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Category

Research Article

Abstract

The Federal Aviation Administration (FAA) requires fire detectors to alarm within one minute of the start of a fire in cargo compartments of airplanes. To determine whether such alarm timing works, investigations of the thermal damage to ceilings and other structures during the early stage of a fire were accomplished to demonstrate compliance with these FAA regulations. The objective was to test the feasibility of predicting convective heat transfer in early stage of a cargo compartment fire by conducting reduced scale (lab scale) experiments. First, the scaling laws was derived and validated. Then, full-scale and half-scale experiments were performed with attention to the heat fluxes from the fires. Similarity between the scaled tests were verified by matching dimensionless fire power profiles. Comparisons between the two-scale results showed good agreement in dimensionless heat fluxes to the ceiling and the rear bulkhead, thereby pointing to the capability of scale modeling as an effective tool for the present purpose.

Keywords

Aircraft cargo fire, Fire plume, Heat flux, Fr-number modeling

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Abstract

The Federal Aviation Administration (FAA) requires fire detectors to alarm within one minute of the start of a fire in cargo compartments of airplanes. To determine whether such alarm timing works, investigations of the thermal damage to ceilings and other structures during the early stage of a fire were accomplished to demonstrate compliance with these FAA regulations. The objective was to test the feasibility of predicting convective heat transfer in early stage of a cargo compartment fire by conducting reduced scale (lab scale) experiments. First, the scaling laws was derived and validated. Then, full-scale and half-scale experiments were performed with attention to the heat fluxes from the fires. Similarity between the scaled tests were verified by matching dimensionless fire power profiles. Comparisons between the two-scale results showed good agreement in dimensionless heat fluxes to the ceiling and the rear bulkhead, thereby pointing to the capability of scale modeling as an effective tool for the present purpose.

Keywords: Aircraft cargo fire; Fire plume; Heat flux; *Fr*-number modeling

Nomenclature

c_p	heat capacity
g	gravitational acceleration
H	height
m	mass loss rate
Q	fire power
Q^*	dimensionless fire power
q	heat flux
q^*	dimensionless heat flux
t	time
t^*	dimensionless time
U	characteristic velocity
ρ_0	density
β_T	volumetric expansion coefficient

Introduction

Prevention of a cargo compartment fire is crucial for flight safety of aircrafts. Current US Federal Aviation Administration (FAA) regulations [1, 2] require that aircraft cargo compartment fire detection systems alarm will be activated within *1 minute* of the start of a fire. Therefore, a better understanding of early stage cargo compartment fire scenarios, especially the heat transfer from the fire induced flow to compartment structures, are essential for demonstrating compliance with the FAA regulations and for optimization of an aircraft design.

Full scale in-fight or ground tests are costly and time consuming, making it quite difficult to guarantee experimental repeatability. Numerical simulations could be helpful, but technical difficulties often arise when constructing the grid system due to the complicated geometry, and the simulations are usually computationally complicated.

Motivated by these considerations, the objective of this study was to examine the feasibility of predicting a cargo compartment fire scenario by performing reduced scale (lab scale) experiments aided by scale modeling. Both full and half scale experiments were conducted and attention was given to the convective

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heat transfer to the ceiling and rear bulkhead in the early stage (1 to 2 minutes) of a fire in a closed compartment.

Scaling rule

The concern is the convective heat transfer from a hot fire plume to the ceiling (and other compartment structures), as shown in Fig. 1. For early stages of a fire, it is reasonable to assume that the point source theory [3] would be applicable for the buoyant fire plume. The fire plume is turbulent, i.e., Grashof number (*Gr*) and Reynolds number (*Re*) are high, and diffusive mass and hear transport are negligible. It is also reasonable to assume that the radiative heat transfer to the surrounding walls would be relatively minor due to the relatively small flame size of the fire source. For these conditions, the characteristic velocity (*U*) for the plume would have the following relationship [4]:

