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An Analysis for Relating Visibility to Smoke Production and Ventilation

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NOTICE

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16. Abstract

The concept of the perfect stirrer is applied to smoke production and removal in ventilated compartments. The analysis results in simple relationships between the logarithm of the light transmission and the characteristic time for an air change in the compartment. In well-mixed enclosures, the analysis demonstrates that the ability to improve visibility through smoke clearance is affected directly by the exponential of the negative of time divided by time for an air change.

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EXECUTIVE SUMMARY

A theoretical framework was developed for use in experimental projects that address smoke venting from aircraft compartments during flight. The concept of the perfect stirrer was applied to smoke production and evacuation in such a manner that light transmission could be related to ventilation rates. The analysis demonstrates the importance of ventilation rates in clearing smoke from well-mixed compartments. The analysis also shows that measurement of the time-history of light transmission during testing is more significant than starting the test with some arbitrary degree of light obscuration.

INTRODUCTION

PURPOSE.

The purpose of this analysis is the development of a theoretical framework for use in experimental projects that address smoke venting from aircraft compartments during flight.

BACKGROUND.

The certification process for Transport Category Airplanes involves certain demonstrations of the capability of removing smoke from the aircraft as described in the Federal Aviation Administration's Order 8110.8 (reference 1). Smoke removal capability is extremely important in the event of an in-flight fire or smoke incident. For instance, the flight deck must be clear of smoke, at least to the degree that allows the flight crew to see the instrument panel during flight. To some degree, smoke venting can be accomplished through use of the aircraft environmental control system. Additionally, there may be other options available such as opening various windows and/or exits at lower altitudes. Nevertheless, at typical cruise altitudes, if cabin pressurization is to be maintained, smoke removal will be handled primarily through the environmental control system.

In the typical transport configuration, air is supplied from powerplant compressors to air conditioning units that adjust the air temperature. From there, the air is distributed to various points in the fuselage. In the passenger cabin, the ventilation air generally flows from ceiling to floor. The air then flows through ducts at the sidewall bottom into the cargo compartments. From there, the air will flow out regulated dump valves to the atmosphere. Other air may be dumped through small orifices to provide ventilation in special cases such as lavatories. The overall ventilation system in some aircraft also involves some recirculation of air.

In testing smoke removal capability, the production and evacuation of smoke can be quantified for engineering purposes with a transmissometer which measures the decrease in light transmission over some specified distance (typically 1 meter, 1 foot, or 3 feet). If a smoke generator were to reduce transmission at some location to 10 percent, a quantitative evaluation might involve finding the time for the transmission to increase to 80 percent.

Nevertheless, there is some reason to expect that the rate of clearing smoke would be strongly controlled by the time for an air change in a given compartment. The smoke evacuation could be treated with a perfect stirrer type analysis which has been successfully used in previous fire related aircraft studies (references 2 and 3). The stirrer analyses employed previously dealt with extinguisher agent dissipation and thermal growth from fires in ventilated enclosures.

The stirrer model is one of two simple approaches that serve as limits to the kind of mixing processes that occur in containers and enclosures. The most straightforward example would be a vessel filled with some particular fluid. This fluid would be constantly replenished from a source at a rate equal to the rate of the loss of this fluid through the vessel exit. Even though the amount of fluid entering and leaving the vessel are known, nothing is known about the path that a given parcel of fluid will follow in the enclosure. One extreme case is where each parcel of fluid follows the identical path as its predecessor and each parcel takes the same amount of time to get from the inlet to the outlet of the vessel. In this extreme case, a parcel of fluid, that was tagged with dye or some impurity at the inlet, would emerge as a slug at the outlet at the time known to be needed for traversing the vessel. The other extreme case is where the fluid parcels follow random paths through the vessel and reside therein for random lengths of time.

In this case, a tagged parcel of fluid would not emerge intact at the outlet. Instead, as soon as the tagged slug entered the vessel, the identifying dye or impurity would be in evidence leaving the outlet at a discrete level related to the dye or impurity amount injected into the system. This extreme case represents thorough and rapid mixing processes within the vessel. In this case, the vessel is considered perfectly stirred. Real-life systems always fall between these extremes. Whether the perfect stirrer is an adequate approximation to a given system is ultimately determined by the predictive capability of a perfect stirrer type analysis.

OBJECTIVE.

The objective of this analysis is the use of the concept of the perfect stirrer to relate visibility to smoke production and ventilation.

ANALYSIS

SMOKE PRODUCTION.

