CHEMICAL ENGINEERING TRANSACTIONS

VOL. 61, 2017

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216

DOI: 10.3303/CET1761170

Development of a Heat Exchanger for Low Pressure Ratio Gas Turbines with the Use of CFD Computations and Thermodynamic Cycle Analysis

Christina Salpingidou[a], Dimitrios Misirlis[b,*], Zinon Vlahostergios[a], Michael Flouros[c], Stefan Donnerhack[c], Kyros Yakinthos[a]

[a]Aristotle University of Thessaloniki, Greece
[b]Technological Educational Institute (TEI) of Central Macedonia, Serres, Greece
[c]MTU Aero Engines AG, Munich, Germany
misirlis@eng.auth.gr

The performance optimization of energy systems is a field of increased research interest for reasons strongly related with economy and environmental sustainability. In this context, a significant amount of effort is provided in the direction of gas turbines performance enhancement targeting the reduction of fuel consumption and pollutants emissions. A significant contributor in this attempt can be found in the use of heat exchangers in recuperative gas turbine configurations which can exploit a significant part of the, otherwise wasted, hot-gas thermal energy content in order to preheat the compressor discharge air before the combustor, thus reducing fuel requirements and pollutants emissions. For the proper operation of the recuperative gas turbine, the integrated heat exchanger should be carefully designed in order to provide a favourable combination of sufficiently high thermal effectiveness with tolerable pressure losses. In addition, when gas turbines for propulsion applications are considered such as in the case of heli engines, heat exchanger weight and dimensions should also be taken into strong consideration. Such an effort is presented in the current work, where a heat exchanger for heli engine applications was designed and assessed. At the first part of this work, a detailed thermodynamic cycle analysis was performed on a low pressure ratio gas turbine configuration, suitable for heli engine applications, the operational conditions of which were based on open-literature available data. At the next stage, a tubular heat exchanger was designed taking into consideration geometrical constraints and heat exchanger operational conditions while for the heat exchanger sizing, literature based heat transfer correlations were applied. The heat exchanger performance was further assessed through the use of detailed computations on a CFD model of the integrated heat exchanger in the heli engine configuration, based on which the heat exchanger pressure loss and heat transfer characteristics were computed. At the final stage of the present work, the heat exchanger effect was assessed on a thermodynamic cycle analysis model of the recuperative heli engine, in which the previously derived heat exchanger performance characteristics were included. The analysis showed that the use of a heat exchanger can provide 10.6 % improvement regarding cycle thermal efficiency and 9.3 % fuel consumption reduction in the heli engine gas turbine configuration in relation to a non-recuperative heli engine of the same technological level showing the significant optimization potential of this technology targeting the achievement of more environmentally friendly and cost-efficient gas turbines for heli engines.

1. Introduction

The optimization of the performance of energy systems has always been in the focal point of engineering applications and research activities targeting environmental and economic sustainability. The latter has become particularly important nowadays due to the increased awareness regarding pollutants emissions and the fluctuating fuel prices. A large part of these research activities have been focused on gas turbine applications for power plant stations, as presented in Yong et al. (2016), aero engine applications, as presented in Schonenborn et al. (2004) or both gas turbines and aero engines, as presented in Salpingidou et

Please cite this article as: Salpingidou C., Misirlis D., Vlahostergios Z., Flouros M., Donnerhack S., Yakinthos K., 2017, Development of a heat exchanger for low pressure ratio gas turbines with the use of cfd computations and thermodynamic cycle analysis, Chemical Engineering Transactions, 61, 1033-1038 DOI:10.3303/CET1761170

