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

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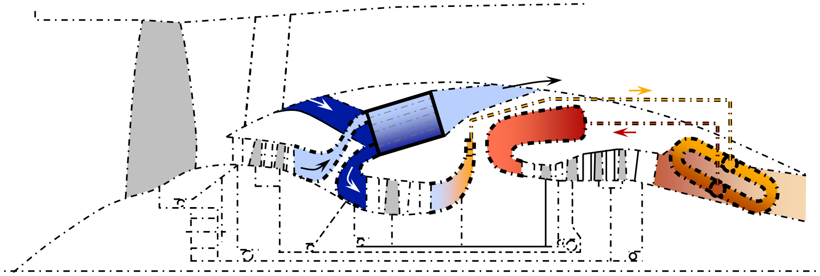
Introduction

- Global air traffic is forecasted to grow at an annual average rate of 5%.

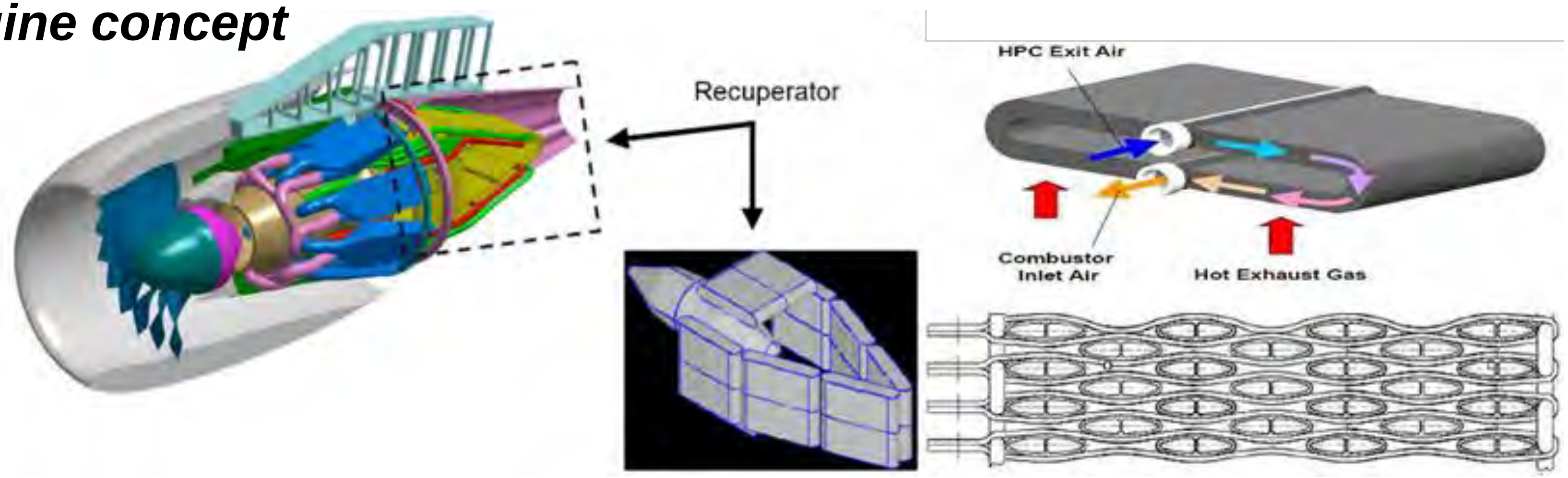
- EU together with the major European manufacturers in the aeronautical industry initiated research actions for the design of environmentally friendly engines.

- The Intercooled Recuperated Aero engine–IRA engine of MTU Aero Engines AG is a promising concept due to its positive impact to aero engine performance and pollutant emissions reduction.
- The IRA engine concept is using an alternative thermodynamic cycle with intercooling and recuperation having a system of heat exchangers (HEXs) installed in its exhaust nozzle.



