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Predicting Smoke Concentration in the Ceiling Jet

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Introduction

Predicting smoke detector response to a growing fire requires calculating the time dependent evolution of the smoke concentration in the ceiling jet. Typically, the temperature rather than the smoke concentration has been used to predict smoke detector response due to the availability of correlations which give ceiling jet temperature[1] and the assumption that the smoke concentration can be related to ceiling jet temperature[2,3]. Using temperature to predict smoke detector activation ignores differences in the production of smoke by burning materials that may completely invalidate a temperature/smoke prediction correlation.

There have been efforts to use computational fluid dynamic (CFD) methods to calculate the smoke concentration in the ceiling jet and with the increased computer power available today, these methods are becoming practical[4,5]. However, there is still a need for an algebraic correlation that would yield smoke concentration in the ceiling jet and not need substantial computer power to obtain the solution. Early work along this line can be found in Alpert's paper on the ceiling jet which resulted in the successful unconfined ceiling jet temperature and velocity correlations[6] in use today. Later, Yamauchi[7] extended Alpert's work to calculate the smoke concentration and smoke detector activation in the ceiling jet when a hot layer was developing. Yamauchi's method required the solution of a set of differential equations in order to define the ceiling jet properties as well as a zone model to define the depth and temperature of the hot layer.

In this paper, an algebraic correlation for smoke concentration in the ceiling jet will be developed. The analysis will be restricted to fires that produce turbulent plumes and can be represented by axisymmetric point sources. Once the smoke concentration is predicted, the activation times for smoke detectors can be calculated using a model for smoke detector activation.

Theory

The development of a ceiling jet algorithm requires the solution of three separate problems. The first problem is to model the smoke plume as it rises from the fire to the ceiling. At the ceiling, the smoke flow turns and forms a ceiling jet that slows and deepens as it flows along the ceiling. The turning region and the ceiling jet flow present the other problems that must be solved.

The Plume Region

In order to develop an algebraic correlation for the smoke concentration in the plume, the following assumptions must be made in order to simplify the equations. The fire will be represented by a point source and is assumed to be axisymmetric. The zone model approximation of homogeneous temperature and particle densities in each layer is assumed. The velocity, temperature, and smoke profiles in the plume will be represented by Gaussian shapes in the radial direction. All air entrained into the plume will be considered to be smoke free.

The mass flux of smoke in a radially symmetric plume can be written as

$$\dot{m}_s(z) = \int_0^{\infty} C_{sp}(r,z)u_z(r,z)2\pi r dr \qquad 1$$

where $C_{sp}(r,z)$ is the mass concentration of smoke particles in the plume and $u_z(r,z)$ is the plume velocity, r is the radial distance from the plume centerline and z is the height above the fire source. The assumed Gaussian profiles for the smoke mass concentration in the plume and the plume velocity are,

$$C_{sp}(r,z) = C_{sp0}(z)e^{-(r^2/\lambda^2\sigma^2)} \qquad 2$$

$$u_z(r,z) = u_{zm}(z)e^{(-r^2/\sigma^2)} \qquad 3$$

where C_{sp0} is the smoke mass concentration for the plume centerline, u_{zm} is the plume centerline velocity, $\lambda\sigma$ is the 1/e width of the plume smoke profile and σ is the 1/e width of the velocity profile. It has been assumed that the smoke profile in the plume is equivalent to the temperature profile in the plume. Integrating Eq.(1) and solving for the maximum smoke mass concentration at the plume centerline gives

$$C_{sp0}(z) = \frac{\dot{m}_s(z)\left(\frac{\lambda^2+1}{\lambda^2}\right)}{u_{zm}(z)\pi\sigma^2} \qquad 4$$

Using the plume correlations developed by Heskestad[8] for b and u_{zm} where b is the plume radius where the temperature has dropped to 0.5 the plume centerline temperature, T(z), z_0 is the location of the virtual point source with respect to the fire surface, and $\sigma = 1.201b$ is the plume radius for the temperature to drop to 1/e of its centerline value assuming a Gaussian distribution,

$$b(z) = 0.12\left(\frac{T(z)}{T_\infty}\right)^{1/2}(z - z_0) \qquad \textbf{5}$$

$$u_{zm}(z) = \frac{1.03(1-\chi_r)^{1/3}\dot{Q}^{1/3}}{(z-z_0)^{1/3}} \qquad \textbf{6}$$

the plume centerline smoke mass concentration becomes

$$C_{sp0}(z) = \frac{27.8\dot{m}_s}{(1-\chi_r)^{1/3}\dot{Q}^{1/3}\frac{T(z)}{T_\infty}(z-z_0)^{5/3}} \qquad \textbf{7}$$

where the distance $z\text{-}z_0$ is the distance above the virtual point source. The temperature ratio, $T(z)/T_\infty$, can be evaluated using Heskestad's correlations for plume centerline temperature, T(z), and location of the virtual point source.

