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A Monte Carlo Approach for the Layout Design of Thermal Fire Detection System

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Abstract. A Monte Carlo approach is developed for the layout design of thermal fire detection system. In contrast to the traditional deterministic approach, the present approach yields not only a specific design for a given objective, but also a probabilistic assessment of the effectiveness of the design which can be used as a basis of comparison for different possible designs. The approach also allows a systematic assessment of the uncertainty in the design process and provides a rational basis for possible design improvements.

Key words: Fire detection system, Monte Carlo method, uncertainty studies

1. Introduction

Fire detection system is required to be installed in a wide range of buildings. Basically, requirements of the systems are described clearly in the prescriptive codes [4]. For numerous reasons such as reducing the false alarm rate [11], thermal detectors are selected. For some projects with new architectural features [5] or special use of the buildings, prescriptive fire codes might not be applicable. Engineering performance-based fire codes (EPBFC) [3, 6, 7, 14] is therefore adopted. There had been numerous arguments in the layout of detector. Cost is not the only issue, architectural features and constants due to structural members in big projects such as large shopping malls are more important. In applying EPBFC for designing thermal detection system, thermal response of the detectors [8, 10] should be considered.

There are many studies on the response of heat detectors to fire-driven flows in the last years [1, 2, 9, 12, 15]. Based on correlations of experimental data and physical modeling, methodologies and concepts have been developed and accepted, in general, by the fire protection community as the basis for design and evaluation of thermal detection system. For a given design objective and detector's characteristics, a standard procedure is now available [13] for calculating the required spacing of ceiling-mounted thermal detectors, if prescriptive codes are not followed.

The proposed design procedure [13] for thermal fire detection system, however, is deterministic. Assessment of uncertainty is not yet provided. For example, there are uncertainties associated with the detector's characteristics. The fire growth rate assumed in the design fire is also uncertain, and this can have a significant impact on the design spacing. Subjective decisions in providing the appropriate conservatism in the design must be made by fire engineers themselves to minimize fire risk associated with such uncertainties.

The objective of the present work is to develop a probabilistic approach in the design of thermal fire detection system. The Monte Carlo sampling technique [17] would be used. This approach generates not only a specific design for a given design objective, but also a statistical assessment of the effectiveness of the design. The uncertainties associated with the fire growth rate and detector's characteristics can also be included in the design and the statistical assessment. This approach is flexible and can be adapted to include specific building characteristics in the development of the design.

Basic theoretical model used in the current deterministic design of thermal fire detection system model is described in Section 2. For the same design objective, results generated by the deterministic approach and the Monte Carlo approach, accounting only for the uncertainty in the fire location, are presented and compared in Section 3. The effect of uncertainties in fire growth rate and building geometry on the design result is assessed by the current Monte Carlo approach in Section 4. Finally, some conclusions on the current approach and some perspectives on its role in the development of engineering performance-based fire codes are presented in Section 5.

2. The Current Thermal Fire Detector Model

The current model is based on the work of Heskestad and Delichatisios [9] on a set of functional relations for the temperature and velocity of fire gases in a ceiling jet. Specifically, the heat release rate $\dot{Q}$ (in kW) of the fire is assumed to grow with time t(in s) according to a power-law relationship as follows:

$$\dot{Q} = \alpha t^{p} \tag{1}$$

where α is a constant for a particular fuel, and p is a positive exponent. To characterize the difference between fuels, a concept of "critical time", t_c (in s), is introduced to describe the fire intensity. t_c is defined as the time at which a power-law fire would reach a heat release rate of 1055 kW. In term of t_c, Equation (1) becomes

$$\dot{Q} = \left(1055/t_c^{p}\right)t^{p} \tag{1a}$$

For a flat ceiling of height H above the fire, the temperature rise ΔT (in °C) and velocity U (in s) of fire gases at a horizontal distance r (in m) away from the fire are given in dimensionless form as the reduced gas temperature ΔT_p^* and reduced gas velocity U_p^* respectively by

$$\Delta T^* = \Delta T/\left[A^{2/(3+p)}(T_a/g)\alpha^{2/(3+p)}H^{(p-5)/(3+p)}\right] = g(t_p^*, r/H) \tag{2}$$

$$u_p^* = u/\left[A^{1/(3+p)}\alpha^{1/(3+p)}H^{(p-1)/(3+p)}\right] = f(t_p^*, r/H) \tag{3}$$

where

$$\Delta T = T - T_a \tag{4}$$

and the reduced time t_p^* is:

$$t_p^* = t/\left[A^{-1/(3+p)}\alpha^{-1/(3+p)}H^{4/(3+p)}\right] \tag{5}$$

and

$$A = g/(C_p T_a \rho_0) \tag{6}$$

In the above equations, T_a is the initial ambient temperature of the room prior to the start of the fire, g is the gravitational constant, C_p and ρ_0 are the specific heat and density of air at the ambient condition respectively.

