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Experimental Study on Recuperative Heat Exchangers in the Exhaust Nozzle of an Aero Engine

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***Abstract*- This work presents the complete effort to model the presence of an integrated system of heat exchangers mounted in the exhaust nozzle of an aero engine which uses an alternative but more efficient thermodynamic cycle. The heat exchangers are operating as heat recuperators exploiting part of the thermal energy of the turbine exhaust gas to preheat the compressor outlet air before combustion and to reduce pollutants and fuel consumption. The presence of the heat exchangers enforces a significant pressure drop in the exhaust gas flow which can affect the overall efficiency of the thermodynamic cycle and the potential benefit of this technology. For this reason it is important to optimize the operation of the system of heat exchangers. The main target of this optimization effort is the minimization of the pressure losses for the same amount of heat transfer achieved. The optimization is performed with the combined use of experimental measurements and CFD methods. The porosity model is taking into account the pressure drop and heat transfer behavior of the heat exchangers and was developed and validated with the use of detailed experimental measurements. For the validation of the CFD model, isothermal experimental measurements carried out for laboratory conditions in a 1:1 model of a quarter of the exhaust nozzle of the aero engine, including four full-scale heat exchangers, were used.**

The CFD results were in good agreement with the experimental measurements and the same flow structures and problematic regions were detected. Thus, a complete 3-D CFD model of the overall exhaust nozzle of the aero engine was created and validated which at the next step formed the basis for the optimization of the overall aero engine installation for real engine operating conditions. The improved design of the aero engine installation presented decreased pressure losses in relation to the initial design and a more balanced mass flow distribution, showing the applicability of the overall methodology and its advantages for producing efficient engineering solutions for similar setups.

Keywords*- *Heat exchanger; Recuperative aero engine; Pours medium, Exhaust nozzle; Computational fluid dynamics.

I. INTRODUCTION

Among aeronautical engineers it is common sense that the modern civil aero engines have reached a high technological level. On the other hand, the demands of various international environmental committees have been now very strict and exigent. These demands, together with the ultimate demand of the lower fuel consumption has led the aero engine manufacturers to start pioneering new innovative engines that will be able to face the competitive future of the civil transport. MTU aero Engines have developed the concept of an intercooled recuperative aero engine (IRA). The concept of a recuperative engine is shown in Fig. 1.

The basic idea is the use of a less conventional, but more efficient, thermodynamic cycle for aircraft engines, which is based on recuperation. Downstream of the turbine exit the exhaust gas is directed through an installation of heat exchangers located inside the exhaust nozzle. Heat transfer is performed between the hot exhaust gas and cooler compressor air. The latter is directed back to the combustion chamber resulting in a better combustion process and consequently lower levels of emissions and better fuel consumption. Both of these have the potential to lead to fuel savings up to 20% and a reduction up to 20% and 80% for CO_2 and NO_x emissions, respectively.

The heat exchangers installed in the exhaust nozzle of an aero engine is shown in Fig-1 and Fig-2 shows a schematic representation of heat exchanger, which is constructed by special profiled tubes

Fig. 1. The recuperative engine. The heat exchangers are installed in the exhaust nozzle.

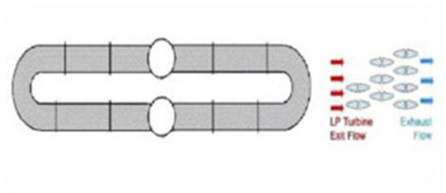


Fig. 2. Side view of the heat exchanger (left) and a hot gas flow through a characteristic passage of the heat exchanger (right).

in order to achieve a minimum possible pressure drop in the exhaust nozzle system.

II .THE CONSTRUCTION OF A MODEL OF EXHAUST NOZZLE

As a first step in the investigation it had been decided to construct a 1:1 model of the quarter of the nozzle operating at laboratory conditions. Four full-scale heat exchangers have also been constructed and assembled together for the modeling of the entire installation inside the exhaust nozzle. The whole construction has been integrated in a wind tunnel. Fig. 3 shows various views form the test-rig and Fig. 4shows a model of the heat exchanger used in the experiments.