The IRA engine concept

IRA engine concept



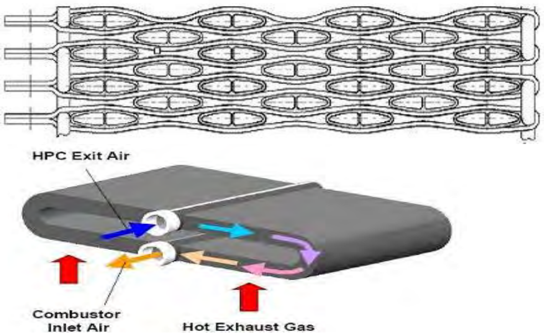
The IRA engine concept with the MTU-heat exchanger

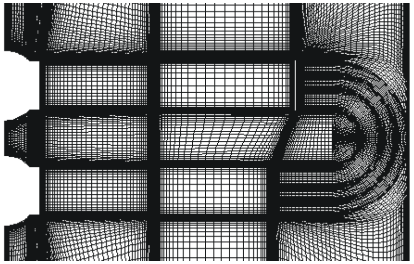
• The thermal energy of the exhaust gas is exploited by the HEXs to preheat the compressor outlet air before combustion and decrease fuel consumption and pollutant emissions.

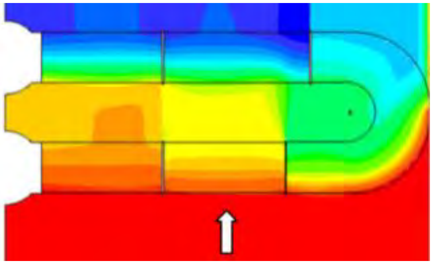
• The proper installation of heat exchangers inside the exhaust nozzle is of critical importance since it directly affects the LP turbine work potential due to the imposed pressure losses.

• Numerical/CFD tools can play a significant role in the optimization of HEXs installation and maximize the benefits of this technology.

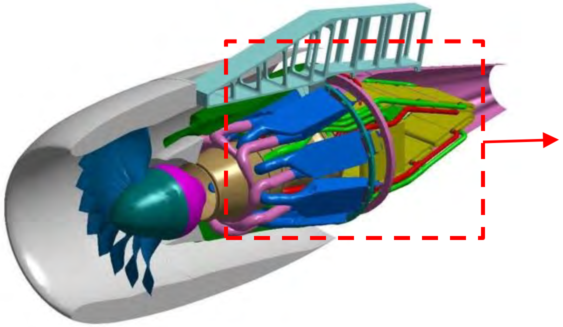
Porosity model concept

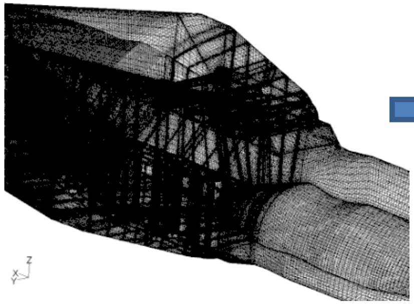


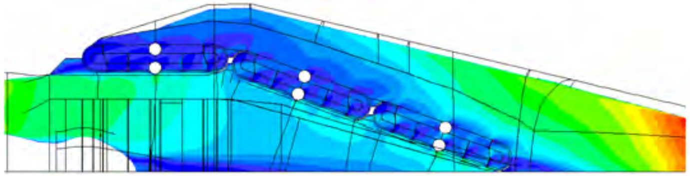




- *Only HEX outline geometry is created - Detailed elliptic tube geometry not modelled*
- *Pressure losses and heat transfer effect is included as source terms in momentum and energy equations.*
- *Correlations are derived through CFD computations and experimental measurements.*







3D CFD computations in which HEXs are treated as porous media

The number of computational points for the detailed 3D-CFD model of the overall nozzle installation, including the HEXs, <u>can exceed 1 billion nodes.</u> To compensate for this problem, HEXs are treated as porous media zones of predefined pressure drop and heat transfer macroscopic behavior.

HEX porosity model correlations

Pressure losses

Outer flow

$$\boxed{\Delta P / L = [(a_0 + a_1 v)\mu U + (b_0 + b_1 v + b_2 v^2)\rho U^2] / L}$$

Inner flow

$$\boxed{f = C_1 (\ln \mathrm{Re})^{C_2}} \qquad \boxed{f = DP_{static} / \left(\frac{l}{D}\frac{\rho U^2}{2}\right)}$$