For t^2-fires whose release rate vary according to the power relation with $p = 2$, Heskestad and Delichatsios [9] developed the following specific relations for ΔT_2^*

$$\Delta T_2^* \begin{cases} 0 & t_2^* > (t_2^*)_f \\ \left[\dfrac{t_2^* - 0.954(1 + r/H)}{0.188 + 0.313r}\right]^{4/3} & t_2^* > (t_2^*)_f \end{cases} \tag{7}$$

where

$$(t_2^*)_f = 0.954(1 + r/H) \tag{8}$$

The dimensionless gas velocity for t^2-fires ($p = 2$) was determined to be

$$\frac{u_2^*}{(\Delta T_2^*)^{1/2}} = \begin{cases} 3.87/(9.115)^{1/2} & r/H \le 0.3 \\ 0.59(r/H)^{-0.63} & r/H > 0.3 \end{cases} \tag{9}$$

The expression for the velocity with r/H of 0.3 is based on work by Zukoski et al. [18].

The above expressions for ceiling gas temperature and velocity can be substituted into the heat transfer equation for the temperature of the thermal sensing element of the detector $T_d(t)$ at and integrated. Using the condition that the initial temperature of the thermal sensing element of this detector is equal to the ambient temperature ($T_d(0) = T_a$), the equations for calculating the response of fixed temperature and rate of temperature rise detectors are, from Beyler [2]

$$T_d(t) - T_d(0) = (\Delta T/\Delta T_2^*)\Delta T_2^* \left[1 - \frac{1 - e^{-Y}}{Y}\right] \tag{10}$$

$$\frac{dT_d(t)}{dt} = \frac{(4/3)(\Delta T/\Delta T_2^*)(\Delta T_2^*)^{1/4}}{(t/t_2^*)D}(1 - e^{-Y}) \tag{11}$$

where

$$Y = \frac{3}{4}\left(\frac{u}{u_2^*}\right)^{1/2}\left(\frac{u_2^*}{(\Delta T_2^*)^{1/2}}\right)^{1/2}\left(\frac{\Delta T_2^*}{RTI}\right)\left(\frac{t}{t_2^*}\right)D \tag{12}$$

and

$$D = 0.188 + 0.313r/H \tag{13}$$

In Equation (12), RTI is the response time index (in $m^{\frac{1}{2}} s^{-\frac{1}{2}}$) which is a measure of the thermal sensitivity of the detector or sprinkler. This is a property of the thermal sensing element itself without external influence such as affecting the convective heat transfer coefficient by the air speed. The RTI can be determined from using the plunge test with a wind tunnel [8, 10].

Equations (1) to (13) constitute a complete mathematical description of the transient response of a thermal detector to a t^2-fire. This is the basis for all current designs of thermal detection systems.

3. Layout Design of Thermal Detection Systems

Spacing of detectors required to respond to a specific fire scenario has to be considered in the layout design. The detector must respond when the fire reaches a certain threshold heat release rate or, if the fire growth rate is known, a specific amount of time.