$$\frac{T(z)}{T_\infty} = 1 + \frac{25}{293}\frac{(1-\chi_r)^{2/3}\dot{Q}^{2/3}}{(z-z_0)^{5/3}} \qquad \textbf{8}$$

$$z_0 = -1.02D + 0.083\dot{Q}^{2/5} \qquad \textbf{9}$$

where D is the fire diameter.

The mass flux of smoke produced by the fire may be calculated using the data provided by Tewarson[9]

$$\dot{m}_s = Y_s\frac{\dot{Q}}{h_c} \qquad \textbf{10}$$

where h_c is the heat of combustion and Y_s^* is the smoke yield fraction. With this substitution, the plume centerline smoke concentration is given by

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* Smoke yield fraction (in grams of smoke produced per gram of fuel burned) is tabulated in many literature sources. Smoke yield fraction can also be obtained by dividing specific extinction area (from the cone calorimeter ASTM 1354) by 8.71×10^3 m^2/kg.

$$C_{sp0}(z) = \frac{27.8 \frac{Y_s}{h_c} \dot{Q}}{(1-\chi_r)^{1/3} \dot{Q}^{1/3} \frac{T(z)}{T_\infty} (z - z_0)^{5/3}} \qquad \textbf{11}$$

The Ceiling Jet Region

The next step is to obtain the smoke concentration in the ceiling jet using the calculated smoke concentration in the plume. Following Alpert's derivation[6] and equating the mass flux in the plume to mass flux at the start of the ceiling jet, Yamauchi[7] developed an equation which related the maximum smoke concentration in the plume at the ceiling, C_{sp0} to the average smoke concentration at the start of the ceiling jet, $C_{s,ave}$ in terms of the Gaussian width ratio λ for the velocity and temperature profiles in the plume.

$$C_{s,ave} = \frac{\lambda^2}{\lambda^2 + 1} C_{sp0} \qquad \textbf{12}$$

Assuming that the smoke concentration in the unconfined ceiling jet can be represented by a half Guassian profile, the maximum smoke concentration in the ceiling jet, C_s is given by

$$C_s(r = 0.18H) = \sqrt{2} C_{sp0}(H) \frac{\lambda^2}{1 + \lambda^2} \qquad \textbf{13}$$

where $\lambda^2 = 1.157$, r is the radial distance from the plume centerline and H is the distance from the surface of the fire to the ceiling .

The smoke concentration in the ceiling jet may be calculated from the smoke mass flux equation by integrating over the vertical dimension, y.

$$\frac{1}{r} \frac{d}{dr} \int_0^\infty \left[C_s(r,y) v(r,y) r dy \right] = 0 \qquad \textbf{14}$$

It has been assumed that there is no entrainment of smoke into the ceiling jet. The resulting spatial averages yield the average smoke concentration in the ceiling jet as a function of r as

$$C_s(r) = C_s(r_c) \frac{r_c v_c h_c}{r v h} \qquad \textbf{15}$$

where the subscript e represents the location where the ceiling jet forms(r_e=0.18H), h is the average thickness of the ceiling jet, v is the average ceiling jet velocity and r is the radial distance from plume center. Using Alpert's correlation for the maximum ceiling jet velocity

$$v = \frac{0.195Q^{1/3}H^{1/2}}{r^{5/6}} \quad 16$$

and fitting Alpert's calculation[6] for ceiling jet thickness to a power law ($h/H=(r/H)^{04}$, 0.18H<r<2.0H), the maximum smoke concentration in the ceiling jet is given by

$$C_{s0}(r) = C_{s0}(r_e)\left[\frac{r_e}{r}\right]^{.57} \quad 17$$

where the ceiling jet is assumed to be a half Gaussian. Replacing $C_{s0}(r_e)$ using Eqs. (8, 11, and 13), the maximum smoke concentration at a radial location from plume center in the ceiling jet for r > 0.18 H is given by

$$C_{s0}(r) = \frac{7.94Y_s\dot{Q}^{2/3}\left(\frac{H}{r}\right)^{0.57}}{h_c(1-\chi_r)^{1/3}\left(1+\frac{0.0853(1-\chi_r)^{2/3}Q^{2/3}}{(H-z_0)^{5/3}}\right)(H-z_0)^{5/3}} \quad 18$$

