Turbine Endwall Contouring Using Numerical Optimization in Combination with the Ice Formation Method

Sven Winkler, Kristian Haase, Bernhard Weigand

Project Description

Today's ever increasing global demand for clean energy generation calls for highly efficient gas turbines with emission rates as low as possible. In modern gas turbines, thermal efficiency is increased by raising the turbine inlet temperature, while the formation of pollutants is decreased by the use of flat, homogeneous temperature profiles in the combustion chamber which reduce peak temperatures. However, both methods cause high thermal loads on the turbine stages, especially on the endwalls of the guide vane rows. Besides the conventional cooling technologies such as thermal coating and film cooling, turbine endwall contouring has proven to be an efficient method for reducing thermal loads on these components.

The goal of the present study is to optimize the guide vane row of a low pressure turbine with respect to endwall heat transfer by developing novel endwall contours which exhibit reduced thermal loading on the turbine's endwall. These new endwall contours are generated by means of a numerical optimization approach consisting of a genetic algorithm in conjunction with three-dimensional fluid dynamics which employs experimentally created ice-contours as initial geometries for the numerical optimization process. These ice-contours are created with the natural optimization technique of the Ice Formation Method. They constitute pre-optimized, constraint-free endwall geometries and their integration in the optimization process ensures fast convergence and helps to maintain an optimization space with fewest restrictions for the numerical optimization process.

Methodology

1 Experiments

The development of the novel endwall contours begins with the **experimental creation of ice-contoured endwall shapes** in a water flow channel. The channel contains a test section with a three-passage linear cascade of the investigated low pressure vane featuring a coolable copper endwall. For the experiments, this endwall is cooled below the freezing temperature of water and a flow is generated in the channel. In this way, different endwall ice-contours can be experimentally created, which depend only on two parameters: the Reynolds number Re_C of the flow and the non-dimensional temperature ratio Θ_C.

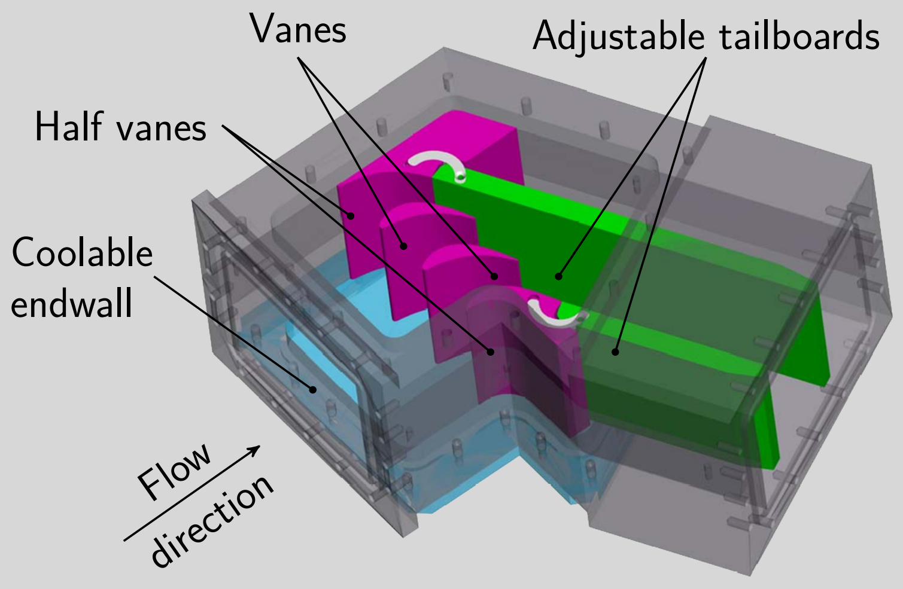


Figure 1: Test section with vane profile

Reynolds Number Re_C

$$Re_C = \frac{u_{ex} C}{\nu_\infty} \quad (1)$$

u_{ex} - vane passage exit velocity
C - vane chord length
ν_∞ - free stream kinmatic viscosity

Temperature Ratio Θ_C

$$\Theta_C = \frac{T_f - T_w}{T_\infty - T_f} \quad (2)$$

T_f - freezing temperature of water
T_W- mean endwall temperature
T_∞- free stream water temperature

2 Digitization and Numerical Domain

The **generated ice-contours are digitized** by means of a laser scanner and integrated in a numerical solution domain. The domain represents one cyclic vane passage between a pressure side and the adjacent suction side of the investigated low pressure profile and the digitized experimental ice-contour constitutes the passage's endwall between the vanes.

