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Evolutionary Optimization of Centrifugal Nozzles for Organic Vapours

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Abstract. This paper discusses the shape-optimization of non-conventional centrifugal turbine nozzles for Organic Rankine Cycle applications. The optimal aerodynamic design is supported by the use of a non-intrusive, gradient-free technique specifically developed for shape optimization of turbomachinery profiles. The method is constructed as a combination of a geometrical parametrization technique based on B-Splines, a high-fidelity and experimentally validated Computational Fluid Dynamic solver, and a surrogate-based evolutionary algorithm. The non-ideal gas behaviour featuring the flow of organic fluids in the cascades of interest is introduced via a look-up-table approach, which is rigorously applied throughout the whole optimization process. Two transonic centrifugal nozzles are considered, featuring very different loading and radial extension. The use of a systematic and automatic design method to such a non-conventional configuration highlights the character of centrifugal cascades; the blades require a specific and non-trivial definition of the shape, especially in the rear part, to avoid the onset of shock waves. It is shown that the optimization acts in similar way for the two cascades, identifying an optimal curvature of the blade that both provides a relevant increase of cascade performance and a reduction of downstream gradients.

1 Introduction

Among the several industrial application of organic fluids, Organic Rankine Cycle (ORC) power systems represent one of the most attractive technology for the exploitation of energy sources featuring medium-low enthalpy level [1]. The performance of the entire ORC power system is crucially dependent on the efficiency of the turbine [2, 3], whose optimization is complicated by the character of organic fluids, which combine low enthalpy drops with high expansion ratios. The design of centripetal or axial turbo-expanders for organic fluids usually leads to machines with a single or a few stages (up to 3), featuring converging-diverging channels and strong shocks at blade outlet regions [4, 5]; such configurations induce limitations in the performance and in the degree of control of the turbine. These inherent difficulties are further amplified by the severe non-ideal effect exhibited by organic vapours in their flow within the machine.

To overcome the aforementioned limitations the novel radial-outflow, or centrifugal, turbine configuration has been recently proposed in [6, 7], receiving scientific recognition and industrial exploitation. The centrifugal turbine can better accomplish the large volumetric flow ratio, thanks to the natural increase of passage area along the flow path, thus limiting the flaring angle without significant increase in meridional velocity; furthermore many stages can be disposed in a relatively compact machine, reducing the cascade expansion ratios, potentially avoiding supersonic flow conditions. For these reasons, the centrifugal architecture allows to increase the aerodynamic performance as well as to enlarge the power control capability.

A research program on the development of novel centrifugal turbines for ORC applications is presently ongoing at Politecnico di Milano, with the aim of proposing specific design guidelines for this technology. To this end, a design methodology has been conceived with a hierarchical approach, following the path laid-down in [8]. The preliminary design of the whole machine was first studied by means of mean-line and throughflow codes [7], then the basic criteria for the aerodynamic design of centrifugal turbine profiles were set-up [9] and the three-dimensional aerodynamics of centrifugal turbine stators and rotors was studied [10].

The present work provides a step forward in the design procedure of centrifugal turbines, by discussing the shape optimization of centrifugal turbine blades. As a matter of fact, the selection of the most suitable profile such non-conventional architecture working with organic fluids cannot rely on empirical methods, but it demands the set-up of a completely new technique based on the combination of aerodynamic indications, high-fidelity computational tools, and systematic optimization strategies. This new procedure is constructed by combining a generalized geometrical parametrization technique, a high-fidelity Computational Fluid Dynamic (CFD) model, and a surrogate-based gradient-free optimization method.

This paper discusses the application of the design procedure to the shape optimization of two centrifugal turbine stators, characterized by different radial effect and aerodynamic loading. The comparison between the two cases allows to highlight the specific design features of centrifugal turbine blades and, eventually, to derive some design guidelines for the aerodynamic design of this class of machines. The paper is organized as follows: at first the procedure for the construction of a first-guess shape for the turbine profile is recalled; then the shape optimization tool for turbomachinery cascades operating with non-ideal fluids is introduced; finally the optimal design of two centrifugal nozzle cascades is extensively discussed.

2 Preliminary Cascade Design

The centrifugal nozzles studied in this work are conceived for implementation in the six-stage centrifugal turbine proposed in [7] for application in high-temperature ORC systems, and using the Siloxane MDM as working fluid. Operating conditions, size, power release, and total-total efficiency of the turbine, as resulting from the preliminary design, are listed in Table 1.