Comparison with Experiments

The experiments conducted by Marrion[10] provide a set of smoke mass concentration measurements at three radial positions in a large room (11.6 m x 6.7 m x 3.05 m) where a smoke layer may form only after the fire source has reached a quasisteady state burning rate. The fire source was a pan of gasoline with a diameter of approximately 0.15 m and a heat release rate of 23 kW was achieved based on a measured mass loss rate with a heat of combustion of 43.7 MJ. The fire source was located 2.13 m below the ceiling. A photometer consisting of a light source and photoelectric cell in accordance with UL 268 was used to measure the smoke obscuration at radial positions in the ceiling jet of 2.13 m, 3.05 m, and 5.18 m. Smoke obscuration is linearly related to smoke mass concentration by Mulholland's correlation[11].

Using the measurements for the 23 kW fire at 30 s, 90 s, and 100 s after ignition, the radial dependence of the measured smoke concentration scales as the inverse radius to the 0.51 to 0.59 power (see Fig. 1) which is in approximate agreement with the exponent of 0.57 in Eq. (18). The smoke concentration in the ceiling jet continues to increase over this interval indicating that either the fire source is not steady or a smoke layer is beginning to develop in the room.

A second gasoline fire with a heat release rate of 33 kW was also used to investigate smoke concentrations at the ceiling although the only complete measurement set was done at the 5.18 m radial position. The smoke concentration should scale as the HRR to the 2/3 power. The ratio of the measured smoke concentration produced by the 33 kW fire divided by the 23 kW fire at 5.18 m is 1.4 and the ratio of the HRR to the 2/3 power is 1.3 which is in good agreement with the measurement.

Returning to the 23 kW fire test, using the values for gasoline, $Y_s = 0.061$, $\chi_r = 0.40$, and $h_c =$ 43 MW/g in Eq. (18) yields a value for the maximum smoke concentration in the ceiling jet at r = 2.13 m of 2.96 x 10^{-2} g/m^3. The optical density at this point is related to the average smoke concentration by

$$K = K_m C_s(r) \qquad \textbf{19}$$

where K_m has a value of 8.71 m^2/g[11]. The resulting value for K is 0.26 m^{-1} while the measured value at 64 s is 0.17 m^{-1}. The smoke obscuration for this experiment increased almost linearly between 34 s and 94 s with the optical density changing from 0.091 m^{-1} to 0.25 m^{-1}, hence the 64 s value represents an average smoke obscuration over the measurement period. The linear increase in the optical density may have been a combination of a developing smoke layer and a nonsteady fire source.

A second experiment was used by Yamauchi to compare with his model. This experiment used a heptane fire in a room 10 m x 6 m with a ceiling height of either 3 m or 4 m. The measurements of smoke obscuration were made 0.05 m beneath the ceiling at a distance of 3 m from the fire center. Using the values for heptane of $Y_s = 0.037$, $h_c = 41.2$ MJ/kg, $\chi_r = 0.33$, and a fire size of 85 kW, the calculated optical density for a ceiling height of 3.0 m is 0.19 m^{-1} while the measured optical density is approximately 0.19 m^{-1} at 60 s where steady state burning first occurs. At a ceiling height of 4 m at 60 s, the measured optical density is 0.14 m^{-1} while the calculated optical density is 0.15 m^{-1}. The smoke concentration in the experiment continues to rise as the upper layer develops and smoke is entrained into the plume and the ceiling jet from the upper layer. Since the only ventilation in the room is at the floor, a smoke layer may have begun to develop by 60 s when the comparisons are made.

Uncertainties were not given in the above comparisons as the experimental uncertainties were not available.

Sensitivity of the Correlation

The sensitivity of the correlation can be put in terms of condition numbers[12]. The first order Taylor series for a function with multiple inputs is

$$f(x_1 + h_1, \ldots, x_n + h_n) \approx f(x_1, \ldots, x_n) + \sum_n h_i \frac{\partial f(x_1, \ldots, x_n)}{\partial x_i} \qquad 20$$

The Taylor series can be non-dimensionalized to be

$$\frac{f(x_1 + h_1, \ldots, x_n + h_n)}{f(x_1, \ldots, x_n)} \approx 1 + \sum_n \left[\frac{h_i}{x_i}\right]\left[\frac{x_i \frac{\partial f(x_1, \ldots, x_n)}{\partial x_i}}{f(x_1, \ldots, x_n)}\right] \qquad 21$$

as long as the function is non-zero at the point of interest. The condition number for input x_i is

$$cx_i = \frac{x_i \frac{\partial f(x_1, \ldots, x_n)}{\partial x_i}}{f(x_1, \ldots, x_n)} \qquad 22$$