al. (2016). For such applications the integration of heat exchangers in recuperative gas turbines configurations provides a promising technology concept through which both fuel consumption and pollutants emissions can be reduced. In this concept, a heat exchanger is installed right after the gas turbine low-pressure turbine since a significant part of the hot-gas waste heat can be exploited so as to preheat the compressor discharge air right before the latter enters the combustor, hence reducing fuel requirements and pollutants emissions. The degree of waste heat exploitation is mainly dependent on the heat exchanger surface with an increase of the latter leading to increased heat exchanger thermal effectiveness values and waste heat exploitation. On the other hand, the use of increased heat exchange surface values can significantly affect the performance of the low-pressure turbine since the imposed pressure losses on the gas-flow can alter the achieved turbine work. These imposed pressure losses are also strongly dependent on the heat exchanger core geometry and the selection of a non-aerodynamically optimal design can further deteriorate the low-pressure turbine performance. As a result for the proper operation of the recuperative gas turbine, the integrated heat exchanger should be carefully designed so as to provide a favourable combination of sufficiently high thermal effectiveness with tolerable pressure losses. The latter becomes particularly important when gas turbines for propulsion applications are considered, such as in the case of heli engines, where heat exchanger weight and dimensions should be taken into strong consideration due to the limited available space for installation and the strong effect that the heat exchanger own weight can have in the overall benefit of this technology since the heat exchanger weight corresponds to a non-detrimental percentage of the overall recuperative heli engine weight.

Taking these parameters under consideration, high-fidelity tools can be utilized for the proper design and performance assessment of a heat exchanger for heli engines. These tools can include computational fluid dynamics models in order to properly capture the heat transfer and fluid behaviour of the heat exchanger, regarding pressure losses and thermal effectiveness, combined with thermodynamic cycle analysis, in order to assess the effect of the heat exchanger waste heat recovery on the overall performance of the heli engine. Such an effort is presented in the current work, where a heat exchanger for a typical heli engine application was designed and assessed. At the first part, a detailed thermodynamic cycle analysis was performed on a low pressure ratio gas turbine configuration, suitable for heli engine applications, the operational conditions of which were selected based on similar applications presented in open-literature, i.e. Shapiro and Levy (1990). At the next step, a tubular heat exchanger was designed taking into consideration the installation geometrical constraints and the operational conditions of the heli engine. Furthermore, for the heat exchanger sizing, literature based heat transfer correlations were initially applied. Then, the heat exchanger performance was assessed through the use of detailed computations on a detailed CFD model of the integrated heat exchanger in the heli engine configuration, based on which the imposed heat exchanger pressure loss and achieved heat transfer effectiveness were computed.

At the final stage of the present work, the effect of the heat exchanger waste heat recovery on the heli engine performance was assessed on a thermodynamic cycle analysis model of the recuperative heli engine, in which the previously derived heat exchanger performance characteristics were included through the use of appropriate pressure loss and thermal effectiveness coefficients, following an approach which has been successfully applied for recuperative turbofan aero engines as presented in the work of Goulas et al. (2014). The analysis showed that the use of a heat exchanger can provide significant improvement in the heli engine gas turbine configuration, leading to noticeable fuel consumption and pollutants emissions reduction.

To the authors' knowledge, this is the first time that a heat exchanger specifically designed for a heli engine application is designed, modelled and computationally assessed regarding flow field development, heat transfer and thermodynamic performance taking also into consideration heli engine geometrical constraints. As a result, the quantification of the benefits of heli engine recuperative cycle shows the strong potential of this technology which will be further investigated in future studies.

2. Heat exchanger basic design

The heat exchanger design aimed at a 0.4 thermal effectiveness value in order to provide a design which would be compatible with the geometrical constraints of a heli engine and also provide manageable weight increase and pressure losses. The used correlations were based on the suggestions of Cengel and Boles (2015) and correspond to heat transfer correlations for flows through tube bundles based on circular tubes. Due to the fact that these correlations are based on experimental measurements in which a non-negligible experimental error is well known to be included, the calculated required heat exchange surface was increased by a factor of 20 %.For the sizing of the tubes dimensions and arrangement, a 0-D tool was developed in a spread-sheet through which the heat exchanger basic dimensions (tubes diameters, length, staggered arrangement and tubes number) were defined. For the estimation of the necessary thermo physical properties, input from Shapiro et al. (1990) were used for the heli engine thermodynamic cycle conditions and input from

Nkoi et al. (2013) were used for the components performance, in a thermodynamic cycle analysis with the use of the Gas Turb11 (Kurzke, 2011) gas turbine analysis software, to derive the appropriate reference temperature and pressure conditions for the heat transfer correlations.

