# INTERCOOLED RECUPERATED AERO ENGINE: DEVELOPMENT AND OPTIMIZATION OF INNOVATIVE HEAT EXCHANGER CONCEPTS

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**Abstract.** At the present paper the main activities, performed in the LEMCOTEC research project focused on the further optimization of the recuperation system of the Intercooled Recuperated Aero engine (IRA-engine) concept are presented. This concept, developed by MTU Aero Engines AG is based on the use of an advanced thermodynamic cycle combining both intercooling and recuperation through a system of heat exchangers mounted inside the hot-gas exhaust nozzle, providing fuel economy and reduced pollutant emissions. The investigation and the optimization efforts of the recuperation system were performed with the use of 2D/3D CFD computations, experimental measurements and thermodynamic cycle analysis for a wide range of engine operating conditions. The optimization activities were based on the development of a customizable numerical tool which was based on an advanced porosity model approach in which the heat exchangers were modeled as porous media of predefined heat transfer and pressure loss behaviour and could also incorporate major and critical heat exchanger design decisions in the CFD computations. The optimization efforts resulted in two completely new innovative heat exchanger concepts, named as CORN (COnical Recuperative Nozzle) and STARTREC (STraight AnnulaR Thermal RECuperator). These concepts were following an annular tubes design inside the hot-gas exhaust nozzle leading to the elimination of swirl effects and to homogeneous flow distribution. Additionally, the two new concepts provided significant benefits in terms of fuel consumption, pollutants emission and weight in relation to more conventional heat exchanger designs proving that further optimization potential for this technology exists.

**Keywords: Heat exchangers, Porosity model, Recuperation, Aero engine optimization**

## INTRODUCTION

The present paper is focused on a large part of the main activities, performed in the E.U. funded LEMCOTEC Collaborative Project, which its key-objective is to reduce air-traffic emissions by improving the thermal efficiency of aero-engines, (http://www.lemcotec.eu/). The enhancement of aero engine performance and the reduction of fuel consumption and pollutant emissions have always been on the focal point of intense engineering optimization efforts for both environmental and economic reasons. A large number of these efforts has been focused on the development of alternative technologies and their incorporation in innovative aero engine concepts. Such a technology concept is implemented in the Intercooled Recuperative Aero-engine (IRA engine) configuration, which is presented in Figure 1a, which combines both intercooling and recuperation.

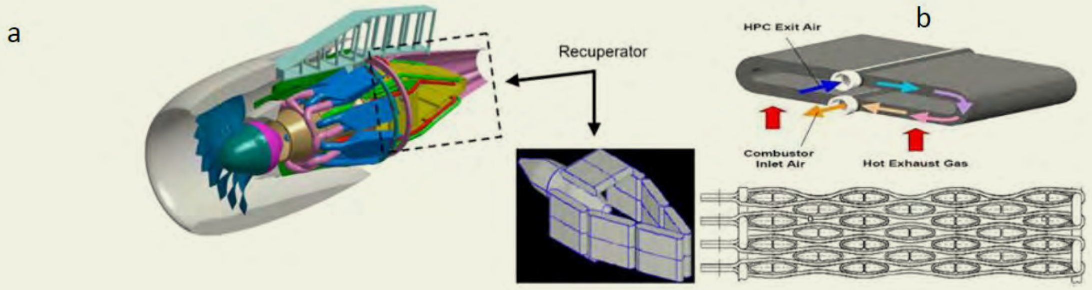

Figure 1a. The IRA - Intercooled Recuperative Aero-engine.
1b. The MTU-heat exchanger.

This concept is based on a system of heat exchangers mounted inside the hot-gas exhaust nozzle and an intercooler placed between the compressor stages. The hot-gas exhaust heat, downstream the low pressure turbine exit is driven back to the combustion chamber and thus, the preheated ambient air enters the combustion chamber with increased enthalpy, providing fuel economy and reduced pollutant emissions. In addition, the use of intercooling, a technology which performs at its best for thermodynamic cycle conditions which facilitate recuperation, contributes to a reduction of high pressure compressor work leading to a further improvement of aero engine efficiency. Both intercooling and recuperation are performed through the use of specially designed and integrated heat exchangers.

