on relatively large-scale fire experiments, which is one reason the author prefers the Heskestad model to other entrainment models. But the Heskestad model is just one of a large number of entrainment models

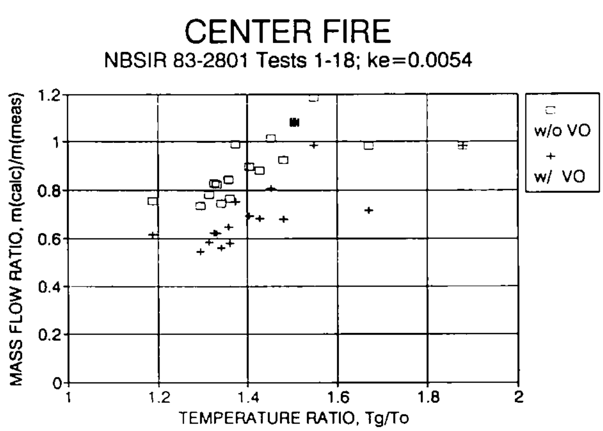

Figure 5a. Mass flow ratio as a function of the temperature ratio for center fires. k_e = 0.0054. (w/VO means with virtual origin; w/o VO means without virtual origin).

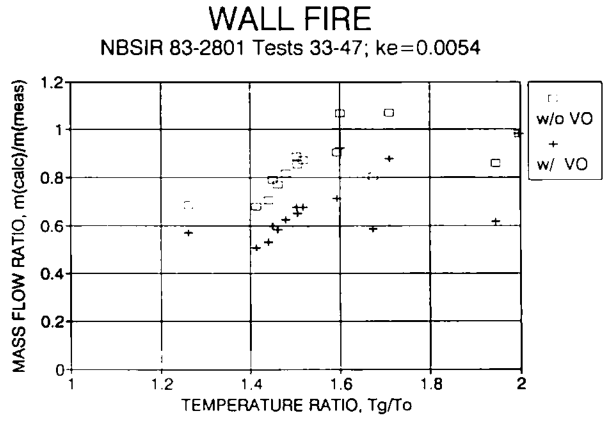

Figure 5b. Mass flow ratio as a function of the temperature ratio for wall fires. k_e = 0.0054. (w/VO means with virtual origin; w/o VO means without virtual origin).

developed for axisymmetric plumes by various investigators (see, for example, Ref. 6, 9 and 10). The number of entrainment models is a reflection of the considerable uncertainty that exists with respect to entrainment in fire plumes, particularly for fires involving realistic fuel configurations. Further research, using realistic fuel configurations, is needed to reduce this uncertainty.

Summary

The linearized mass balance estimate developed here applies strictly to scenarios where Equation 13 applies. This occurs when the layer height, calculated per Equation 15 or 16, descends to the elevation of the flame height, z_L, expressed by Equation 9. If the layer height is above this flame height, then the appropriate plume entrainment equation to use would be Equation 14, which is nonlinear. Consequently, the mass balance cannot be solved explicitly when Equation 14 applies.

There are reasons to expect that this mass balance estimate will improve for fires larger than those used for the experimental comparisons. As the flame extends into the hot gas layer, the assumptions regarding this flame extension and the 200°C temperature criteria for use of Equation 2 should be realized. For most naturally ventilated enclosure fire scenarios where a serious hazard exists, it is expected that the near region correlation expressed by Equation 13 will be more appropriate than the classical plume equation expressed by Equation 16 because the hot gas layer is likely to equilibrate near or below the flame region. Any errors caused by extension of Equation 13 to the far plume region should be conservative in view of the much more rapid entrainment rate, and consequent temperature decay, expressed by Equation 14. The imposition of the ventilation limit expressed in Equations 3 and 17 will also tend to minimize errors, since the ventilation limit will be reached sooner for higher entrainment rates.

Nonetheless, users of this methodology should compare the effective flame height, z_L, and the layer interface height H_L–H_f. The flame height should extend into the hot gas layer for the linear entrainment rate correlation expressed by Equation 8 to apply. Beyond this range, the iterative solution of the mass balance equations is necessary, unless it can be established that ventilation limited flow will occur.

The approximate nature of this solution should be recognized, particularly in view of the linearized equations used. At the same time, the approximate nature of the vent flow equation (Equation 1) should be recognized in view of the assumption of a uniform gas temperature. Similarly, the engineering relations used for fire plume entrainment calculations must be considered as approximate, being subject to variations due to fuel configuration, heat release rate, air currents induced by vent flows and other factors. Consequently, the linearized solution developed here for mass flow calculations in naturally ventilated enclosure fires can be expected to have an accuracy approaching the accuracy of an "exact" solution, but with the advantage of being closed-form and consequently amenable to hand calculation.

NOMENCLATURE

A_o = Opening area (m^2)
C_d = Orifice flow coefficient
D = Effective fire diameter (m)
H_B = Height from floor to bottom of opening (m)
H_D = Height of thermal discontinuity above bottom of opening (m)
H_f = Height of fire above floor (m)
H_L = Height of layer above bottom of opening (m)
H_o = Opening height (m)
k_e = Entrainment coefficients (Units vary depending on fire type and region)
k_{LF} = Location factor
[illegible] = Line burner length (m)
$\dot{Q}$ = Mass flow rate (kg/s)
= Heat release rate (kW)
W_o = Opening width (m)
z = Elevation coordinate (m)
ρ = gas density (kg/m^3)

Subscripts

c convective
e efflux
f fire
i influx
L layer, flame height
max maximum
o ambient, opening, virtual origin

Superscripts

per lineal length

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