When $|cx_i| < 1$ the model answer will change by a smaller precentage than the input changes. For example if $cx_i = .5$ for some model then a 10 % change in x_i will lead to approximately a 5 % change in the model answer. The input x_i is said to be insensitive if $|cx_i| < 1$. If $|cx_i| > 1$ the model's answer will change by a larger percentage than the change in the input. If $cx_1 = 1.5$ a 10 % change in x_1 leads to approximately a 15 % change in the output of the model. For $|cx_i| > 1$ the input x_i will be defined as sensitive. If $|cx_i| >> 1$ for any x_i then the problem is said to be ill defined. For example if $cx_i = 20$ then for a difference of 5 % in x_i the model results change by approximately 100 %.

The sensitivity of the model to the inputs of the experiments cited previously is presented in the table shown below. Each row represents one experiment and presents the calculated smoke concentration, the optical density and seven condition numbers representing the seven variables in the correlation. Marrion is the test referred to earlier by Marrion. Yam3 and Yam4 are the 3 m and 4 m ceiling experiments by Yamauchi.

Experiment	Smoke Con. (g/m^3)	Optical Density (m^{-1})	cY_s	ch_c	cH	cr	$c\chi_r$	cQ	cD
Marrion	0.029	0.26	1.0	-1.0	-0.97	-0.57	0.28	0.66	-0.11
Yam3	0.021	0.19	1.0	-1.0	-0.84	-0.57	0.22	0.64	-0.19
Yam4	0.017	0.15	1.0	-1.0	-0.94	-0.57	0.20	0.66	-0.15

The model is well conditioned since all the condition numbers are one or less. The three most sensitive inputs are the mass fraction of smoke, Y_s, the heat of combustion, hc, and the height of the ceiling above the fire surface, H. Of moderate sensitivity are the heat release rate, Q, and the radial distance, r. The least sensitive but not insignificant inputs are the radiative fraction, χ_r, and the diameter of the fire, D.

In comparing the algorithm with experiments, the mass fraction of smoke, Y_s, and the HRR, Q, will introduce the largest uncertainties into the calculation. The geometrical terms should be known to a high degree of accuracy and the heat of combustion is well known for many materials. While the mass fraction of smoke is given for many materials, the question of whether the fire is strictly flaming or is a combination of flaming and smoldering will introduce uncertainty into Y_s.

Discussion

The equation to predict smoke concentration in the ceiling jet is quite similar to Alpert's correlation for excess temperature in the ceiling jet in that the total heat release rate appears as the 2/3 power, the height of the ceiling above the source scales as the 5/3 power and the 1/r radial dependence for the smoke concentration, 0.57, is extremely close to Alpert's value of 0.67. These similarities explain why temperature correlations can be used to estimate smoke detector activation. The key to using a smoke/temperature correlation depends on the ratio of the smoke yield to the heat of combustion, Y_s/h_c. When the fire in question involves materials that have a similar ratio to the materials used to develop a smoke/temperature correlation, the smoke/temperature correlation should provide reasonable results as long as coagulation effects and smoke deposition to surfaces are insignificant and the primary cooling effects come from entrainment of ambient air. The user of a smoke/temperature correlation must ensure that the correlation was developed with materials that are similar in the ratio Y_s/h_c to the fire scenarios that the user is interested in modeling.

The present smoke concentration algorithm is only valid for unconfined ceilings where a smoke layer has not developed and only provides maximum smoke concentration calculations for the ceiling jet and plume centerline. Additional experiments would be desirable in order to determine the algorithm's accuracy for other fuels and geometries.

When using the correlation for smoke mass concentration, it should be remembered that the radiative fraction and the smoke yield fraction will both be dependent on fire size with the smoke yield fraction also being dependent on the fuel and whether the fire is ventilation limited. For the small fire sizes typically required to activate smoke detectors, these considerations may be of only limited importance.

