STEAM TURBINE CASCADE OPTIMIZATION USING CONTROLLED RANDOM SEARCH ALGORITHM AND CFD TECHNIQUES FOR ORC APPLICATION

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Abstract. *This paper presents a methodology for performance optimization of a steam turbine cascade using Controlled Random Search Algorithm and CFD techniques for ORC (Organic Rankine Cycle) application. The steam turbine cascade is parameterized to achieve the maximum efficiency while using differents organics fluids. The main objective of this work is to attain the maximization C_l/C_d ratio from a preliminary design. The approach to find the maximum C_l/C_d ratio is based in optimization algorithms. The controlled random search algorithm (CRSA) was chosen for the optimization process. The otimization algorithm (CRSA) is integrated with CFD techniques, using schemes automatic building of parameterized geometries and meshes via "script files" with editing commands written in Tlc/Tk language, wich will be interpreted by the commercial software ICEM-CFD®, in batch mode. Finally, for the numerical calculation, the commercial software FLUENT® is used with fluids properties, real gases model, turbulence model and boundary conditions set through "journal files". In this paper, R245fa and Toluene are used as working fluids. Results of drag, lift and pressure distribution are reported. This metodology allows making corrections in the initial project of the cascade shape without using a lot of computational effort.*

Keywords*: ORC, Optimization, CFD Techniques, CRSA.*

1. INTRODUCTION

The accelerated consumption of fossil fuels has caused many serious environmental problems such as the destruction of the ozone layer, global warming and air pollution. Emissions of carbon dioxide related to energy consumption have increased worldwide from 30.2 billion metric tons to 35.2 billion metric tons in recent years and will be around 43.2 billion metric tons in 2035. Due to these projections, new energy conversion technologies are required to use energy resources suitable for power generation without causing environmental pollution. Low-grade sources of heat are considered as candidates for new sources of energy. Organic fluids are typical sources of low grade heat available as an alternative for the production of electricity using power turbine cycles.

In this sense, researchers have committed a lot of efforts to develop methods for optimal design based on genetic algorithms to find the best design point. Recently, [6] dealt with a method of maximizing the efficiency of the steam turbine based in genetic algorithms. This method has a number of functions that are taken as constraints. Thus the optimal geometry and aerodynamic parameters are solved using the genetic algorithm.

Researchers are more and more using CFD techniques because through certain defined geometry and with the use of correct boundary conditions it is possible to calculate the local and global variables of the flow field.

The fundamental basis of almost every CFD problems is the Navier–Stokes equations, which define any single-phase fluid flow. However, it is not possible to only use CFD techniques when dealing with a great number of geometrical and flow parameters. Then, in order to attain the correct solution it is best to use an optimization algorithm (AO).

Recently, [5] classified surrogate models into four main categories: (i) data-fitting models, where an approximation of the expensive function is constructed using an available data bank; (ii) variable convergence models, where the expensive function depends of the numerical solution of a partial differential equation with a relaxed stopping criterion; (iii) variable resolution models, where a hierarchy of grids is used and the surrogate model is just the costly evaluation tool but run on a coarse grid; (iv) variable fidelity models, where an hierarchy of physical models is used. The first category is focused in this paper.

2. TURBINE CASCADE DESIGN

The preliminary design of a turbine begins using one-dimensional modeling techniques. The thermoaerodynamic design of a turbine involves handling a large amount of parameters associated with mechanical calculations to obtain the final geometry for the context in which the turbine is intended.

In general, the design consists in the search of some basic geometrical parameters for the rotor blades - the design variables - in order to maximize the turbine efficiency. Figure 1 illustrates the basic steam turbine cascade configuration.