The air velocity inside the wind tunnel is appropriately chosen in order to model the operation of the exhaust nozzle for ground ambient conditions. Since the scope of the construction of this rig was only the Investigation of the flow development inside the nozzle, it has been decided to work with cold air, although this is not true in reality. Nevertheless, the results of the study can be characterized quite informative, since they can give a very good picture of the flow development, as it will be shown later.

Fig. 4. Views of the test-rig. Left: the exhaust nozzle together with the outlet section. Middle: inlet section of the exhaust nozzle. Right:
The heat exchanger installation inside the nozzle.

Fig. 4. A 1:1 model of the heat exchanger.

III. VELOCITY DISTRIBUTION INSIDE THE EXHAUST NOZZLE

The air velocity measurements have been carried-out by using a three-hole pitot-static probe which is capable of measuring the magnitude of the air velocity and its orientation. In other words, it can give the air velocity vector at the measurement stations. Additionally, the probe can simultaneously measure the value of the total (and static) pressure at the same stations. Fig.5 shows the selected measurements planes within the exhaust nozzle. In order to have as much information as possible of the developed flow field, it has been decided to cover various planes, all of which are located in characteristic positions useful for the derivation of the pressure losses and mass flow distribution of each heat exchanger.

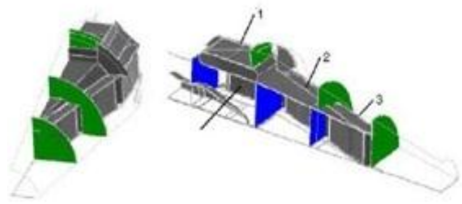


Fig. 5. The measurement planes inside the exhaust nozzle model and the numbering of the heat exchangers.

Another region inside the exhaust nozzle which needs special attention is the one located downstream the cone. The flow measurements, shown in Fig. 6, indicated a recirculation region of the developed flow, probably due to the shape of the cone and in combination with the existence of the heat exchangers installation. Since the total pressure loss through the exhaust nozzle is of primary interest, it is clear that the cone must be redesigned in order to prevent the large wake behind it, shown as a recirculation zone.

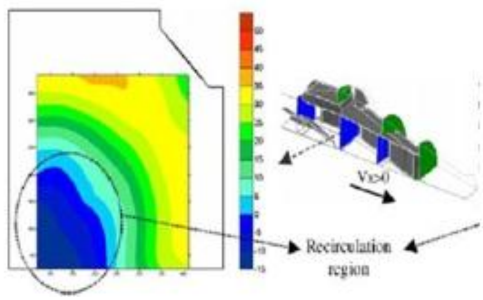


Fig. 6. Contour plots and measurements of the axial velocity downstream the cone. Dark blue corresponds to negative values.

IV. COMPUTATIONAL FLUID DYNAMICS

In order to proceed to the optimization of the installation of the heat exchanger, CFD calculations have been performed in the 2D meridional plane of the nozzle. Although it has been concluded through the experimental work that the flow development is 3D, it has been decided to start the optimization procedure in two dimensions. As a first target, the pressure losses should be lower than the initial design and additionally, the flow distribution through the heat exchangers should be evenly distributed in order to achieve an optimum efficiency.

The CFD steps for the optimization can be summarized as following:

• Perform a modeling for the present setup of the heat exchangers.
•Compare the results with the experimental data.
•Proceed to the optimization trials in order to achieve minimum pressure losses plus better flow distribution.

