Thermal design optimisation in turbomachinery elements

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Summary

Design optimisation techniques are a new frontier in engineering planning. Usually designers use "*cut and try*" methods in developing their projects, taking advantage of their Company's Databases and internal know-how. Optimisation algorithms can additionally support these systems and give a relevant improvement to the development time and design quality.
In its R&D department , AVIO Group has began some projects in order to test the capabilities of modeFRONTIER, when coupled with its own internally developed 1-D CFD software applied to turbo machinery problems.
The 1-D code was developed in collaboration with several Universities and was validated in several heat transfer problems by AVIO Group in the past decade.
In this paper we illustrate some results obtained applying this methodologies to the aero-thermal field, and, in particular, to the turbine blade cooling design.
The cooling systems of turbine blades use a percentage of the compressed air that cannot so be used in the main engine thermodynamic cycle. The reduction of this percentage, without decreasing the cooling effectiveness is one of the most important tasks in blade design. In fact, this reduction would grow up the whole engine performances.
We show the results obtained applying a Genetic Algorithm to an impingement cooling system acting on a simple test geometry. Particularly, a part of this work is focused on the choice of a variable set that allows to reduce the number of degree of freedom, with the minimal loss of flexibility. This will be useful when dealing with non-simple, three dimensional and high computational costing problems.

Keywords

Optimisation, turbine blade, cooling system, Genetic Algorithms

0. Introduction

The multi-objective optimisation techniques were applied to the design of an impingement cooling system for gas turbine blades. This system consists in a series of air jets impinging on the internal surface of a blade in order to cool it.

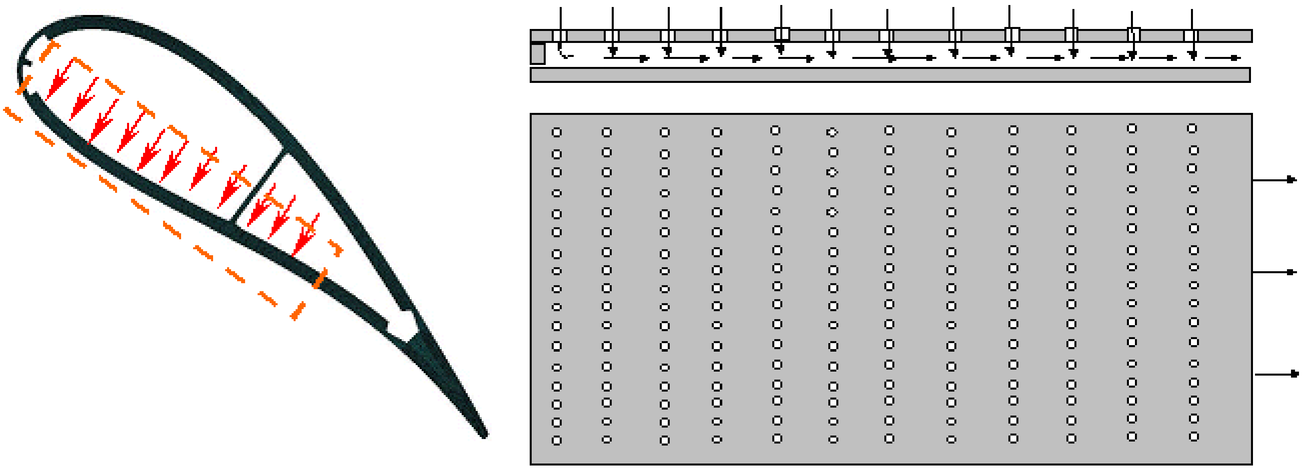

Figure 1: Impingement cooling system for gas turbine blades

The standard design of the impinging plate adopts a uniform hole diameter and a uniform hole distribution. AVIO GROUP developed a 1-D code (BLADECOOL) which computes the air mass flow and the heat transfer coefficient on the internal surface of the blade.
Due to the high non-linearity of the system, small changes in the diameters or in the jets distribution produce relevant changes in the cooling performances.
For this reason and as a consequence of the high number of parameters involved, AVIO GROUP used slight perturbations of the standard design in order to improve the cooling efficiency.
In this frame, the optimisation techniques played an important role in the management of a high number of variables, constraints and objectives and in the design of more efficient solutions.
The 1-D model of the impinging plate was easily parameterised and linked to the optimisation software modeFRONTIER.
The holes dimension and distribution is defined by more than 20 variables, a series of geometrical constraints have to be respected for constructive reasons and three independent objectives have to be reached: to maximize the average value of the heat transfer coefficient, to minimize its standard deviation and to minimize the air mass-flow.
The Design of Experiment techniques were used to perform a screening of the plate and the statistical study of input-output correlations highlighted the relevant parameters and their influence on the performances of the system.
A Multi Objective Genetic Algorithm steered the research towards a series of dominating solutions and the optimal jets distributions and dimensions lead to the comprehension of the fluid-dynamic behaviour of the channel.
Before a detailed description of the problem and of the optimisation procedure, the following chapter gives an overview of the entire AVIO GROUP project.

