PP06: INTERCOOLED RECUPERATED AERO ENGINE: EARLY DEVELOPMENT STAGES AND OPTIMIZATION OF RECUPERATION BASED ON CONVENTIONAL HEAT EXCHANGERS

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Abstract. In the last two decades, the European Union, in collaboration with main European aero engine manufacturers, Universities and Institutes funded a number of research efforts aiming at the design of innovative aero engines operating on advanced thermodynamic cycles presenting reduced fuel consumption and pollutant emissions, promoting the fulfillment of year 2020 ACARE targets. A part of these activities was focused on an innovative advanced aero engine concept, the Intercooled Recuperated Aero engine (IRA-engine), developed by MTU Aero Engines AG, using an alternative thermodynamic cycle combining both intercooling and recuperation. Under this concept recuperation is achieved by the integration of a heat recuperation system based on heat exchangers mounted inside the hot-gas exhaust nozzle. The recuperation system exploits the exhaust hot-gas energy to preheat the compressor discharge air before the latter enters the combustion chamber, resulting in reduced fuel consumption and pollutants emission. The present paper focuses on the early optimization stages of the IRA-engine recuperation system based on the MTU developed state-of-the-art U-type tubular heat exchanger, performed in AEROHEX and NEWAC projects, aiming mainly at the minimization of heat exchangers pressure losses. The optimization was performed with CFD computations in which the heat exchangers were modelled as porosity models of predefined heat transfer and pressure loss macroscopic behaviour, validated through experimental measurements. For the optimization various customized 3-D models of the recuperation system were developed and investigated which led to considerable pressure loss reduction with positive effects on fuel consumption and pollutants emissions reduction.

Keywords: recuperative aero engines, heat exchangers, porosity models, fuel consumption reduction, pollutant emissions reduction

INTRODUCTION

Commercial aviation presents a history of successful technological advancements affecting the lives of millions of people globally. As air traffic grows at an annual rate of about 5%, the need to increase aero engines efficiency and reduce NOx, CO2 and other gaseous emissions becomes more urgent to mitigate their negative environmental footprint, e.g. on global warming. In the last two decades, the European Union, in collaboration with main European aero engine manufacturers, Universities and Institutes funded a number of research efforts aiming at the design of innovative aero engines operating on advanced thermodynamic cycles presenting reduced fuel consumption and pollutant emissions, promoting the fulfillment of year 2020 ACARE targets. A part of these activities was focused on an innovative advanced aero engine concept, the Intercooled Recuperated Aero engine (IRA-engine). This concept which is developed by MTU Aero Engines AG and is presented in Figure 1a is using an alternative thermodynamic cycle combining both intercooling and recuperation. In the IRA-engine cycle, recuperation is achieved by the integration of a heat recuperation system based on heat exchangers mounted inside the hot-gas exhaust nozzle. The recuperation system exploits the exhaust hot-gas energy to preheat the compressor discharge air before the latter enters the combustion chamber, resulting in reduced fuel consumption and pollutants emission.

The present paper focuses on the early optimization stages of the IRA-engine recuperation system, performed in AEROHEX and NEWAC projects, aiming mainly at the minimization of heat exchangers pressure losses since their effect on the overall aero engine cycle was identified as significant. The IRA-engine recuperation system is based on use of various heat exchangers placed in a specific arrangement inside the hot-gas exhaust nozzle and is based on the MTU developed state-of-the-art U-type tubular heat exchanger (HEX) which is presented in Figure 1b. As it can be seen, the MTU-developed heat exchanger consists of elliptic tubes placed in a 4/3/4 staggered arrangement in order to provide increased heat exchange surface area and thus, increased heat exchanger effectiveness coupled with reduced outer flow pressure losses.The heat exchangers of the IRA-engine are operating as heat recuperators focusing on the exploitation of the waste heat energy of the low pressure turbine exhaust gas so as to preheat the high pressure compressor discharge air right before combustion and decrease the fuel consumption and gas pollutants emissions. Detailed information about this technology is presented in the works of Wilfert and Masse (2001), Wilfert et al. (2007), Schonenborn et al. (2004) and Albanakis et al. (2009).

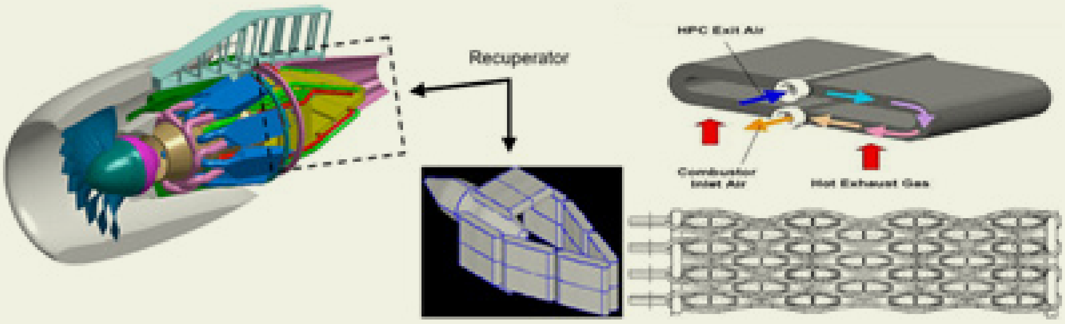

Figure 1a. The IRA - Intercooled Recuperative Aero-engine. 1b. The MTU-heat exchanger.