V. OPTIMISATION OF INSTALLATION

The optimization is performed only by means of CFD modeling and, as already
written above, is based on the computational setup of the existing installation. The average values of the main flow parameters, together with the mass flow distribution through each one of the heat exchangers were similar to the measured ones in the experiments, presenting, also, the same trends. Thus, it has been decided to continue the optimization effort with the 2D approach. The results will be considered again as indicative and of course a 3D CFD modeling must be performed in the future. Fig.7 shows the regions inside the exhaust nozzle where the optimization should be focused on.

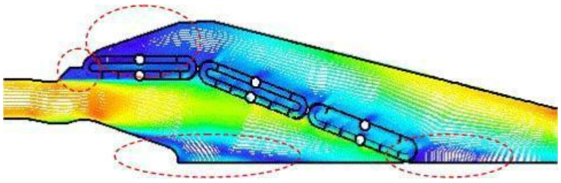
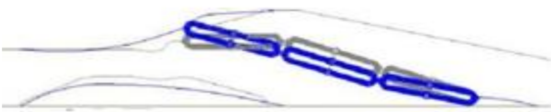


Fig. 7. Computational results for the 2D modeling. Regions contributing to the pressure losses which should be taken into account for the optimization.

In this figure the recirculation regions of the flow are within the indicated areas. These regions, together with the mass flow distribution in the frontal areas of the heat exchanger contribute to additional pressure losses beyond the primary pressure loss associated with the flow through the heat exchangers. The final arrangement is shown in Fig.8 together with the original one.



shows the setup before and after the use of the ramp.

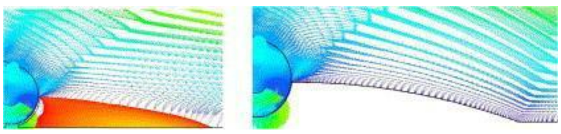


Fig. 8 Minimization of the separation region downstream the last heat exchanger. Left: original geometry. Separation is indicated with the plain color. Right: proposed new geometry with the use of a ramp. There is no separation.

1. The separation region located downstream of the last heat exchanger has been minimized with the use of a ramp connected to the heat exchanger. Fig. 8

2. The large formed cavity located before the first heat exchanger (horizontally placed) has been minimized by designing a new geometry for the cover of the exhaust nozzle in this region, Fig.9

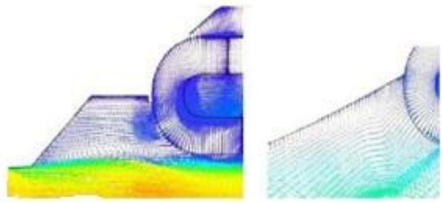


Fig. 9. Redesign of the exhaust nozzle cover at the inlet section for the minimization of the formed cavity near the first heat exchanger. Left: original geometry. Right: proposed new geometry.

3. The geometry of the cover of the exhaust nozzle downstream the first heat exchanger has been modified in order to obtain a better distribution of the flow field downstream the heat exchanger. This modification helped to minimize any backflow from the heat exchanger to the core flow, as it has been measured and computed for the original configuration, Fig.10

Fig. 8. Original (grey color) and optimized (dark grey color) heat exchanger installation inside the exhaust nozzle for the minimum occurrence of pressure losses through it. The achievements with the new configuration can be mainly summarized as follows:

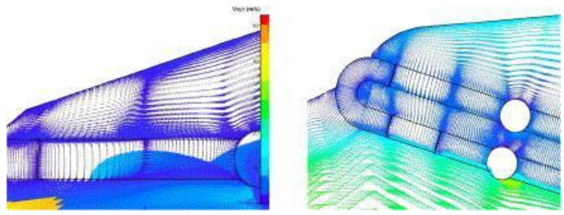


Fig.10. Redesign of the exhaust nozzle covers downstream the heat exchanger in order to minimize the backflow form the first part of the heat exchanger to the core flow. Left: original geometry. Right: Proposed new geometry.