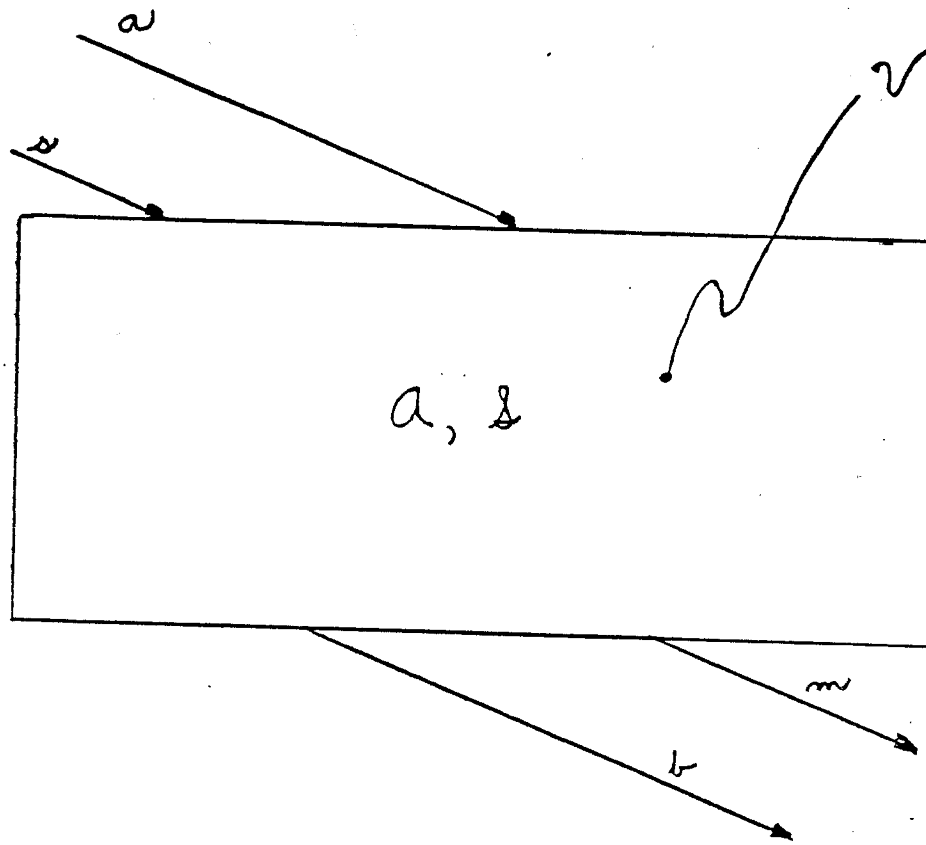
Figure 1 shows a hypothetical enclosure of volume denoted by V. The volume contains a population of air molecules designated by A and a population of smoke particles designated by S. The volume is ventilated with the entry of quantity a of air molecules per minute and the loss of quantity m of air molecules per minute. The smoke source produces quantity s of smoke particles per minute and quantity b smoke particles leave the enclosure each minute with the ventilation air. For simplicity, the analysis will be an isothermal one so that the quantities a and m will be identical. Tied into this assumption is the approximation that the smoke particles take up no volume. Thus, the total number of air molecules will be constant in the analysis.

At any given time, the amount of smoke can be described by the following conservation relationship.

$$S = S_O + \int sdt - \int bdt \qquad (1)$$

That is, the number of smoke particles at any time in the enclosure is the initial number plus those added by the smoke source minus those lost through ventilation. Using the perfect stirrer assumption, the following relation results.

$$\frac{b}{m} = S/A \qquad (2)$$



a	MOLECULAR ENTRY RATE
s	SMOKE PARTICLE PRODUCTION RATE
m	MOLECULAR LOSS RATE
b	SMOKE PARTICLE LOSS RATE
a	INSTANTANEOUS MOLECULAR POPULATION
s	INSTANTANEOUS POPULATION OF PARTICLES
v	ENCLOSURE VOLUME

FIGURE 1. CONTROL VOLUME

This says that the ratio of smoke particulates to air molecules leaving the enclosure is identical to the instantaneous overall mixture in the enclosure. Thus, combining equations 1 and 2, the following equations result in integral and differential form, respectively.

$$S = S_o + \int s dt - \int mS/A \, dt \tag{3}$$

$$\frac{d}{dt} S = s - mS/A \tag{4}$$

For constant rates of smoke production, s, equation 4 can be rearranged to

$$\frac{d}{dt} \ln (s - mS/A) = \frac{-m}{A} \tag{5}$$

Upon integration and exponentiation, this becomes

$$s - mS/A = B \exp (-mt/A) \tag{6}$$

Since m/A is the time for one air change, τ, equation 6 can be rearranged to give the time dependence of the number of particulates in the enclosure

$$S = \tau (s - B \exp (-t/\tau)) \tag{7}$$

In the case where S is zero at time zero, B is identical to τs and the particulate population becomes

$$S = \tau s (1 - \exp (-t/\tau)) \tag{8}$$

For long periods of time, equation 8 approaches an asymptotic value.

$$S \approx \tau s \tag{9}$$

This demonstrates that the higher the ventilation is, the lower the ultimate particulate population will be.