The best possible location of a thermal detector is directly over the fire. If there are specific hazards to be protected, the design should include detectors directly overhead or inside of the hazard. In areas without specific hazards, the design approach generally accepted by the fire protection community is to space the detector evenly in a rectangular pattern across the ceiling. When the detectors are evenly spaced, the point that is the farthest from any detector will be in the middle of the four detectors as shown in Figure 1. For a given detector spacing S, and a given detector actuation temperature, T_{act}, and detector characteristics RTI, the detector response time and heat release rate can be determined from Equations (1) to (13) with a radial distance of

$$r = S/2^{1/2} \tag{14}$$

As an illustration of the design process, a fire detection system is now designed for an unsprinklered manufacturing building using fixed-temperature heat detectors. The parameters of the illustration is selected to correspond exactly to those of example 1 presented in reference [13] to allow for a direct comparison of the different design approaches. Specifically, the area being considered has a large flat ceiling 3 m high. Ambient temperature is assusmed

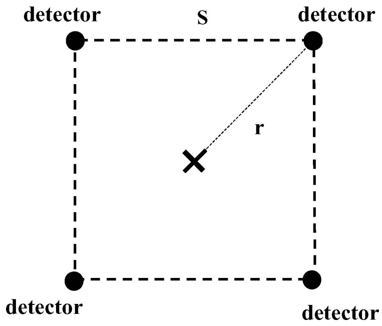

Figure 1. Positions of evenly spaced detectors and the location of the point (mark X) which is farthest from any of the detector.

to be 10°C. The fire scenario involves the ignition of a stack of wooden pallets. The pallets are stacked 1.5 m high. Fire tests show that this type of fire follows the $p = 2$ power-law equation with a t_c of approximately 150 s. The fixed-temperature heat detector available has a RTI of approximately 100 $\mathrm{m}^{1/2}\mathrm{s}^{1/2}$ and an actuation temperature of 57°C. The plant fire brigade feels that they can control and extinguish the fire if the fire can be detected when the fire reaches a heat release rate of approximately 1500 kW. The design goal is thus to determine the appropriate detector spacing such that at the time of the detector activation, the heat release rate of the fire is less than 1500 kW. For the fire with a t_c of 150 s, the goal for the detecting time is about 180 s.

3.1. The Determinstic Approach

The known parameters for the design problem are:

$$\begin{aligned} H &= 1.5\ \mathrm{m} \\ T_a &= 10^\circ\mathrm{C}(283\ \mathrm{K}) \\ \alpha &= 1055/150^2 = 0.047(\mathrm{kW/s^2}) \\ \mathrm{RTI} &= 100\ \mathrm{m}^{1/2}\mathrm{s}^{1/2} \end{aligned}$$

The detector needs to reach a temperature of 57°C in 180 s. Equations (1) to (13) can be solved iteratively to yield a detector spacing S of about 7 m ($r = 5$ m). The detail of the solution process is also given in reference [13].

3.2. The Monte Carlo Approach

There are clearly many uncertainties associated with the assumed fire scenario (location of the fire, the fire growth rate, height of the wooden pallets when the fire begin, etc.) which can change significantly the predicted detector spacing. The Monte Carlo approach [17] will be effective in illustrating the effect of these uncertainties.

Consider first the effect of the location of the fire. Since the fire can start at any location below the ceiling, the actual detection time can be significantly shorter than that predicted by the deterministic approach (which utilizes the longest possible distance between the fire and the detector). An architect, for example, might thus want to use a large detector spacing (>7 m) for the fire detection system for the same design objective based on consideration of economic and other factors. The Monte Carlo approach can be used to provide a rational evaluation for any proposed variation from a deterministic design.

Specifically, the fire will be assumed to occur anywhere under the ceiling with a uniform probability distribution. For a given detector spacing S, a large number of calculations (N) are carried out to yield a distribution for the heat release rate at the time of detection. The number of cases (N_f) in which the heat release rate exceeds the desgin objective can be computed. A failure probability can then be evaluated as

$$F = \frac{N_f}{N} \tag{15}$$

The failure probability for different detector spacing generated with $N = 50{,}000$ (larger number yield essentially the same result) is shown in Figure 2. As expected, the failure probability is zero up to a spacing of 7 m and the rises rapidly to 0.5 for $S = 12$ m. The

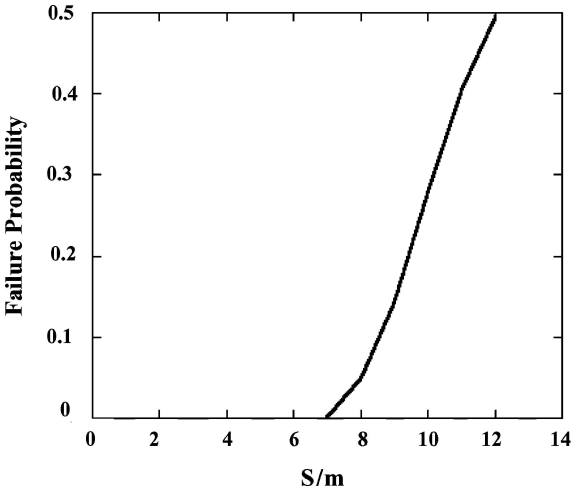

Figure 2. Failure probability for different detector spacing.

