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Numerical Modeling of Heat Exchangers in Gas Turbines Using CFD Computations and Thermodynamic Cycle Analysis Tools

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The optimization of energy systems such as gas turbines presents a continuous technological challenge both for economic and environmental reasons. The use of heat exchangers in gas turbines for exhaust gas waste heat recovery can strongly contribute in this direction since it can lead to significant improvement of gas turbine performance and reduction of fuel consumption and pollutant emissions. For proper implementation of a heat exchanger in gas turbines and the maximization of its benefits, engineers should be in the position to assess the most important operational characteristics such as the inner and outer pressure losses and the effectiveness. For this purpose, validated numerical tools are developed since they can provide time- and cost-efficient methods to assess the performance of various heat exchanger designs for gas turbine applications. The current work deals with the modeling of a state-of-the-art heat exchanger for gas turbine aero engine applications with the use of high-fidelity 2D and 3D CFD computations. The derived numerical results were validated against experimental measurements and the heat exchanger characteristics were integrated into the thermodynamic cycle model of the gas turbine/aero engine.
In this paper the analysis was performed in the following steps:

1. Creation of a 2D CFD model of the heat exchanger core outer flow and its validation using experimental measurements
2. Creation of a 3D CFD model of the heat exchanger for both flows (inner/outer) including the effect of heat exchanger material.
3. Computations using the 3D CFD model were performed for a wide range of operational conditions leading to the derivation of heat exchanger characteristics, inner and outer pressure losses and thermal effectiveness as functions of its operating conditions.
4. Development of a 0D thermodynamic cycle model of the gas turbine aero engine application and incorporation of the previously derived heat exchanger operational characteristics.
5. Parametric analysis and performance assessment of the gas turbine thermodynamic cycle with the incorporated heat exchanger characteristics and further optimization of the thermodynamic cycle.

This analysis is based on a heat exchanger design which was developed by MTU Aero Engines AG. The results demonstrate the potentials of the heat exchanger integration in a gas turbine/aero engine for significant performance improvement and fuel consumption reduction.

1. Introduction

Nowadays, a large number of engineering research activities is focused on the optimization of the performance of energy systems – e.g. intensifying heat transfer (Stehlík et al., 2014) and a number of works on technology, modelling and policy (Yong et al., 2016). In the last 15 years, various research activities

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targeting the performance optimization of gas turbines with a particular interest in aero engine applications have taken place within the framework of major research projects funded by European Union in close collaboration with the main European aero engine manufacturers, Universities and Research Institutes. A large part of these research activities (i.e. AEROHEX, NEWAC, LEMCOTEC projects) was focused on the implementation of waste heat recovery recuperation in aero engines applications in an attempt to meet the stringent environmental targets set by ACARE (Advisory Council for Aeronautics Research in Europe) aiming at a 20 % reduction on CO_2 and 80 % on NO_x emissions (compared to the year 2000 levels). The integration of heat exchangers in aero engines for the exploitation of the exhaust gas waste heat in order to preheat the compressor discharge air before the latter enters the combustion chamber, can lead to a significant reduction of fuel consumption and pollutants emissions and thus, a significant improvement of gas turbine performance. However, the heat exchangers integration in aero engines, which is typically implemented with the mounting of heat exchangers downstream the low pressure turbine (LPT) inside the exhaust nozzle, can strongly affect the expansion degree of the LPT due to the imposed pressure losses by the heat exchangers. These imposed pressure losses are strongly related with the heat exchange surface which is directly linked with the heat exchanger effectiveness i.e. the minimization of the pressure losses can lead to a heat exchanger of reduced heat exchange surface and thus, reduced effectiveness leading to limited exhaust gas waste heat exploitation. Thus, as it is evident, a trade-off between these parameters must be taken into consideration in order to maximize the benefits of this technology. As a result, the development of numerical tools for the a priori proper estimation of the most important operational characteristics of a heat exchanger (i.e. inner/outer pressure losses and effectiveness) can be of significant value since they can provide time- and cost-efficient methods to assess the performance of various heat exchanger designs for gas turbine aero engine applications. The present work presents such an approach for the modeling of a state-of-the-art heat exchanger for gas turbine applications with the use of high-fidelity 2D and 3D CFD computations, validated against experimental measurements, and the integration of the assessed heat exchanger characteristics in a thermodynamic numerical model of a gas turbine aero engine application.