Heat transfer

Outer flow

$$\boxed{\overline{Nu}_{D_{eq}} = C \,\mathrm{Pr}^m \,\mathrm{Re}^n}$$

$$\boxed{h_{Gas} = \frac{k(T) Nu_{D_{eq}}}{D_{eq}}}$$

Inner flow

$$\boxed{Nu_D = C' \,\mathrm{Pr}^{m'} \,\mathrm{Re}^{n'}}$$

$$\boxed{h_{inner} = \frac{k(T) Nu_D}{D}}$$

$$U_{overall} = \frac{1}{\frac{1}{h_{Gas}} + \frac{1}{h_{inner}}}$$

$$q_{local} = U_{overall}\left[T_{outer\ flow} - T_{inner\ flow}\right] S_{exchange}$$

Additional information in Yakinthos et al. GT2015-42408, ASME Turbo Expo 2015

Porosity model implementation

$$
\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho U\\ \rho V\\ \rho W\\ \rho E\end{bmatrix}+\frac{\partial}{\partial x_i}\begin{bmatrix}\rho U_i\\ \rho U_i U+P\delta_{ij}\\ \rho U_i V+P\delta_{ij}\\ \rho U_i W+P\delta_{ij}\\ \rho E U_i+PV_i\end{bmatrix}=\frac{\partial}{\partial x_i}\begin{bmatrix}0\\ \mu\left(\frac{\partial U}{\partial x_i}+\frac{\partial U_i}{\partial x}\right)-\frac{2}{3}\mu\frac{\partial U_\kappa}{\partial x_\kappa}\delta_{ij}\\ \mu\left(\frac{\partial V}{\partial x_i}+\frac{\partial U_i}{\partial y}\right)-\frac{2}{3}\mu\frac{\partial U_\kappa}{\partial x_\kappa}\delta_{ij}\\ \mu\left(\frac{\partial W}{\partial x_i}+\frac{\partial U_i}{\partial z}\right)-\frac{2}{3}\mu\frac{\partial U_\kappa}{\partial x_\kappa}\delta_{ij}\\ \left(\mu\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)-\frac{2}{3}\mu\frac{\partial U_\kappa}{\partial x_\kappa}\delta_{ij}\right)U_j-k\frac{\partial T}{\partial x_i}\end{bmatrix}-\frac{\partial}{\partial x_i}\begin{bmatrix}0\\ \overline{\rho u u_i}\\ \overline{\rho v u_i}\\ \overline{\rho w u_i}\\ \overline{\rho u_j u_i}+\overline{\rho T u_i}\end{bmatrix}+\begin{bmatrix}0\\ \frac{(a_0+a_1\nu)}{L}\mu U+\frac{(b_0+b_1\nu+b_2\nu^2)}{L}\rho U|U|\\ \frac{(a_0+a_1\nu)}{L}\mu V+\frac{(b_0+b_1\nu+b_2\nu^2)}{L}\rho V|U|\\ \frac{(a_0+a_1\nu)}{L}\mu W+\frac{(b_0+b_1\nu+b_2\nu^2)}{L}\rho W|U|\\ U_{overall}(T-T_{inner})S_{exchange}\end{bmatrix}
$$

total specific enthalpy

$$
\frac{\partial}{\partial l}[\rho u_{inner} h_{total}] = U_{overall}(T_{inner}-T)S_{exchange}
$$

$$
\frac{1}{U_{overall}}=\frac{1}{h_{outer}}+\frac{1}{h_{inner}}
$$

$$
h_{total}=h_{static}+\frac{1}{2}u^2{}_{inner}
$$

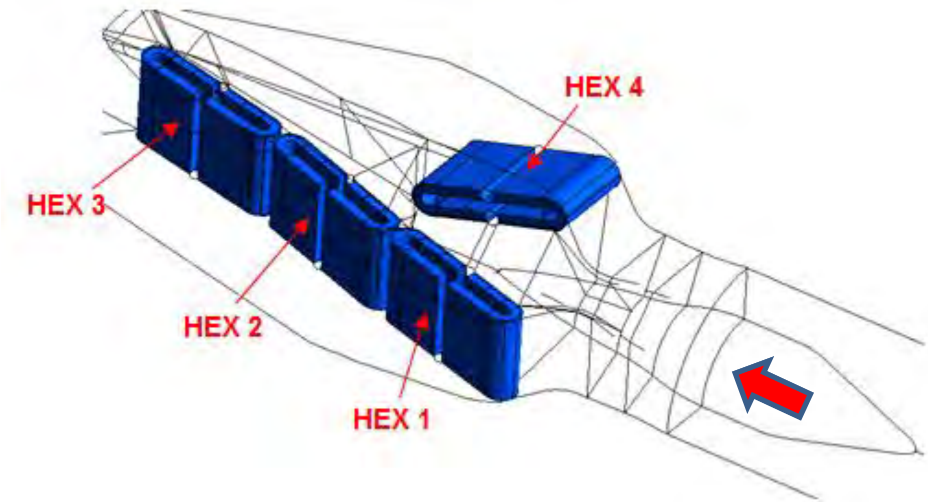
$$
\frac{\partial}{\partial l}P_{tot\_inner}=\frac{f\rho u^2{}_{inner}}{2D}
$$