OPTIMIZATION OF RECUPERATION BASED ON CONVENTIONAL HEAT EXCHANGERS

Due to its direct positioning inside the exhaust nozzle, right after the low pressure turbine, the heat exchangers can impose significant pressure losses which can strongly affect the aero engine performance and the achieved produced work resulting in the degradation of recuperation technology benefits. As it is profound, due to cost and conditions limitations, the conducting of an optimization campaign for the heat exchangers installation inside the exhaust nozzle is of particular importance. For this reasons, the optimization was performed mainly with 3D CFD computations in which the heat exchangers were modelled as porosity models of predefined heat transfer and pressure loss macroscopic behaviour, validated through experimental measurements. Details about the porosity model approach can be found in Missirlis et al. (2009, 2010) and Yakinthos et al. (2006, 2007). The optimization efforts started from the reference (AEROHEX) nozzle configuration, shown in Figure 2.

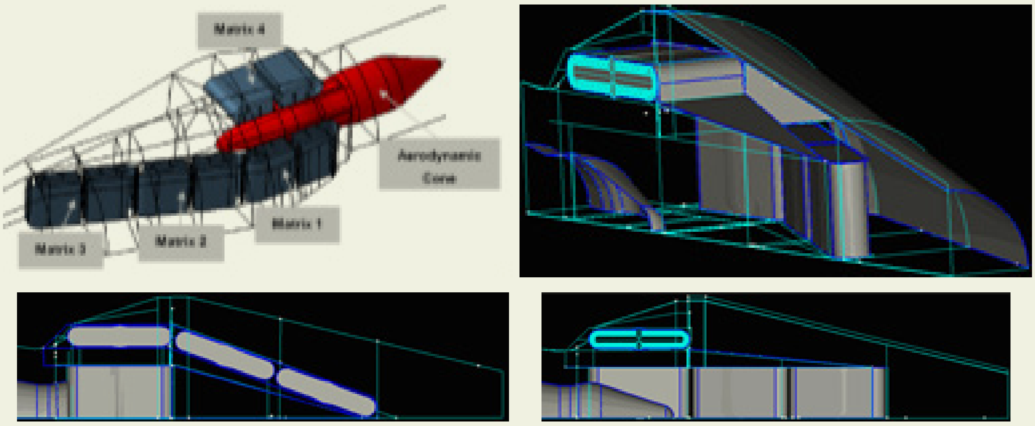

Figure 2. Reference nozzle configuration (AEROHEX) setup– 1/4 nozzle representation

Figure 3. Reference nozzle configuration (AEROHEX) test-rig – 1/4 nozzle representation

In this configuration the heat exchangers were placed in a 0/20/20/0 orientation. For this arrangement experimental measurements on a specially constructed test-rig, presented in Figure 3, were carried-out and CFD computations, mainly with the Shear stress Transport (SST) turbulence model of Menter (1994), following the porosity model approach were performed, Figure 4 shows the CFD grid, and a detailed inside look at the flow was derived, revealing major flow separation regions and secondary flow 3D (swirl) effects resulting in increased pressure losses as presented in Figure 5.

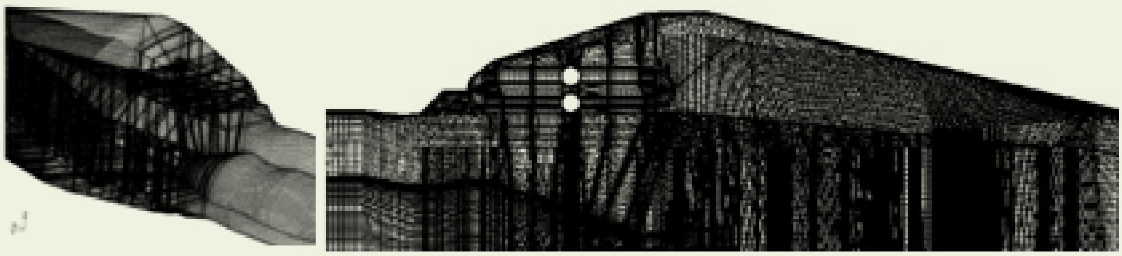

Figure 4. Reference nozzle configuration (AEROHEX) CFD grid – 1/4 nozzle representation