$$U \sim \sqrt{gH} Q^{*1/3} \quad (1)$$

where

$$Q^* = Q/(\rho_0 c_p g^{1/2} H^{5/2} \beta_T^{-1}) \quad (2)$$

To match the Froude number (*Fr*) for scale modeling of fire plume development in a closed compartment [5], it is imperative to match the Q^* because:

$$Fr = U/\sqrt{gH} \sim Q^{*1/3} \quad (3)$$

The dimensionless time t^* and the dimensionless convective heat flux q^* to the compartment walls would then be defined as:

$$t^* = t/\sqrt{H/g} \quad (4)$$

$$q^* = q/(\rho_0 c_p g^{1/2} H^{1/2} \beta_T^{-1}) \quad (5)$$

For more details about the nondimensionalization process, refer to the reference [6].

Validating the scaling rule

Full-scale and half-scale numerical simulations were performed using the software Fire Dynamic Simulator (FDS) [7, 8] to validate the scaling laws. Turbulence was treated by means of the Large Eddy Simulation (LES); Fig. 2 shows a schematic of the numerical domains. For the full-scale simulation the compartment was 3.5 m long, 2.3 m wide and 2.3 m high. The fire power Q (kW) was imposed on the top surface of a "burner" of size 0.5 m × 0.5 m × 0.5 m located on the center, ground surface. The ceiling was 0.1 m thick and the thermal conductivity was assumed to be 1.0 W/(m-K) and the outer surface of the ceiling was set as a constant of 300 K; heat fluxes to the center ceiling were recorded during the simulations. Uniform meshes were used and the mesh sizes were 0.1 m × 0.1 m × 0.1 m for both the full and half-scale sizes.

Fig. 3(a) shows the imposed Q profiles for both full and half-scale; the half-scale simulation model for Q was scaled by a factor of $0.5^{2.5} \approx 0.177$, and the firing

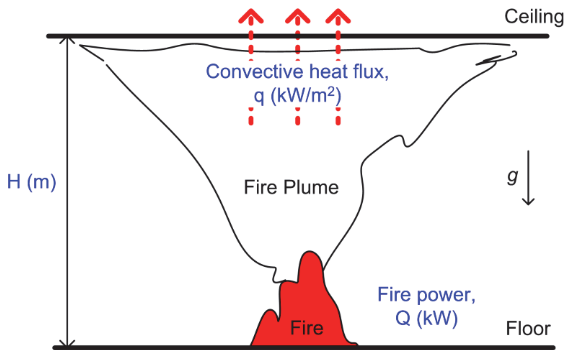

Fig. 1.Schematic of a fire plume.

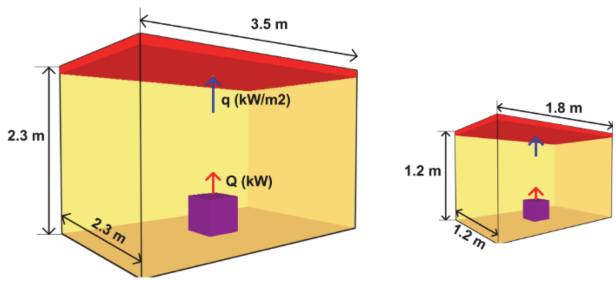

Fig. 2. Schematic of the numerical domains for the full-scale (left) and the half-scale (right) simulations.

