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PRELIMINARY DESIGN PROCEDURE DEVELOPED FOR THE THERMAL AND FLUID DYNAMIC ANALYSIS OF A GENERIC COOLING TECHNOLOGY

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INTRODUCTION

The preliminary design holds an important role in the turbine cooling system design, because it is the first design step and has to outline the cooling system performances. In this phase it is suitable to analyse different cooling technologies, changing the main geometrical drivers and the external boundary conditions, in order to obtain the desired arrangement between thermal, aerodynamic and structural performances. The preliminary design has to be fast, exhaustive and accurate enough, due to the essential requirement of comparing a lot of configurations.

The object of this paper is the description of a preliminary design procedure developed for the thermal and fluid dynamic analysis of a generic cooling technology. The direct mathematic resolution of the equations characterizing the flow in a duct requires the knowledge of the mass flow, pressure and temperature at inlet. If these boundary conditions are not known, it is necessary to use an iterative approach. For this reason in this paper is presented first the cooling system solution, imposing inlet boundary conditions, then the solution with generic boundary conditions assigned.

In the first part two solvers are compared in terms of accuracy and computational velocity. The second part concerns the iterative element solution, using a dimensionless approach, when generic boundary conditions are imposed.

ELEMENT SOLUTION ASSIGNING BOUNDARY CONDITIONS AT INLET

To describe the thermal fluid dynamic of a fluid evolving in an element, the one-dimensional continuity, momentum and energy conservation equations must be solved. It is possible to solve these equations in many ways, depending on the accuracy requested and the correlations implemented. The most general approach to evaluate elements pressure losses and heat transfer involves a duct subdivision with control volumes (CV) and by consequence the discretization of the differential equations. Two solvers are developed, the first one is simpler and faster but less accurate, the second one is computationally more onerous but more precise.

The first solver assumes that the cooling system is equivalent to a steady state heat exchanger, with coolant physical properties independent from temperature and pressure. This main hypothesis simplifies the energy equation integration, so it is possible to split the element resolution in a preliminary thermal solution and a subsequent fluid dynamic solution. The thermal solution requires some further hypotheses: the internal and external heat transfer coefficients have to be constant, the metal properties independent from the temperature, and finally film cooling effectiveness is considered known. In this model, the heat transfer coefficients and adiabatic wall temperatures are unrelated to the fluid dynamic variables, i.e. velocity, Mach number and pressure. Despite the availability of the solution of simplified thermal problem, it is still necessary to divide the heat exchanger in control volumes for the pressure losses evaluation. The first solver makes easier the choking condition

analysis, because the knowledge of the outlet temperature, in consequence of the thermal solution, allows starting the calculus from the outlet section, computing a new inlet pressure.
Unlike the first solver, the second one integrates both energy and momentum equations in each control volume, without assuming any simplifying hypothesis: the fluid properties, friction coefficient and heat transfer coefficients are estimated in each control volume.
To compare the two solvers, in terms of computational demand and accuracy, a preliminary analysis has been provided using reference geometry and fluid parameters resulting in low mach at inlet and high mach at outlet section. Adaptive meshes are investigated as well, using both temperature and pressure as driver parameters. In Figure 1 Mach number and total pressure versus CV number is shown, comparing solvers and meshes (adaptive or not).