The development, so far, assumes that ventilation is present and fixed during smoke generation. If ventilation were turned off during smoke production, the particulate population growth might be described by the smoke production rate times time or

$$S = st \tag{10}$$

Clearly the smoke versus time profile generated by equation 10 would be quite different from that generated by equation 8.

Because it is transmission of light and visibility that is the area of interest in this type problem, the smoke equations are more useful when translated into transmission type equations.

A simplified transmission equation is written as follows

$$I = I_o \exp (-l\ C_n\ \sigma) \tag{11}$$

Where I is the transmission of light across a distance l in the presence of particulates, I_o is the transmission when no particulates are present, Cn is the concentration of particulates, and σ is some particulate cross-section that absorbs light. From the earlier development, Cn is the total number of particulates, S, divided by the enclosure volume, V. Thus, equation 11 can be rewritten as

$$\ln (I/I_o) = -l\sigma\ S/V \tag{12}$$

Using S from equations 8 and 10, respectively, the relationship for transmission becomes

$$\ln (I/I_o) = -l\ \sigma \tau s \left(1 - \exp (-t/\tau)\right) /V \tag{13}$$

for the ventilation case and

$$\ln (I/I_o) = -\ l\ \sigma\ st/V \tag{14}$$

for the case of no ventilation.

A detailed use of equations 13 and 14 for predictive purposes would involve knowledge of the average optical cross-section, σ, and the number of smoke particles produced per unit time, s. In practical engineering applications, neither is measured. Equations 13 and 14 are actually helpful in cases involving test design. For instance, if the desired transmission reduction were 90 percent, a smoke generator that could achieve this in a given period of the time in one size enclosure, would need a different amount of time in an enclosure of different volume. Additionally, these equations show that the transmission curve will evidence a characteristic shape depending on whether the enclosure is ventilated or not, so long as the air in the enclosure is well mixed. Additionally, since the unknown quantity in these expressions is a product of σ and s; if the transmission at a given point in time is measured, the equations can be empirically solved to find σ s. From this one data point, the time history of the transmission can be predicted.

SMOKE EVACUATION.

The same type development used for smoke production can be used for smoke evacuation, once the smoke generator stops. The derivation of the expression is virtually identical to that used in reference 2 for the dissipation of fire extinguisher agents in a ventilated enclosure. For the case of smoke evacuation, the relationship will be

$$S = S_p \exp (-t/\tau) \tag{15}$$

where S_p is the number of smoke particles present in the enclosure when the smoke generation stops. Use of equation 11 leads to the following relationship

$$-\ln (I/I_o) = l\ S_p\ \sigma \left[\exp (-t/\tau)\right] /V \tag{16}$$

Once again, finding the transmission at a known time during the removal of smoke allows an empirical solution for σS_p and the rest of the smoke removal can then be predicted in terms of light transmission. What is most significant about equation 16 is the dependence on the time for an air change, τ. To the extent to which an enclosure is well mixed during smoke clearing tests, the ability to get rid of smoke depends on the time for an air change. In a perfectly stirred enclosure, the logarithm of the inverse transmission ratio ($\ln I_o/I$) will drop 63 percent during each air change. Thus, the effectiveness of clearing smoke can be just as easily demonstrated with relatively modest amounts of smoke. The critical data to be taken is the actual time history of transmission.

DISCUSSION

The accuracy of the relationships developed to relate light transmission to smoke production and evacuation is dependent on the degree to which the air in the enclosure can be considered well-mixed. In the case of smoke that is buoyant, a ventilation system driving air from top of the enclosure to the bottom would probably represent a well-mixed situation. In contrast, a case of buoyant smoke in a ventilation system where air flows from bottom to the enclosure top would result in higher apparent ventilation rates found from the time-history of the optical transmission. The opposite conclusions could be drawn from cases of negatively buoyant smoke.

The relative buoyancy of smoke would also be a significant factor in evaluation of smoke evacuation on a localized basis within a large enclosure. For instance, if smoke were produced within a small curtained area of a larger enclosure, the smoke would tend to clear the area more rapidly if it were strongly positively or negatively buoyant. These buoyant effects would allow chimney type flows to develop within the small enclosure, provided there were gaps at the top and bottom of the enclosure for air entry and departure.

The actual use of this analysis can be seen in figure 2. In this sample exercise, the following data were used: enclosure volume of 4000 cubic feet, enclosure air change time of 3 minutes, and light transmission length of 3 feet. A smoke generator of constant rate was assumed to operate at a constant rate for 3 minutes with the enclosure ventilation in operation. At 3 minutes, smoke generation ceased and the light transmission percentage over 3 feet was reduced to 10 percent at that point. Figure 2 shows both the logarithm of the transmission ratio and the transmission ratio over a 12-minute period. These graphs were generated through the use of equ tions 13 and 16. Entire families of such curves could be generated by parametrically varying the ventilation times. In this particular case, approximately 9 minutes are needed to increase transmission from 10 percent to 90 percent.