1. AVIO project and methodology

The study of the impinging plate was the first part of an AVIO GROUP project which was intended to evaluate the potential of the optimisation techniques applied to the design of turbine blades cooling systems.
After the optimisation of a 1-D model, the same techniques were applied to a 2-D model, which computes the convective heat transfer both on the internal and external sides of the blade, considering also the conductive heat transfer in the solid region.

The third phase of the project linked modeFRONTIER to a 3-D CFD code (CFX) in order to optimise the tip area of high pressure rotor blades. The second and third phase of the project are not the object of this paper.
As the complexity of the model increases from 1-D to 3-D, the computational time per simulation grows. At the same time the number of simulations needed to find the optimal solution increases with the number of input variables and objectives. Hence it is very important to reduce the number of parameters when dealing with 3-D models.
For this reason the 1-D phase was approached with two different methodologies: a complete one, which considers 24 independent parameters, and a simplified one, which introduces a series of mathematical links between the parameters and thus reduces the number of variables to 10.
The comparison of the general and simplified solutions gave important information about the possibility to apply a simplified approach without loss of generality and flexibility. This aspect is essential in order to evaluate the feasibility of optimisation projects applied to complex systems.
Following the two approaches are referred to as “Project A” for the general method and “Project B” for the simplified one.

2. Process Flow

The process flow is the logic procedure which integrates a computational code with an optimisation software, and thus allows the automatic analysis of several different configurations of the cooling system in order to find the optimal designs with respect to the specified objectives and constraints.
In Figure 2 a schematic representation of a process flow is reported.
The process flow starts with the definition of the parameters and integrates the 1-D code BLADECOOL in modeFRONTIER. The link between the parameters and the code is represented by the INPUT FILES, which contain the parameters and are read by the code.
The kernel of the process flow is represented by a BATCH SCRIPT, which automatically launches the fluid-dynamic solution for a given configuration of the impingement plate.
At the end of the simulation the response of the system is acquired by modeFRONTIER and is assigned to the OUTPUT VARIABLES. This process is cyclically repeated for different configurations of the impingement plate.
An initial series of analysis is planned with a Design Of Experiment method (DOE), then an optimisation algorithm can be used to find the optimal solutions of the problem.
The solution of a multi-objective problem is not unique, but is defined by a series of Pareto dominating designs: the Pareto criterion states that design_X dominates design_Y, if design_X improves at least one objective without worsening any other objective with respect to design_Y.