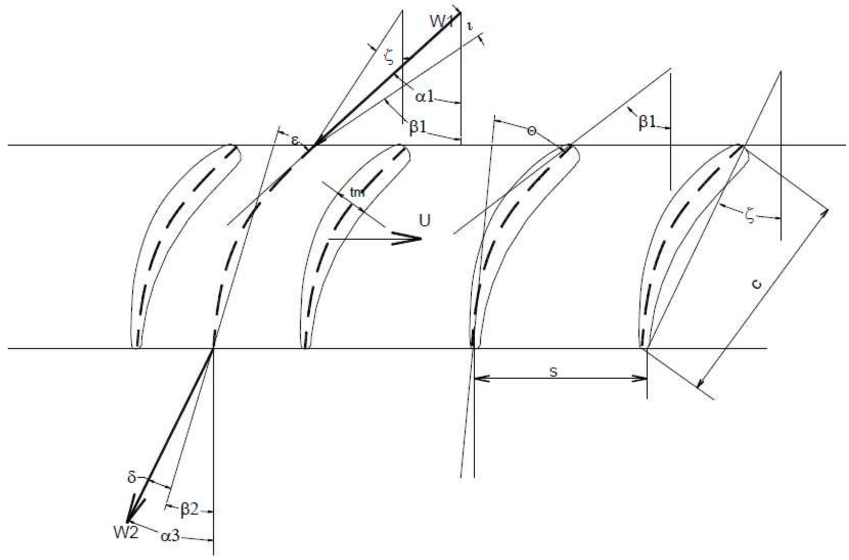


Figure 1. Cascade Configuration.

For the turbine blade design, the camber line was estimated using the inlet and exit relative angle. This was done graphically by a *script* written in Tcl/Tk language that can be interpreted by the software ICEM-CFD®. Given the chord length (c), the tangents to the leading and trailing edge of the chord were constructed by the inlet (β_1) and outlet (β_2) relative angle as shown in Figure 2. The tangents were brought to an intersection with each other and subdivided into equal distances. The envelope to the inner region of the connecting lines is the camber line. Once the camber line was constructed, a NACA 6519 profile was superimposed and the new profile was generated.

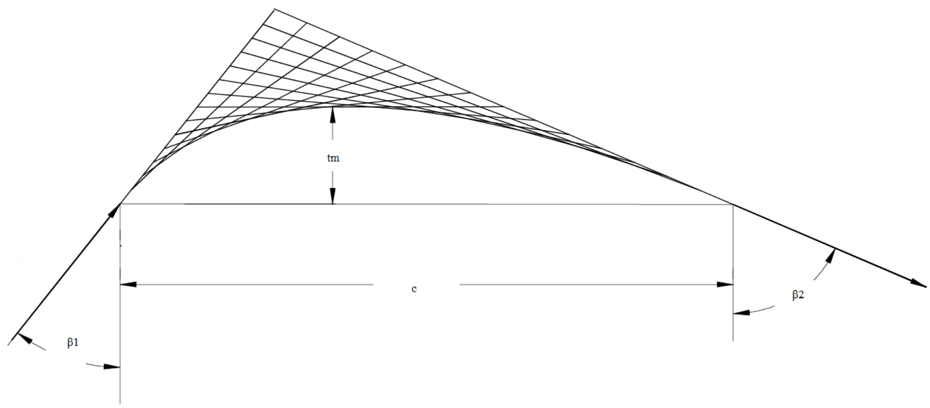


Figure 2. Camber Line Generation Methodology.

3. Optimization Method

For the optimization process was chosen a global stochastic optimization algorithm known as Controlled Random Search Algorithm (Controlled Random Search Algorithm - CRSA). The CRSA is an algorithm based on a set population, so Genetic Algorithms and Differential Evolution. The CRSA from an initial population of individuals over a consistent region of the problem promotes iterative substitutions of the worst individuals by the best, willing that the population shrink up around the global optimum.

Defined as $\{Sp = x \in R^n : x_j^L \le x_j \le x_j^U, j = 1,......., n\}$, where $x_j^l \le x_j \le x_j^U$ represent the lower and upper bounds respectively for n coordinates of x. The point x^* is a global minimum of f if $f(x^*) \le f(x)$, $\forall x \in Sp$. Besides the side constraints used in the definition of Sp, other restrictions may be imposed.