Fluid	$P_{T,in}$	$T_{T,in}$	P_{out}	Ω	*Diameter*	*Power*	*Efficiency*
MDM	10 bar	274 C	0.17 bar	3000 rpm	1.0 m	1.27 MW	86.9%

Table 1. 6-stage turbine conditions, size and performance

The layout of the turbine consists in six stages which share the reaction degree (equal to 0.5), the discharge flow angle (equal to 66.7 deg, opposite in sign between stators and rotors), and the radial chord (equal to 26 mm). With these choices, a smooth shape of the meridional channel is achieved. The throughflow analysis, performed with the in-house code TzFlow [11] and extensively reported in [7], indicated that the flow remains mostly subsonic.

The present work discusses the optimal aerodynamic design of the first and sixth nozzle cascades of the turbine, re-named CN-I and CN-VI in the following. As usual in turbomachinery applications, a preliminary (or baseline) shape for the blades is first defined using simple criteria, then the initial configuration is optimized using a systematic technique. In the present study, the baseline shape of the two profiles was defined by applying the concepts proposed in [9], in which aft-loaded profiles featuring a smooth acceleration are shown to be suitable centrifugal turbine cascades (at least for flow turning within 70 deg). The mean-line of the profiles is then assigned as elliptic arc, whose aspect ratio is determined after a parametric study. Then, a conventional distribution of thickness is applied to the mean-line to construct the blade. The blade geometric angles are assigned imposing null incidence and deviation estimated by resorting to the correlation of Ainley & Mathieson. The resulting profiles, originally constructed in the Cartesian coordinate system, are finally mapped on the polar coordinate system using a conformal transformation, in order to maintain the geometric angles of the blade.

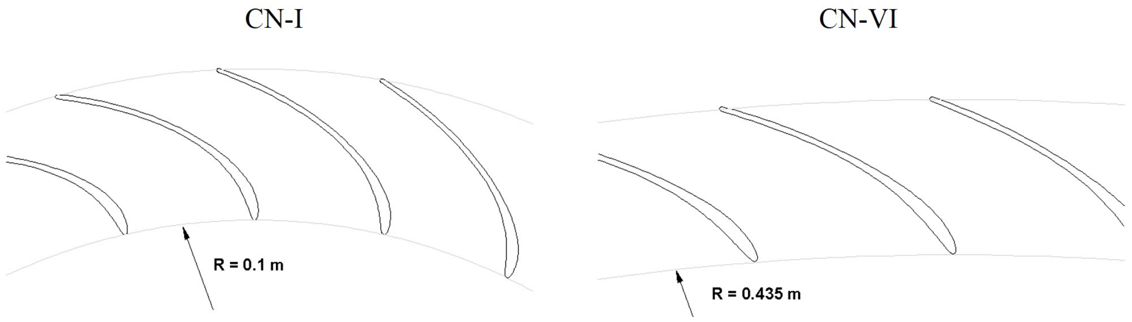

Figure 1. Preliminary design of the CN-I and CN-VI cascades of the centrifugal turbine

The CN-I cascade was constructed in order to deflect the flow from purely meridional (radial-outward) flow to 66.7 deg; the blade number, selected using the Zweifel criterion, resulted equal to 28. The distribution of thickness was taken from that of a lightly loaded low-pressure axial turbine. The CN-VI cascade was constructed to deflect the flow of 40 deg, using the same thickness distribution of the first nozzle; the blade number resulted 82. Figure 1 reports the layout of the two nozzle cascades under consideration, constructed by applying the aforementioned procedure. These blades were the starting point for the application of the systematic optimization technique, which is described in the next Section.

3 Optimization Technique

The progress in computational capability, the increased fidelity of CFD models, and the improving effectiveness of optimization algorithms have triggered the development of novel design tools to determine the optimal shape of aerofoils and turbomachinery blades. Among the techniques presently available, deterministic adjoint-based methods [12, 13] and heuristic evolutionary methods [14, 15] are nowadays object of intense application and research in Aerodynamics. Evolutionary methods, in particular, are of interest as they allow to explore a wide range of feasible solutions [16] without being 'intrusive' with respect to the source flow model, as they only require the use of direct calculation tools.

In this work, the shape-optimization of the centrifugal nozzles is carried out by applying the in-house design package FORMA (Fluid-dynamic OptimizeR for turbo-Machinery Aerofoils) recently set-up at Politecnico di Milano. The optimization strategy, briefly recalled in the following, is constructed by combining three main bricks, namely a geometry-parameterization code, a high-fidelity and experimentally validated CFD solver, and a surrogate-based evolutionary algorithm.