Symbols

b	1/e width of plume [m]
C_{sp}	particulate /smoke mass concentration in the plume [kg/m^3]
C_s	particulate /smoke mass concentration in the plume [kg/m^3]
cx	condition number [dimensionless]
h	vertical scale length of the ceiling jet [m]
h_c	heat of combustion of fuel [kJ/kg]
H	height of ceiling above the surface of the fire [m]
K	optical density
m_s	mass of smoke [kg]
$\underline{m}_s$	rate of production of particulate/smoke mass by the fire [kg/s]
Q	heat release rate [kW]
r	radial distance from plume centerline [m]
T	plume centerline temperature [K]
T_∞	ambient gas temperature [K]
u	gas velocity in plume [m/s]
u_{zm}	plume centerline velocity [m/s]
v	ceiling jet velocity [m/s]
v_c	ceiling jet velocity where ceiling jet forms [m/s]
Y_s	mass fraction of smoke produced by the fire
z	height above fire [m]
z_0	location of virtual point source with respect to the fire [m]
λ	Gaussian width ratio
ρ	density [kg/m^3]
χ_r	radiative fraction

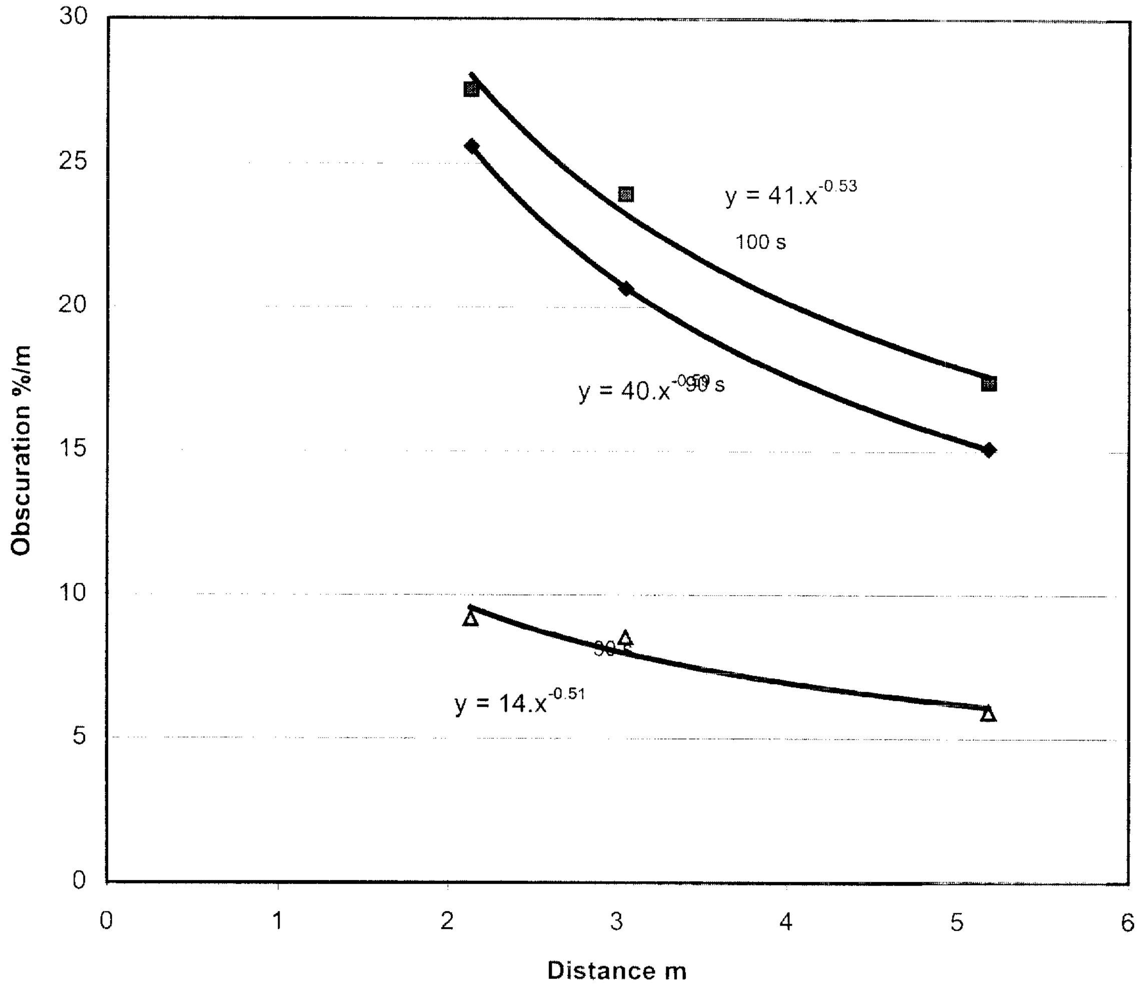

Figure 1 Plot of the measured smoke obscuration as a function of distance at 30 s, 90 s, and 100 s after the start of a 23 kW gasoline fire.

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