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Heat Release Rate of Objects Burning in Cargo Compartments

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16. Abstract

The heat release rate of objects burning in a relatively large, simply ventilated cargo compartment is reconstructed from the oxygen consumption history of the exiting gas stream, assuming perfect mixing of the combustion gases in the compartment. The model was calibrated using a premixed propane gas burner to generate a variety of well-defined heating histories. Qualitative agreement between actual and computed heat release rate histories is obtained when the duration of the burning is on the order of 1/2 of the mixing time of the compartment. This research supports efforts by the Federal Aviation Administration to develop new certification requirements for aircraft cargo compartment fire detectors.

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INTRODUCTION

To support the development of more reliable fire detectors and facilitate their certification for commercial aircraft, the Federal Aviation Administration (FAA) is conducting research to generate a complete and reproducible fire signature typical of a luggage article burning in a cargo compartment [1 and 2]. Aircraft manufacturers primarily use photoelectric smoke detectors, and to a lesser extent ionization detectors, to comply with FAA regulations for fire detection in cargo compartments of commercial aircraft. The photoelectric detectors rely on smoke particles entering a chamber where they either reflect or attenuate a light beam to produce an alarm. While effective at detecting smoke, these detectors also alarm when airborne particles or moisture are detected. The current ratio of false alarms to real fires in commercial aircraft cargo compartments is on the order of hundreds-to-one [3]. The low reliability (< 1%) of current fire detectors is costly to airlines, so detectors are being developed that alarm only after multiple fire products are sensed, e.g., optical extinction, temperature, carbon monoxide, hydrocarbons, etc. The location of the fire source and the movement of fire products within the cargo compartment is important for optimum placement of fire detectors. A computational fluid dynamics (CFD) model is being developed in combination with an experimental program to address this issue [1]. The CFD model requires a well-characterized fire product source. A composite sample was developed for this purpose, which is comprised of several different plastics in the approximate ratio found in passenger luggage [2]. The history of heat release rate, smoke density, and combustion gas composition of the plastic composite in flaming and nonflaming modes was measured in a bench-scale fire (cone) calorimeter to obtain its fire signature [2]. Full-scale testing of luggage articles and the plastic composite in a ventilated Boeing 707 cargo compartment revealed that the fire signature deduced from the exhaust gases was smeared due to volumetric mixing in the cargo compartment. Consequently, a simple mixing model was evaluated to determine whether time-deconvolution of the exhaust gas history could be used to provide the fire signature of a burning object in the (relatively) large cargo compartment of a commercial passenger jet. The model was evaluated by comparing known heat release rate histories in the cargo compartment from a premixed propane burner to those calculated from the mixing model using the oxygen consumption history of the exhaust gases.

MIXING MODEL

Figure 1 illustrates the basic physical flow problem. Relevant quantities are the fixed volumetric flow (leak) rate, $\dot{V}_{in} = \dot{V}_{out} = F$, of ambient air at oxygen mass fraction $[\mathrm{O}_2^o] = 0.23$ through a well-mixed control volume, V_o (the cargo compartment volume) at atmospheric pressure. The mass flow rate of oxygen leaving the control volume at constant air density ρ is

$$\dot{m}_{out} = \frac{d\left(\rho V[\mathrm{O}_2]\right)}{dt} = \rho[\mathrm{O}_2]\frac{dV}{dt} + \rho V\frac{d[\mathrm{O}_2]}{dt} \qquad (1)$$

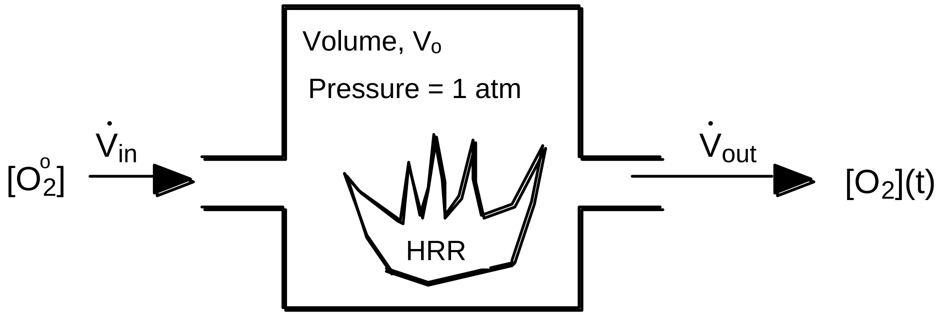

FIGURE 1. COMPARTMENT FIRE MODEL

The mass rate of oxygen consumption by the fire having a heat release rate (HRR) (watts) resulting from burning fuel having heat release per mass of oxygen consumed, E (MJ/kg-O_2), in the cargo compartment is