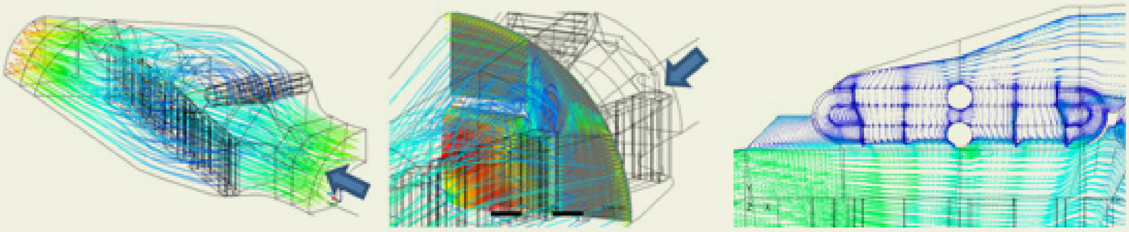

Figure 5. Reference nozzle configuration (AEROHEX) CFD results – 1/4 nozzle representation

Targeting the further optimization of the recuperator various customized 3-D models of the recuperation system were developed, being always based on the MTU-developed tubular heat exchanger, and investigated numerically through additional similar CFD computations. These attempts, performed in the NEWAC project, led to various optimization modifications, presented in Figure 6, which were incorporated in a dedicated test-rig, presented in Figure 7, in which experimental measurements were carried-out for validation purposes.

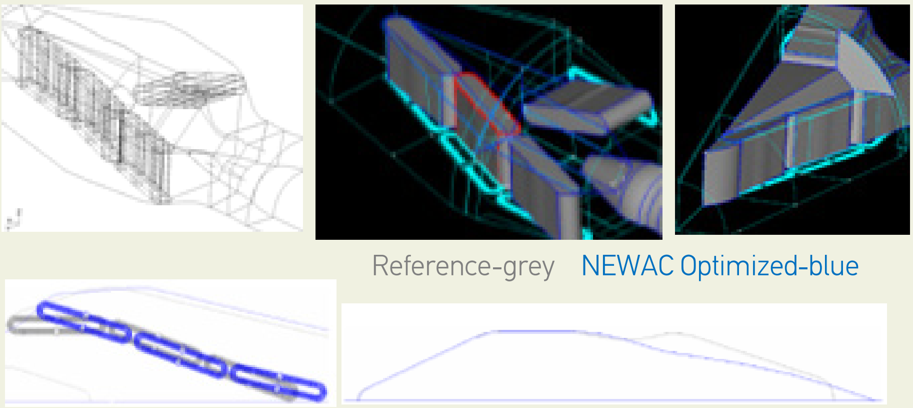

Figure 6. NEWAC optimized case. Modifications in relation to the reference case

Figure 7. NEWAC optimized case test-rig– 1/4 nozzle representation

The following modifications were mainly focused on changes on the orientation of HEX matrices 1/2/3/4 is now at 17/20/13/17 degrees, redesign of the aerodynamic cone in order to minimize the recirculation region downstream the cone, additional changes in the nozzle guiding walls, the addition of an aerodynamic ramp after HEX matrix 3 and adaptation of the HEX bow region covers. These modifications resulted in the significant decrease of the secondary flow losses, due to swirl effects and recirculation regions, and to the achievement of a much more homogeneous flow field distribution (especially through the HEXs of the installation which are placed upstream and encounter significant flow recirculation) which led to the decrease of the flow velocity maxima and to reduced pressure losses. As a result, the NEWAC optimized case provided more than 15% reduced pressure losses in relation to the Reference case, while achieving the same HEXs effectiveness value.

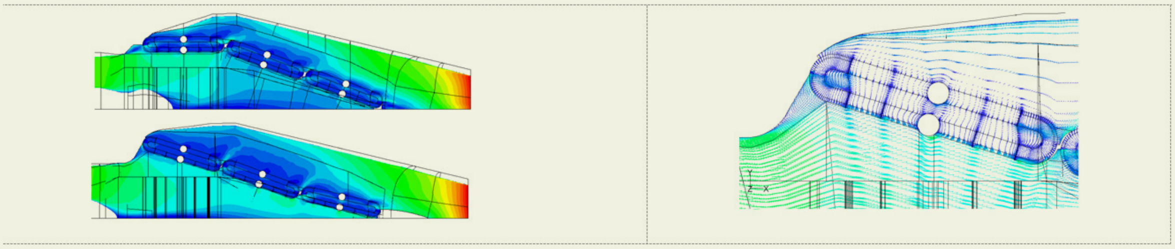

Figure 8. NEWAC optimized case CFD results – 1/4 nozzle representation
(Left: velocity magnitude qualitative comparison in relation to Reference case, Right: velocity flow at the inlet HEXs)

At the final step of the analysis, the major characteristics of the recuperator installation of both concepts were incorporated in GasTurb 11, (Kurzke, 2011) and their effect on the IRA-engine thermodynamic cycle was quantified. The results, showed that the NEWAC optimized nozzle could achieve a specific fuel consumption reduction of ~1.0% with positive effects also on the decrease of pollutants emissions as a result of the considerable pressure loss reduction.

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