distribution of heat release rate at the time of detection, however, is anti-symmetric with a larger concentration in region with lower heat release rate. The distribution for cases with $S = 7$ m and $S = 10$ m are shown in Figure 3. The average heat release rate at the time of detection together with values bounded by one standard deviation are shown in Figure 4. These data are valuable for a risk based and/or cost-benefit based design for thermal fire detection system. For example, if a builder is willing to accept a design in which the design objective (1500 kW) is met by the average value plus one standard deviation of the heat release rate at the time of detection, a detector spacing of 8 m can be used for the design.

4. A General Monte-Carlo Based Design of Thermal Detection Systems

In addition to the uncertainty of the fire location, the Monte Carlo approach can be used to readily account for other uncertainty in the fire scenario. In this section, the uncertainty in the fire growth rate and the height of the wooden pallets when the fire begin will be considered and their effects on the design will be assessed.

In cases for which the exact fuel involved in a fire cannot be known, the designer must rely on available data on common materials. One example of such data is a set of values for α and t_c generated from a series of furniture calorimeter tests done at the National Bureau of Standard [16]. These data are now available from standard reference [8] and is presented as a discrete probability and probability density distribution in Figure 5. These data will be used to illustrate the effect of uncertainty in the heat release rate.

Since the stack of wooden pallets has an initial height of 1.5 m, the initial location of the fire can physically be of any values in the range of 0 to 1.5 m. To assess the effect of this uncertainty, the present work will assume a uniform probability for the value of H in the range from 1.5 to 3 m.

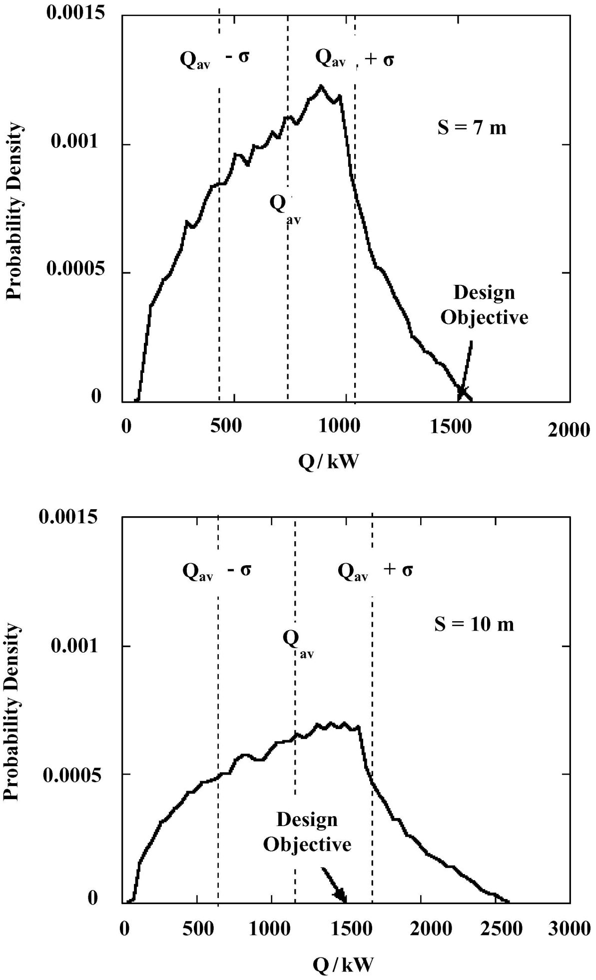

Figure 3. Probability distribution of heat release rate at time of detection for the case with $S = 7$ m and 10 m. The average value (Q_{av}) and standard deviation (σ) are also shown in the figure.