$$\dot{m}_{fire} = \frac{-HRR}{E} \tag{2}$$

The mass flow rate of oxygen entering the control volume is

$$\dot{m}_{in} = \rho[O_2]\frac{dV}{dt} + \rho V\frac{d[O_2]}{dt} = \rho\dot{V}_{in}[O_2^o] \tag{3}$$

since $d[O_2]/dt = 0$ for incoming air at $[O_2] = [O_2^o] = 0.23$. The mass balance for oxygen is

$$\dot{m}_{in} - \frac{HRR}{E} = \dot{m}_{out} \tag{4}$$

Substituting equations 1, 2, and 3 into equation 4 gives the instantaneous HRR of the fire in terms of the oxygen concentration of the combustion gas stream exiting the well-mixed compartment

$$\frac{d[O_2]}{dt} - \frac{F}{V_o}\left\{[O_2^o] - [O_2]\right\} = \frac{-HRR(t)}{\rho V_o E} \tag{5}$$

A system response time is defined as $\tau = V_o/F$ and a heat release constant as $C = \rho V_o E$. The oxygen consumption is defined as $\theta(t) = [O_2^o] - [O_2](t)$, such that $d\theta/dt = -d[O_2]/dt$ so that equation 5 takes the simplified form

$$HRR(t) = \frac{C}{\tau}\left\{\theta + \tau\frac{d\theta}{dt}\right\} = \rho EF\left\{\theta + \tau\frac{d\theta}{dt}\right\} \tag{6}$$

The model parameters C and τ were evaluated using a propane burner in the cargo compartment to generate known HRR histories

$$HRR(t) = \chi \rho_p h_c^0 \dot{V}_p(t) \tag{7}$$

where $\dot{V}_p$ (m^3/s) is the instantaneous propane flow rate and ρ_p = 1.83 kg/m^3 (STP), h_c^0 = 46.36 MJ/kg, and χ are the density, net heat of complete combustion, and combustion efficiency of propane, respectively. The combustion efficiency χ was assumed to be unity for the premixed propane-air burner.

EXPERIMENTAL

Testing was conducted in a B-707 cargo compartment shown schematically in figure 2. The cargo compartment has volume V_0 = 25.8 m^3 and contains a perforated duct that is used to extract air and combustion products out of the compartment at a rate F = 0.012 m^3/s using a calibrated exhaust fan. This arrangement is meant to simulate an in-flight air leak from the cargo compartment through the cargo door seals due to the pressure difference at altitude. A combustion gas sample was drawn from the exhaust duct outside the compartment and filtered before passing through a continuously reading oxygen analyzer (Rosemount OM11EA). Oxygen concentration data were recorded electronically at 2-second intervals. A premixed propane gas burner was placed in the center of the cargo compartment, as indicated in figure 2, for model validation testing. For some experiments, a 0.5-m-diameter electric fan was placed in the cargo compartment to improve circulation (mixing).

