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Experimental and numerical analysis of thermally dissipating equipment in an aircraft confined compartment

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HIGHLIGHTS

- Experimental and numerical analysis of a populated aircraft crown compartment.
- Results show a stratified thermal environment with minimal ventilation interaction.
- Heat transfer on dissipating equipment surfaces varies as a function of position.
- Enthalpic correction was used to give good approximation between 2D and 3D results.

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ABSTRACT

Aircraft confined compartments are subject to a wide range of boundary conditions during operation which leads to the setting up of complex internal thermal environments. These compartments require strict thermal management to ensure safe and reliable operation of installed systems. This work investigates the thermal and fluid flow fields in one such compartment – the crown area in a fuselage of a commercial aircraft which contains thermally dissipating equipment. Experimental heat transfer and PIV measurements are compared to 3D numerical simulations and are shown to be in very good agreement. There was found to be significant thermal stratification present due to the ventilation not penetrating into the bulk of the fluid. Convective heat transfer coefficients on the surfaces of the dissipating equipment varied as a function of their location, with the highest values occurring when they are placed close to the ventilation inlet. An enthalpic correction was applied to 2D simulations leading to significantly reduced solution times, and results which give a good approximation of the 3D model results.

This type of detailed study of aircraft confined compartments is necessary to improve understanding of the flow regimes present in these areas, and leads to optimal positioning of installed systems in terms of thermal management, as well improving global thermal aircraft model predictions.

1. Introduction

The increasing complexity of modern commercial aircraft requires manufacturers to implement equally complex systems for thermal management due to emerging technologies, such as more electrical and bleedless aircraft power systems [1–4]. The increased use of composite over aluminium in aircraft structures also poses a new challenge [5–8]. The thermal behaviour of a composite aircraft is clearly different from an aluminium one and as a result, higher internal ambient temperatures can be reached which can lead to reliability and safety issues when aircraft systems are placed in confined compartments of the aircraft.

The tool used at present to predict the heat transfer in the confined compartments at the design stage is the global thermal model, which allows the aircraft structure, systems and ambient environmental temperatures to be determined at different mission points. The model is built from a 3D geometrical model of the aircraft and includes blocks representing the various systems [2]. Examples of the obtained fuselage skin temperature for a ground and take-off case are shown in Fig. 1, where the highlighted running fuel pumps can be identified as a source of heat during take-off [9].

The developed models however, can be inaccurate due to these block simplifications and the use of estimated heat transfer coefficients as they do not take into account local thermal issues that can arise in relatively large compartments. Including a detailed model of the system equipment leads to a significant increase in computational costs which becomes impractical for virtual prototyping [10].

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Nomenclature

A	area (m^2)
c_p	specific heat capacity (J kg^{-1} K^{-1})
D	depth (m)
d	diameter (m)
E_b	black body emissive power (W m^{-2})
F	view factor (–)
g	gravity (m s^{-2})
H	height (m)
H'	internal height (m)
h	specific enthalpy (J kg^{-1})
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
I	electrical current (A)
J	radiosity (W m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
n	number of image pairs (–)
$\dot{q}$	heat transfer rate (W)
q''	heat flux (W m^{-2})
T	temperature (K)
t	transient time step (s)
U	velocity magnitude (m s^{-1})
$\overline{U}$	time-averaged velocity magnitude (m s^{-1})
u	velocity component in x-direction (m s^{-1})
V	voltage (V)
v	velocity component in y-direction (m s^{-1})
x, y	Cartesian coordinates (m)

Acronyms

Al	aluminium
CFRP	carbon fibre reinforced polymer
PC	polycarbonate
PIV	particle image velocimetry
RMSD	root mean square difference
SEPDC	secondary electrical power distribution centre

Greek symbols

β	thermal expansion coefficient (K^{-1})
ε	emissivity (–)

Subscripts

adj	adjusted
avg	average
in	inlet
fus	fuselage
l	left
out	outlet
R	Route G dissipating element
r	right
rad	radiation
ref	reference
S	SEPDC dissipating element

Detailed studies of the fluid and thermal flow fields in the main passenger cabin to improve passenger and crew comfort and reduce the spread of airborne disease have been popular [11–14], but there has only been recent detailed investigations to characterise the thermal environments in confined compartments with the aim of increasing the prediction capabilities of the global model while also decreasing its computational size. Butler et al. [15] presented a methodology to optimise equipment placement in fuselage confined compartments and developed models to predict the convective heat transfer coefficients of equipment in a crown compartment. Stafford et al. [10,16] and Geron et al. [17] developed compact thermal-fluid models for the mixed convection regimes for equipment in an aircraft avionics bay and for an unpopulated fuselage compartment for inclusion in global thermal models. Gur et al. [18] conducted a parametric design study to optimise the APU compartment and demonstrated its inclusion in a global model.

The aim of this work is to conduct a detailed experimental and numerical study of an aircraft fuselage crown compartment in order to improve the understanding of the fluid and thermal flow fields present in this area. The crown compartment is defined as the confined area between the passenger cabin and the external fuselage as shown in Fig. 2. The area corresponds to a complex configuration in terms of geometry, air volume, installed systems and ventilation. This investigation deals with the time the aircraft is on the ground during turn around when systems are still operational and the fuselage experiences high skin temperature due to solar heating (as seen in Fig. 1a). During this time, the installed systems will generate heat, warming the surrounding air. Ventilation exiting from the passenger cabin enters the crown before circulating into other confined areas. Hot climatic conditions can lead to temperature gradients across different internal and external surfaces. Radiation heat exchange between surfaces can also play a significant role. All of this leads to the setting up of a conjugate heat transfer problem and a complex thermal environment inside the compartment. With the increased use of composite materials and additional electrical systems, the need for characterisation and understanding of any possible safety or reliability issues with equipment placed in confined areas of aircraft has become imperative.

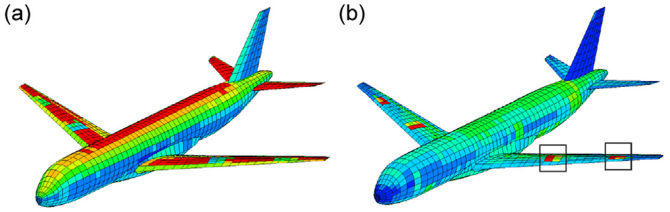

Fig. 1. Global thermal aircraft model results for fuselage skin temperature. (a) Ground case, (b) take-off case, from Liscouët-Hanke [9] used with permission.

This work forms part of the overall European FP7 funded MAAXIMUS (More Affordable Aircraft through eXtended, Integrated and Mature nUmerical Sizing) project. The project aims to develop a new methodology for the fast development and right-first-time validation of a highly optimised composite fuselage due to a coordinated effort between virtual structure development and composite technology. This work is part of the thermal section of the project which is developing heat transfer models for avionic equipment in aircraft confined compartments in the next generation of commercial aircraft.

2. Experimental analysis

This section describes the experimental test rig and procedure. An experimental analysis was deemed necessary not only to