The CRSA is an algorithm based on the generation of a population of starting points P of N points randomly generated on the space explored, following an iteration process converges to a global minimum by procedures purely heuristic [1] [2].

The basic CRSA minimization is described as follows (adapted [1] and [2]):

1. Generation of the initial population P of N random points in Sp: $P = \{x_l ... xN\}$. Determination of the worst point, h and the best point l , this is, points P with the best and worst values of the function, f_h e f_l, respectively. If the stopping criterion is always satisfied, then stop (for example, stop if f_h - $f_l < \varepsilon$, where ε is an obtained tolerance).
2. Generation of the test points p to replace the worst point h.
3. If p is infeasible ($p \notin Sp$), follow back to step 2 (or change p, making it feasible).
4. Evaluate $f_p = f(p)$. If p is unsatisfactory ($f_p \ge f_h$), proceed to step 2.
5. Update the set of points P replacing the current worst point by point test: ($P \leftarrow P \cap \{p\} / \{h\}$). Find h and f_h in new P. If $f_p < f_l$, then set p, f_p as new l, f_l.
6. If the stopping criterion is satisfied, terminate, otherwise proceed to step 2.
7. The two main differences between the CRSA's available refer to: (i) mode generation point attempt (step 2), (ii) access to an optional local search phase where the best point is the latest in the population (where $f_p < f_l$ in step 5). It should be noted that all versions assume that $N >> n$; as a general rule, it is suggested typically $N_{Population}$ = 10 (n + 1) [12] [13].

4. CASCADE OPTIMIZATION

Cascade analysis still represents a fundamental tool in turbomachinery design context. Relying on 2-D flow models, cascade flow computations are much faster than 3-D models of similar physical complexity.

Prior to optimization process certain steps should be prepared, for example, the definition of a computational domain and mesh generation. The 2-D meshes are generated by a *script* written in Tcl/Tk language that can be modified by the optimizer and interpreted by the software ICEM-CFD® (Fig. 3). Care is taken in the refinement of the mesh near the wall in order to properly quantify the friction stresses.

The organic fluid type is defined based on the thermodynamic properties, density and dynamic viscosity. The initial hypotheses, the discretized forms of transport equations are solved iteratively, and the solution must converge.

Real gases, as opposed to a perfect or ideal gas, exhibit properties that cannot be explained entirely using the ideal gas law. The NIST (National Institute of Standards and Technology) real gas model that use the Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures as an ANSYS FLUENT® shared library (REFPROP v7.0) was used to evaluate the thermodynamic and transport properties of the working fluids.

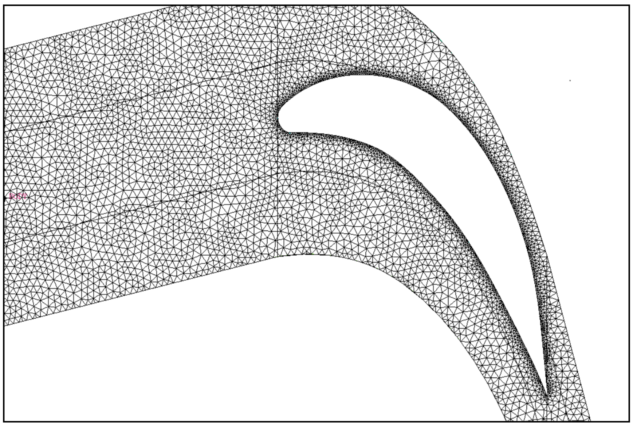


Figure 3. Cascade 2-D Hexahedrical Mesh.

The mass flow is set at the cascade inlet and the pressure at the cascade outlet. Periodic boundary conditions (Fig. 4) are considered for reducing the computational domain to a unique periodic region around an airfoil. The turbulence model Spalart-Allmaras (SA) with wall functions is chosen since these enable realistic responses for aerodynamics problems [3, 8].