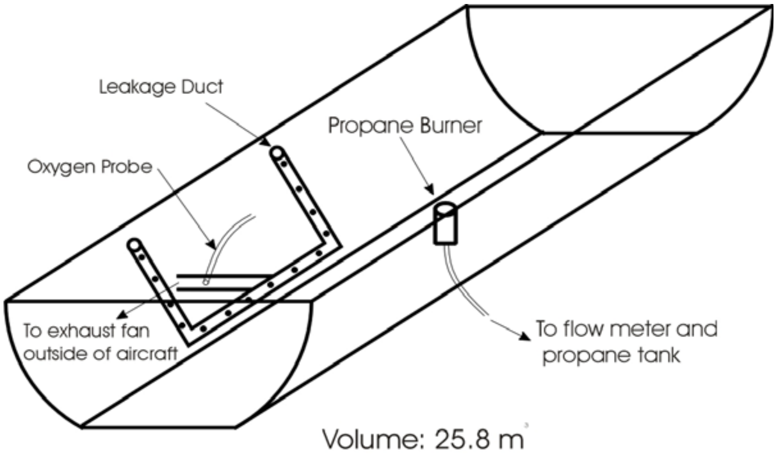

FIGURE 2. CARGO COMPARTMENT USED FOR FULL-SCALE TESTING

RESULTS

Figure 3 compares the cargo compartment model to a step change in HRR followed by a gradual but monotonic decrease over the test interval. Equation 6 was fit to the data for the oxygen concentration history extracted from the cargo compartment exhaust gases during the test with τ = 28 minutes and C = 447 MJ giving the best visual representation. The response time was defined as the time required for the oxygen concentration to reach (1–1/e) = 63% of the equilibrium value after a step change in HRR. In all cases, the total heat calculated from oxygen consumption was within a few percent of the nominal value for the mass of propane burned for the test. These empirical (best-fit) values for C and τ are compared in table 1 to calculate values $C = \rho V_0 E$ and $\tau = V_0/F$ assuming ρ(air) = 1.35 kg/m^3 (STP), and E = E (propane) = 12.78 MJ/kg-O$_2$ is the ratio of the net heat of combustion of propane (46.4 MJ/kg) to the oxygen/propane mass ratio (r = 3.629).

The empirical value for C is well within the uncertainty of the calculated value, assuming 5% accuracy of the tabulated and measured quantities. However, the empirical response time τ is significantly less than the calculated value, suggesting that the hot, buoyant combustion products from the propane burner improved mixing. The heat release rate of the propane burner estimated from the oxygen concentration of the exhaust gases without deconvolution (τ = 0 on the right-hand side of equation 6) is also plotted in figure 3, showing the extent of HRR smearing due to volumetric mixing in the compartment.

TABLE 1. COMPARISON OF CALCULATED AND BEST-FIT PARAMETERS FOR PROPANE BURNER CALIBRATION OF CARGO COMPARTMENT MODEL

Parameter	Calculated	Fit of Equation 6
C	445 MJ	447 MJ
τ	36 min	28 min

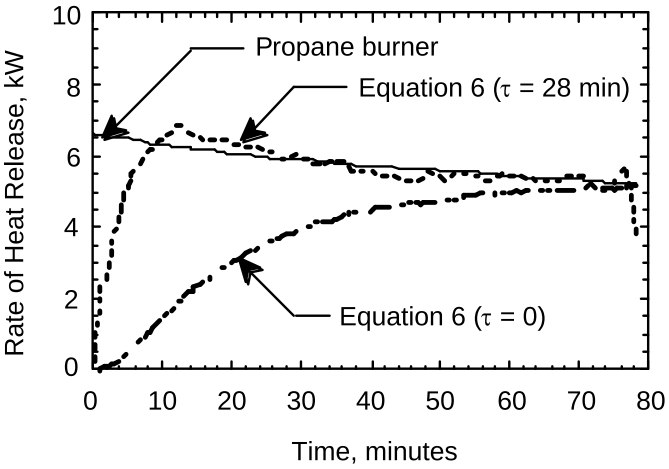

FIGURE 3. STEP CHANGE HRR HISTORY IN CARGO COMPARTMENT COMPARED TO EQUATION 6 WITH (τ = 28 min) AND WITHOUT (τ = 0) DECONVOLUTION OF THE OXYGEN CONSUMPTION DATA

Figure 4 compares a 10-minute square wave HRR history in the cargo compartment to the deconvoluted HRR history computed from the oxygen consumption data using equation 6 (τ = 28 minutes) with and without the use of the circulation fan. Figure 4 shows that forced circulation of the air and combustion products inside the cargo compartment reduces the mixing (response) time by a few minutes, as evidenced by the higher fidelity of the computed HRR.

However, despite the moderate (≈ 10%) improvement in HRR fidelity, the fan was not used in subsequent experiments to preserve the natural pattern and history of smoke movement in the compartment.

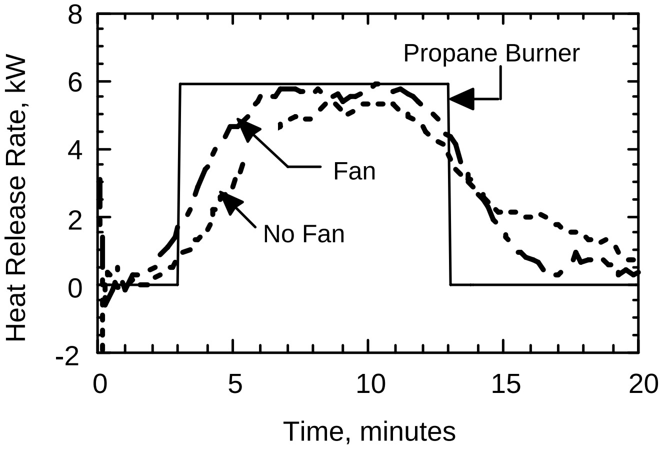

FIGURE 4. SQUARE WAVE HRR HISTORY IN CARGO COMPARTMENT COMPARED TO EQUATION 6 WITH AND WITHOUT THE USE OF A CIRCULATION FAN