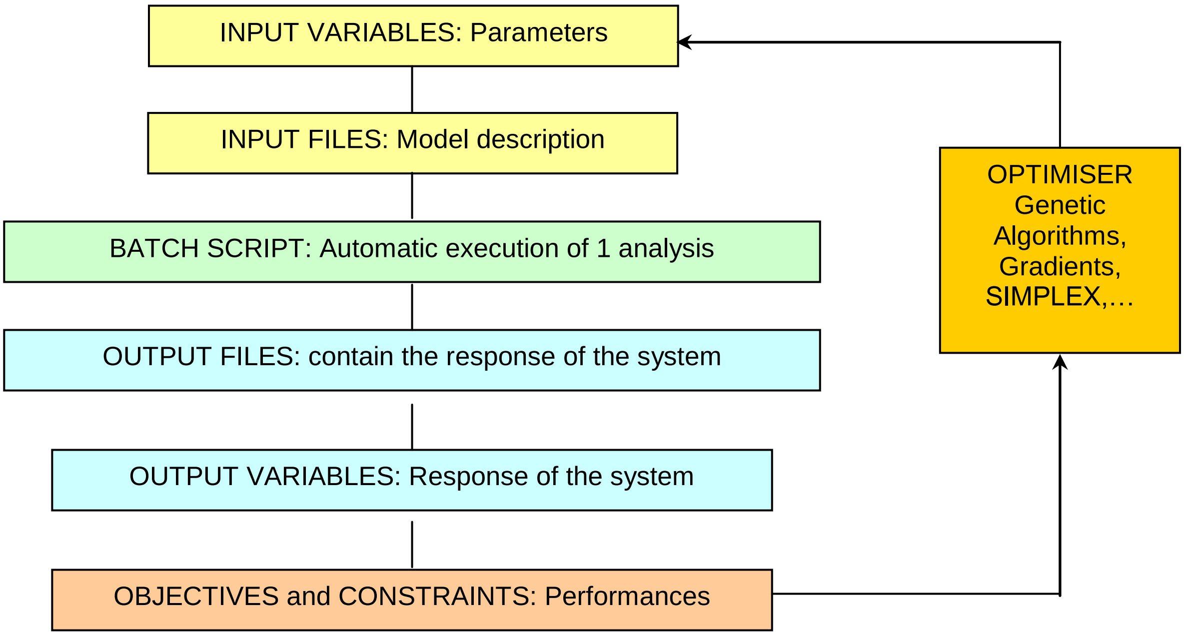

Figure 2: Process Flow

3. Project A: input variables and objectives

Project A considered 12 parallel rows of impinging jets defined by 24 input variables:

- 12 diameters: $d_i \in [3.0e-4m; 4.7e-4m]$
- 12 pitch-diameter ratios: $x\_d_{i-1}^{i} = \dfrac{pitch_{i-1}^{i}}{d_i} \in [5;15]$

The axial position of each air jet ax_i is computed with the following expression:

$$ax_i = ax_{i-1} + x\_d_{i-1}^{i} * d_i \qquad \forall \quad i = 1,\dots,12$$

and 12 constraints have to be checked $x\_d_{i}^{i+1} = \dfrac{pitch_{i}^{i+1}}{d_i} \in [5;15]$.

The standard design of the plate is defined by:

$$d_i = 3.85e-4m; \quad x\_d_{i-1}^{i} = 11 \qquad \forall i = 1,\dots,12$$

The space of possible solutions is a 24-dimensional space. If ten possible values are considered in the range of definition of each variable, the total number of combinations is 10^24.
Given the geometrical data, the inlet total pressure, the inlet total temperature and the outlet static pressure, the AVIO GROUP code BLADECOOL computes the total air mass-flow, the HTC distribution on the blade surface and the pressure distribution in the channel.
In the process flow the objectives are defined by the following expressions:

$$\begin{cases} \min(objM) = \min(total\_air\_mass\_flow) \\ \max(objHTC) = \max\left\{ \dfrac{\sum_{1}^{12} HTC_i \left(\dfrac{ax_{i+1} - ax_{i-1}}{2} \right)}{Ltot} \right\} \\ \min(objSTDEV) = \min\left\{ \sqrt{\dfrac{1}{11} \sum_{i=1}^{12} (HTC_i - HTC_{AVE})^2} \right\} \end{cases}$$

4. Project A: optimisation procedure

After the definition of the process flow, a set of initial experiments has to be planned.
The Design of Experiment (DOE) phase has to provide a base of designs, which are then used as the starting point for the optimisation.
The DOE analysis can also be used for a preliminary statistical study in order to determine the significance of the input variables and to understand how the objectives are influenced by the parameters. If some parameters are not relevant, the problem can be simplified fixing these variables to their medium values before the beginning of the optimisation.
The initial set of experiments was composed by 2600 simulations and was planned using the SOBOL algorithm (a pseudo-random sequence which assures a uniform distribution of points in the solutions space).
The input-output correlations were computed with the T-student test and all the input variables came out to be significant for the performances of the cooling system, hence no parameters can be fixed.
Starting from the DOE results, the aim of the first optimisation phase is to achieve all the three objectives independently. The Multi Objective Genetic Algorithm (MOGA) needs an initial generation of designs and looks for new solutions applying three operators: selection of the best designs, cross-

over (two designs are combined in order to generate two new configurations) and mutation (random variation of a design).
The initial population for the MOGA was composed by 150 designs extracted by the DOE sequence and 34 generations were created (globally about 5000 configurations).
The following scatter plot (ObjHTC ; ObjM) show the performances of the DOE configurations and the improvements obtained with the first optimisation phase. The two read lines give an idea of the Pareto frontiers (relative to this plane) at the end of the DOE and multi-objective phases.