3.1 Geometry Parameterization Method

In shape optimization methods, it is common practice to parametrize the geometry with piecewise functions, so to control the shape by moving a limited number of so-called Control Points (CPs). In the FORMA package, B-Spline curves are used to parameterize the line of the blade profile; the global and local control of the shape provided by the use of B-Splines makes them a powerful tool for aerodynamic designs [18]. The position of the CPs their range of variation define the design space of the optimization problem. Piecewise lines of order 3 are used in this work. More details on the parametrization technique can be found in [17].

To set-up the optimization, at first an approximate representation of the baseline blade shape is constructed using a B-Spline curve, defined and manipulated by the position of the CPs; once the number and the spacing of the CPs is prescribed, the coordinates of the CPs are found via a least squares interpolation method. In the FORMA package, the pressure and suction sides of the blade are generated as a unique B-Spline curve, filleted by a circular-arc trailing edge.

3.2 Computational Flow Model
To evaluate the performance of the blade configurations progressively identified by the optimization algorithm, high-fidelity CFD simulations are performed using the ANSYS-CFX solver. Turbulence effects are introduced using the $k - \omega\ SST$ model, ensuring wall y^+ below unity all along the blade profile. To properly introduce the non-ideal thermodynamic behavior of MDM, a look-up table approach was used. The look-up table was constructed by sampling the Span-Wagner Equations of State [19] though the thermodynamic library *FluidProp* [20]; tabulated transport properties were also introduced. Since the object of this study is the optimization of the profile, a quasi-3D flow model is used, considering a straight stream-tube.

Calculations were performed on structured grids composed by hexahedral elements. Grids composed by 50 kcells in the blade-to-blade surface were found to provide the optimal trade-off between computational cost (10 minutes for a CFD simulation on a 16-processor Linux cluster) and fidelity of result (5% overestimate in the entropy production with respect to the grid independent value [9]). The mesh was re-generated for each CFD run performed throughout the optimization process. The performance of the optimized blades, as well as the computed flow fields reported in this paper, were evaluated by using a grid independent mesh.

The reliability of the flow model here used was assessed against experiments performed by the authors themselves on a cold-flow gas turbine stage installed at Politecnico di Milano [21].

3.3 Surrogate-Based Optimization Strategy
The optimization technique applied in this work is based on Genetic Algorithms (GAs). GAs are attractive as they allow to deal with oscillating and non-smooth objective functions, as well as to easily handle constrained and multi-objective optimization problems [22]. Furthermore, GAs are global optimization methods and, hence, are best suited in presence of a multiplicity of local optima (a situation that cannot be excluded a priori in aerodynamic design).

Nevertheless, GAs require a massive application of the direct computational tool, that in case of CFD often result in an unacceptable computational burden. To tackle this cost, a surrogate evolutionary strategy was applied in this study. This technique is conceived so that the GA operates only on a surrogate model of the objective function. To be effective, the surrogate model has to be a reliable representation of the objective function; in surrogate-based strategies the model is initialized and progressively updated during the optimization, so that the shape is optimized while the reliability of the surrogate improves. Among the surrogate models available [23], the analytical Kriging formulation was used in this work to approximate the objective function. The Kriging formulation is based on a set of interpolation methods and allows to properly approximate complex surfaces featuring sharp curvature changes, even in presence of highly irregular distributions of interpolation points. This makes the Kriging model suitable for complex optimization problems such as the design of transonic turbomachinery.

The surrogate model is initialized by interpolating a database of configurations tested with the CFD model. To improve the reliability of the surrogate model, a Surrogate-Based Global Optimization (SBGO) is applied. In SBGO, the model is 'trained' by adding progressively the optima found in the previous iterations to the initial database. By virtue of this strategy, the global strategy results computationally efficient, even though the convergence is not guaranteed. However, a previous study on the optimization of an axial supersonic turbine [17], as well as the preliminary trials made on the present centrifugal configuration, did not show convergence issues if a sufficiently large initial data-base is assigned.

The FORMA package was assembled making use of the object-oriented framework Dakota [24]. A single-objective GA was used as optimization tool, by resorting to the JEGA library (Java Engine for Genetic Algorithms). After a preliminary parametric study, the GA was set-up with a population size of 300 generations, a crossover rate of 0.8, and a mutation rate of 0.02; elitism was also used as a selection technique. To determine the Kriging parameters, the Surfpack library was employed; universal Kriging formulation was used, with non-zero covariance based on a Gaussian correlation function. In order to initialize the surrogate model, a Latin Hypercube technique was used, with a population equal to 10 times the number of design variables.