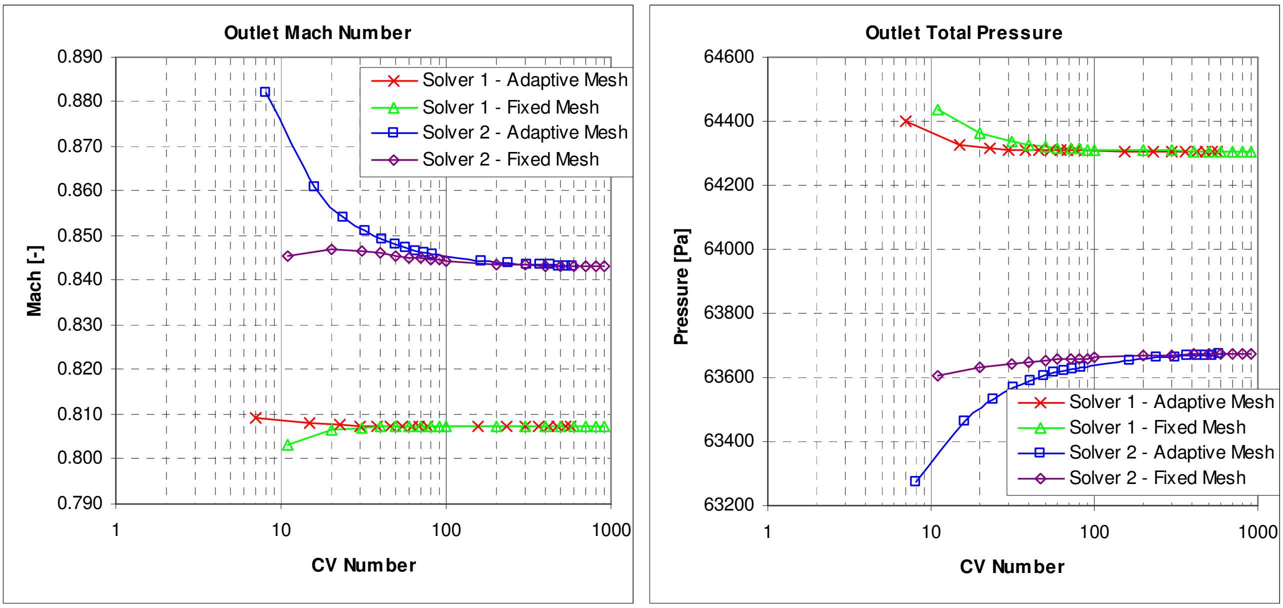

Figure 1: Mesh and solver influence on outlet Mach number and total pressure

Supposing that the most accurate solution is obtained by Solver 2, it is clear that in the reference conditions the first solver underestimates the outlet Mach number by 4% and, consequently, the pressure losses. The second solver requires more CV than the first one to obtain a correct convergence and, unlike the first solver, converges better using a fixed mesh. This behaviour is due to the algorithm used to adapt the CV length. This algorithm neglects temperature dependence of the fluid properties, resulting in a very useful tool in case of solver 1, which works at constant fluid properties, and less appropriate with solver 2 which is a more general solver.

ELEMENT SOLVER ASSIGNING GENERIC BOUNDARY CONDITIONS

The fluid dynamic computation of one dimensional steady state heat exchanger, assigning generic boundary conditions, requires an iterative approach due to the nonlinearity of the relation between coolant mass flow and pressure losses. Furthermore, if the evolving fluid is compressible and the velocity is high, the effect of the temperature is not negligible. For these reasons an iterative procedure is developed, particularly suited to high Mach flows, typical of blade cooling applications.
Because this tool must be used in a preliminary design phase, the algorithm has to be fast, in terms of convergence velocity, and stable. The computational demand depends on how many times the element solver is called in the iterative procedure, and on the convergence velocity as well. To improve these aspects, dimensionless variables and response surfaces are implemented.

The first step is to determine the most suitable dimensional variables, typical of a turbine blade cooling system and, by consequence, the definition of the main dimensionless numbers. Subsequently every element is characterized by two relatively accurate response surfaces instead of the two energy and momentum conservation laws, thus a faster and more stable iterative procedure is obtained. In the most general case the response surfaces are a non linear relation between pressure ratio, temperature ratio, Reynolds number, dimensionless mass flow and dimensionless temperature. The solver algorithm is characterized by two phases: in the first one the cooling system is solved, supposing inlet boundary conditions, so many times as required by the definition of the adimensional response surfaces coefficients; in the second phase, using these response surfaces, the dimensional working point is determined, consistently with the imposed boundary conditions, by a non linear solver. The most delicate issue is the resolution of a non linear equations system, which requires algorithms such as Newton or inexact Newton method, and so on. At this stage of the convergence the solution accuracy is affected by the response surfaces coefficients which must be refined by a progressive updating of the response surfaces, using the last element solution. In the preliminary implementation of the algorithm, a jacobian matrix is used to resolve the non linear equations system.