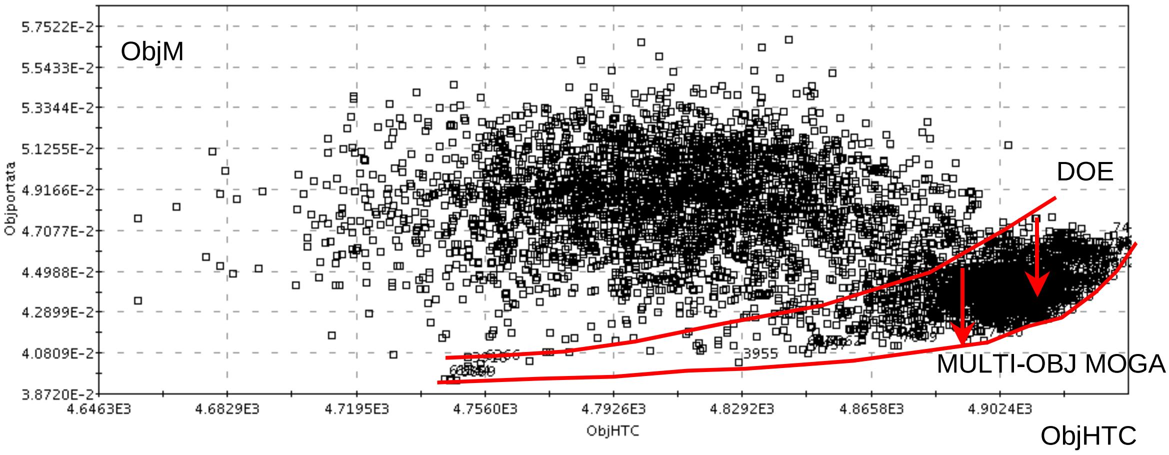

Figure 3: ObjM versus ObjHTC

The next chart compares the two Pareto frontiers also with the standard design (BASE) of the impingement plate.

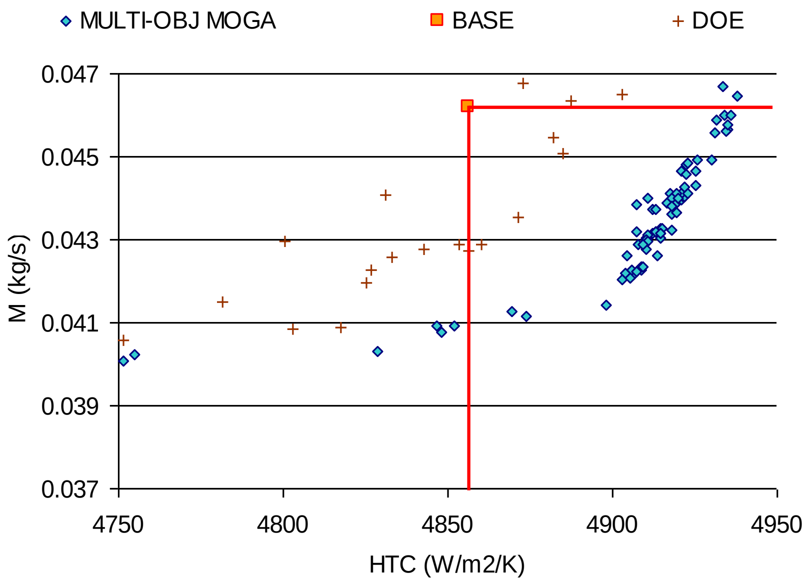

Figure 4: ObjM versus ObjHTC: DOE and MOGA Pareto frontier

The MOGA algorithm found a set of designs which at the same time reduce the mass-flow and increase both the heat transfer coefficient and its uniformity on the blade surface. The DOE and MOGA designs in the right-low quadrant dominate the BASE configuration.
After the multi-objective phase the AVIO designers decided to turn the HTC objectives into constraints and to look for solutions which reduce the compressor spilled air mass-flow.

Referring to the BASE performances: ObjHTC = 4856.4 [W/m2/K] and ObjSTDEV = 83.7 [W/m2/K], the second optimisation phase considered two constraints and one objective:

$$\begin{cases} \min \{ObjM\} \\ Constraint\ HTC \geq 4856.4 \left[\dfrac{W}{m^2 K}\right] \\ Constraint\ STDEV \leq 83.7 \left[\dfrac{W}{m^2 K}\right] \end{cases}$$

The single-objective phase was approached both with the MOGA and with the SIMPLEX algorithm obtaining the same results.

5. Project A: final results

The final single-objective phase found solutions which keep the same HTC average value of the base design and which considerably reduce both the air mass-flow and the HTC standard deviation.
Table 1 confirms that the single objective optimisation concentrated on mass-flow reduction, but also a more uniform HTC distribution was obtained.

CONFIGURATION	BASE	BEST MOGA	BEST SIMPLEX
MASS-FLOW [kg/s]	4.6211E-2	3.8635E-2 -16.4 %	3.8786E-2 -16.1 %
AVERAGE HTC [W/m^2/K]	4856.4	4856.6	4856.8
HTC STANDARD DEVIATION [W/m^2/K]	83.7	52.7	52.1

Table 1: Project A: BASE, best MOGA and best SIMPLEX designs

In Figure 5, Figure 6 and Figure 7 the history charts show the behaviour of the average HTC, of the air mass-flow and of the HTC standard deviation during the entire optimisation procedure.