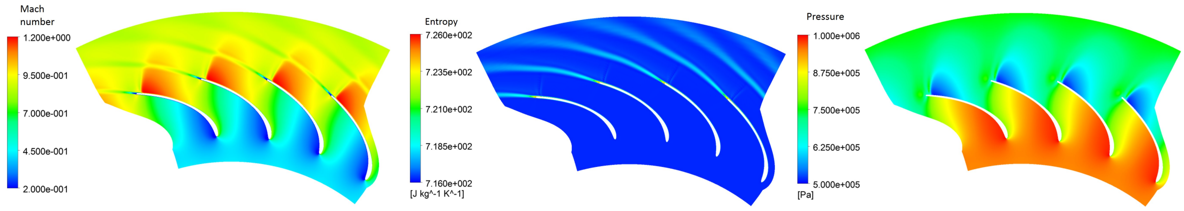

Figure 2. CN-I flow field for the baseline shape: Mach number distribution (left), entropy field (center), pressure field (right)

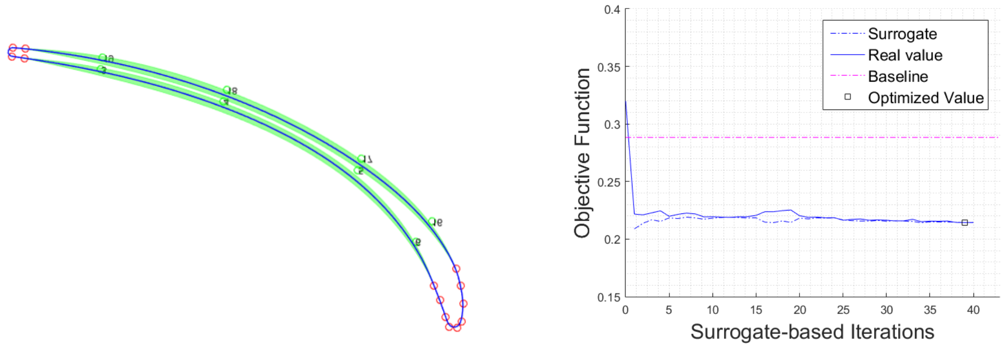

Figure 3. CN-I optimization process. Left: Design space. Right: Convergence

4 Results

In this Section, the FORMA package is applied to the configurations of interest, with the aim to both obtain an optimal shape and derive design remarks. The optimization of CN-I is first considered, then optimal design of the CN-VI is presented.

4.1 First-Stage Centrifugal Nozzle

The CN-I has to provide conventional flow deflection for turbine applications, but it exhibits a very significant radial effect, as a 25% change in radius and then of meridional cross-section occurs along the blade radial extension. In such a configuration the application of conformal mapping to profiles with a rear curvature leads to blades with high backbone length with a large and curved semi-bladed region downstream of the throat. This makes critical the design of the rear suction side of the blade, especially considering the transonic flow conditions.

These critical aspects are well visible in Figure 2, which reports about the Mach number, entropy and pressure distributions for the CN-I in the baseline configuration. Even though the target cascade-exit Mach number is below 1, a significant over-speed is established in the rear part of the profile downstream of the throat, with local Mach number exceeding 1.2. This feature results in a relatively strong shock just upstream of the trailing edge. This is detrimental for the turbine efficiency for both direct and indirect reasons, as such a shock reduces both the performance of the nozzle itself and that of the subsequent rotor, and also induces a severe aerodynamic forcing on the rotor blades.

Aiming at maximizing the turbine performance, the shape optimization of CN-I has to focus on the rear part of the profile. To this end, the baseline geometry was parametrized as reported in Figure 3-left, namely with 21 CPs in total and 8 CPs movable (of $\pm 0.4 mm$ in vertical direction), resulting in the design space highlighted in green in the figure. Both the leading edge and trailing edge regions of the profile are kept unchanged during the design process, for different reasons. The four CPs on the trailing edge are crucial to constraint the thickness (for structural reasons) and to guarantee the required regularity in a region where the B-spline of the profile is merged with the circular-arc of the trailing edge. The leading edge region is