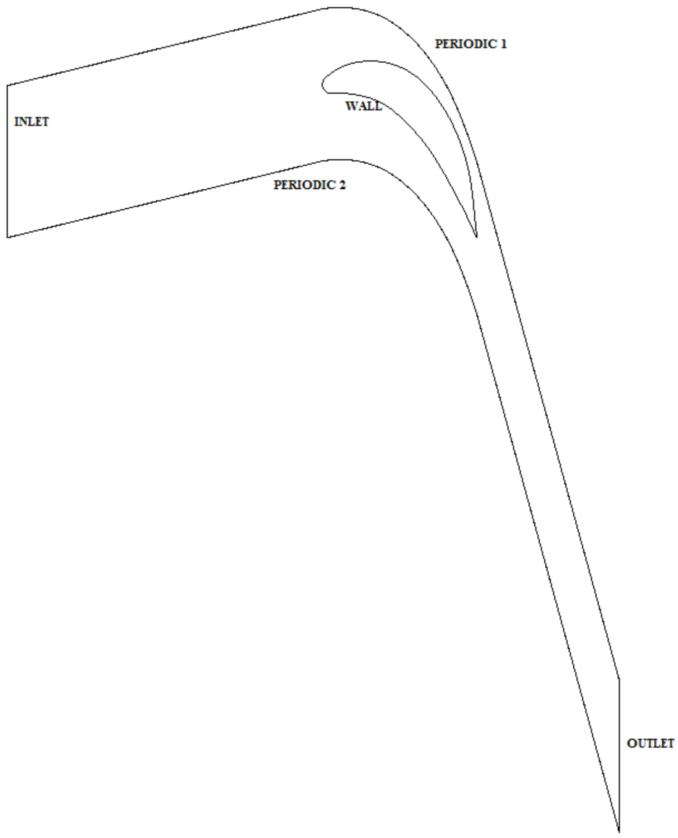


Figure 4. Boundary Conditions and Relative Domain

The drag and lift coefficients are calculated with basis on the magnitude of the mean velocity vector (W_∞). Drag coefficient is computed: first, the difference of total pressure between cascade inlet and outlet is evaluated and the following loss coefficient ζ_r is computed [9].

$$\zeta_r = \frac{P_1 - P_2}{(\rho/2)W_2^2} \tag{1}$$

The outlet mass average quantities are evaluated by control line (line/rake) located at a distance of a chord length from the trailing edge. Hence, the drag coefficient is computed by the following relationship:

$$C_d = \frac{\zeta_r \cos^3\beta_\infty}{(s/c)\cos^2\beta_2} \tag{2}$$

This methodology for calculating the drag coefficient avoids numerical errors associated with the integration of the blade surface forces.

Lift coefficient is then computed:

$$C_l = 2(s/c)\left[\tan\beta_1 + \tan\beta_2\right]\cos\beta_\infty - C_d \tan\beta_\infty \tag{3}$$

4.1 Process Integration Methodology

According to [4], to optimize complex systems, it is necessary to use methods of process integration, this is, CFD flow calculation and optimization algorithms. These methodologies contribute significantly to the development of engineering optimal designs.

For the cascade optimization the integration of all processes (CRSA → script.dat → ICEM-CFD ® → Journal. File → Fluent ®) in which the CRSA is the administrator of the process written in FORTRAN® is made.

The flowchart of Figure 5 illustrates the integration process, where the input and output files are used as a bridge for dates transfer.