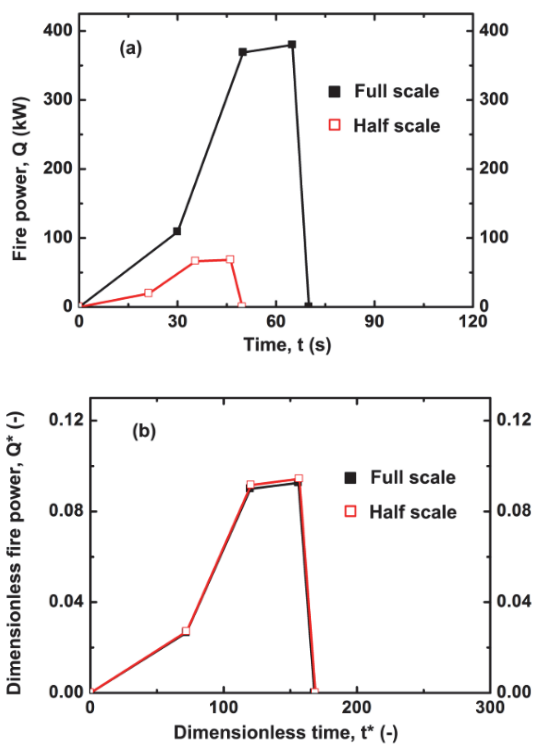

Fig. 3. (a) Imposed fire power and (b) dimensionless fire power for both the full-scale and half-scale numerical simulations.

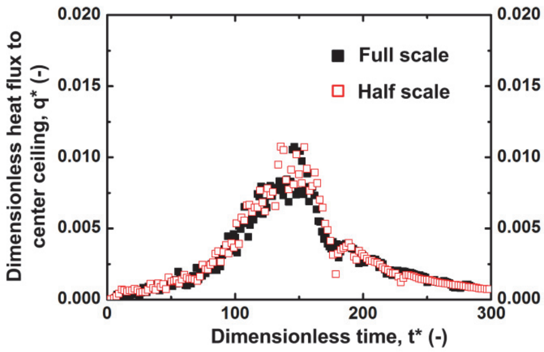

Fig. 4. Computed dimensionless heat fluxes (average of five sets of data) to the center of the ceiling; heat flux data were sampled every 0.2 s in the simulations.

duration was scaled by a factor of $0.5^{0.5} \approx 0.707$, to ensure identical Q^* profiles with the full-scale. Fig. 3(b) confirms that the Q^* profiles overlapped each other.

Fig. 4 shows the computed dimensionless q^* values as a function of t^*. The full-scale and half-scale results were in good agreement with each other; hence, the scaling was accomplished appropriately. This outcome was confirmed by also changing the grid sizes, implying the scaling rule would be insensitive to the grid size within the parameters used when the same turbulent model was to be applied.

Experimental testing

Fig. 5 illustrates the geometry and important dimensions of the full-scale and half-scale experimental facilities. The compartment was cylindrical with flat floors constructed on the bottom; the longitudinal axis of the cylinder was horizontal. Outside of the ceiling of the cylinder representing the rear bulkhead of a cargo compartment of an airplane and is where electrical