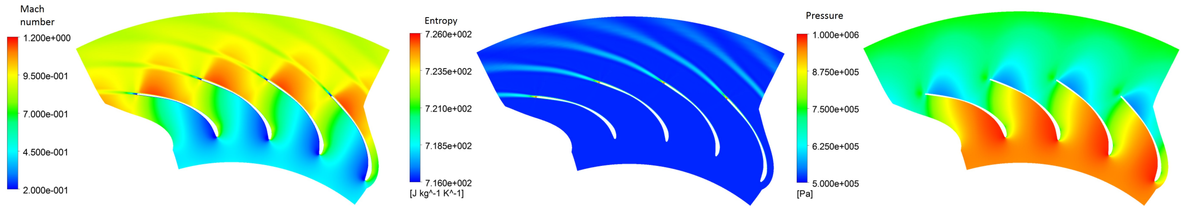

Figure 4. CN-I flow field for the optimal shape: Mach number distribution (left), entropy field (center), pressure field (right)

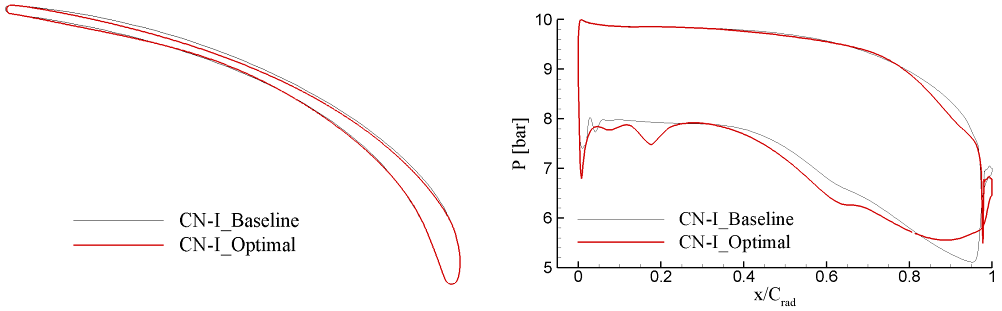

Figure 5. CN-I baseline / optimization comparison. Left: Blade profiles. Right: Pressure distribution.

kept fixed as, apparently, it has a weak effect on the performance and a reduction of movable CPs results in a reduction of design variables and, eventually, in a significant limitation of the computational burden. The mass-averaged entropy production between the inlet section and a section placed 0.2 C_{rad} away from the blade trailing edge is used as Objective Function.

Figure 3-right reports the convergence process of the surrogate-based optimization, and indicates that after the initialization the surrogate function already exhibits a satisfactory reliability. A marginal improvement is, however, achieved in the following 50 iterations, resulting in a reduction of entropy production of about 30% with respect to the baseline configuration. Considering the cost of each CFD run, the whole optimization required about 1 day of calculation (using the aforementioned 16-processor cluster machine).

Figure 4, which reports the flow field for the optimal configuration with the same scheme of Figure 2, clarifies that the improvement in performance is achieved by a reduction of the over-speed on the rear suction side of the blade, which results in a much weaker shock. The weakening the shock induces a reduction of both shock losses and wake losses, as the effects of shock-boundary layer interaction are also minimized. As a result, the total pressure loss coefficient, defined as $Y = (P_{T,in} - P_{T,out})/(P_{T,in} - P_{out})$, drops from 4.4% of the baseline configuration to 3.3% of the optimal configuration (Y was evaluated on a section placed half a C_{rad} downstream of the trailing edge, where most of the mixing has already occurred).

By considering the detailed shape of the baseline and optimal blades, reported in Figure 5-left, it can be observed that both the mean line and the thickness distribution change for the optimal blade. In particular, the optimization drives the design towards a profile with an increased curvature and a reduction of thickness in the central region of the blade, followed by a more flat mean line and a newly increased thickness in the rear section. Figure 5-right, which provides the pressure distribution on the profiles, highlights that the shape modification allows to reduce the over-speed in the rear suction side as well as to eliminate the abrupt pressure rise induced by the shock at the trailing edge. The pressure side, instead, exhibits almost the same trend of the baseline profile. This is a fairly expected result as in this kind of transonic profiles the flow mechanisms occurring on the suction side are the major sources of loss.