A Monte Carlo simulation with $N = 50{,}000$ is carried out to determine the heat release rate at the time of detection accounting for the above uncertainty. The failure probability for different detector spacing is presented in Figure 6. The failure probability calculated without accounting for the uncertainty is also shown in the same figure for comparison. Because of the increased probability of a fast fire growth rate (smaller t_c), the failure probability increases for a given detector spacing. A detector spacing of about 3 m is now required to meet the design objective of detecting all fires prior to a heat release rate of 1500 kW.

The distribution for the heat release rate at the time of detection for two detector spacings is shown in Figure 7. It is interesting to note that the qualitative behavior of the distribution is different from those of Figure 3. Uncertainties in the fire scenario affect not only the

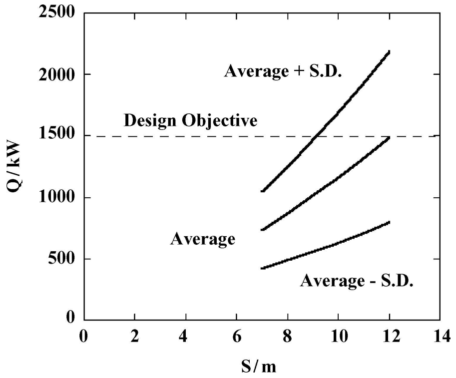

Figure 4. Average value plus and minus one standard deviation of the heat release rate at detection predicted by the Monte Carlo method.

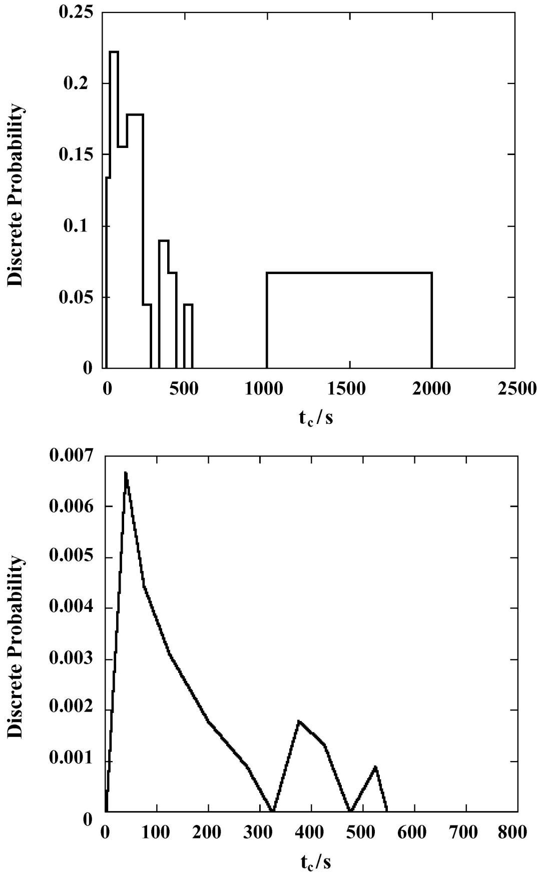

Figure 5. Discrete probability and probability density for the range of t_c generated by the furniture calorimeter tests of NBS.

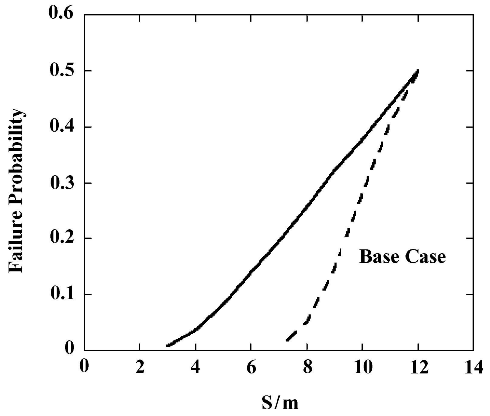

Figure 6. Failure probability for different detector spacing accounting for the uncertainty in t_c and H (the base case corresponds to results with constant t_c and H presented in Figure 2).