## OPTIMIZATION OF HEAT EXCHANGER CONCEPTS

The present work is focused on the optimization of the heat exchangers geometries and installation in order to maximize the recuperation benefits, specifically targeted for IRA engine. More details about the IRA engine concept can be found in (Boggia & Rüd, 2004), (Wilfert et al., 1999). The implementation of recuperation in IRA engine is performed through the mounting of a number of heat exchangers inside the hot-gas exhaust nozzle, downstream the low pressure turbine. The basic heat exchanger (HEX) of the IRA engine, which was invented and developed by MTU Aero Engines AG and was used for the initial HEX performance studies, is presented in Figure 1b. It consists of elliptically profiled tubes placed in a 4/3/4 staggered arrangement targeting high heat transfer rates and reduced pressure losses. Additional information of the HEX operation can be found in (Schonenborn et al., 2004). The HEX tubes geometry and arrangement can significantly affect the turbine expansion and thus, degrade the produced turbine work, due to the imposed pressure losses. The overall heat exchanger design plays a critical role in this direction since the pressure losses are directly linked to the available heat exchange surface and its geometry, which in its turn strongly affects the HEX effectiveness and the exhaust gas waste heat exploitation. As a result, a compromise is necessary to be taken into account between the HEX design parameters in order to achieve the maximization of recuperation benefits. Towards this direction, the development of accurate and validated numerical tools is of particular importance since they can provide time- and cost-efficient design solutions which can lead to the a-priori estimation of the HEX major operational characteristics (i.e. pressure losses and effectiveness). These operational characteristics can then be integrated in a thermodynamic cycle analysis of the aero engine in order to assess the recuperation effects on aero engine efficiency and fuel consumption. Thus, these tools can significantly contribute to the development, assessment and optimization of various innovative heat exchanger concepts which otherwise could not be affordable in laboratory (due to time and cost limitations).

Source terms for pressure losses in the momentum equations

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho U\\ \rho V\\ \rho W\\ \rho E\end{bmatrix}+\frac{\partial}{\partial x_i}\begin{bmatrix}\rho U_i\\ \rho U_i U+P\delta_{ij}\\ \rho U_i V+P\delta_{ij}\\ \rho U_i W+P\delta_{ij}\\ \rho E U_i+PV_i\end{bmatrix}=\frac{\partial}{\partial x_i}\begin{bmatrix}0\\ \mu\left(\frac{\partial U}{\partial x_i}+\frac{\partial U_i}{\partial x}\right)-\frac{2}{3}\mu\frac{\partial U_k}{\partial x_k}\delta_{ij}\\ \mu\left(\frac{\partial V}{\partial x_i}+\frac{\partial U_i}{\partial y}\right)-\frac{2}{3}\mu\frac{\partial U_k}{\partial x_k}\delta_{ij}\\ \mu\left(\frac{\partial W}{\partial x_i}+\frac{\partial U_i}{\partial z}\right)-\frac{2}{3}\mu\frac{\partial U_k}{\partial x_k}\delta_{ij}\\ \left(\mu\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)-\frac{2}{3}\mu\frac{\partial U_k}{\partial x_k}\delta_{ij}\right)U_j-k\frac{\partial T}{\partial x_i}\end{bmatrix}-\frac{\partial}{\partial x_i}\begin{bmatrix}0\\ \rho\overline{uu_i}\\ \rho\overline{vu_i}\\ \rho\overline{wu_i}\\ \rho\overline{u_ju_i}+\rho\overline{Tu_i}\end{bmatrix}+\begin{bmatrix}0\\ \boxed{\begin{matrix}\frac{(a_0+a_1v)}{L}\mu U+\frac{(b_0+b_1v+b_2v^2)}{L}\rho U|U|\\ \frac{(a_0+a_1v)}{L}\mu V+\frac{(b_0+b_1v+b_2v^2)}{L}\rho V|U|\\ \frac{(a_0+a_1v)}{L}\mu W+\frac{(b_0+b_1v+b_2v^2)}{L}\rho W|U|\end{matrix}}\\ \boxed{U_{overall}(T-T_{inner})S_{exchange}}\end{bmatrix}$$

Source terms for HEX heat transfer in the energy equation

Figure 2. Implementation of pressure loss and heat transfer source terms in the porosity model.