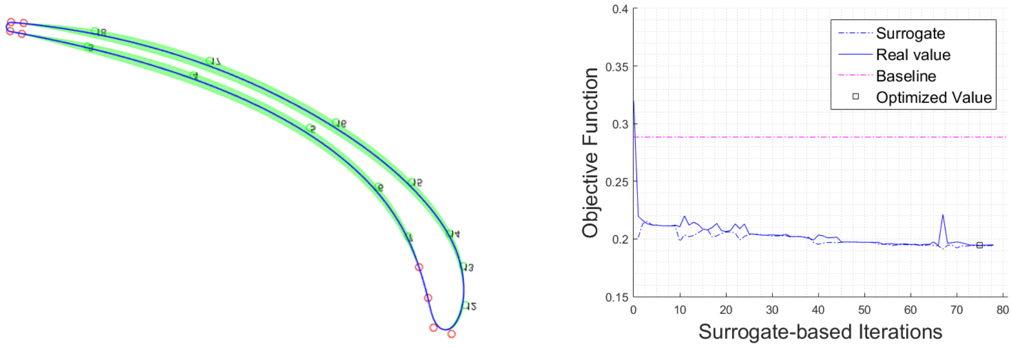

Figure 6. CN-I advanced optimization process. Left: Design space. Right: Convergence

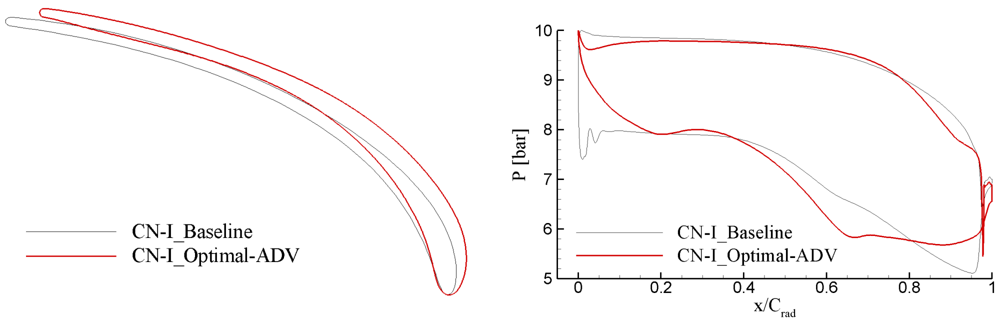

Figure 7. CN-I advanced optimization result. Left: Mach number distribution. Right: entropy field.

The pressure distribution provided in Figure 5 also shows that significant adverse pressure gradients affect the front area of the profile. Even though the calculations suggest that these pressure gradients do not induce local separations, in an effort of further improving the cascade performance it would be beneficial to smooth the pressure distribution in the front area by a proper re-design of the blade. However, the geometry modifications required to improve the front area of the blade are trivial and, hence, they do not need the application of an automatic technique. For this reason, a new baseline profile was constructed by modifying the front part of the blade both in terms of mean-line inclination (which is now inclined by 10 deg at leading edge, instead of being radial as in the first design) and in terms of thickness (which is now 50% larger than in the previous case up to mid-chord length, and is smoothly reduced in the rear half of the profile to become equal to the original one at the trailing edge). The newly-constructed baseline blade was then parametrized by using 21 CPs, 12 of them are movable (by $\pm 0.4mm$) in such a way that the entire suction side of the blade can be modified. The new baseline blade and the corresponding design space are provided in Figure 6-left. The convergence process of this second 'advanced' optimization, reported in Figure 6-right, confirms the smooth and regular trend observed previously, and shows a further minimization with respect for the first optimization

The resulting optimal blade differs significantly from the original baseline configuration. The curvature of the mean-line is increased in the front and central part of the blade, so to impose a higher local flow turning; conversely, the blade becomes almost straight in the semi-bladed region, so to avoid severe over-speed in the rear suction side. The impact of these features on the pressure distribution on the blade can be appreciated in Figure 6-right, which shows that the advanced optimization has both eliminated the severe adverse pressure gradients in the front area and further flattened the pressure distribution in the rear suction side.

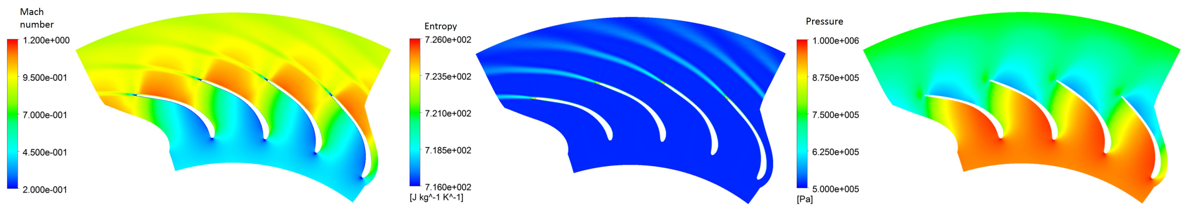

Figure 8. CN-I flow field after the advanced optimization: Mach number distribution (left), entropy field (center), pressure field (right)

