Sub-Scale Analysis of New Large Aircraft Pool Fire-Suppression

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Overview

There is speculation about the applicability of current aircraft rescue firefighting (ARFF) protection standards for New Large Aircraft (NLA) such as the Airbus A380 and Boeing 777. Current protocol is based on traditional aircraft; in comparison NLA are characterized by unusually large dimensions, composite material integration, as well as enhanced passenger and wing loading, and stored fuel in non-conventional locations. A study is underway to develop an aircraft-crash-fuel spill-fire-suppression (ACFFS) simulation framework to quantify fuel dispersal and to estimate firefighting agent application requirements for accidental scenarios of high interest. This approach is favorable because it is less expensive and more practical than conducting full-scale experiments. The current work discusses the results of partial NLA fire-suppression experiments conducted in moderately controlled, indoor environmental conditions at 1:10-scale. The purpose of this work was to generate an in-house experimental validation data set to support development of the aircraft pool fire-suppression component of the ACFFS simulation framework. Preliminary design, set-up, and performance of the aircraft pool fire-suppression model is also discussed.

Introduction

NFPA 403 reports the minimum extinguishing agent discharge requirements and response capability for ARFF services at airports based on the theoretical critical area-practical critical area (TCA/PCA) method. The TCA/PCA method is based on ARFF response estimates from over 40 years ago, has questionable validity with respect to NLA, and does not account for non-linear, three-dimensional aircraft crash dynamics or modern aircraft designs. The ACFFS simulation framework is an alternative approach to the TCA/PCA method that uses high-fidelity finite element analysis (FEA) and computational fluid dynamics (CFD). It enables the consideration of physical dynamics that occur during an actual ACFFS event, including post-crash aircraft geometry, fuel spill distribution, wind velocity effects, and fire suppression techniques. The program objective is to predict the severity of ACFFS scenarios so that an alternative or potential modification to the TCA/PCA method may be considered.

The technical approach is as follows: (1) perform dynamic FEA of survivable aircraft crashes, (2) perform high-fidelity CFD analysis of resultant pool fire and suppression, (3) evaluate the severity of ACFFS scenarios, and (4) validate the simulation methodology using aircraft crash, fire, and suppression experiments to determine its degree of reliability. The current work discusses progress on Part 4 and preliminary findings on Part 2 of the ACFFS approach.

Experimental Set-up

Fire-suppression experiments were conducted on a 1:10-scale partial NLA steel mockup designed to resemble the major mid-body features of the Airbus A380 engulfed in a 3.05-m (10-ft) diameter JP-8 pool fire. The current experiments were carried out in a quonset-style indoor fire test facility in a calm atmosphere. A fuel pan scale recorded the change in fuel mass to determine the fuel

regression rate. Thirty-one K-type thermocouples recorded a combination of fire perimeter (4), fuel surface (5), mockup surface (15), and axial centerline fire plume temperatures (7). Four water-cooled, Gardon-style dual heat flux gages positioned 90-degrees apart and around the fire perimeter recorded total and radiation heat flux. A single infrared and two standard cameras were positioned ±45-degrees off-axis with respect to the mockup hull to record each fire test.

Ten pool fire-suppression trials were conducted, five with the fire pool only and five that included the 1:10 NLA mockup. A trial began by floating 76 liters (20 gal) of JP-8 overtop 371 liters (98 gal) of tap water and then manually igniting the JP-8 with a propane torch. A 60-s pre-burn period then occurred so that fire conditions could fully-develop. Four fire suppression nozzles positioned 90-degrees apart near the base and perpendicular to the fuel pan then discharged agent. The nozzles delivered a combined 43 l·min^{-1} (11.3 gal·min^{-1}) of agent at 480 kPa (70 lb·in^{-2}) until the fire was extinguished. The nozzles were 30-degree stainless steel fan nozzles manufactured by BETE. The agent was premixed Mil-spec 3% AFFF discharged via a modified (no air injection) Tri-Max 30 acting as a pressurized cylinder. The agent had an approximate 3:1 expansion ratio, and the fixed nozzle system delivered approximately 78 percent of the agent to the fuel pan.

Experimental Results

Key experimental results are summarized in Table 1. In general, it was found in pool fire only suppression trials that JP-8 burned at an increased rate, thus generating a greater heat release rate compared to trials that included the mockup. The increased heat release rate caused the relative total and radiation heat flux measurements along the fire perimeter to similarly increase. The mockup presence also caused the extinguishment time to increase significantly thereby decreasing extinguishment efficiency. Fire intensification was observed immediately after suppression started. This phenomena resulted in a peak total heat flux rise of 126 and 170 percent over the mean heat flux recorded during the pre-burn period for the pool fire only and mockup cases, respectively. Fire perimeter thermocouple measurements recorded a minor lag in temperature rise while the mockup was present. Fire plume thermocouple measurements did not record a significant disparity with and without the mockup during the pre-burn period. However, mockup trials consistently recorded fire plume temperature peaks during fire intensification on the order of 100 K higher compared to pool fire only measurements. Mockup surface thermocouple measurements consistently recorded increased temperature magnitudes toward the interior of the mockup hull and lesser values closer to its extremities.