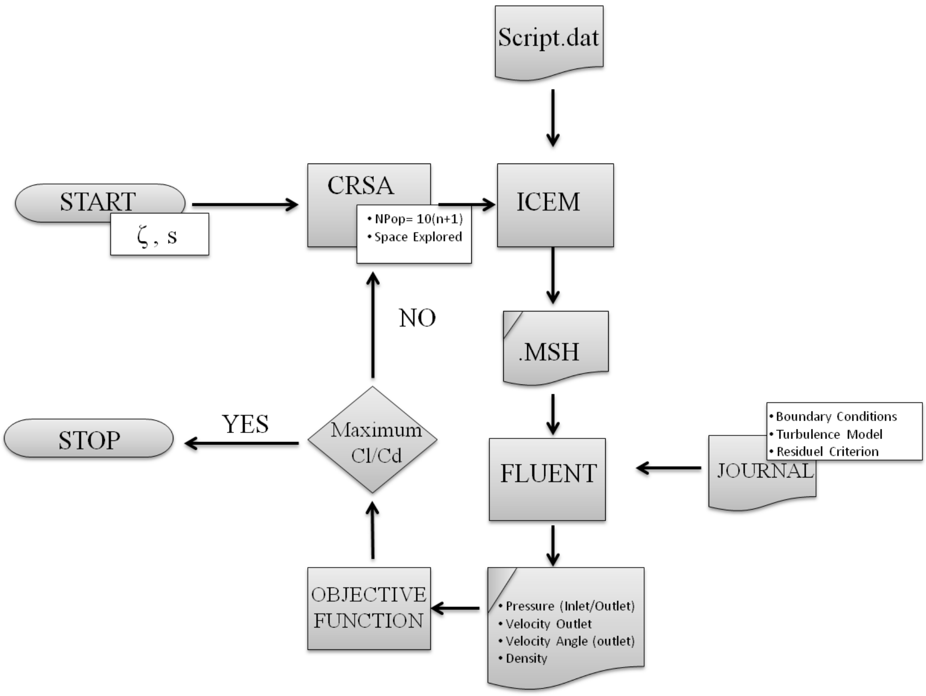


Figure 5. Process Integration Structure.

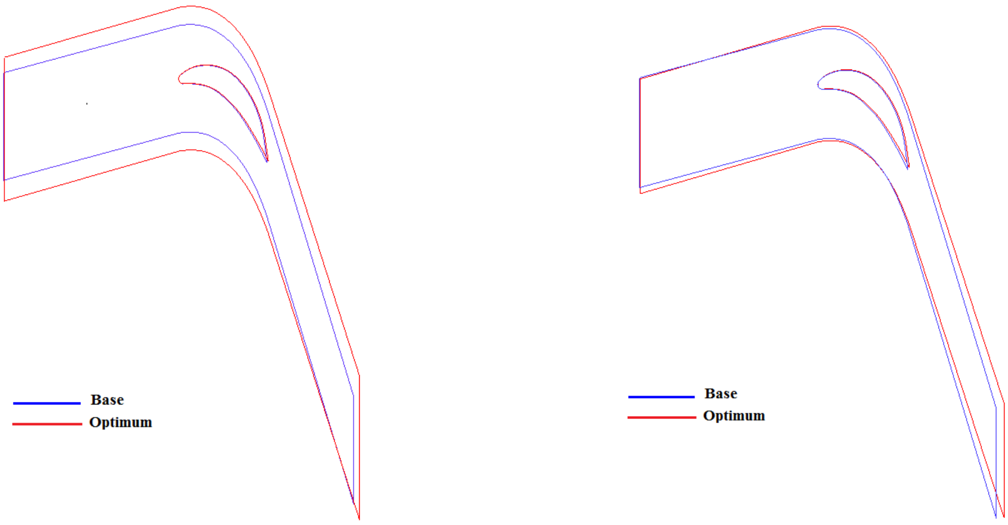
5. OPTIMIZATION PROCESS RESULTS

The results of the optimization process were obtained by integrating the CRSA with the CFD, as previously described (See Figure 5). From the command line in DOS in Fortran, a "script" generated in ICEM runs and a mesh is generated, after meshing, a file "journal.jou" created in Fluent runs and then the calculation of the flow starts, after an average of 700 iterations, the convergence in the solution is attain. Each new call of the objective function that maximizes the ratio C_l / C_d, a new geometry and mesh is generated and results of drag coefficient and lift coefficient are obtained; this process continues until finding the optimal solution. The results obtained are shown in Table 1.