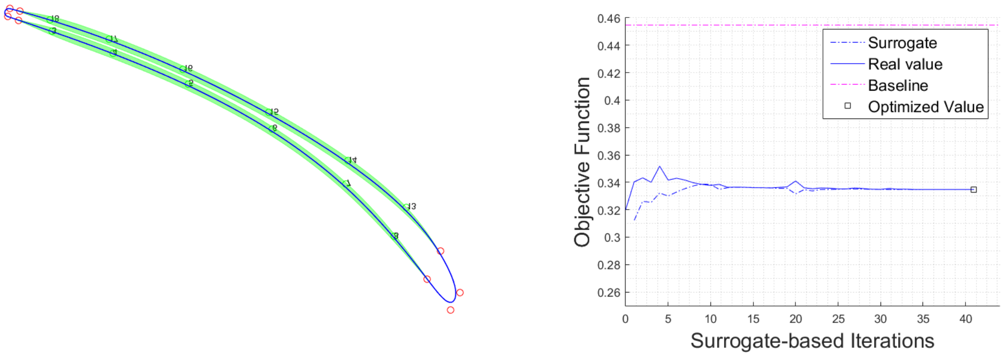

Figure 9. CN-VI optimization process. Left: Design space. Right: Convergence

The aerodynamics of the cascade benefit from these improvements, as visible in Figure 8. The pressure and Mach number distributions highlight the reduced gradients in the leading edge region as well as the further weakening of the rear shock, which eventually result in a weaker wake and reduced losses. The corresponding loss coefficient Y further reduces to 3.1%.

On the whole, the systematic optimization has allowed to improve the pressure distribution along the entire blade profile resulting in a reduction from 4.4% to 3.1% in the loss coefficient, which meas an improvement of 30% in relative terms. The dramatic weakening of the shock in the rear part of the profile is expected to also improve the aerodynamics of the subsequent rotor, which is placed 0.2 C_{rad} away from the CN-I trailing edge.

4.2 Sixth-stage centrifugal nozzle

The optimization strategy was applied for the optimal design of the CN-VI cascade, which features a low aerodynamic loading (flow deflection of 40 deg) and transonic condition; full details on the preliminary design of the blade and the three-dimensional aerodynamics of the cascade can be found in [10].

The baseline shape of the CN-VI blade was still constructed using an elliptic-arc mean-line and the same thickness distribution used for the baseline CN-I blade. The blade was parametrized using 20 CPs, 12 of them can be moved by $\pm 0.4mm$ in vertical direction, as shown in Figure 9-left. The convergence process, reported in Figure 9-right exhibits the usual smooth trend, in which it is apparent that the surrogate achieves a satisfactory reliability 10 iterations after the initialization.

The effectiveness of the optimization can be appreciated by comparing the flow fields reported in Figures 10 and 11, which refer to the baseline and optimal configurations respectively. As observed for the CN-I cascade, the use of an elliptic-arc mean line allows to control the expansion process in the bladed channel, but not in the semi-bladed rear suction side, resulting in a relatively strong shock close to the trailing edge. The optimization acts on the blade so to increase the mean-line curvature in the central section of the blade, while making more straight the rear suction side of the blade. The result is an anticipated acceleration of the flow and a

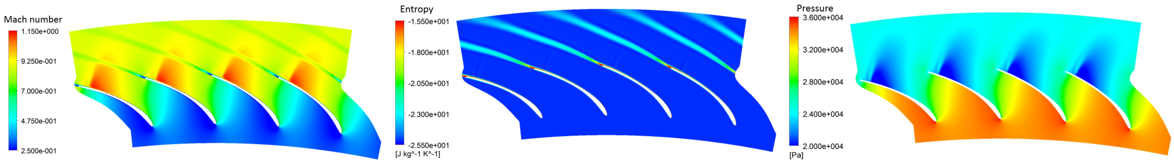

Figure 10. CN-VI flow field for the baseline shape: Mach number distribution (left), entropy field (center), pressure field (right)

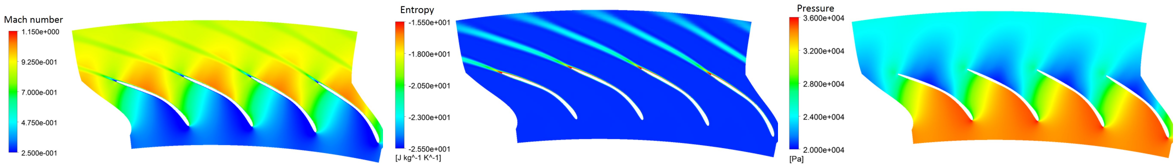

Figure 11. CN-VI flow field for the optimal shape: Mach number distribution (left), entropy field (center), pressure field (right)