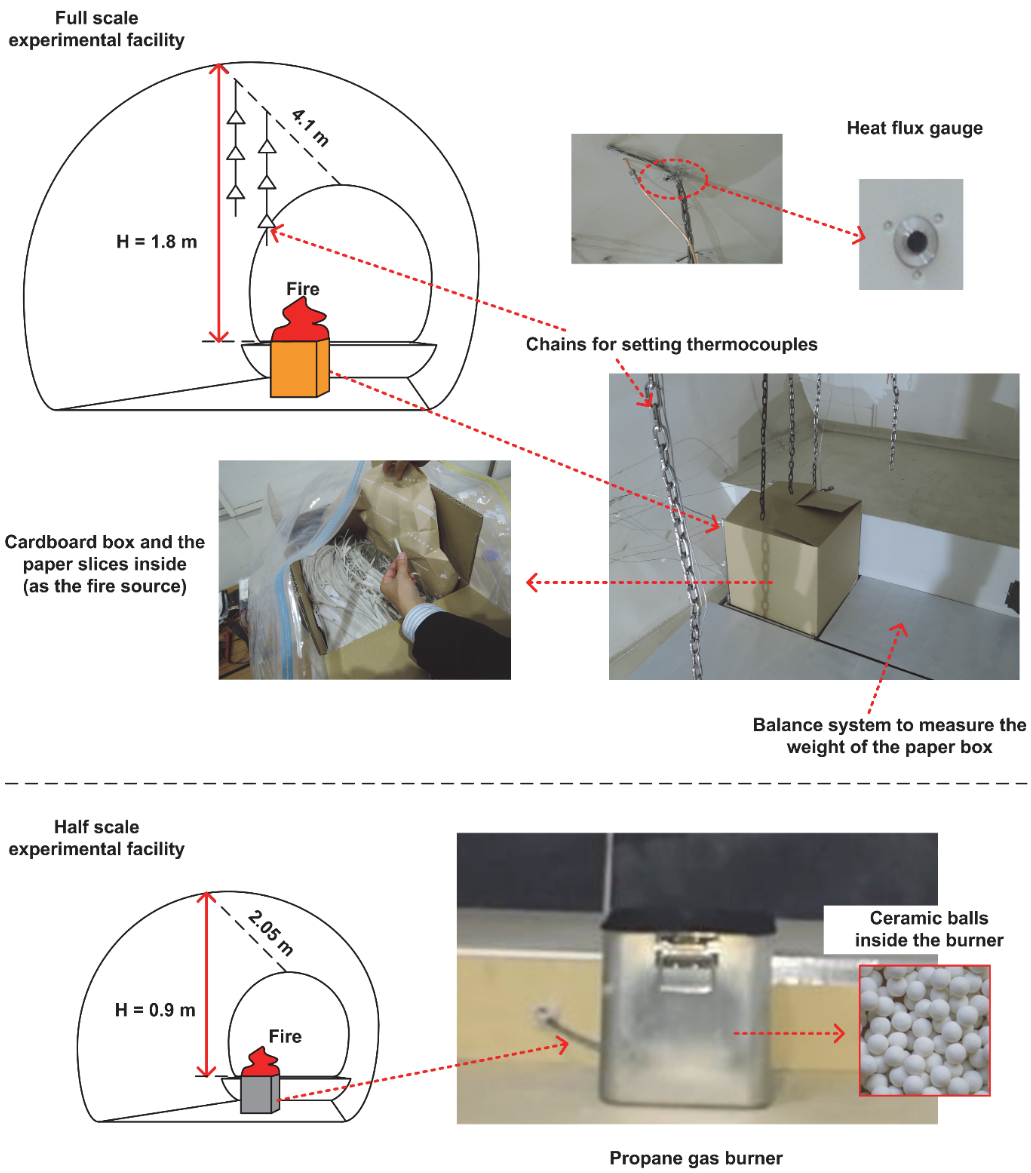

Fig. 5. Illustrations of the full scale (up) and the half scale (down) experimental facilities.

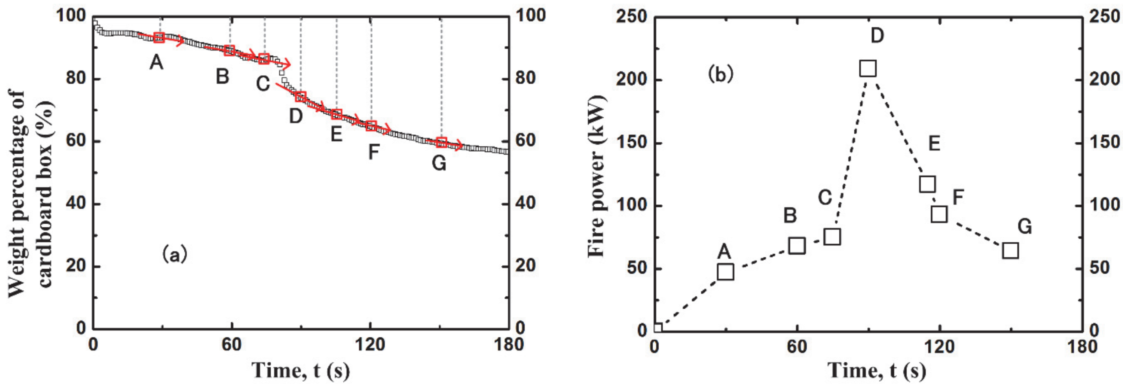

Fig. 6. Full scale experimental results: (a) weight profile of cardboard box and (b) calculated fire powers at selected moments A, B, C, D, E, F and G.

