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Thermal analysis and modeling of surface heat exchangers operating in the transonic regime

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ABSTRACT

Surface coolers for tightly packed airbreathing propulsion are proposed to evacuate the heat loads from the lubrication circuit. This paper demonstrates the capability of integrated bypass-flow surface heat exchangers to cope with the high cooling demands from innovative engine architectures. The present publication describes the experimental and numerical methodology to model the thermal performance of a surface cooler within an aero-engine. Experiments were carried out in a dedicated facility that reproduced transonic engine conditions, allowing the determination of surface temperature distribution with infrared thermography. The thermal convective process was characterized by means of an ad-hoc three dimensional inverse heat conduction approach. An unprecedented energy model was then developed to analyze the sensitivity of the heat exchanger capacity to different engine operating conditions. The results indicate that the investigated concept may provide up to 76% of the estimated lubrication cooling requirements during take-off of a modern gas turbine power plant.

1. Introduction

Lubrication heat load is of particular relevance in the design of any future energy related system. The architectural complexities of novel propulsion engines [1] and the growing importance of electronic devices [2] are drawing the current oil cooling capacity to its operational limit [3]. Hence, adequate thermal management of the engine system is mandatory to allow the continuous evolution towards more efficient and less polluting aero-transportation systems.

Future aircraft engine designs aiming to decrease specific fuel consumption, such as the open rotor, geared turbofan, and contra-rotating turbofan, are characterized by compact gas generators. The additional mechanical transmission components (gear boxes, bearings) increase the heat dissipation to the lubricant [1], hence saturating the currently available cooling sources. Fuel is the primary cooling source due to its high density and thermal conductivity, allowing the design of compact Fuel Cooled Oil Cooler heat exchangers. In addition fuel/oil coolers do not affect the aerodynamic performance of the engine and allow regenerative cycle modification. However, the capacity of the fuel as a cold source is limited by the maximum allowed temperature in the tank [4] which is a particular concern for future high speed and all-composite airframes [5]. When this limit is reached it becomes imperative to explore alternative heat exchange methods.

In the present work, the use of aerodynamically optimized air cooled oil cooler (ACOC) heat exchangers is considered as an alternative to ensure the correct operation of all the mechanical components, within the bypass duct of a turbofan engine during the flight envelope, keeping oil and fuel within its functional limits. Although, this concept has been proposed in various patents [6,7], it has been scarcely addressed in the public literature. In a similar context, Filburn et al. [8] presented an oversimplified analysis of the heat released by finned heat exchangers. The literature is profuse in heat exchangers with extended surface or finned surface as a common design choice to augment the heat transfer process [9]. The increase of effective heat exchange area enhances the cooling capacity [10] and additionally, the proper aerodynamic design of the fins might lead to an improvement of the heat transfer coefficients. However, investigations are generally focused in heat exchangers for low velocity air flow applications, and references to finned heat exchanger performances in high-speed flows are scant. The present paper focuses on the aero-thermal process induced within a surface integrated finned air/oil cooler immersed in a transonic bypass flow, as shown in Fig. 1a).

The bypass flow downstream of the fan is characterized by transonic flow velocities and swirl angles ranging between 40 and 50°. The heat exchanger model was tested in a unique three dimensionally shaped transonic wind tunnel, represented in

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Nomenclature

a	coefficient of exponential fit
b	coefficient of exponential fit
K_f	thermal conductivity of the fluid (W/m K)
h	convective heat transfer coefficient (W/m^2 K)
Ma	Mach number
Pr	Prandl number
Q	wall heat flux (W/m^2)
R^2	quality of the linear fit
R	objective function
T	temperature (K)
Y	measured temperature (K)
V	flow velocity (m/s)
Greek symbols	
η	heat exchanger efficiency
ρ	fluid density (kg/m^3)
μ	fluid viscosity (N s/m^2)
Acronyms	
ACOC	air cooled oil cooler
IGV	inlet guide vanes
IHCM	inverse heat conduction method
IR	infrared
PIX	pixel
Subscripts	
0	total condition
ad	adiabatic condition
b	base
exp	experimental
in	inlet
max	maximum temperature
out	outlet

Fig. 1b) and c), that duplicates the core/bypass flow separator (splitter) at real scale and capable of reproducing the streamlines curvature of the engine representative flow.