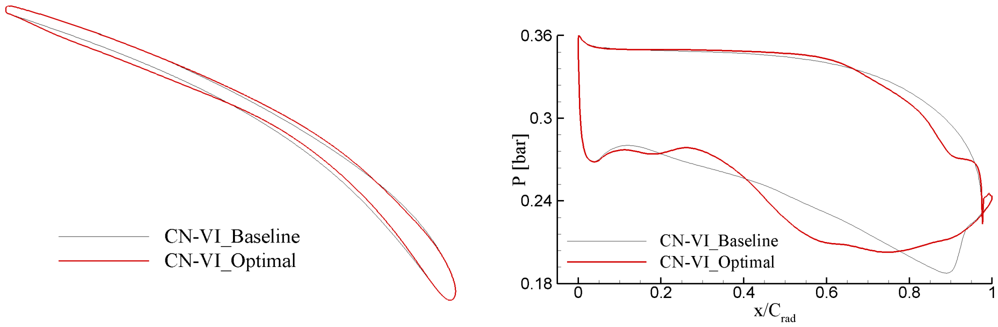

Figure 12. CN-I advanced optimization result. Left: Mach number distribution. Right: entropy field.

much lower over-speed, so that the shock close to the trailing edge is completely eliminated. These features are well visible in Figure 12, which provides a direct comparison between the blades and pressure distribution on the surface.

As a result of these shape modifications, the total pressure loss coefficient drops from 3.1% of the baseline configuration to 2.8% of the optimal cascade; furthermore, the pressure and Mach number gradients downstream of the CN-VI cascade are drastically reduced, with beneficial effects on the subsequent rotor, which is placed 0.2 C_{rad} downstream of the trailing edge.

5 CONCLUSIONS

This paper has presented the application of an evolutionary shape-optimization technique to the design of non-conventional centrifugal nozzles for application in ORC turbines. The technique, implemented in the in-house optimization package FORMA, makes use of a geometry-parametrization tool, an high-fidelity flow solver, and a surrogate-based evolutionary algorithm.

Two cascades have been considered, featuring different flow turning and radial extension, namely the first and the sixth nozzle of a six-stage radial-outflow turbine. The baseline shape of the blades, constructed by means of analytical tools, are parametrized via B-Splines, whose local control capability allowed a detailed shape reconstruction while preserving surface smoothness. The generalized thermodynamic treatment required to deal with the non-ideal gases featuring ORC turbines is achieved via a look-up-table approach, and is introduced straightforwardly into the optimization thanks to the non-intrusive character of the evolutionary strategy. To tackle the computational cost of the optimization, the genetic algorithm is coupled to a Kriging surrogate model. The selection of the design space and the convergence process have been highlighted to show the path of the optimization and the related computational cost.

The application to a novel cascade configuration has shown that the systematic optimization is able to improve significantly the performance of the nozzles and to reduce the pressure and velocity gradients at the inlet of the subsequent rotors. If the reduction of loss coefficient achieved for the first and last stator were extended to the remaining ones, a gain in 0.5% in the turbine efficiency would be achieved. This is a relevant result, especially because the estimated efficiency of the baseline turbine is relatively high (87%). Moreover, application of the same technique to the rotor blades would provide a further direct performance increase. Finally, all the stages would achieve a secondary benefit from optimization, especially from the structural point of view, thanks to the much more uniform flow released by optimized blade rows. These considerations clearly demonstrate the potential of a systematic blade optimization for multi-stage centrifugal turbines.

The analysis of the optimal blades has shown that centrifugal cascades are highly sensitive to the distribution of blade curvature. In particular, the aerodynamics of centrifugal nozzles is complicated by the inherent enlargement of meridional cross-section along the blade, which couples with the local flow deflection and with the non-ideal volumetric behaviour of the fluid. Simple assumptions on the functional form of the blade mean-line do not allow to control properly such effects, resulting in a relevant over-speed and in the onset of shocks in the rear suction side of the blade. Thanks to the flexibility and the generality of the systematic optimization technique here applied, optimal distributions for the mean-line curvature and the blade thickness are determined along the profiles. The trends obtained for the two different cascades exhibit similar features, which might be used to set-up generalized design remarks for centrifugal nozzles.

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