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OPTIMAL BLADE SHAPES FOR VISCOUS DENSE GAS FLOWS THROUGH TURBINE CASCADES

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ABSTRACT

Dense Gases are single-phase vapors of molecularly complex fluids operating close to saturation conditions. In such a region, the perfect gas law is invalid and has to be replaced by more complex equations of state. In recent years, great attention has been paid to certain fluids, known as the Bethe—Zel'dovich—Thompson (BZT) fluids, which are theoretically predicted to exhibit in the vapor phase, for a whole range of temperatures and pressures above the upper saturation curve, negative values of the Fundamental Derivative of Gasdynamics Γ [1], *i.e.* reversed isentrope concavity in the *p-v* plane. In the transonic and supersonic regime, this can lead to nonclassical gasdynamic behaviors, such as expansion shocks and mixed waves. A particularly interesting application is represented by efficiency enhancement in Organic Rankine Cycles (ORCs). ORCs' working fluids are in fact heavy organic compounds with large heat capacities. Interestingly, some of the organic fluids used in ORCs also possess BZT properties. One major source of losses in ORC turbines is due to wave drag, as they usually operate in the transonic/supersonic regime: the use of a BZT fluid could avoid shock formation and, ideally, allow isentropic turbine expansion. Unfortunately, simply utilizing a BZT working fluid is not sufficient to maximize the reduction in losses. Operating the turbine cascade at a pressure and temperature near the thermodynamic region where BZT effects appear is also necessary. On the other hand, the thermodynamic region where BZT effects appear, i.e. the inversion zone, is of quite limited extent. As a consequence, a reduction in the cascade pressure ratio is also required in order to operate the cascade entirely within the inversion zone. Now, it is known from thermodynamic theory that a too small pressure ratio leads to poor global thermal cycle efficiency. Thus, the development of BZT Organic Rankine Cycles needs to find a reasonable tradeoff between two opposite requirements: on the one hand, turbine expansion must happen as close as possible to the inversion zone, in order to get maximal benefit from BZT effects, on the other one, the turbine pressure ratio must be sufficiently high for achieving high global cycle efficiency and power output. Previous studies about inviscid and viscous dense gas flows through turbine cascades [2] have shown that the use of a BZT working fluid allows, for a given cascade pressure ratio, an efficiency improvement of about 3% over air, and even greater benefits with respect to steam. The benefit is obtained for a range of thermodynamic conditions whose extent depends on the cascade pressure ratio. Namely, the higher the pressure ratio, the harder is to exploit dense gas effects to obtain improved cascade efficiency over a large range of conditions. Efficiency improvements observed in previous studies were simply due to the special nature of the working fluids, as the blade shapes considered were typical gas turbine blade sections, not specifically adapted for dense gas flows.

The objective of the present study is to find optimal blade shapes providing high turbine efficiency over a large range of operating conditions for turbulent flows trough highly loaded turbine cascades, characterized by high values of the pressure ratio. To this end, a multi-point optimization of the blade shape is undertaken, using a multi-objective genetic algorithm.

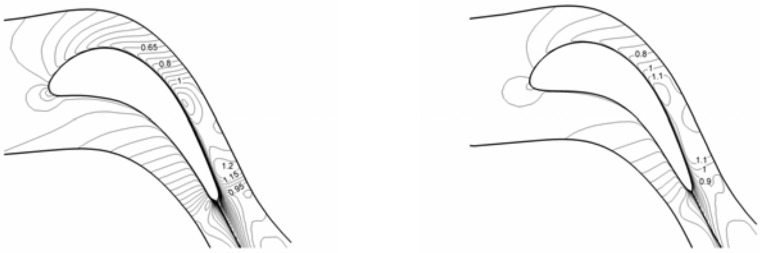
Viscous dense gas flows are modeled by the compressible Reynolds-Averaged Navier-Stokes equations for single-phase, non-reacting flows, completed by the realistic equation of state of Martin-Hou [3], and by the simple Baldwin-Lomax turbulence model. A structured grid solver (SGS), using the third-order accurate centred scheme of Ref. [4] is used. The solution is advanced in time using a four-stage Runge-Kutta scheme. Local time-stepping, implicit residual smoothing and multigrid are used to efficiently drive the solution to the steady state.

The flow solver is coupled with a multi-objective genetic algorithm (MOGA). Genetic algorithms have proved their interest with respect to gradient-based methods because of their high flexibility and also because of their ability to find global optima of multi-modal problem. The MOGA applied in this study is the Non-Dominated Sorting Algorithm (NGSA) proposed by Srinivas and Deb [5]. For multi-objective problems, a Pareto-based genetic algorithm is applied. The MOGA has been

previously validated for the optimization of airfoil shapes in dense gas flows [6,7]. In order to select a proper starting population for the genetic algorithm, the representation of the design space is previously investigated through a Design of Experiment (DOE) procedure. In this study the Sobol sequence technique is adopted. Sobol algorithm creates sequences of "n-tuples" that fill the "n-space" more uniformly than random sequence.

Shape optimization of turbine cascades has been studied through a DOE technique, and a MOGA. Blade shape is parameterized using Bezier polynomials, starting from the baseline profile VKI LS-59. Sixteen control points are imposed to parameterize the profile. Globally the optimization problem depends on twenty-five variables. Geometric constraints are imposed on the maximum blade thickness and on the trailing edge thickness. Computations were performed using a C-grid 192x16 cells with average non-dimensional height of the closest cells to the wall approximately equal to 5×10^{-5}. All computations have been performed with fixed inlet angle of 30° and pressure ratio of 1.82. For dense gas flows, inlet thermodynamic conditions, i.e. the thermodynamic operation point, should be also specified. First, a single-objective shape optimization for a diatomic perfect gas (γ=1.4) has been computed in order to maximize turbine efficiency (defined as real-to-ideal static enthalpy drop). In this case, sonic exit conditions are imposed. A preliminary DOE over 400 individuals allows to select the initial population and to reduce the number of independent variables, discarding those variables that do not influence the objective function more than a given threshold. The solution for the baseline blade is characterized by an oblique shock at about 70% the chord and a second shock attached to the trailing edge. Efficiency is 83.2%. In the solution after shape optimization the oblique shock is nearly suppressed and the remaining shock is weaker with respect to the reference case and efficiency grows to 86.9%. Then, preliminary inviscid computations are performed using the heavy fluorocarbon PP10 as the working fluid. Different runs are considered with different operating conditions. Here again, a DOE has been preliminarily run to properly initialize the population of the GA. For each configuration, a parametric study of cascade efficiency at off-design conditions has been performed. The use of a BZT working fluid has a beneficial effect, related to reversed sound speed variation in dense gases, leading to a reduction of the maximum Mach number at the wall. The mechanism leading to efficiency improvement is a reduction in the maximum Mach number: major gains come from a significant weakening of the trailing edge shock for the optimized configuration. This is related to lower values of Γ at the rear part of the suction side, causing slower growth of the Mach number when the flow re-expands downstream of the first shock.

Finally, a multi-objective optimization for viscous dense gas flows also have been performed. Cascade efficiency has been optimized at several operating points in order to obtain blade shapes providing high system efficiency over a large range of conditions.



(a) (b)

Fig. 1: Iso-Mach lines for baseline and optimized cascades. a) perfect gas, VKI LS-59; b) optimized configuration for perfect gas.

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