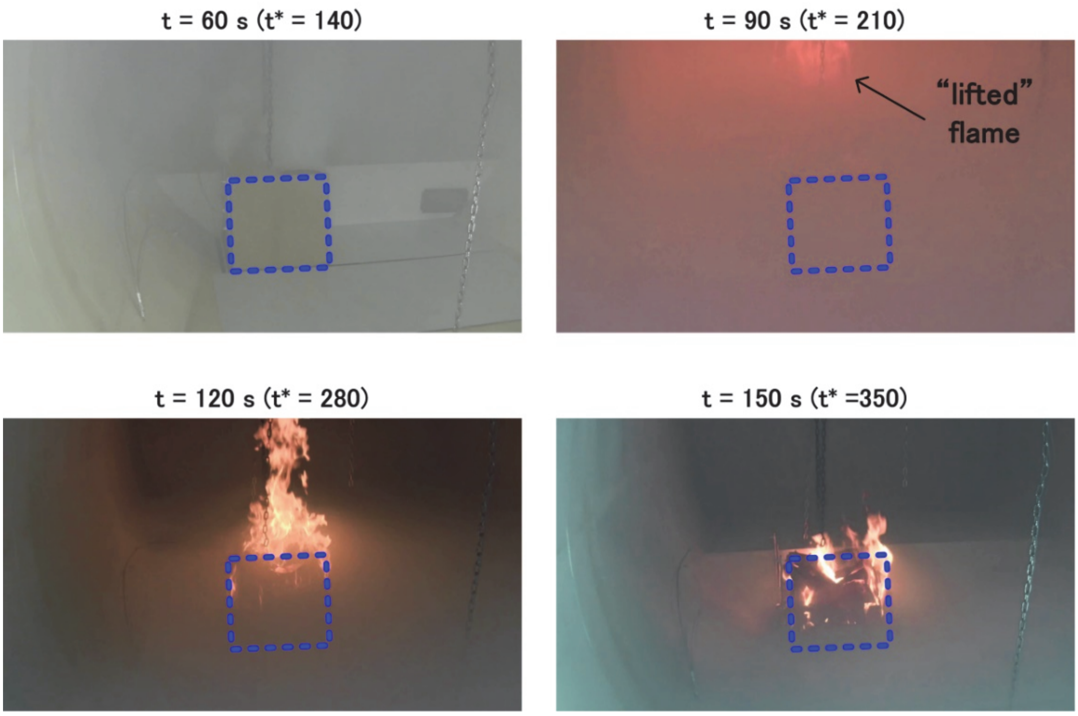

Fig. 7. Time sequential flame pictures for the full scale experiment at t = 60 s, 90 s, 120 s and 150 s (t^* = 140, 210, 280 and 350).

devices including cables are typically located; these devices and electrical components would be critical to airplane operation. Predictions of potential thermal damage to these components is critical from a fire safety point of view.

For the full-scale experiment, a cardboard box filled with paper slices was burned to simulate a cargo compartment fire. The total weight was near 2.2 kg, including 1.1 kg for the cardboard box and 1.1 kg for the paper slices inside. Electrified nichrome wires were embedded in the paper slices as the ignitor to start a fire according to FAA guidelines [9].

During experiments the weight of the cardboard box was monitored using a scale located under the floor and the flame behavior was recorded using several video cameras; the heat fluxes to the center ceiling and the rear bulkhead were measured by using heat flux gauges.

The geometry of the half-scale compartment was very similar to the full-scale one except for the full-scale tests used a homemade propane gas burner as the fire source; in this burner, the flame emanated from a stainless kitchen pot filled by ceramic balls. During testing, the propane flow rates were manually controlled by needle valves and recorded using mass flow meters.