For the analysis, the state-of-the-art heat exchanger (HEX) which was invented and developed by MTU Aero Engines AG (www.mtu.de) was used, which is presented in Figure 1. This heat exchanger consists of specially designed and profiled elliptic tubes placed in a 4/3/4 staggered arrangement aiming at increased heat transfer rate and reduced pressure losses. Additional information can be found in the work of Schonenborn et al. (2004). In addition, the analysis of the aero engine thermodynamic cycle performance was performed on the intercooled recuperative (IR) turbofan aero engine design, which is developed by MTU, where a number of HEXs are integrated inside the hot-gas exhaust nozzle in order to exploit the exhaust hot-gas high enthalpy and preheat the compressor discharge air before the latter enters the combustion chamber. In this setup, the compressor discharge air passes inside the heat exchangers elliptic tubes and is heated by the hot-gas passing around the heat exchanger tubes. Additional details regarding the IR concept can be found in the design project of Boggia et al. (2004) and Wilfert et al. (2007) presenting the conceptual core.

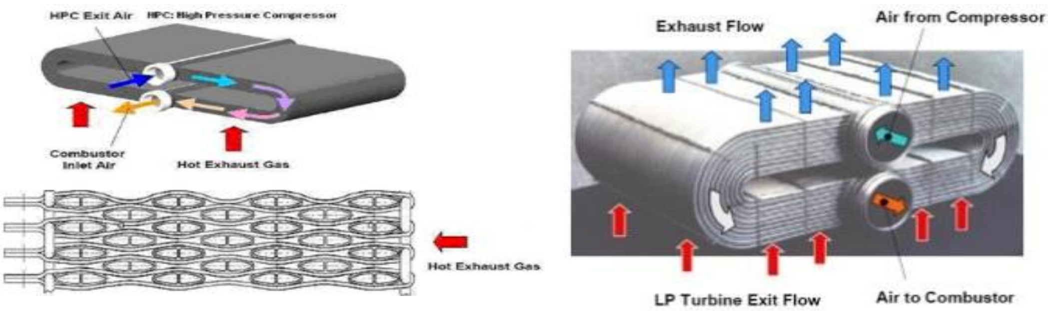


Figure 1:The MTU-heat exchanger (4/3/4 core)

2. Creation of a 2D CFD model of the heat exchanger core outer flow and experimental validation

For the determination of the outer flow pressure losses and heat transfer a 2D CFD model corresponding to the geometry of a characteristic flow path through the heat exchanger tubes was created as it can be seen in Figure 2. Regarding the boundary conditions the mass flow, total temperature and turbulence intensity were applied at the inlet while the static pressure was imposed at the outlet. At the heat exchanger elliptic tubes, two different conditions were applied i.e. adiabatic conditions and constant wall temperature conditions, which were supplied by the thermo mechanical model of MTU, Schonenborn et al. (2004), referring always to the HEX conditions during the IR engine operating conditions. Furthermore, periodic conditions were applied to the top and bottom boundaries. The computations were performed in a CFD model consisting of ~350000 computational nodes (after some initial computations with various grids in order to check the grid independency of the results). The CFD computations were performed with the use of the Shear Stress Transport (SST) low-Reynolds turbulence model, as presented in Menter (1994) with the Ansys/Fluent CFD software. Additional computations were also performed with the use of the low Reynolds stress omega RSM model that is based on the omega equations and LRR model, Wilcox (1998).

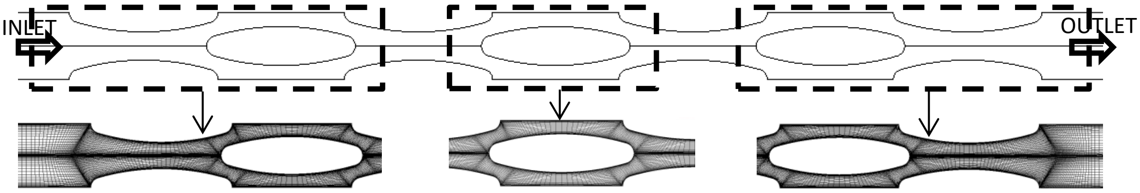


Figure 2: The 2D CFD model of the HEX flow path

For the validation of the 2D CFD model the computational results were compared in relation to the experimental data of Albanakis et al. (2009) and are presented in Figures 3 and 4 where a close agreement is presented. The 2D CFD results were also validated in close agreement in relation to the experimental measurements presented in the work of Goulas et al. (2014).