Figures 5 and 6 compare equation 6 with and without deconvolution of the oxygen consumption data to different multistep HRR histories in the cargo compartment generated by the propane burner without forced circulation. Equation 6 cannot capture transient data for which the duration of the event Δt is significantly less than the mixing time of the compartment, i.e., $\Delta t << \tau$, as evidenced by attenuated HRR for short duration pulses in figures 5 and 6.

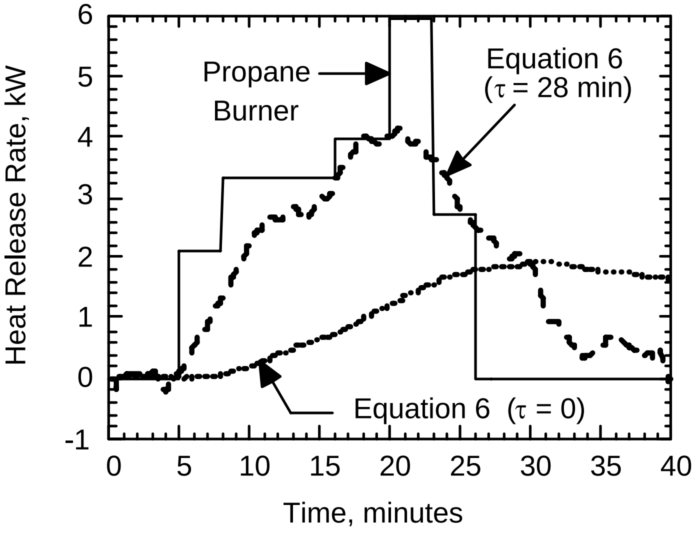

FIGURE 5. MULTISTEP HRR HISTORY IN CARGO COMPARTMENT COMPARED TO EQUATION 6 WITH (τ = 28 min) AND WITHOUT (τ = 0) DECONVOLUTION OF OXYGEN CONSUMPTION DATA

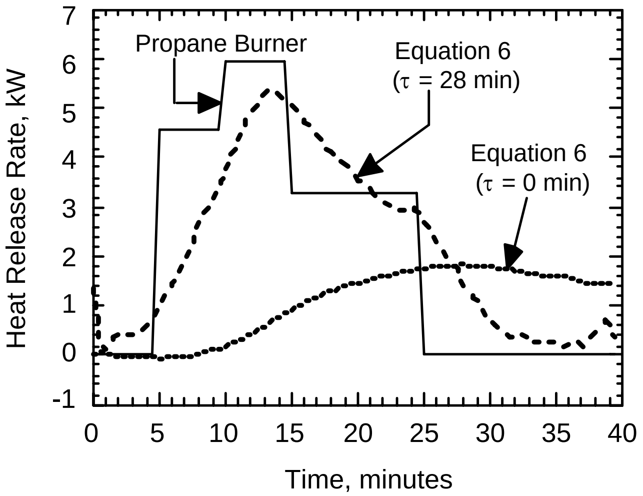

FIGURE 6. MULTISTEP HRR HISTORY IN CARGO COMPARTMENT COMPARED TO EQUATION 6 WITH AND WITHOUT DECONVOLUTION OF OXYGEN CONSUMPTION DATA

The average correlation coefficient between the actual and deconvoluted HRR histories plotted in figures 3 through 6 is $R = 0.7$, which is a reasonable estimate of the fidelity of the technique for the conditions of this test. Regardless of HRR fidelity, the total heat release (J) computed from the time integral of equation 6 was always within a few percent of the nominal value obtained by multiplying the mass of propane burned during the test by its net heat of complete combustion.

CONCLUSIONS

A perfect mixing model was used to reconstruct the heat release rate history, HRR(t), of an object burning in a constantly ventilated compartment using the oxygen consumption history of the exhaust gases. Reasonable HRR fidelity (≈ 70%) can be obtained when the duration of the burning event is on the order of one-half the volumetric mixing time of the compartment. Under these conditions, the model reproduces fire signatures of burning objects reasonably well using the physical dimensions and ventilation rate of the compartment.

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