Results and discussion

Fig. 6(a) shows time sequential weight profile of the cardboard box during full-scale fire experiments. The

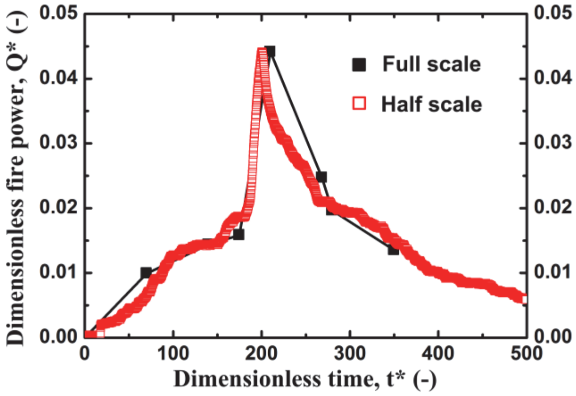

Fig. 8. Dimensionless fire powers for full and half scale experiments.

mass loss rates (m, kg/s) were calculated at t = 30 s, 60 s, 75 s, 90 s, 105 s, 120 s, and 150 s (marked as A to G in the figure). By assuming a constant combustion heat of 17,300 kJ/kg [10], the mass loss rates were converted into fire power, as plotted in Fig. 6(b).

Fig. 7 shows representative images of the flame at t = 60 s, 90 s, 120 s and 150 s for the full-scale experiments. At t = 60 s, the combustion of the paper slices inside the cardboard box was relatively weak due to a lack of air. Intense smoke was generated and rose toward the ceiling. After the top surface of the cardboard box was burned, a sufficient supply of air to the paper became possible, resulting in more intense flaming combustion at t = 90 s; with the increase in intensity, and the flame height became greater. Then, as the oxygen concentration in the compartment was dramatically decreased

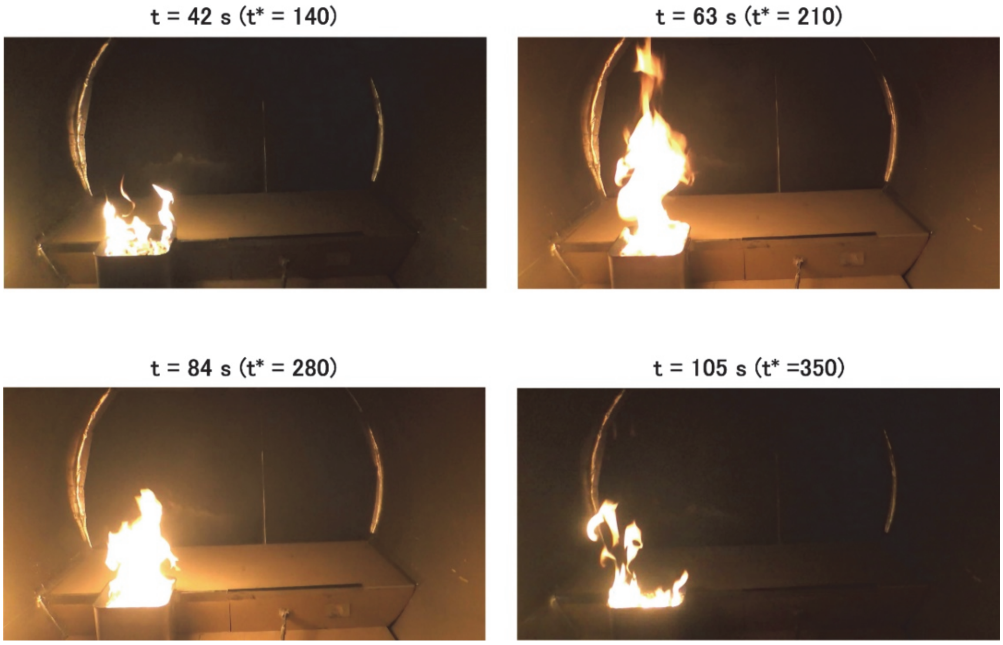

Fig. 9. Time sequential flame pictures for half scale experiments at t = 42 s, 63 s, 84 s and 105 s (t^* = 140, 210, 280 and 350).