Table 1. Results obtained from the optimization process with CRSA.

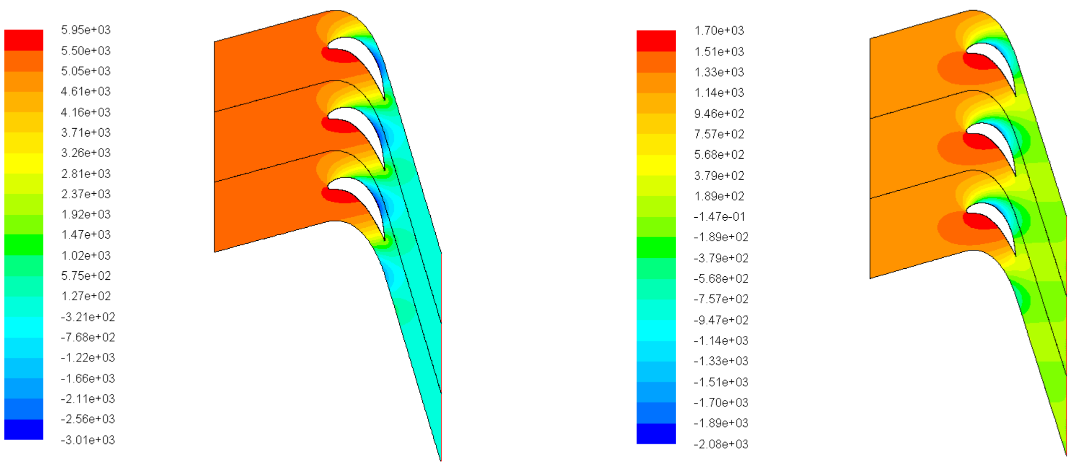
Fluid/organic	Cascade	ζ Stagger angle	s (m) pitch	C_l	C_d	C_l/C_d
R245fa	Base	43,263	0,01025	1,0128	0,0353	28,6931
	Optimum	42,378	0,01370	0,6889	0,0031	220,7864
Toluene	Base	43,263	0,01025	1,4020	0,0667	21,0283
	Optimum	42,121	0,01070	0,3467	0,0009	402,196

In the results presented in table 1 it is possible to observe that the pitch of the R245fa cascade has greater influence on the increase in the aerodynamic performance. However, the stagger angle, in both fluids, had little influence on the cascade efficiency. It should be noted also; that the cascade initial design, is based on the cascade calculation of a gas turbine flow [7], therefore, a consequence of the values of C_l C_d ratio has improved considerably from the initial design to the optimized for ORC. Figure 6 shows the comparison between the initial cascade geometry and the optimized cascade, it can be seen that in both situations the effects of the stagger angle are similar.