additional 1D transport equations for inner flow modelling

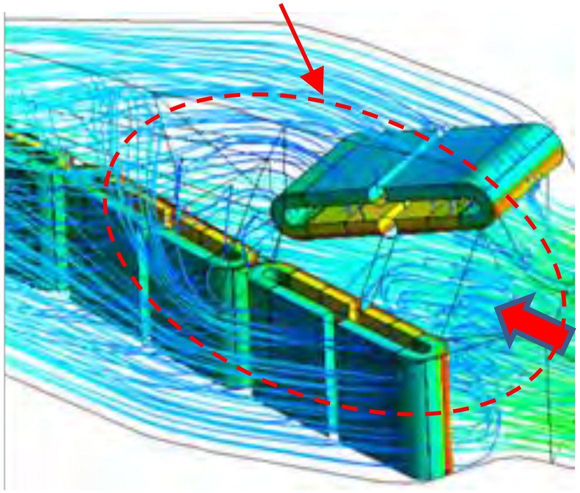
inner flow total pressure

Major heat exchanger design decisions can be incorporated by the numerical integration of HEX geometrical characteristics (e.g. tubes collectors number, tubes core arrangement).

NEWAC nozzle configuration

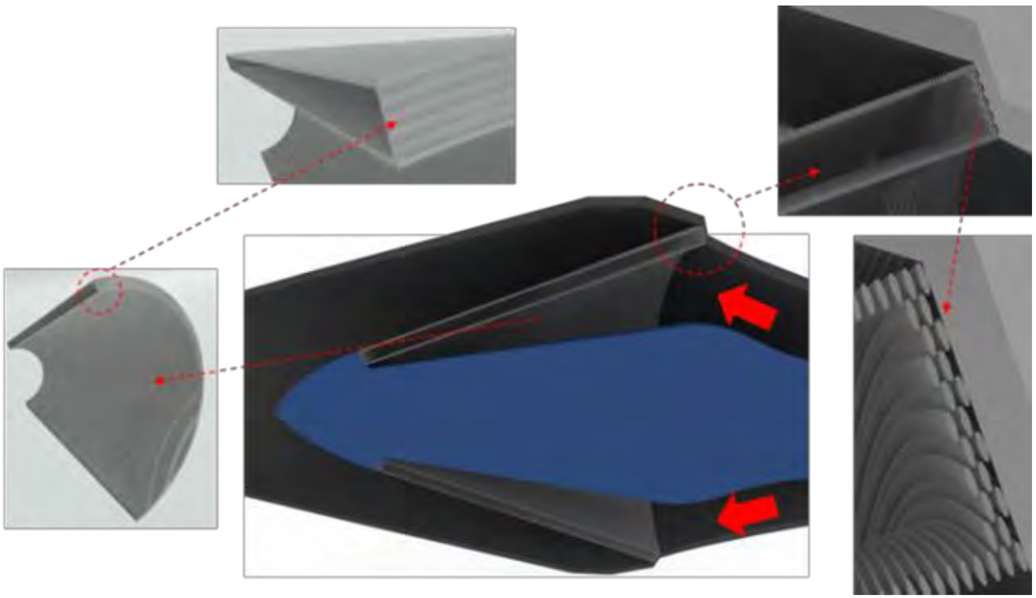


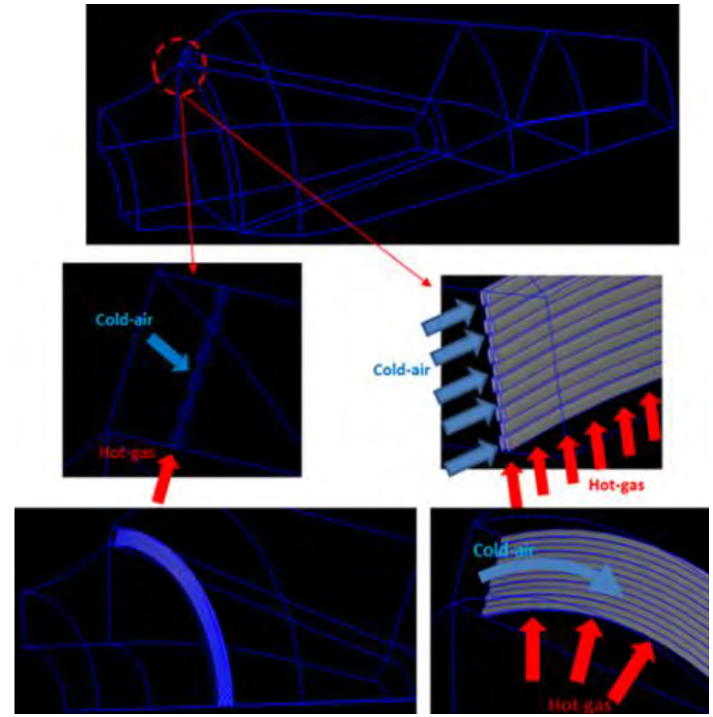
Strong swirl effects exist



- 4 HEXs per quarter of the exhaust nozzle.
- HEXs 1-2-3-4 are placed at angles 17-20-13-17 degrees in relation to axial flow.
- Strong swirl effects are formed which increase pressure losses and deteriorate the HEXs performance and recuperation benefits in the aero engine cycle.