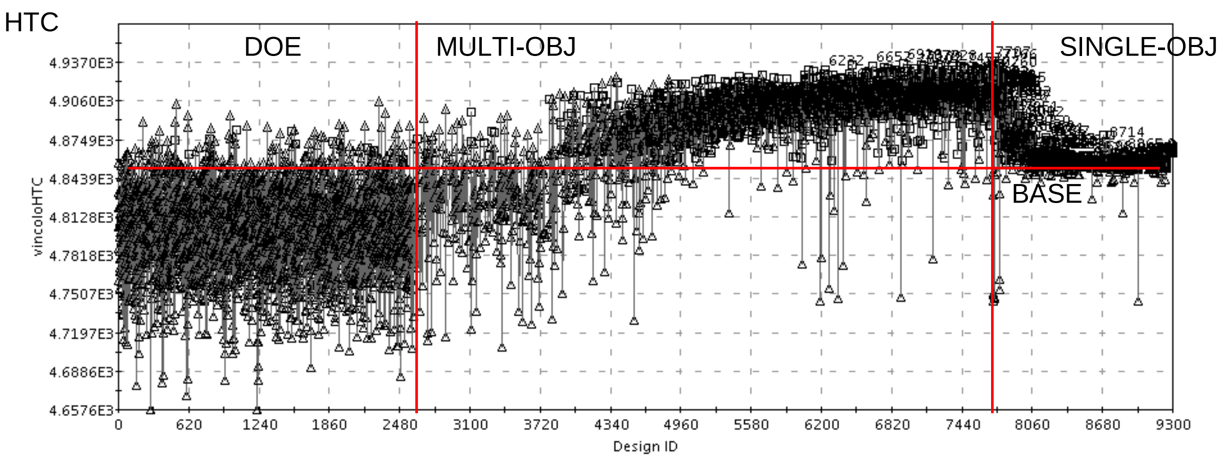

Figure 5: History chart: average HTC values

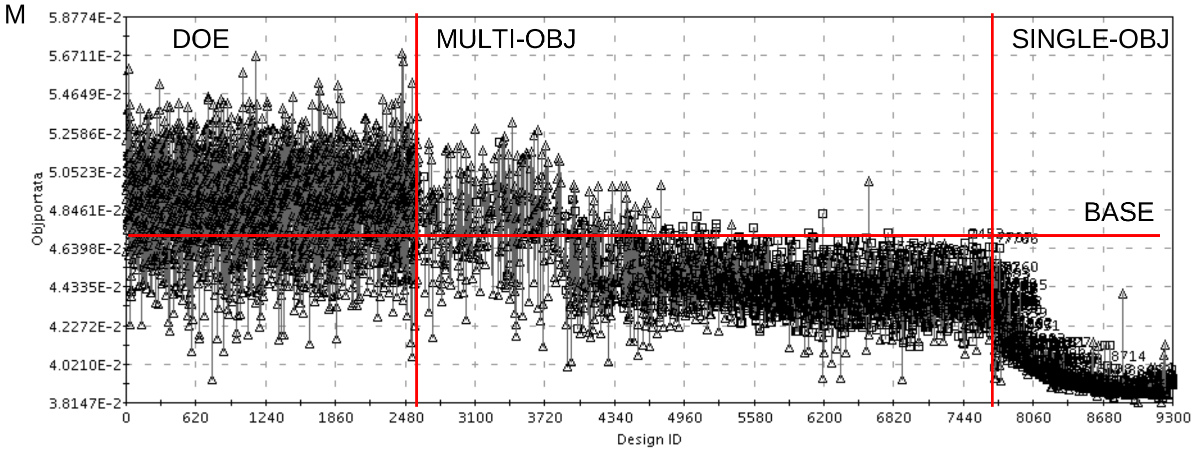

Figure 6: History chart: air mass-flow

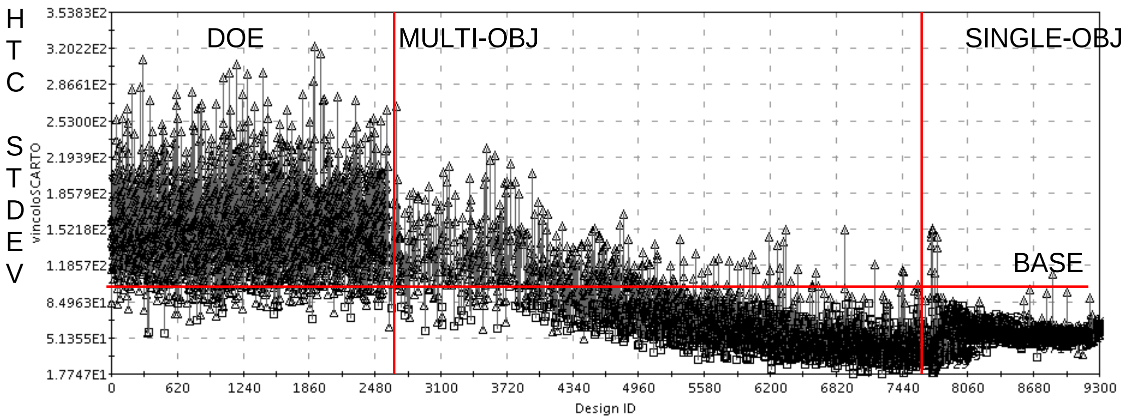

Figure 7: History chart: HTC standard deviation

The following scatter plot compares the two Pareto frontiers (single and multi objective phases) in the (HTC; Mass-flow) plane.

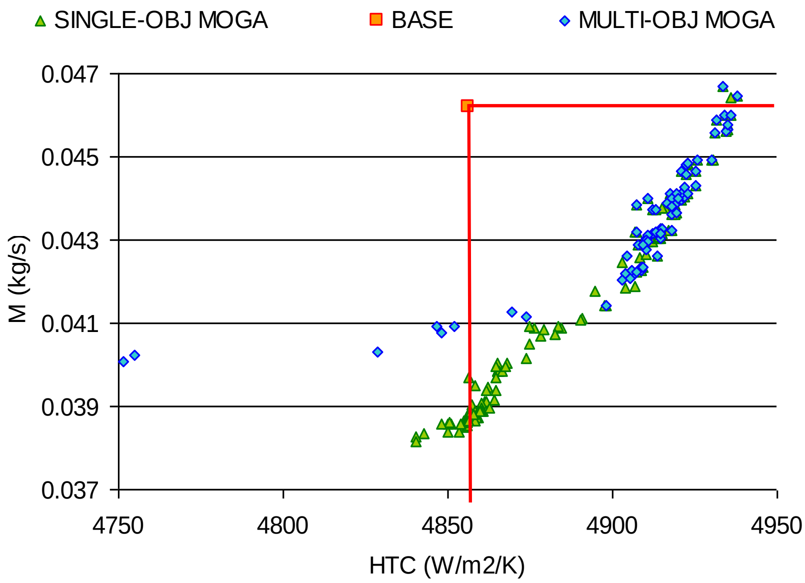

Figure 8: ObjM versus HTC: single and multi-objective Pareto frontiers

6. Project B

After the general approach, also a simplified description of the impinging plate was set.
The aim of this second project is to understand if the same solution found by the general approach can be found with a reduced number of input variables and with a lower number of simulations.
This aspect can be crucial when the complexity of the model and the computational time grow (2-D or 3-D models).
The position and the diameter of the holes are defined by two polynomial functions using 10 parameters.
The position of the air jets on the impingement plate is described by a third order Bezier curve. This function is determined by four parameters: the position of the first row ax_1, the position of the last row ax_{12} and the position of two internal rows ax_m and ax_n
The diameter distribution is defined by a cubic curve, which is determined by 6 parameters: considering a plane (L ; d) with $L \in [0;1]$, the points $(0;d_1),(L_a;d_a),(L_b;d_b)$ and $(1;d_{12})$ identify the cubic curve from which the diameters d_i are extracted.
The same constraints and objectives of Project A are considered for the simplified approach.
Also the optimisation procedure was speeded up: the number of DOE designs is the minimal required to have a good starting point for the multi-objective optimisation.
Since the number of parameters is reduced, also the number of simulations needed to converge to the optimal solutions decreases both during the multi and single objective phases.