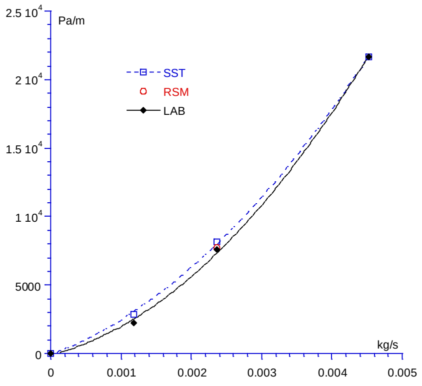


Figure 3: Static pressure drop per unit HEX length (from inlet to outlet) comparison

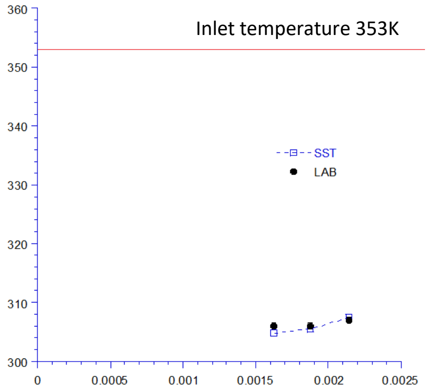


Figure 4: Outlet static temperature comparison (inlet temperature equal to 353 K for all cases)

This 2D CFD model was used as the basis to create an additional 2D CFD model corresponding to a HEX 10:1 scale experimental setup (corresponding to straight HEX core geometry) which is presented in Figure 5.

Figure 5: HEX core 10:1 experimental setup

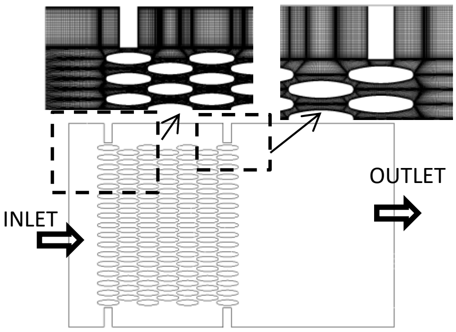
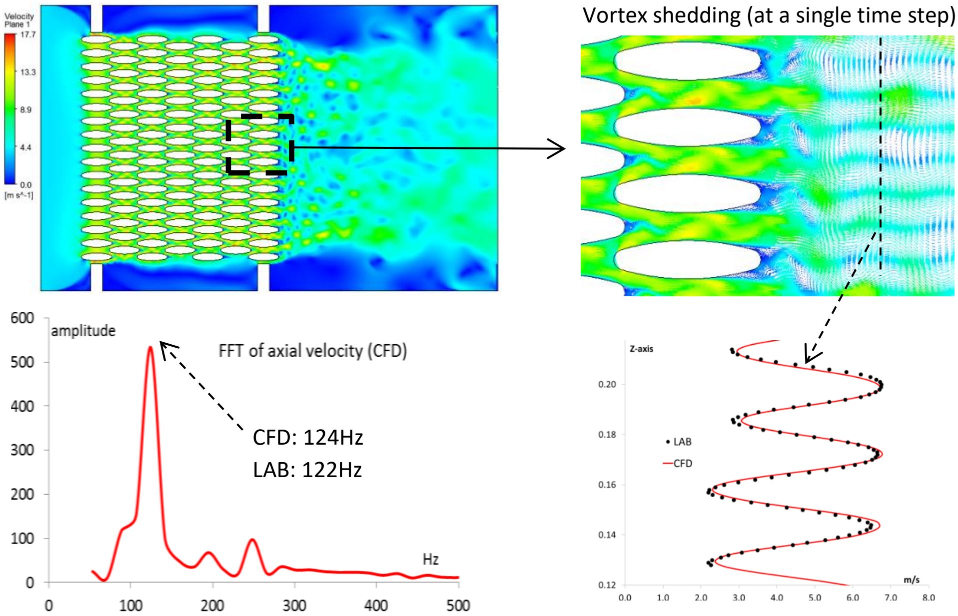