Table 1: Test Results Summary

Case	Mean Fuel Regression Rate (g·m^2·s^{-1})	Mean Total Heat Release Rate (MW)	Mean Total Perimeter Heat Flux (kW·m^{-2})	Mean Radiation Perimeter Heat Flux (kW·m^{-2})	99% Extinguishment Time (s)	Extinguishment Efficiency (l·m^{-2})
Pool Fire Only	38.2±1.4	12.8±0.45	26.7±0.93	21.2±1.4	30.4±4.5	2.30±0.34
1:10 NLA Mockup	31.8±1.3	10.6±0.43	24.8±0.65	17.1±1.0	40.2±6.9	3.04±0.52
% Difference	16.8	16.8	6.94	19.3	32.2	32.2

Note: The values reported are in terms of mean ± standard deviation

Computational Model Set-up

The fire-suppression model used was based on an Euler-Lagrange CFD framework available in ANSYS Fluent v16.x to govern the combustion and agent application processes, respectively. A partially-premixed combustion model using the flamelet generated manifold approach was used to

govern chemical reaction kinetics. A 22-species Jet A surrogate skeletal reaction mechanism based on the composite combustion of 72.7-percent decane, 18.2-percent hexane, and 9.1-percent benzene by mass was used to generate the flamelet. The SST κ-ω Reynolds-Averaged Navier-Strokes (RANS) turbulence model was chosen for its accuracy in resolving turbulent flow around bluff bodies such as the mockup. The discrete ordinates radiation and single step Khan and Greeves soot model provided radiation and soot interaction. Agent spray dynamics were accounted for using the discrete phase model (DPM) to simulate AFFF solution droplet transport, as well as droplet heating, evaporation, and boiling. Two-way turbulence, heat, and mass transfer coupled the gaseous combustion and agent droplet phases.

The indoor fire test facility was approximated using a three-dimensional, cylindrical-shaped domain. The domain floor and ceiling boundaries were modeled as an adiabatic no-slip wall and the surrounding far-field as a pressure outlet. A fuel vapor velocity inlet defined the fire inlet boundary with its conditions extrapolated from the fuel regression rate and the thermodynamic properties of JP-8 vapor at its boiling point. The mockup surface was modeled as a thin wall with shell heat conduction thermally coupled to the surrounding gaseous flow field. Agent spray conditions were defined as DPM flat-fan-atomizer injection types with delivery conditions consistent with the experiment.

Computational Model Preliminary Findings

Preliminary CFD model findings of note show that the mean fire perimeter temperature, fire plume temperature, and mean heat release rate values are similar to experimental results given the range of uncertainty associated with each experimentally measured value in a fire test environment (i.e., 10 to 20 percent for temperature comparisons and 20 to 40 percent for heat flux comparisons). Mean perimeter heat flux, fire intensification, fire plume puffing frequency, mockup surface profile trends compared to infrared camera data, and agent delivery efficiency are among other parameters that compared well with preliminary CFD model results. Notable differences observed showed a modeled increase in the mockup surface heat-up rate as well as a modeled decreased rate of soot production compared to experiments. Quantification of CFD model uncertainty and other factors to quantify its ability to accurately predict flame extinction is currently in progress.

Conclusions

Experimental results suggest major full-scale aircraft pool fire suppression characteristics were reproducible in an indoor 1:10-scale test environment with extinguishment efficiencies reported similar to that of an analogous full-scale aircraft pool fire environment. A fixed ARFF-style agent delivery system provided reliable extinguishment results while removing the uncertainty added by man-in-the-loop firefighting. Fire intensification was shown to be significant, likely due to the rapid increase in air entrainment coupled with the agitation of the fuel surface-vapor interface by the agent spray. The presence of the mockup significantly lowered the fire heat release rate while still extending the extinguishment time compared to pool fire only conditions. This phenomena was likely due to the blockage effect imposed by the mockup to not only limit the effective range of the agent spray, but also in hindering the turbulent fuel-air mixing in the flow regime adjacent to the fuel pan. Preliminary CFD model findings suggested that aircraft pool fire-suppression behavior can be modelled to estimate most of the significant parameters that govern fire suppression for a particular aircraft-pool fire environment. Analysis of the CFD model's overall uncertainty as well as its ability to accurately predict flame extinction is currently in progress.