	ALGORITHM	PROJECT A	PROJECT B
DOE	SOBOL	2600	60
MULTI OBJECTIVE	MOGA	5000	3000
SINGLE OBJECTIVE	MOGA	1500	1500
TOTAL number of runs		9100	4560
CPU time per simulation		1 minute	1 minute
TOTAL TIME		6.3 days	3.1 days

Table 2: Optimisation procedure

7. Comparison of Project A and Project B

The final Pareto frontiers in the (HTC; mass-flow) plane are almost the same for the general and simplified projects (Figure 9). This confirms that the simplified model found the same solutions both during the multi-objective phase and during the single objective step.
Relevant mass-flow reduction and more uniform HTC distributions, without reducing the average HTC value, were found both with Project A and with Project B (Table 3).
The best design of Project B is even better than the optimal solution of Project A.
This is mainly due to the fact that Project B adopted continuous functions to describe the position and the diameter of the air jets. This continuity allows only a gradual diameter variation (Figure 10), which as a consequences produces gradual HTC and mass-flow changes (Figure 11 and Figure 12). This aspect guarantees a good fluid-dynamic behaviour for the system.
The same continuity is not assured by Project A, which considers 12 independent diameters and 12 independent positions.
Figure 10, Figure 11 and Figure 12 show that Project A and Project B tend to the same solution, but probably a larger number of simulations should have been performed with the general approach to converge to the same solution found by Project B.
In fact the space of possible solutions a is 24-dimensional space in Project A and a 10-dimensional space in Project B.
Figure 10 and Figure 11 show that the diameter and the mass-flow gradually increase in the channel for the two optimal solutions, while the BASE design has a uniform diameter and an almost uniform mass-flow distribution.

On the other side, the HTC is high at the beginning of the channel for the BASE configuration, and it rapidly decreases, while it is more uniform and does not decrease for the two optimal solutions (above all for Project B).

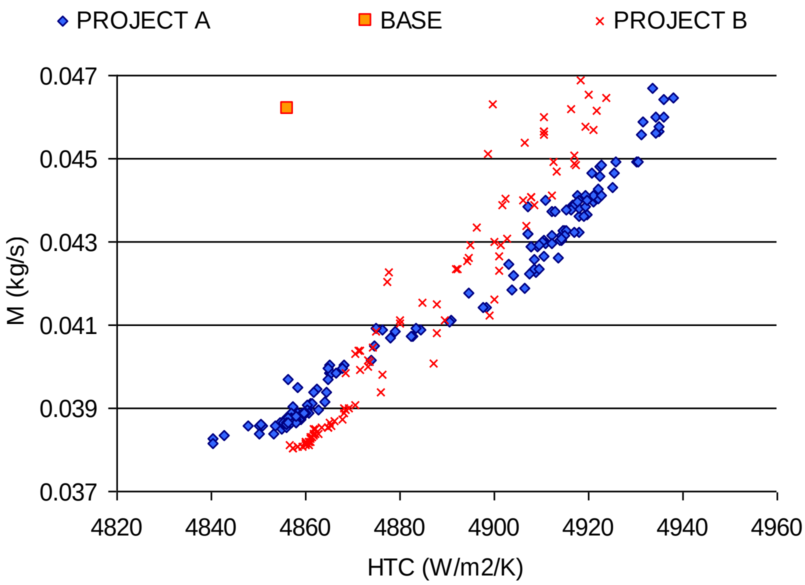

Figure 9: ObjM versus HTC: BASE design and final Pareto frontiers for Project A, Project B

The following table summarises the results of the two projects compared to the BASE design:

CONFIGURATION	BASE DESIGN	BEST DESIGN PROJECT A	BEST DESIGN PROJECT B
MASS-FLOW [kg/s]	4.6211E-2	3.8635E-2 **-16.4 %**	3.8048E-2 **–17.7%**
AVERAGE HTC [W/m^2/K]	4856.4	4856.6	4857.3
HTC STANDARD DEVIATION [W/m^2/K]	83.7	52.7	38.1