Figure 6: HEX 10:1 2D CFD model

In this setup, detailed isothermal pressure and velocity measurements have been carried out in planes perpendicular to the mean flow using Hot Wire and LDA techniques, for the velocity measurements, and Pitot-Static tubes for the pressure measurements. Details can be found in Goulas et al. (2003). The 2D CFD model consisted of ~1.7 million computational nodes. The computations were performed with the use of the low-Reynolds Omega Reynolds Stress model in Ansys/CFX CFD software.

Due to the unsteady nature of the flow as strong vortex shedding was occurring downstream the elliptic tube trailing edge, the flow field was computed as unsteady (the selected time step was equal to 0.03 ms corresponding to ~1/275 period). The CFD results were in close agreement with the experimental measurements as presented in Figure 7.



Axial velocity (CFD) Fast Fourier Transformation (FFT)

Time-averaged axial-velocity comparison (downstream last tube trailing edge)

Figure 7: CFD results of the 2D model and comparison with experimental measurements

3. 3D CFD computations on a model of the heat exchanger for both flows (inner/outer) including the effect of heat exchanger material

After the validation of the 2D CFD model a detailed 3D CFD model (of similar quality and grid points distribution) consisting of approximately 5.5 million computational nodes was created. The 3D CFD model was composed by three flow domains, the inner flow domain (corresponding to the compressor discharge flow path), the outer flow domain (corresponding to the hot-gas flow path) and the elliptic tubes material solid domain, which is presented in Figure 8.

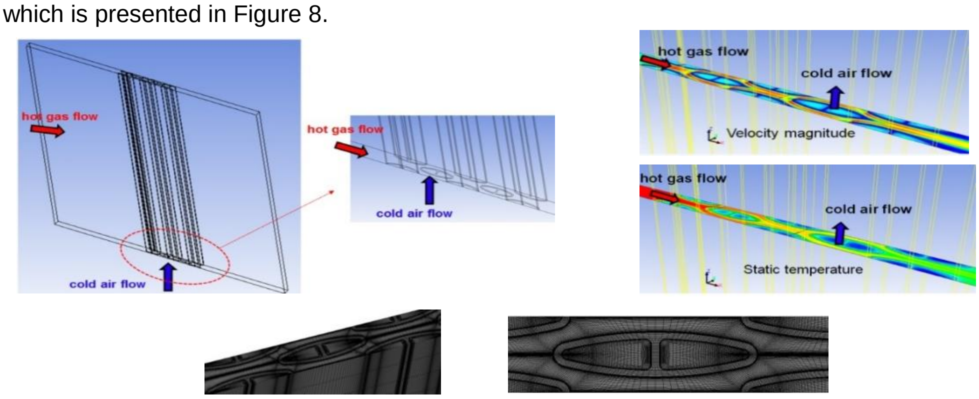


Figure 8: 3D CFD model

CFD computations were performed using the SST turbulence model, for a wide range of operational conditions corresponding to the HEX conditions during the IR aero engine operational conditions, Schonenborn et al. (2004). From the analysis of the CFD results the major heat exchanger characteristics i.e. inner and outer pressure losses and thermal effectiveness, for the HEX core straight part, were estimated. The computational results of the 3D CFD model were also used for the development of a macroscopic heat transfer and pressure losses porosity model of the heat exchanger which could be easily implemented for 3D computations inside the aero engine hot-nozzle and provide time efficient and computationally affordable computational results, as presented in Yakinthos et al. (2015).

