Thermal instrumentation, test and modeling of surface coolers in representative aerodynamic conditions

The recent technological developments in the aeronautical domain and the continuous search for more efficient engine architectures demands a parallel investigation on advanced oil cooling strategies. The usual cold sources like the inlet air stream and the fuel circuit are approaching their limits as new engine designs are exploited. The higher level of complexity on the mechanical systems requires an adequate thermal management of the systems. The heat removal by the aircraft structure will be limited by the use of composite materials with lower operational temperature and thermal conductivity properties. Furthermore, the limitation on the maximum fuel temperature decreases the viability of the fuel tank as a cold source.

The present work is included in the research frame of novel engine cooling strategy. It has the objective to quantify the thermal performance of an Air Cooled Oil Cooler (ACOC) heat exchanger assembled on the inner wall of the secondary duct of a turbofan. The goal of such design is to use the available surface as a heat exchanger between the air and the oil. In order to increase the thermal performance, the wet area is increased by adding longitudinal fins, reaching the required heat dissipation power. Such a design implies a strong compromise between the aerodynamic penalties, (introduced by the increased drag) and the thermal performance of the heat exchanger.

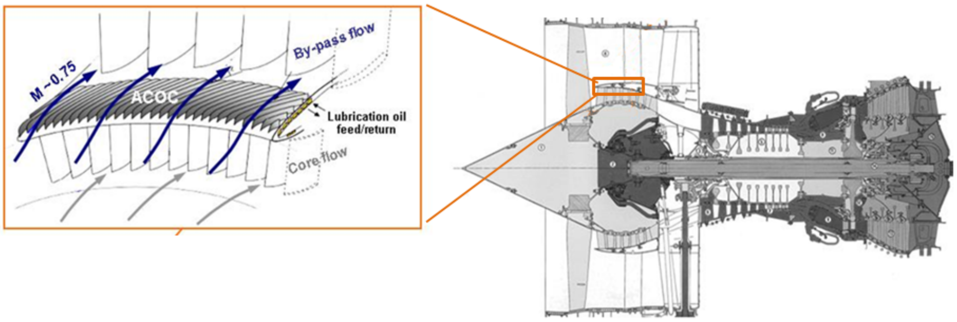

Fig. 1 Air Cooled Oil Cooler (ACOC) concept

The developed research presents an innovative aero-thermal study by testing the new heat exchanger concept in a 3D shaped transonic wind tunnel capable of reproducing the flow condition within the bypass of an engine. Innovative data processing approaches, based on inverse heat conduction methods (IHCM), were developed and employed during the course of this work.

Inverse heat conduction methods provide the possibility to reconstruct the convective wall heat flux responsible for the surface temperature evolution during an experimental test. This approach, when coupled with spatial temperature transducers such as Infrared Thermography (IR), contributed to an important increase of flexibility. This fact allowed the analysis of models with non-negligible three dimensional heat conduction effects. The implemented IHCM was based on an iterative Alifanov procedure. Conjugate gradient methods with the adjoint problem were used as a minimization technique. The coupling of the inverse heat conduction solver with a commercial finite element program (COMSOL MULTIPHYSICS) provided the possibility to solve a generalized transient 3D IHCP.

For validation purpose, numerical and experimental methodologies were developed to test the solver for a variety of situations. This process revealed to be of paramount importance to understand the sensitivity of the method to different parameters that typically govern the heat transfer process. The validation was obtained by imposing a known heat flux on a surface of the numerical domain. Afterwards, the resulting temperatures were used as an input to the IHCM.

Finally the estimated heat flux was compared with the exact one and the errors quantified. Heat fluxes with strong temporal and spatial discontinuities revealed to be more difficult to estimate. The influence of noisy measurements was attained by adding artificial noise on the input temperatures. The robustness of the procedure to this important parameter was verified. Fig. 2 illustrates the numerical validation performed on the ACOC geometry. The study revealed the capability of the developed methodology to recover the adiabatic heat transfer coefficient and the adiabatic wall temperature with an average uncertainty below 20%.

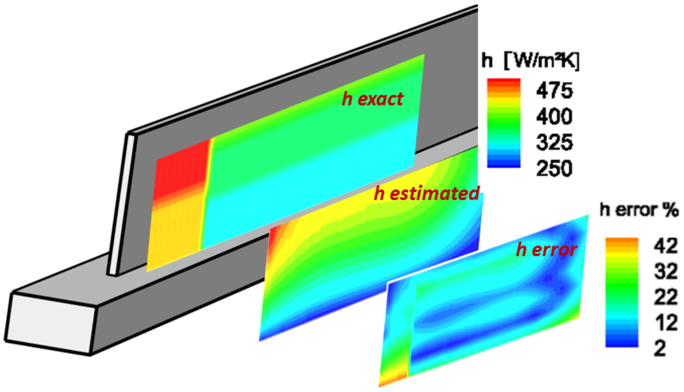

Fig. 2 Numerical Validation of the inverse heat conduction post-processing method

The wind tunnel, specifically designed for the aerodynamic research, was able to replicate the air flow conditions on the by-pass flow of a turbofan. For the thermal research the test section walls were adapted to support direct IR optical access to the model. However due to the complexity of the geometry, full optical access on one complete fin was not possible. Therefore the 3D heat transfer process over one full fin was retrieved using the developed IHCM. The test was performed on a model with continuous fins along the axial direction of the engine.