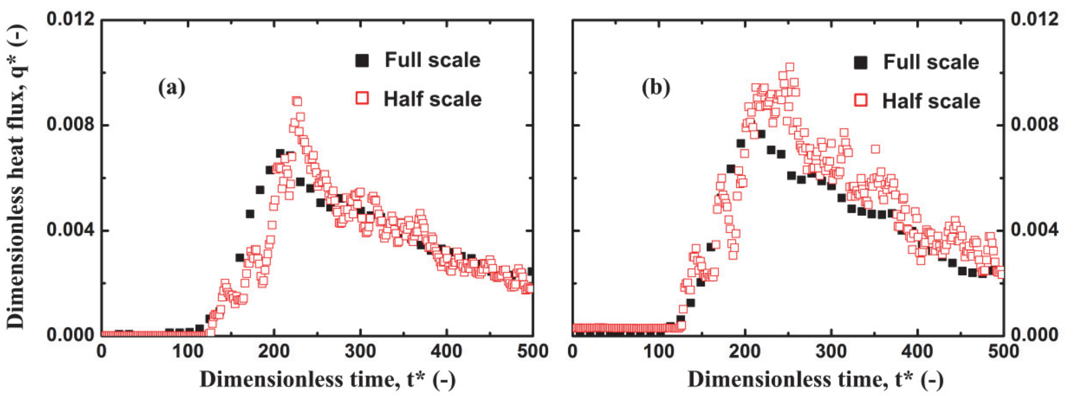

Fig. 10. Dimensionless heat fluxes to (a) center ceiling and (b) front face of the rear bulkhead. Heat flux data are sampled every 1.0 s and 0.05 s for the full scale and the half scale tests, respectively. Plots in this figure are based on temporal average for every 5 raw data.

along with an increase in combustion products such as CO_2), the combustion intensity decreased (at t = 150 s). Afterward, smoldering combustion was found to occur over a long time.

During the half-scale experiments, the flow rate of propane gas was carefully adjusted to match the Q^* of that for the full-scale experiments. As a consequence, a satisfactory agreement between Q^* of the full-scale and half-scale experiments can be seen in Fig. 8.

Fig. 9 shows representative images of the flames during half-scale experiments at t = 42 s, 63 s, 84 s and 105 s. Comparison of Fig. 7 and 9 indicates that the half-scale experiments qualitatively reproduced the combustion performance of the full-scale test in terms of the evolution from weakly burning at t^* = 140 to the strongest burning at around t^* = 210, and then eventually to a mild burning at t^* = 350.

Fig. 10 presents the dimensionless heat fluxes to the center of the ceiling and surface of the rear bulkhead for both the full-scale and half-scale experiments. Good agreement was found between these results for q^* Fig. 10(a) and 10(b). Moreover, the maximum q^* was slightly over predicted by the half-scale experiments, potentially a result related to the radiative heat transfer from a sooty flame to the surrounding walls would become increasingly important as the scale was decreased. Additionally, both full-scale and half-scale results show that q^* to the front surface was relatively higher than that to the ceiling center. This difference was ascribed to stagnated high-temperature jet flow toward the ceiling in comparison to no stagnation toward the bulkhead wall surface.

Conclusions

The early stages of a fire in a modeled aircraft cargo compartment were studied by performing half-scale experiments based on a scale modeling concept. In the half-scale experiments, a simple homemade propane gas burner was employed to simulate a cardboard box fire that was used in the full-scale experiments. The dimensionless fire power of the fire in the full-scale testing was reproduced in the half-scale testing by adjusting the fuel flow rate. Heat fluxes to the center ceiling and the front face of the rear bulkhead were measured, and good agreement in the dimensionless heat fluxes were observed.

It is to be noted that the half-scale experiments tended to predict higher convective heat fluxes than the full-scale experiments because of more pronounced radiative heat transfer in the half-scale testing. Fortunately, such an overestimate was coincident with the "conservation principle" in fire safety studies. Therefore, scale modeling was an effective and efficient tool to predict features of fire in an aircraft cargo compartment, thereby enabling potential improvements in safety designs.

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