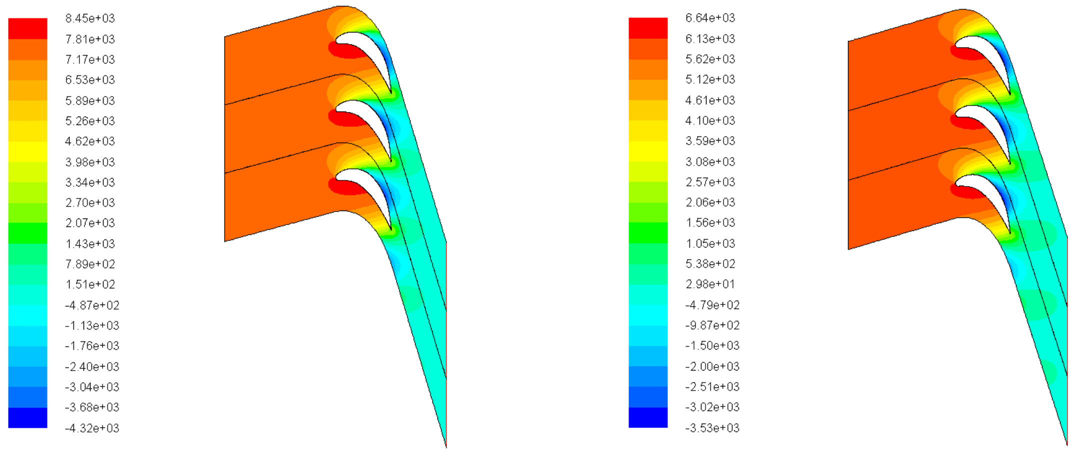


Optimum Cascade - R245fa Optimum Cascade - Toluene
Figure 6. Base and Optimum Cascade Comparison.

Figures 7 and 8 show a well established static pressure contours in the flow field, which means a properly mesh discretization.

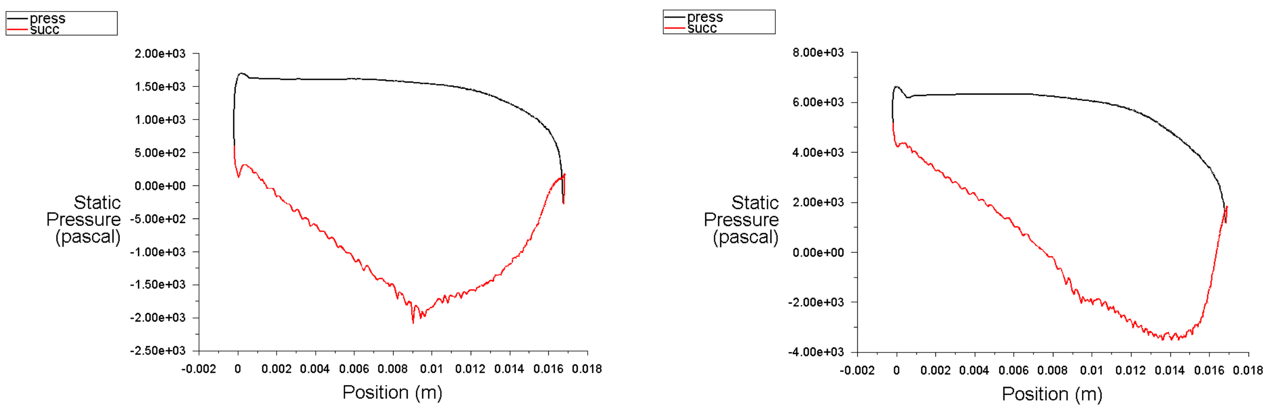


Base Cascade - R245fa Optimum Cascade - R245fa
Figure 6. Static Pressure Contours.



Base Cascade - Toluene   Optimum Cascade - Toluene

Figure 7. Static Pressure Contours.



Optimum Cascade - R245fa   Optimum Cascade - Toluene

Figure 9. Static Pressure Distribution.

Figure 8 shows the static pressure distributions of the optimized organic cascade profiles, there are small fluctuations in the pressure distributions, which may be a consequence of the numerical process, or the need to improve refining the mesh near the wall. Situations that are being analyzed for organic fluids through the calculation of Y +.

6. CONCLUSIONS

Based on the design methodology of a gas turbine cascade, it is possible, through optimization techniques and CFD flow calculations, to find an optimum cascade to work with different organics fluids. As a first approach, we analyzed two fluids, with two design variables (pitch and stagger angle). For the optimization process, we used a heuristic algorithm CRSA (Controlled Random Search Algorithm), being effective in finding the optimal solution. Results of a C_l C_d ratio showing the effects of the design variables (pitch and stagger angle) towards different organic fluids were reported. Future work will be carried out in order to introduce the tri-dimensional effects on the ORC turbine stator - rotor, aiming to optimize the isentropic efficiencies of this kind of machines.

7. ACKNOWLEDGEMENTS

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