- CFD computations using the SST (Shear Stress Transport) turbulence model in Fluent.
- HEXs are modelled with the use of a porosity model approach.

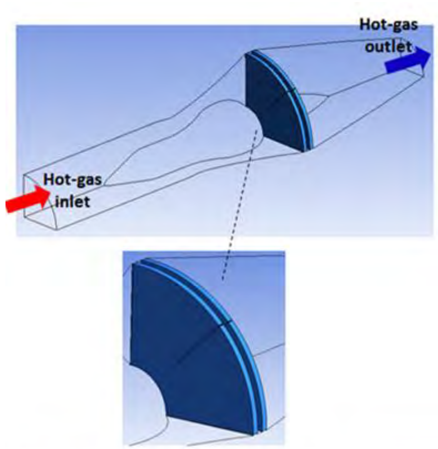
CORN (COnical Recuperative Nozzle)

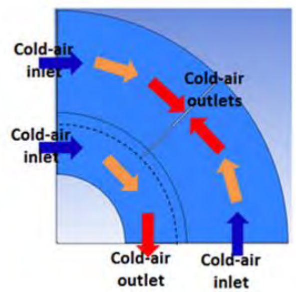


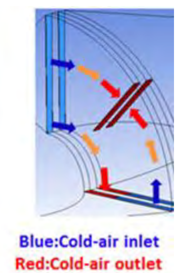


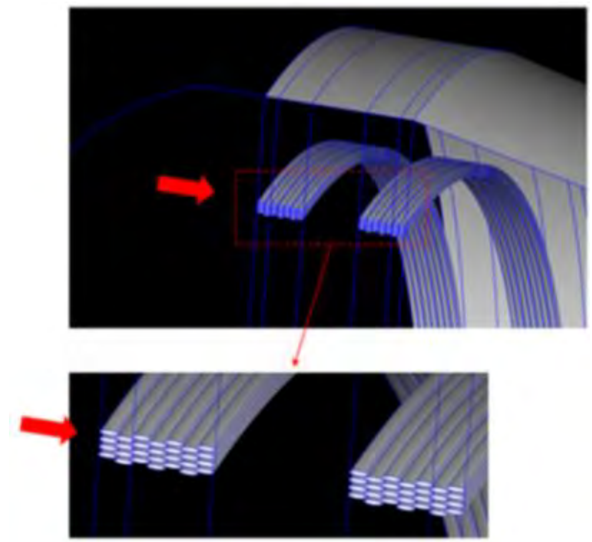
- The recuperator elliptic tubes are annularly bent inside the hot-gas exhaust nozzle by maintaining also a conical arrangement in space.
- The concept provides increased hot-gas available flow path and decreased flow velocity and pressure losses through the heat exchanger.