The derived heat exchanger design is presented in Figure 1. As it can be seen, a disk-shaped annular wrap-around cross-flow heat exchanger concept was followed following the suggestions of McDonald (2003) since this approach provides good aerodynamic gas flow paths resulting in reduced pressure losses and limited need for external ducting and thermal expansion devices. In addition, the basic dimensions of the designed heat exchanger were respecting the heli engine installation geometrical constraints (e.g. maximum and minimum radius, heat exchanger axial length etc.). In this concept the compressor discharge air is circulating inside the circular tubes in the radial direction, while the turbine outlet hot-gas flow is flowing around the circular tubes, as it is presented in detail in Figure 1. This concept was further refined through the proper design of the staggered tube arrangement core, which consisted of two banks of different tubes arrangement i.e. 3/3/3 and 4/4/4, while a two-pass cross flow configuration was selected in order to further enhance the achieved heat transfer between hot-gas flow and compressor discharge air.

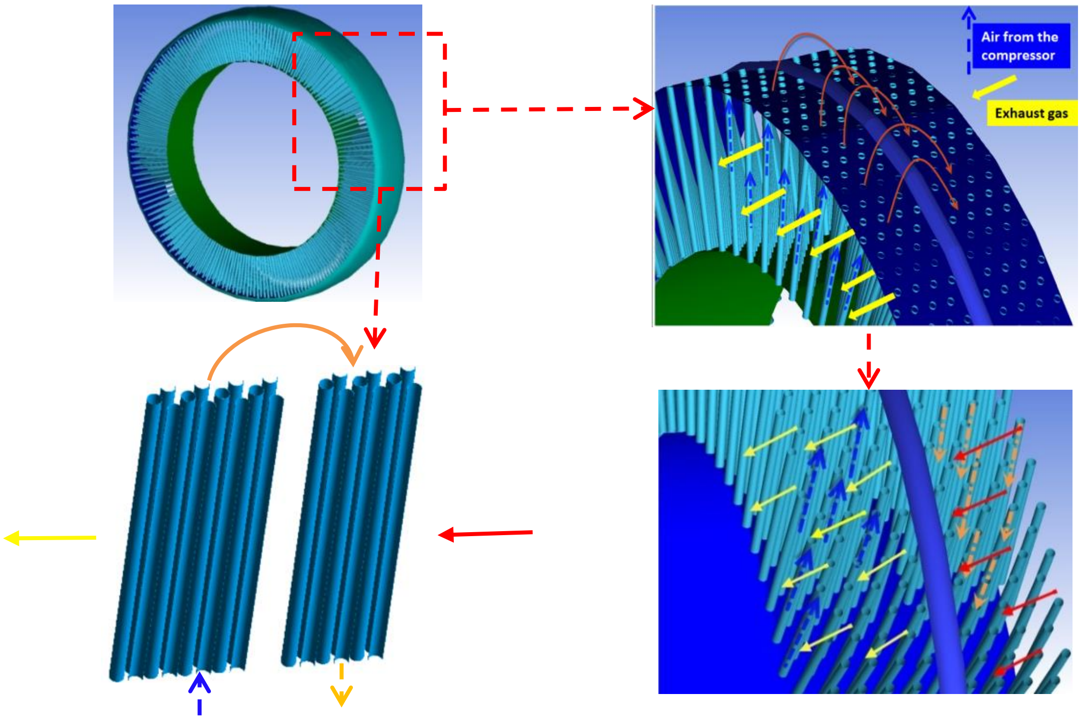

Figure 1: Heat exchanger design for the heli engine perspective view and enlarged views in the heat exchanger core (flow currents are indicated with different colours)