The experiments were started by imposing an initial wall temperature (T_{wi}) to maximize the temperature difference between the wall and the flow temperature (T_f) resulting in higher heat flux values. Fig. 3 illustrates the wall temperature evolution and the power imposed to the heaters (Q) during the experiments. After thermal steady state was reached (1) the blow down was started. When steady flow conditions were attained the heaters were turned off (2). The wall temperature was monitored during the entire process by the infrared camera. Based on a linear fitting between the measured wall temperature and the computed heat flux, the adiabatic condition was obtained by extrapolating the fitted curve to null heat flux. The correspondent temperature is the adiabatic wall temperature (T_{ad}) while the slope represents the adiabatic heat transfer coefficient (h_{ad}).

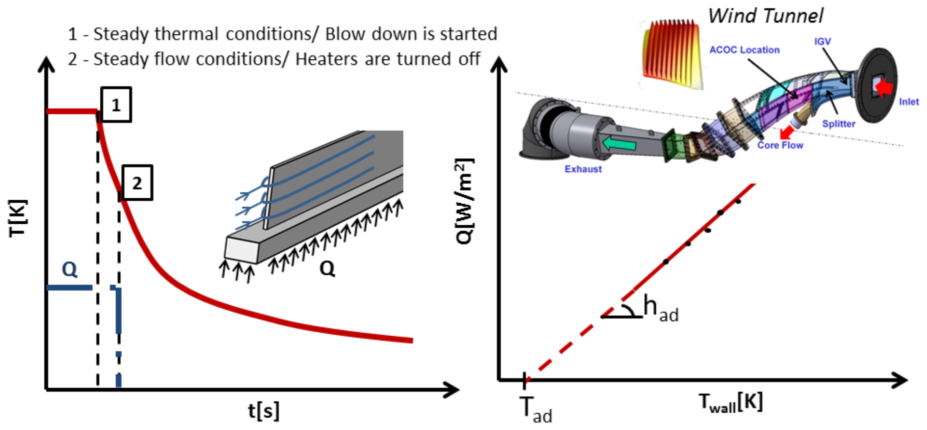

Fig. 3 Experimental methodology and post-processing approach to compute h_{ad} and T_{ad}

Fig. 4 a) depicts the results obtained for the lateral wall of the fin. The adiabatic heat transfer coefficient presents a maximum at the leading edge, followed by an exponential decrease along the axial direction (for X>50 the results were neglected due to the high uncertainty at these locations). Such evolution in the streamwise direction is in accordance with the one expected for a turbulent boundary layer. The values of the adiabatic wall temperature proved to be similar to the total inlet flow temperature. Fig 5 b) shows the estimated values of h_{ad} and T_{ad} on the bottom surface that revealed to be higher when compared to the lateral wall of the fin. The values of the h_{ad} in the bottom surface decreased in fins flow passage.

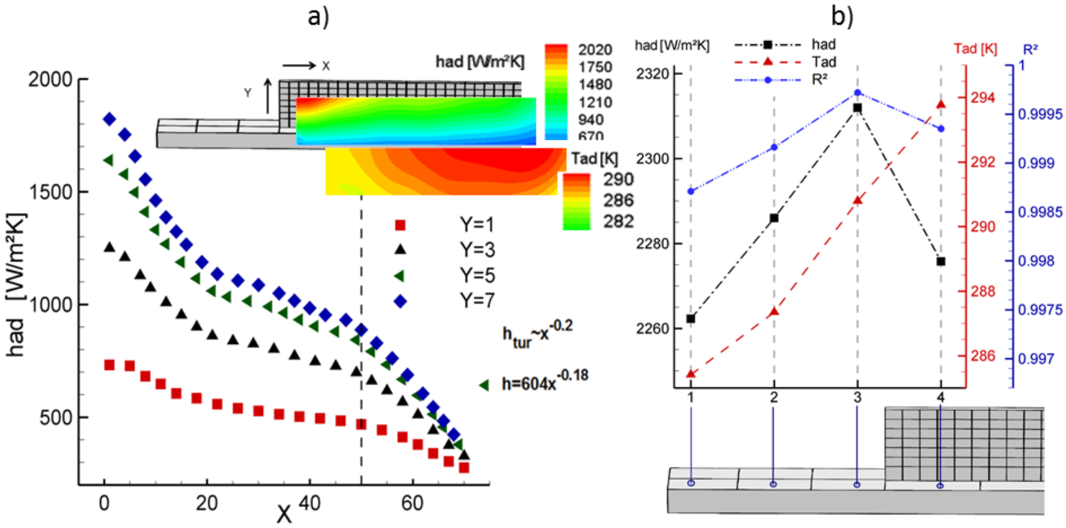

Fig. 4 h_{ad} and T_{ad} distribution on the lateral of the fin a) and on the bottom surface of the model.

The developed data processing technique allowed the determination of the adiabatic heat transfer coefficient and the respective adiabatic wall temperature along the walls of the heat exchanger. An estimation of the heat dissipation capacity of the studied surface cooler is now possible by imposing the expected boundary condition, for the air flow and the oil, at engine operating conditions.