Table 3: Optimal solutions for Project A and Project B

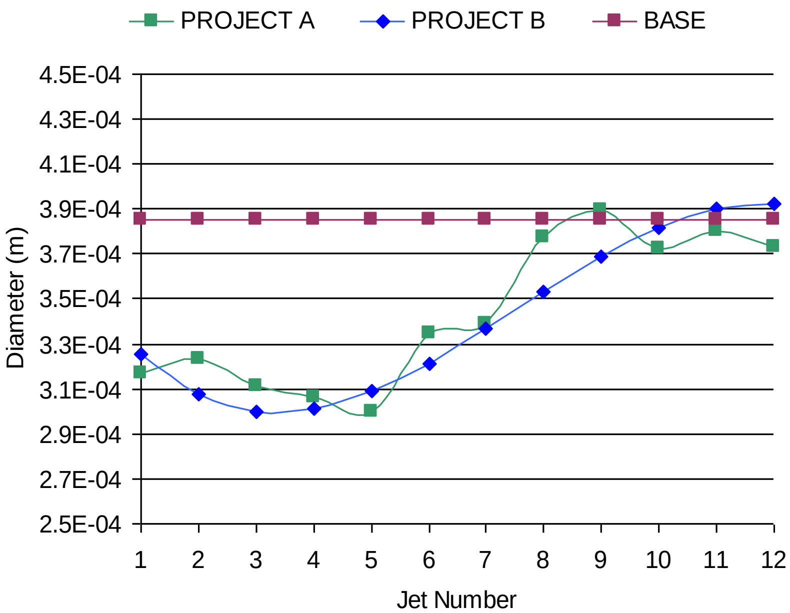

Figure 10: Optimal diameter distribution for Project A and Project B

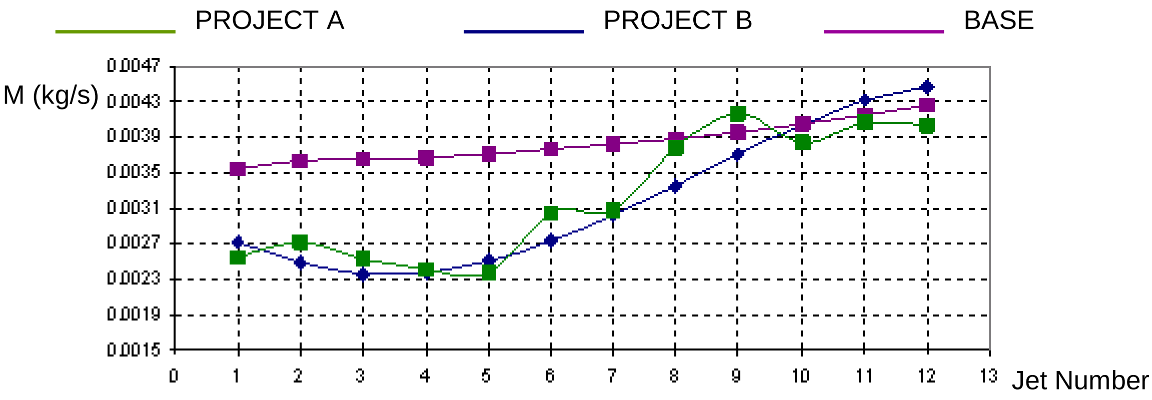

Figure 11: Mass-flow distribution on the plate: BASE configuration versus optimal designs

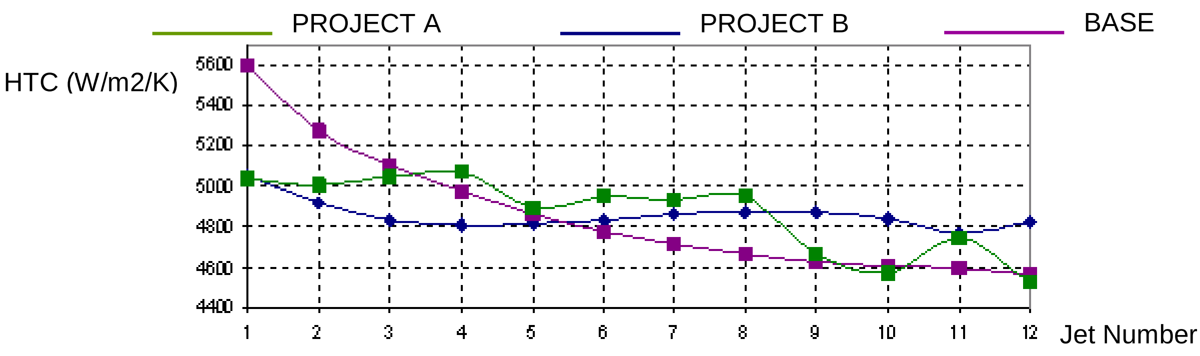

Figure 12: HTC distribution on the blade: BASE configuration versus optimal designs

Conclusions

The two parallel projects of the impingement plate demonstrated the potential of the optimisation techniques applied to the design of turbine blades cooling systems.
The standard configuration used by AVIO can be considerably improved.
Adopting an increasing hole diameter, a relevant mass-flow reduction and a more uniform heat transfer coefficient can be obtained, keeping the same average HTC on the blade surface.
The comparison between the general and the simplified approach proved that the same solution can be found with a reduced number of parameters and with a faster optimisation procedure.
The optimal solution found by the simplified project is better than the optimal solution of the general project: this is due to the continuity of the diameter distribution in the simplified approach.
However, it must be pointed out that the information given by the general approach were useful to define the two polynomial functions used in the simplified project.
It was verified that reducing the order of the two polynomial functions further on, the simplified project could not find the same solutions found by the general approach.
Hence a minimum number of parameters have to be introduced in the process flow in order to avoid lack of generality in the simplified approach.

References

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