3. CFD modeling and results

At the next step, a detailed CFD model consisting of $5.5 \cdot 10^6$ computational points, corresponding to a slice of the heat exchanger design, was created which is presented in Figure 2. The CFD model included three different domains, the first one corresponding to the compressor discharge air flow inside the circular tubes, the second one corresponding to the solid tube walls and the third one corresponding to the hot-gas flow around the circular tubes, as presented in Figure 3. The CFD computations were performed in Ansys CFX CFD software (2015), with the use of the Shear Stress Transport (SST) low-Reynolds turbulence model of Menter (1994). The selection of SST turbulence model for the CFD computations was based on the conclusions of the work of Missirlis et al. (2011) in which the SST turbulence model provided the best results in comparison to experimental measurements for a tubular heat exchanger of elliptic profiles for recuperation application. Since the SST turbulence model belongs to the low-Reynolds number family, special care was provided during the creation of the computational grid in order to ensure an appropriate grid refinement near the tube walls, so that the computed y+ value there was in the range of 1-3. In this direction, previously acquired knowledge of the necessary grid refinement values from Missirlis et al. (2011) was included during the grid creation process in order to place the first computational cell from the walls properly (a normal distance of approximately 10^{-2} mm was used).

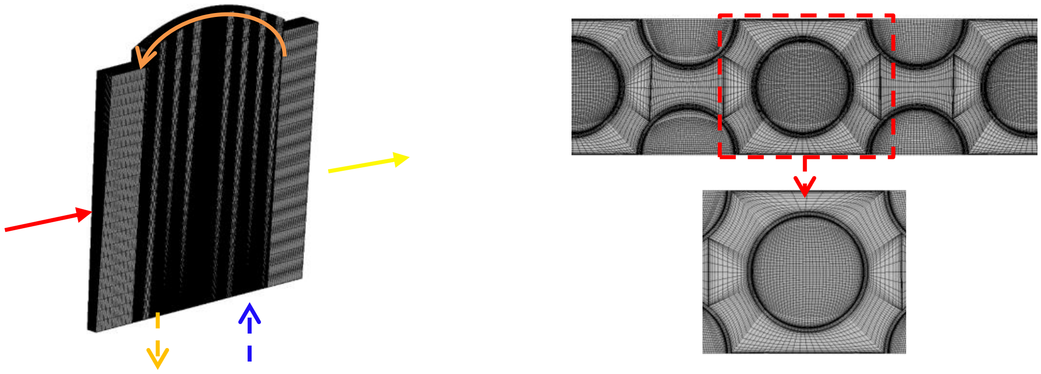

Figure 2: Computational grid for the heat exchanger CFD model with enlarged view near the tubes core

The computational nodes were created following an hexaedral philosophy with the use of various computational domains (all of which combined created the overall computational domain) in order to arrange the computational cells in a way that the corresponding cell angles would not create skewed cells (the vast majority of cell angles was ranging from 75 ° to 90 ° while the cells expansion ratio was always kept below 1.2). The transport equations of the SST model are presented in equations 1 and 2, which are solved together with the momentum and energy equations (not presented here due to space limitation reasons).

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial\left(\rho U_j k\right)}{\partial x_j}=\frac{\partial}{\partial \chi_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial k}{\partial x_j}\right]+\mu_t S^2-\beta' \rho k \omega \tag{1}$$

$$\frac{\partial(\rho \omega)}{\partial t}+\frac{\partial\left(\rho U_j \omega\right)}{\partial x_j}=\frac{\partial}{\partial \chi_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]+\alpha_3\frac{\omega}{k}\mu_t S^2-\beta_3 \rho \omega^2+(1-F_1)2\rho\frac{1}{\sigma_{\omega 2}\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{2}$$

where F_1 and F_2 are blending functions of the wall distance and the flow variables, ω is the specific turbulence dissipation, ε is the turbulent dissipation and μ_t is the eddy viscosity. Additional information for the blending functions regarding their formulation functions can be found in ANSYS CFX Modeling Guide (2015). For the CFD computations for all the transported variables a high resolution advection scheme was adopted which was based on the study of Barth and Jespersen (1989). Regarding the thermo physical properties (density, thermal capacity, dynamic viscosity, thermal conductivity) which were applied in the CFD computations, temperature dependent values were applied in all domains using data of Cengel and Boles (2015) and data from international open literature.