In order to validate the ability of response surfaces to characterize the element behaviour, a test on reference geometry is shown. The cooling system is tested in 180 working points, comparing the solver results with the response surfaces results. The test is performed changing inlet mass flow, pressure and temperature and evaluating the outlet conditions by the element solver. These results are compared with the pressure and temperature ratios predicted by the response surfaces, tuned using only the fist 10 working points. The test confirmed the ability of the response surface to predict the real behaviour of the element, being the mean error around 2%.

Another test is performed in order to evaluate the convergence velocity of the iterative procedure. The convergence velocity, defined as iterations number requested to obtain the right solution, is estimated changing the pressure boundary conditions. The Figure 2 shows the iterations number and Mach number versus pressure ratio.

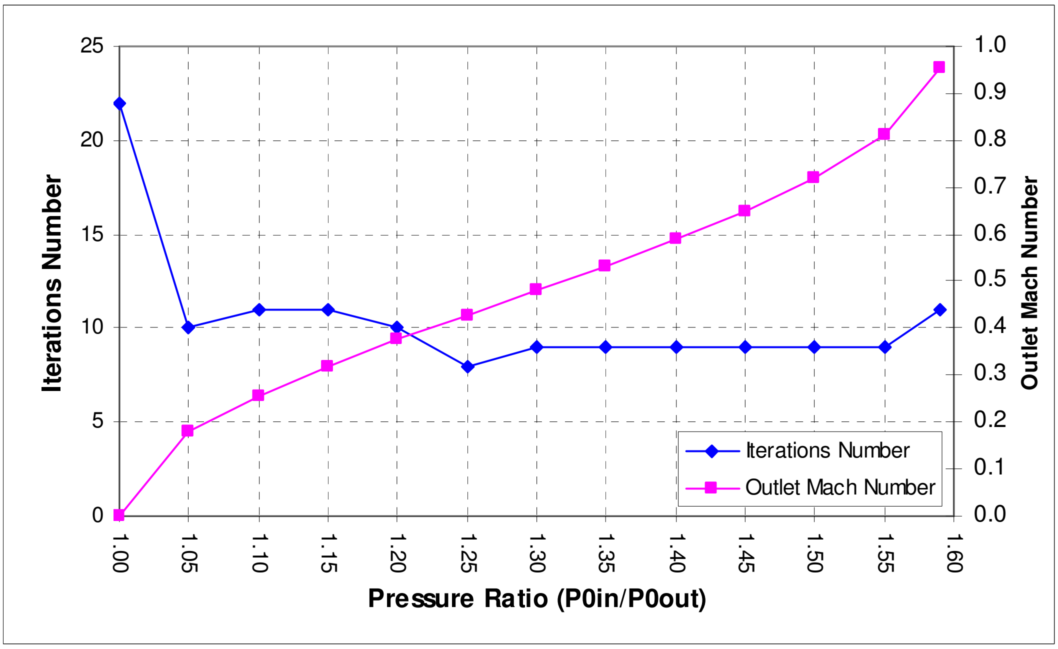

Figure 2: Convergence velocity and Mach number versus pressure ratio

The number of required iterations is about 10, independently from the outlet Mach number and the pressure ratio.

CONCLUSIONS

In this paper the main aspects of a preliminary design tool for vane and blade cooling systems technologies are discussed. The cooling system is modelled as steady state one-dimensional heat exchanger, with compressible fluid evolving.

Two element solvers are developed, the first one is simpler and faster, due to simplifying hypotheses, whereas the second one is more accurate but computationally more onerous.

A comparison between the two solvers, changing the type mesh and the control volumes number, is executed. It shows the possibility to obtain solutions characterized by a good accuracy with the first solver as well.

Afterwards an iterative procedure to solve the cooling system, assigning generic boundary conditions, is implemented. It uses a dimensionless approach and allows describing the elements behaviour by adimensional flow functions and quadratic response surfaces.

Two tests are performed to validate the good property of response surfaces to characterize the element behaviour. In the first one reference geometry is tested in several fluid dynamic conditions, calculating the outlet mass flow, pressure and temperature both with element solver and response surfaces. The test shows a good ability of response surface to characterize the element behaviour. In the last test the convergence velocity is evaluated changing boundary conditions. It highlights a very good convergence velocity of the procedure.