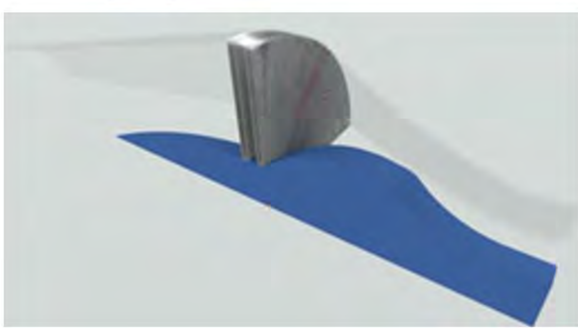
STARTREC (STraight AnnulaR Thermal RECuperator)

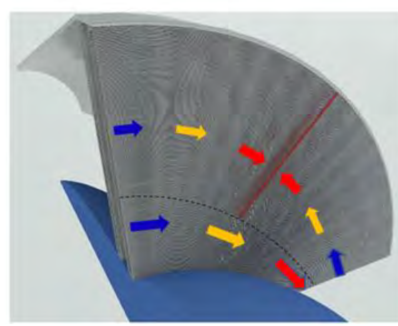








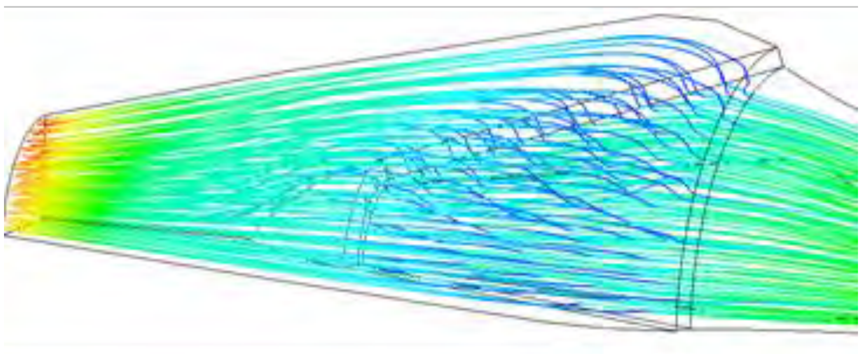




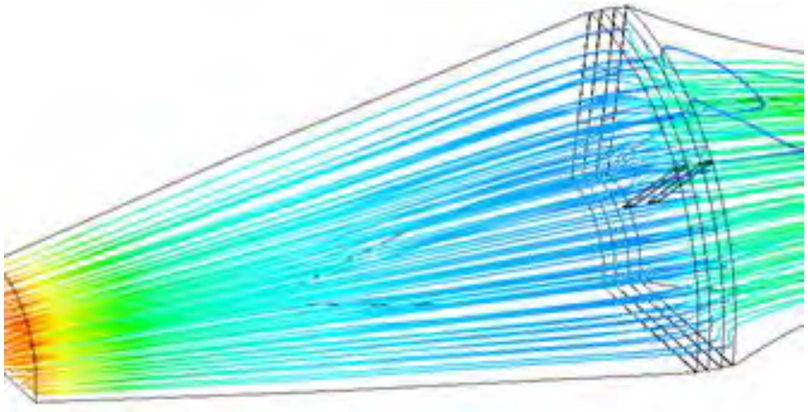
- The recuperator elliptic tubes are annularly bent inside the hot-gas exhaust nozzle.
- The recuperator is placed normal to the hot-gas main flow direction.