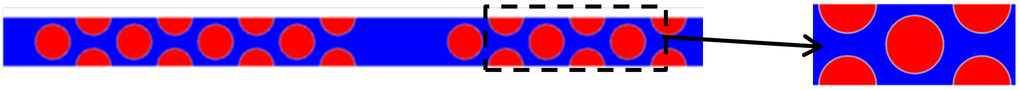

Figure 3: View of the three computational domains arrangement inside the heat exchanger core (red: cold-air flow, grey: solid tube walls, blue: hot-gas flow)

Regarding the applied boundary conditions, the mass flow was prescribed in both fluid domain inlets together with the static temperature and turbulence intensity values, while static pressure was imposed in both fluid domains outlets. Rotational periodicity conditions were applied in order to exploit the periodic nature of the heat exchanger geometry and reduce its necessary computational size. Moreover, the applied boundary condition values (mass flow, pressure, temperature) were derived from the heli engine thermodynamic cycle conditions. Typical views of the velocity and temperature distribution inside the heat exchanger are presented in Figures 4a and 4b. As it can be seen, the flow field is being characterized by two main regions, the main flow region away from the tube walls and the recirculation regions being developed at the back part of the tube walls, especially after the last row tubes. Similar flow patterns are presented also for the temperature field distribution. These patterns are in complete accordance with the conclusions presented in Missirlis et al. (2011) and have a direct impact on the local heat transfer coefficients of the circular tubes with increased values being achieved in the circular tubes ‘leading edges’ and lower values near their ‘trailing edges’ regions.

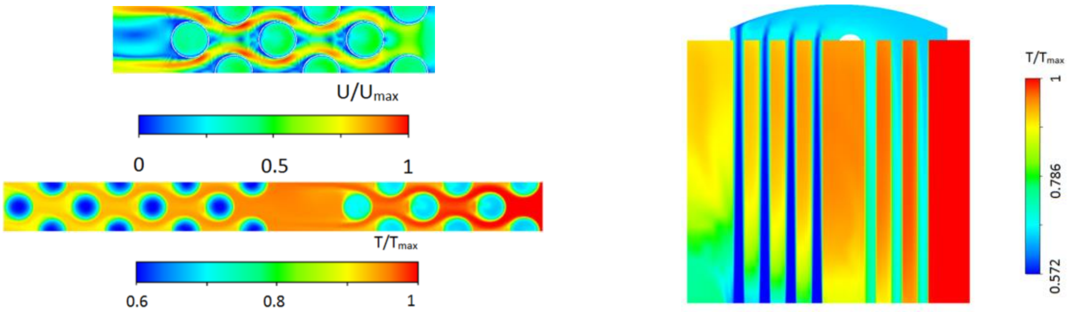

Figure 4: (a) Non-dimensional velocity and temperature distribution inside the heat exchanger core. (b) Non-dimensional temperature distribution inside the heat exchanger core (axial middle plane)

The analysis of the CFD computations showed that the heat exchanger provided an achieved thermal effectiveness of 0.39, a value very close to the initial evaluation of 0.4. In addition, the heat exchanger design resulted in very limited pressure losses in both flow currents since the pressure loss percentage (in relation to the inlet pressure value) was 0.1 % and 0.2 % for the cold-air and hot-gas flow currents respectively.

4. Thermodynamic analysis on heli engine

The last part of this work was focused on the quantification of the benefits of recuperation with the previously presented heat exchanger on a heli engine gas turbine application. The heli engine operational conditions and parameters were selected based on similar analyses presented in international literature, and more specifically in the work of Shapiro et al. (1990), which are summarized in Table 1. Similar conditions are also presented in the work of Nkoi et al. (2013).