The literature dedicated to this type of aero-thermal process at transonic regimes is scarce in contrast with multiple studies performed at low Reynolds and Mach numbers [11–13]. Hence, the present transonic tunnel with infrared optical access allowed unprecedented analysis of the convective process in high speed flows.

The three dimensional shaped surface cooler model is depicted in Fig. 2a). During the 20–40 s test the internal heat conduction process is complex, where typical mono or bi-dimensional assumptions [14] would fail. For this reason, an innovative processing technique based on a transient three dimensional inverse heat conduction method (IHCM) had to be employed. This technique, coupled with robust finite element solvers and thermal imaging methods, models complex geometries by considering the full three dimensional (3D) heat transfer problem.

The inverse heat conduction problem is mathematically ill-posed due to the instability created by the unavoidable noise in the measurements. Several mathematical regularization techniques were developed in the past to allow for a stable solution of these problems [15]. In the present research, an iterative regularization, proposed by Alifanov [16], was coupled with a three dimensional finite element solver (Comsol®) [17]. Prior to the final

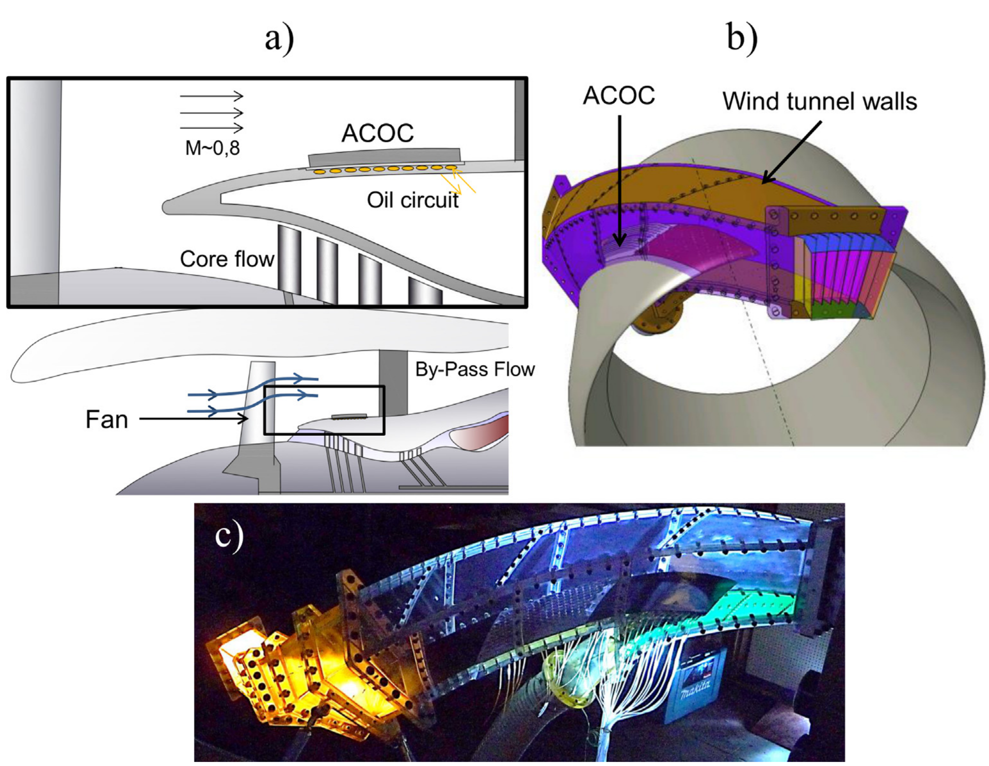

Fig. 1. Illustration of the ACOC location with a detailed view of the investigated domain, a); artistic view of the three dimensional shaped test section, b); image of the experimental test section, c).