At the present work the development and optimization of innovative heat exchanger concepts, focused on the Intercooled Recuperated Aero Engine, are presented which are an evolution of the original MTU HEX design. The investigation and the optimization efforts of the present work were performed with the use of 2D/3D CFD computations, experimental measurements and thermodynamic cycle analysis for a wide range of engine operating conditions. The optimization activities were mainly based on the use of an innovative customizable 3D numerical tool which could efficiently model the heat transfer and pressure loss performance of the heat exchangers of the IRA-engine installation. The developed numerical tool was based on an advanced porosity model approach in which the heat exchangers were modelled as porous media of predefined heat transfer and pressure loss correlations which have been previously derived through detailed CFD computations and experimental measurements and are numerically incorporated in the CFD computations by the addition of appropriate source terms in the momentum and energy equations, as presented in Figure 2. The innovative customizable 3D numerical tool could also incorporate major and critical heat exchanger design decisions in the CFD computations by supporting the numerical integration of heat exchanger geometrical characteristics (e.g. tubes collectors number, streams flow splitting and mixing, tubes core arrangement). Additional details about the customizable numerical tool can be found in (Yakinthos et al., 2015). At the first stage of the present investigation, the NEWAC nozzle configuration, related to the NEW Aero engine Core concepts/NEWAC research project, was investigated with the use of CFD computations (following also a porous media approach for the heat exchangers), presented in detail in Figure 3a. This nozzle configuration corresponds to a quarter of the overall nozzle installation due to the heat exchangers symmetric arrangement. The NEWAC nozzle configuration consists of 4 heat exchangers (HEXs) per quarter of the exhaust nozzle. The HEXs 1-2-3-4 are placed at angles 17-20-13-17 degrees in relation to the axial flow direction. As it can be seen in Figure 3b, strong swirl effects are formed inside the NEWAC nozzle which increase pressure losses and deteriorate the HEXs performance and the recuperation benefits in the aero engine cycle. The CFD computations were performed using the SST (Shear Stress Transport) turbulence model of Menter (Menter, 1994), for a wide range of HEX conditions as presented in (Schonenborn et al., 2004). Additional details can be found in (http://ec.europa.eu/research/transport/projects/items/newac_en.htm), (Yakinthos et al., 2010), (Missirlis et al. 2010).

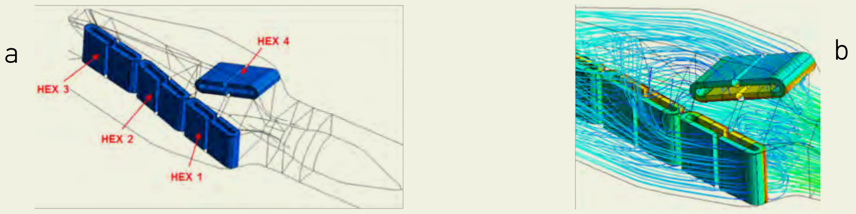

Figure 3a. NEWAC nozzle configuration, 3b. Swirl effects in NEWAC nozzle.

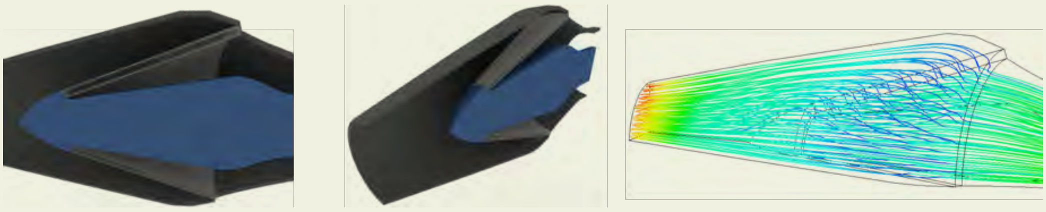

Figure 4. CORN (COnical Recuperative Nozzle) geometry and velocity streamlines.

