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Review

Numerical investigation of the heat transfer in an aeronautical composite material under fire stress

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A B S T R A C T

The use of composite materials for aeronautical applications has been growing since several years because of the opportunity to produce lightweight structures reducing the fuel bills and emissions. The need for fireproof certification imposes costly and time consuming experiments that might be replaced or complemented in the years to come by numerical calculations. The present work creates a CFD numerical model of a fireproof test. As an example, a composite part located in an aircraft APU (auxiliary power unit) which provides electric power to the aircraft is investigated. A numerical calibration of the flame is conducted according to the fireproof standards. After that, a comparison between three different turbulence models shows that the k–ε *realisable* turbulence model is the more suitable for fireproof numerical tests with discrepancies lower than 16% between computed values and measured ones. The influence of an internal air jet is observed for velocities from 1 to 10 m/s. The results demonstrate a good evaluation on how this could reduce the wall temperatures and ensure the requirements of the certification rules compare to the actual external thermal protection used to ensure the certification requirements. Indeed, final temperature reductions up to 45% are found at reference point on the structure with the highest value of air jet velocity.

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1. Introduction

The use of composite materials for aeronautical applications (such as structural and semi-structural air frame [1], turbine engine component [2], spacecraft re-entry thermal protection [3] and other thermal insulator [4,5]) has been growing since several years because of the opportunity to produce high strength, high stiffness and lightweight structures [6] reducing the fuel bills and emissions [7]. The growing use of these materials leads to technical and design challenges to comply with safety standards and certifications, especially when fire safety requirements are concerned. Composite materials have a large potential to increase the fire hazard due to the flammable nature of the organic matrix which leads to loss in stiffness, strength and creep resistance causing distortion and collapse of composite structure [8]. Recently, the European Aviation Safety Agency (EASA) reported in its Annual Safety Review in 2013 [9] that the second most frequent cause of fatal accidents involving aeroplanes was the fire/smoke post-impact cause during the last four years. This highlights the need to carry out experimental and numerical researches to improve our understanding and ability to predict the thermal behaviour of thermo-structural aeronautical composite parts under fire stress. These parts which are dedicated to firewall applications or located in designated fire zones should meet a fireproof requirement and they have to pass fire tests according to ISO 2685 [10] or FAA-AC20-135 (FAR-25) [11] standards. The testing involves the immersion of the component under study into a standard flame which is intended to be a realistic scenario of an in-service or post-impact fire event. Both standards use an oil burner to heat the part with a minimum temperature of 1100 °C for 15 min.

Concerning other experimental and numerical modelling approaches, there is a large number of literature works dealing with the fire safety in different subject of the aeronautical engineering area [12–22]. Indeed concerning aircraft material engineering, Neumeyer et al. [12] studied the fire behaviour and mechanical properties of an epoxy resin for aircraft interior with addition of flame retardant. Burns et al. [13] investigates the compression failure of carbon fibre-epoxy laminates used modern aircraft for load-bearing structures when they are exposed to fire.

Regarding numerical simulation full scale simulation have been conduct by Wang and Jia [14] to define the characteristics of the flame spread over cabin interiors compared to full-scale aircraft-fire experiment and the show a reasonable approximation to the measured flashover time. Song et al. [15] performed a CFD simulation on aircraft full-size fuel tank to discuss of shrinkage ratio to develop future aircraft fuel tank made of composite materials who reach the metal material performance. In her work Oztekin [16] focused on the heat and mass transfer due to a small-fire in an aircraft cargo compartment to model in-flight fire consequences. Previously, Galea and Markatos [17] developed a numerical model of fire development in aircraft for different scenario. The smoke transport subject has been studied by Blake and Suo-Anttila [18] who validate a smoke transport model which could be used to enhance the fire detection system certification process by identifying worst-case locations for fires, optimum placement of fire detector sensors within the cargo compartment. Mouritz [19] focused on the smoke toxicity of fibre–polymer composites used in Aircraft and gives an overview of the health hazards with the smoke released from burning aircraft composite materials. The aircraft evacuation theme, which is the one of the most important parameter in post-crash fire event, was studied by Yang et al. [20], Liu et al. [21] and Miyoshi et al. [22] who deal with passenger evacuation with different conditions.

Despite the existence of several works on fire safety in aircraft engineering presented above, there is to our knowledge a lack of data dealing with numerical calculations on aircraft full-size parts regarding fire certification, such as the work of Sikoutris et al. [23] who present the potential and the applicability of such calculation to model the burnthrough response of aluminium and composite structure subject to a gas burner used in certification process. The aim of this work is to develop a 3D numerical simulation approach using a CFD code to investigate the predictivity of a numerical fireproof test. This numerical step is expected to complement (if not, to replace, depending on certification agencies) experiments during the development phases of the composite parts before the certification test and to reduce the development costs. This numerical tool would help engineering designers to choose between different composite materials and designs options to avoid critical temperature increases at certain locations and to avoid perforation in these full-size parts during fireproof tests.

The next section of the paper is dedicated to the description of the experimental setup and the third one presents the physical and numerical modelling approaches. In the fourth section, the structure temperature fields are compared for three different turbulence models to the experimental data to evaluate the predictivity of the proposed numerical approach. Then the results are discussed. The feasibility of replacing a thermal protection by an internal air jet is also presented in this paper as first design case.

2. Experimental setup

To be labelled “fireproof” as it is requested in most of the APU part (Auxiliary power unit) specifications and according to the related standards [10,11], the plenum has to resist 15 min to a calibrated flame. The Figs. 1 and 2 present respectively a picture and an overview of the experimental setup. The composite part is located at 100 mm from the outlet of the cone burner above a vibrating table (sinusoidal vibration of 0.4 mm amplitude and 50 Hz frequency). The oil burner (kerosene–air) operates with a kerosene flow rate of Q_v^{carb}=1.94 ×10^{-6}m^3/s and the air flow rate is adjusted to Q_v^{air}=2.5 ×10^{-2}m^3/s to generate a diffusion flame (Equivalence ratio approximately equal to 0.88) with: (i) Flame temperature of 1100 °C measured at 100 mm and (ii) Heat flux of 120 kW/m^2. The flame temperature is measured at 100 mm by a six thermocouples rack. When the temperature is adjusted and stabilized around 1100 °C the heat flux is measured, thanks to a specific device where water is circulating along a copper pipe exposed to the flame. The water flow rate and temperature are 6.28 × 10^{-5}m^3/s and 25 °C respectively. According to the standards, the minimum temperature increase has to be 5 °C. Two thermocouples (noted TC 1 and TC 2) are located in the plenum internal surface to monitor the internal wall temperatures (cf. Fig. 3) and two cameras are used to record the experimental fire test.

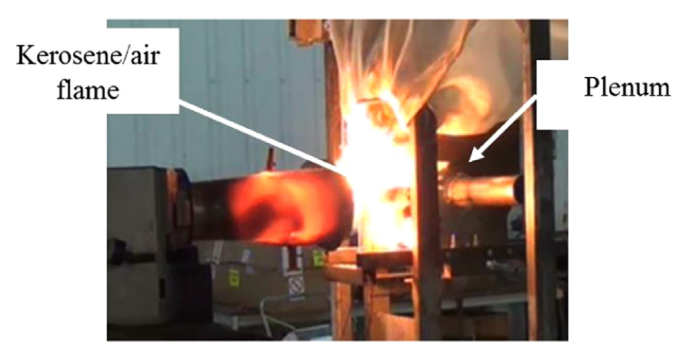

Fig. 1. Photograph of the fire test bench.