4. The geometry of the cone placed after the engine shaft has been also redesigned so as to prevent the creation of the large recirculation region, which has been measured during the experiments and has been also found in the CFD modeling of the original arrangement. Additionally, during the redesign of the cone, the need for a better and optimized mass flow distribution through the heat exchangers has been taken into account. This action was also combined with the change of the angles of inclination for all heat exchangers. Various trials led to the final design (shown in Fig.8), which has proven to give a minimized separation region downstream the cone and a satisfactory distribution of the mass flow through each heat exchanger. For the cone especially, Fig. 12 shows that there is no recirculation region after the new proposed shape.

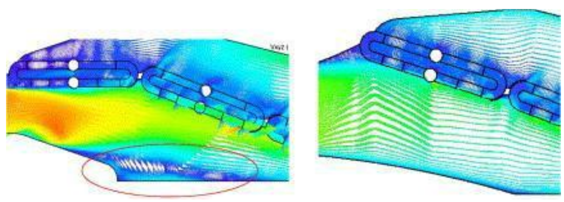


Fig.12. Minimization of the recirculation region located downstream the cone. Use of a proposed alternative geometry. Left: original geometry. Right: proposed new geometry of the cone.

These four briefly described actions led to a lower value for the pressure drop. The computed values for the dimensionless coefficients L for the new arrangement are shown in Table 1 in comparison with the ones obtained for the original arrangements. It is clearly shown that the new arrangement presents a smaller pressure drop, thus it can be used as a base configuration for future 3D CFD computations. Additionally, Table 1 shows the mass distribution at the frontal area of each heat exchanger for the new arrangement and in comparison with the original one. Again, a better distribution is obtained with the proposed new heat
exchanger installation. The same summarizes the new computed values of the flow parameters after the optimization of the arrangement of the heat exchangers and in comparison with the ones computed with the original arrangement.

	Mass flow through heat exchanger 1 (%)	Mass flow through heat exchanger 2 (%)	Mass flow through heat exchanger 3 (%)	Δptotal	Δpstatic	Ltotal (%)	Lstatic (%)
CFD original arrangement	10.24	39.68	50.09	1754 Pa	2159 Pa	1.691	2.087
CFD optimized arrangement	27.10	33.66	39.24	1148 Pa	1542 Pa	1.106	1.490

CONCLUSION

An alternative technology for the improvement of the aero engine thermodynamic cycle has been presented. The basic idea is the re-use of the engine's hot exhaust gas enthalpy in order to preheat the compressor air directed to the engine's combustion chamber. The heat transfer is performed with the use of a system of heat exchangers installed in the exhaust nozzle, downstream the low-pressure turbine. In order to ensure an optimum operation of the engine, the pressure losses due to the existence of the heat exchangers have been investigated both experimentally and computationally. The measurements showed that there is an unsatisfactory mass flow distribution through each heat exchanger primarily caused by the original chosen arrangement. Additionally, the geometry of the nozzle exit cone leads to a flow field with large recirculation regions, which are in large part responsible for the large values of the measured pressure losses.

In a second step, the flow field through the heat exchanger has been investigated with the use of computational fluid dynamics. The modeling was based on a 2D approach for the nozzle symmetry plane located in the meridional section. The heat exchangers have been modeled as porous media with a pressure drop law, which is a function of the mass flow through them.

This approach facilitates the mesh construction of the individual heat exchangers since they are treated as blocks, i.e. defined flow zones having a pressure drop defined by a simple function. The computational results presented a satisfactory agreement in comparison with the experimental
measurements. Additionally, the computational results gave significant information about the flow regions contributing to the pressure losses, primarily related to recirculation regions. The 2D computational modeling has been treated in order to proceed to the optimization of the arrangement. The optimization has been mainly focused on the minimization of the recirculation regions together with the examination of alternative setups of the heat exchangers in order to have a better mass flow distribution through them, an action which surely leads to lower values for the pressure losses. The future actions should be focused on a 3D computational modeling based on the optimized 2D arrangement, followed by experimental validation.

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