Table 1: Heli engine parameters.

Parameter	Value
Compressor Efficiency	0.78
Power Turbine Efficiency	0.9
Compressor Pressure Ratio	11.2:1
Heat exchanger cold-air pressure losses	0.1 %
Heat exchanger hot-gas pressure losses	0.2 %
Turbine Inlet Temperature (TIT)	1,400 K
HEX Effectiveness	0.39
Engine airflow	5 kg/s

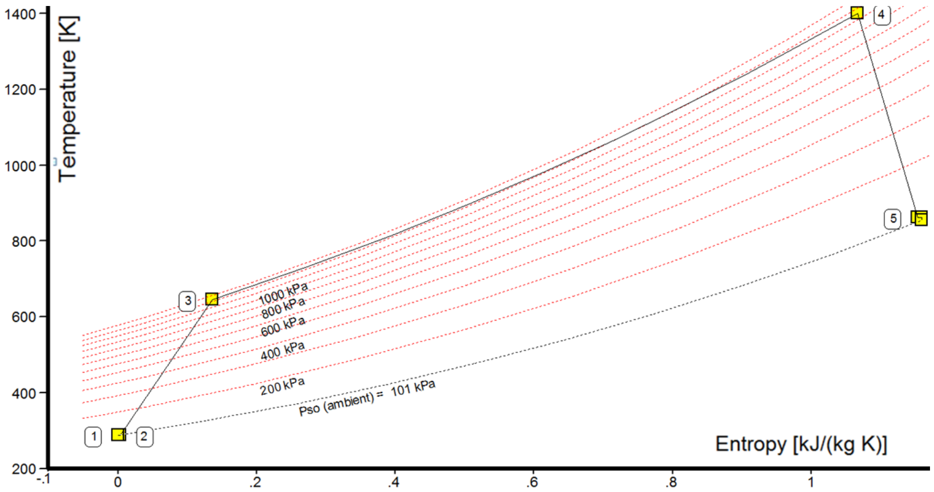

Figure 5: The heli engine thermodynamic cycle in Gas turb11

At the next step a 0-D thermodynamic cycle model of the heli engine was set in GasTurb 11 gas turbine analysis software, presented in Figure 5, in which the previously derived operational characteristics of the designed heat exchanger (i.e. inner/outer pressure losses and heat exchanger effectiveness) were incorporated together with the cycle components main parameter (e.g. compressor and turbines efficiencies etc.) and a performance analysis was performed. The comparison of the recuperative heli engine results with the ones of a non-recuperative heli engine of the same technological level showed a ~10.6 % improvement regarding cycle thermal efficiency and a more than 9.3 % fuel consumption reduction. These results clearly reflect the significant optimization potential of heat exchanger recuperation in order to achieve fuel consumption and pollutants emission reduction, towards to more environmentally friendly and cost efficient gas turbines.

5. Conclusions

In the present work, a heat exchanger for heli engine applications was designed and assessed. The heat exchanger pressure loss and thermal effectiveness characteristics were calculated through the use of detailed computations on a CFD model corresponding to a characteristic flow path of the heat exchanger core of the integrated heat exchanger in the heli engine configuration. At the final stage, the heat exchanger effect on a heli engine was assessed through thermodynamic cycle analysis in relation to a simple, non-recuperative, heli engine configuration for similar conditions. The comparison showed that the use of a heat exchanger in a heli engine application has a strong potential and can provide significant improvement regarding fuel consumption and pollutants emissions reduction in relation to a non-recuperative heli engine, indicating the need for further investigation in this direction.

Acknowledgments

The authors wish to acknowledge financial support provided by the Research Committee of the Technological Education Institute of Central Macedonia, under grant SAT/MC/140115-1/01.
Christina Salpingidou would like to thank Alexander S. Onassis Public Benefit Foundation for the scholarship.

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