4. Thermodynamic analysis of a recuperative aero engine

At the next step a 0-D thermodynamic cycle model of the intercooled recuperative (IR) aero engine, which was developed by MTU Aero Engines AG, was developed in CAPE-OPEN/COFE flowsheet environment with COCO (CAPE-OPEN to CAPE-OPEN) simulator software, COCO (2016)). In the thermodynamic cycle model the previously derived operational characteristics of the heat exchanger (i.e. inner/outer pressure losses and heat exchanger effectiveness) were incorporated together with the cycle components characteristics (i.e. compressor and turbines efficiencies, bleeds, intercooler pressure losses and effectiveness) and a performance analysis was performed for IR engine operational conditions (i.e. take-off, average cruise, max climb) in order to assess the heat exchanger effect on the overall aero engine operational cycle (details about the HEX and IR conditions can be found in (Goulas et al., 2015) focusing on pressure drop and heat transfer and (Schonenborn et al., 2004). The analysis showed that in relation to a conventional non-recuperative aero engine the IR engine could provide a ~14 % benefit in the overall efficiency, corresponding to ~12 % specific fuel consumption reduction. More details can be found in Goulas et al. (2014).

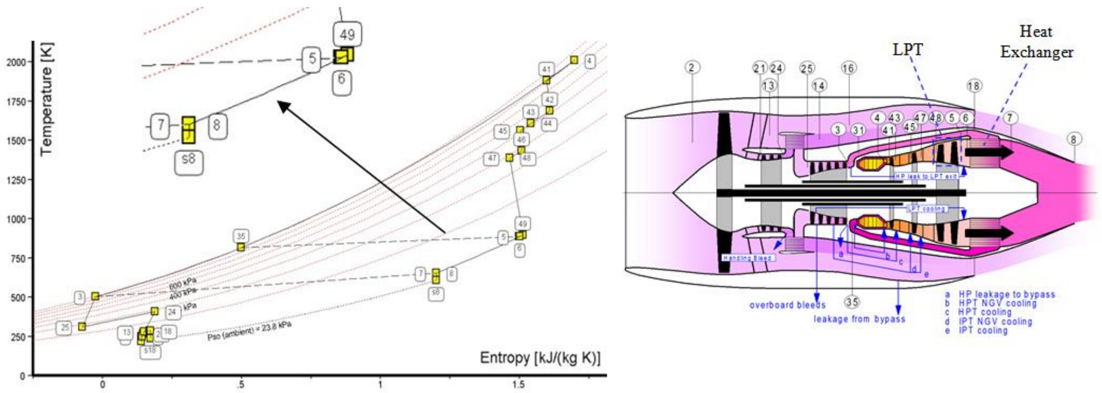


Figure 9: The MTU intercooled recuperative cycle (average cruise conditions) in Gas turb11

The developed CAPE-OPEN/COFE cycle model was further validated in relation to the well-established GasTurb 11 (Kurzke, 2011) gas turbine analysis software, presented in Figure 9, and provided results in close agreement with GasTurb11 in terms of thermal, propulsive and overall efficiency having an average deviation of ~0.5 %. It must be mentioned that the developed CAPE-OPEN/COFE cycle model is completely customizable and thus, can provide a wide range of optimization capabilities in relation to GasTurb11 (which provide limited flexibility in aero engine architectures setup), so that it can be used as an optimization tool in further studies targeting thermal efficiency optimization and fuel consumption reduction.
At the final part of the present work, various heat exchanger designs were considered and assessed with the use of the developed numerical CFD tools, and the heat exchangers characteristics were incorporated in the IR thermodynamic cycle CAPE-OPEN/COFE model in order to calculate their effect on the aero engine cycle performance. The first results showed that significant optimization potential still exists targeting specific fuel consumption and pollutants emission reduction leading to a more environmental friendly and cost efficient aero engine operation.

5. Conclusions

At the present work a methodology for the numerical modelling of heat exchangers in gas turbines, with a particular interest in a recuperative aero engine application, was presented. The methodology was based on a combination of high-fidelity 2D and 3D CFD computations that were validated against experimental measurements, and 0-D thermodynamic cycle analysis tools. The derived numerical tools were used for the determination of the major heat exchanger characteristics i.e. inner and outer pressure losses and effectiveness, which were later integrated into the developed thermodynamic cycle model of the aero engine. The analysis was based on a state-of-the-art tubular heat exchanger while the thermodynamic cycle performance assessment was performed on an intercooled recuperative (IR) turbofan aero engine concept. The results demonstrated the potentials of the heat exchanger integration in a gas turbine/aero engine for significant performance improvement and fuel consumption reduction especially when the optimization is performed with validated numerical tools in order to provide more time and cost efficient results.

Acknowledgments

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