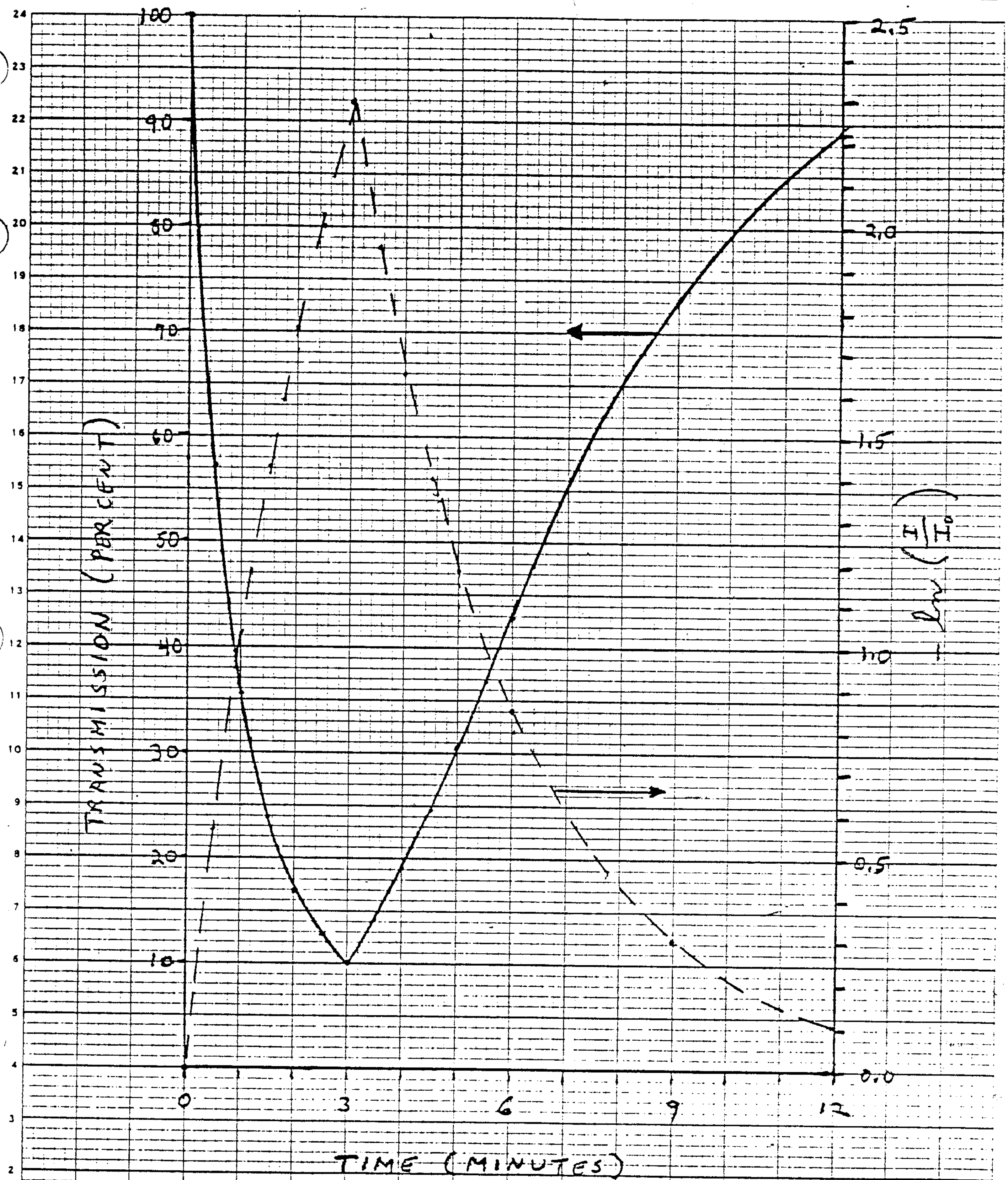


FIGURE 2 — PREDICTED SMOKE HISTORY

CONCLUSIONS

The application of the technique of the perfect stirrer to the analysis of smoke production and evacuation leads to the following conclusions:

1. Changes in light transmission during smoke production and evacuation are strongly affected by ventilation rates.

2. The time history of the light transmission during smoke evacuation is more significant to measure and document, in comparison to prescription of some arbitrary peak obscuration for determining the capability of smoke evacuation.

3. The perfect stirrer concept can be used to relate visibility to smoke production and ventilation in a convenient manner.

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