SEVENTH FRAMEWORK PROGRAMME

Swirl effects



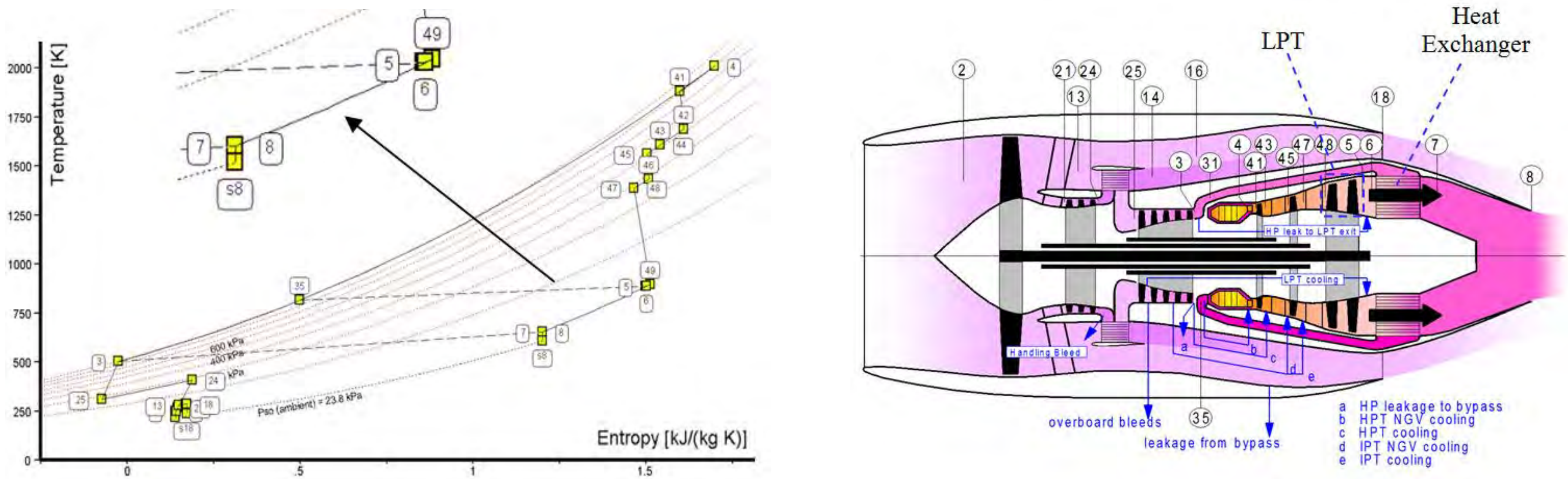
CORN



STARTREC

- Both concepts provide more homogeneous flow distribution and reduced secondary flow losses in relation to the NEWAC nozzle configuration.
- Complete elimination of swirl effect for CORN
- Reduction of swirl effects for STARTREC

Thermodynamics analysis of the aero engine



Thermodynamic cycle analysis in GasTurb11 for Average Cruise conditions

- The major characteristics of the heat exchangers installation were incorporated in a thermodynamic cycle analysis in GasTurb 11.
- The CFD results for the total pressure losses and the effectiveness of the heat exchangers system were incorporated in the cycle analysis through the use of appropriate coefficients.

Comparative results of recuperation concepts

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%

Comparison in relation to a conventional (non-intercooled and non-recuperated) aero-engine of similar technology level with the IRA engine.

- CORN concept provides the best performance in terms of specific fuel consumption reduction and a small decrease in weight.
- STARTREC concept, even though it provides a smaller specific fuel consumption reduction, leads to significant weight reduction.

Conclusions

- Optimization activities of the recuperation system of the Intercooled Recuperated Aero engine (IRA-engine) concept were performed.

- The investigations were performed with the use of CFD computations, experimental measurements and thermodynamic cycle analysis.

- The optimization activities were based on the development of a customizable numerical tool which was based on an advanced porosity model approach and could incorporate major and critical heat exchanger design decisions.

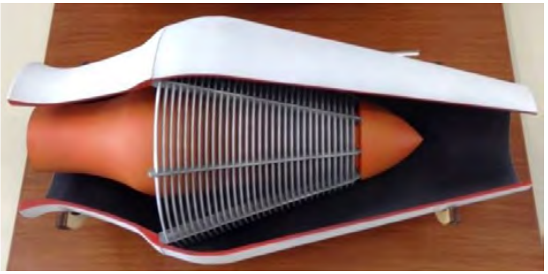
- The heat exchangers were modeled as porous media of predefined heat transfer and pressure loss behaviour.

Conclusions

- 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.

- 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.



Acknowledgments

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