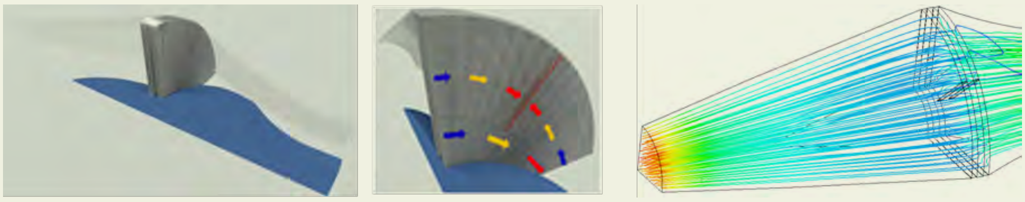

Figure 5. STARTREC (STraight AnnulaR Thermal RECuperator) geometry and velocity streamlines.

At the next steps, additional investigations targeting the optimization of the HEXs installation inside the hot-gas exhaust nozzle were performed through additional similar CFD computations and the use of the customizable numerical tool. The optimization efforts resulted in two completely new innovative HEX concepts, named as CORN (COnical Recuperative Nozzle) and STARTREC (STraight AnnulaR Thermal RECuperator), presented in Figures 4 and 5 respectively. Both concepts were based on the MTU HEX original tubes. These concepts were based on the use of innovative heat exchanger designs, following an annular tubes arrangement inside the exhaust nozzle, leading to the reduction (for the STARTREC concept) or complete elimination (for the CORN concept) of swirl effects and a more homogeneous flow distribution with reduced secondary flow losses in relation to the NEWAC nozzle configuration.

At the final stage, the major characteristics of the heat exchangers installation of both concepts were incorporated in GasTurb 11, (Kurzke, 2011) and their effect on the thermodynamic cycle of the IRA, was quantified and compared in relation to a conventional non-intercooled and non-recuperated aero-engine of similar technology level with the IRA engine. The results, summarized in Table 1, showed that the two new concepts provided significant benefits in terms of specific fuel consumption (corresponding to a direct fuel burn and pollutant emissions reduction) and weight, proving the strong optimization potential of this technology. As it can be seen, the CORN concept provided the best performance in terms of specific fuel consumption reduction and a small decrease in weight, while the STARTREC concept, even though it provided a smaller specific fuel consumption reduction, led to a HEX setup of significant weight reduction.

Table 1. Comparative results of recuperation concepts

| Case | **SFC reduction** (in relation to a conventional aero-engine) | **Heat exchangers weight reduction** (in relation to NEWAC) |
|---|---|---|
| NEWAC nozzle | 12.3% | 0 |
| CORN | 13.1% | ~5% |
| STARTREC | 9.1% | ~50% |

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## REFERENCES

Boggia S. and Rüd K., 2004. *Intercooled recuperated aero engine.* In Proceeding of Deutscher Luft- und Raumfahrt Kongress. Dresden, Germany.

http://ec.europa.eu/research/transport/projects/items/newac_en.htm

http://www.lemcotec.eu/

Kurzke J., 2011, Design and Off-Design Performance of Gas Turbines, GasTurb 11

Menter, F.R., 1994, *Two –Equation Eddy-Viscosity Turbulence Models for Engineering Applications,* AIAA Journal, Vol 32(8), pp. 1598-1605.

Missirlis, D., Yakinthos, K., Seite, O., Goulas, A., 2010. *Modeling an installation of recuperative heat exchangers for an Aero engine.* In Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air. Glasgow, UK

Schonenborn, H., Simon, B., Ebert, E. and Storm, P., 2004. *Thermomechanical design of a heat exchanger for a recuperative aero engine.* In Proceedings of ASME Turbo Expo 2004, Power for Land, Sea and Air. Vienna, Austria

Wilfert G., Sieber J., Rolt A., Baker N., Touyeras A. and Colantuoni S., 2007. *New environmental friendly aero engine core concepts.* In Proceedings of ISABE 2007 conference. Beijing, China.

Yakinthos, D. Misirlis, Z. Vlahostergios, M. Flouros, S. Donnerhack, A. Goulas, 2015 *BEST STRATEGIES FOR THE DEVELOPMENT OF A HOLISTIC POROSITY MODEL OF A HEAT EXCHANGER FOR AERO ENGINE APPLICATIONS.* In Proceedings of ASME Turbo Expo 2015: Power for Land, Sea and Air. Montreal, Canada

Yakinthos, K., Missirlis, D., Seite, O., Vlahostergios, Z., Goulas, A., 2010. *Modeling the operation of a heat exchanger for aero engine applications for real engine operating conditions.* In Proceedings of 8th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements. Marseille, France