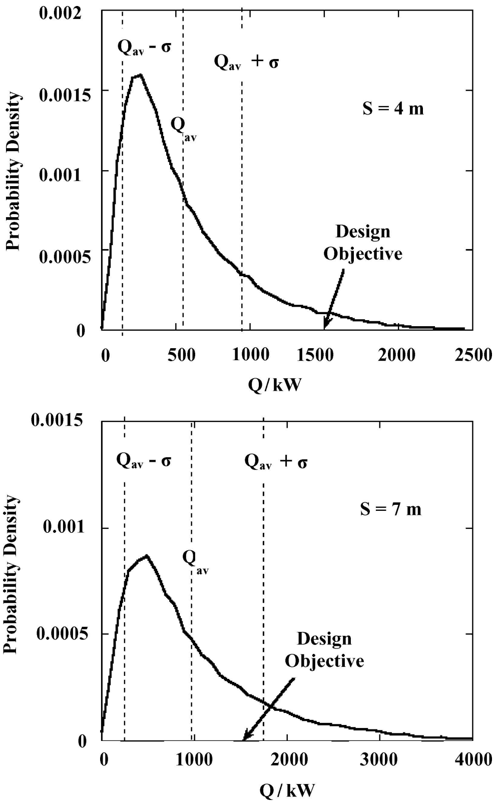

Figure 7. Probability distribution of heat release rate at time of detection for the case with $S = 4$ m and 7 m, accounting for the uncertainty in t_c and H.

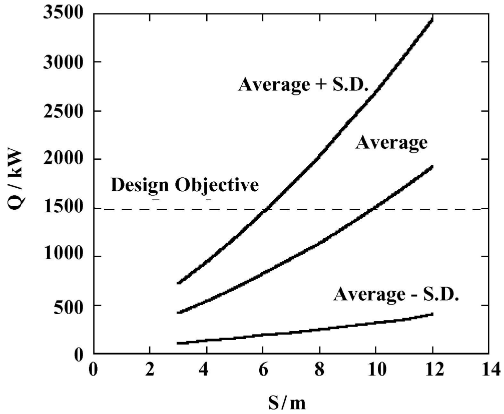

Figure 8. Average value plus and minus one standard deviation of the heat release rate at detection predicted by the Monte Carlo method, accounting for the uncertainty in t_c and H.

average value of the heat release rate at detection, but also the overall distribution. Finally, the average heat release rate at the time of detection, and its value plus and minus one standard deviation are shown in Figure 8. The inclusion of uncertainties leads to a wider spread of the predicted value for heat release rate at detection. This behavior can have important implication in the development of risk based and/or cost-benefit based design of thermal detection system.

5. Conclusion

The deterministic approach for the layout design of thermal fire detection system is shown to be quite limited in terms of its capability to assess the effect of uncertainties in the assumed fire scenarios. Utilizing an illustrative example, the Monte Carlo approach [17] is shown to be effective not only in developing a design for the given design objective, but also in providing a statistical assessment of the design and the possible alternatives. The method also provides a rational basis to account for the effect of uncertainties in the assumed fire scenarios. The Monte Carlo method is thus an effective approach for design applications in the development of engineering performance-based fire codes [3, 6, 7].

It should be noted that there are many other uncertainties, beyond those considered in this work, associated with the design of thermal fire detection system. While the present approach can be readily expanded to account for additional uncertainties, the expansion should be done carefully. Assigning an arbitrary probabilistic distribution to a physical parameter (e.g., variation of RTI, multiple fire source, a non-t^2 fire, etc.) without a careful physical and mathematical consideration can lead to an increase in the overall uncertainty of the model's prediction and thus defeat the purpose of the Monte Carlo approach. As shown by the difference between Figures 4 and 8, the inclusion of additional parameters can have significant effect on the model's prediction. Indeed, the choice of parameters and the associated probabilistic distributions to be included in the analysis is an important step for the overall effectiveness of the Monte Carlo approach. This issue is currently under active consideration and will be presented in future publications.

Nomenclature

A	dimensionless constant (Equation (6))
C_p	specific heat of gas
D	dimensionless parameter (Equation (13))
g	gravitational constant
H	height above fire
p	positive exponent in heat release rate
$\dot{Q}$	heat release rate
RTI	response time index of detector
S	detector spacing
r	radial distance from fire plume axis
t	time
t_c	critical time
t_p^*	reduced time
T	gas temperature
T_a	ambient temperature
T_d	detector temperature
u	instantaneous velocity of fire gas
u_p^*	reduced gas velocity
Y	dimensionless parameter (Equation (12))
α	fire intensity coefficient
ΔT	increase above ambient in gas temperature
ΔT_d	increase above ambient in detector temperature
ρ_0	density of ambient air

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