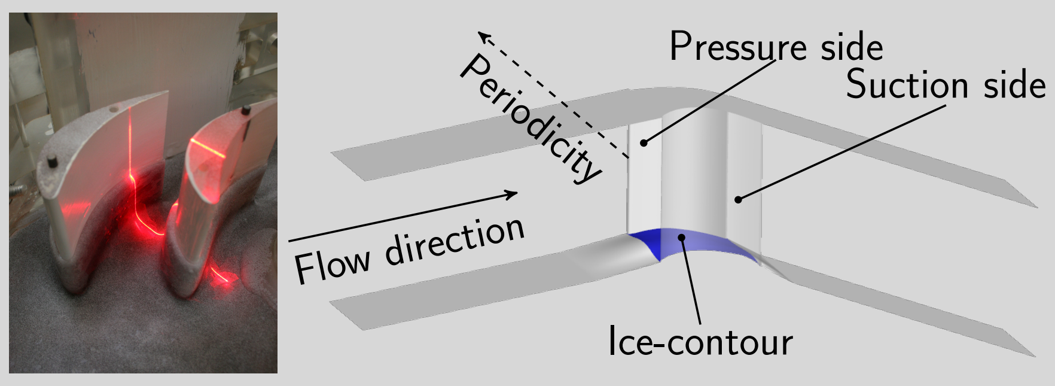


Figure 2: Digitization of ice-contours and solution domain

3 CFD Simulations

Numerical Setup:

- Program: ANSYS Fluent
- Steady, compressible flow
- Solver: SIMPLE
- Turbulence: SST Model
- Equation Discretization: Second Order

Performing CFD simulations with the domain above, using air as working fluid and a temperature difference from the hot gas to the endwall, allows for identifying the ice-contours' potential for reducing endwall heat transfer at gas turbine conditions. This determines the level of pre-optimization of the experimental ice-contours.

4 Parametrization and Problem Definition

In the next step, the **digitized ice-contours are parametrized** to make them accessible for the subsequent numerical optimization. The parametrization uses 3 Bézier splines in crosswise direction and 1 Bézier spline at the rear suction side of the vane profile, each defined by 4 control points. This parametrization allows for a geometric description of the endwall surface by only these control points. Specifying the number of generations, the number of individuals per generation and the goal function finally completes the problem definition for the numerical optimization.

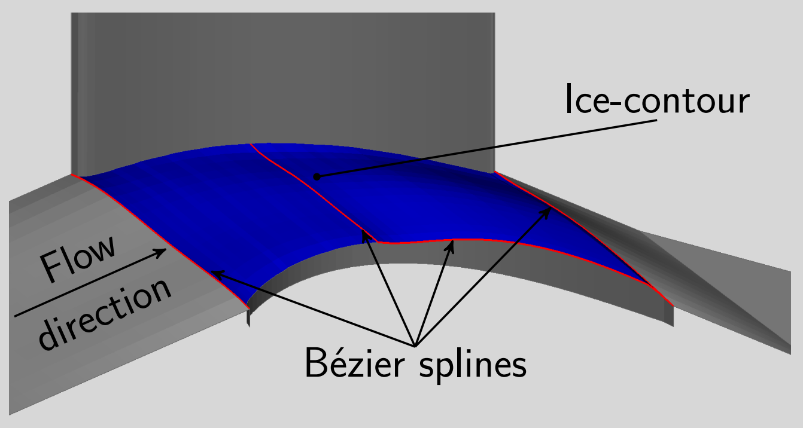
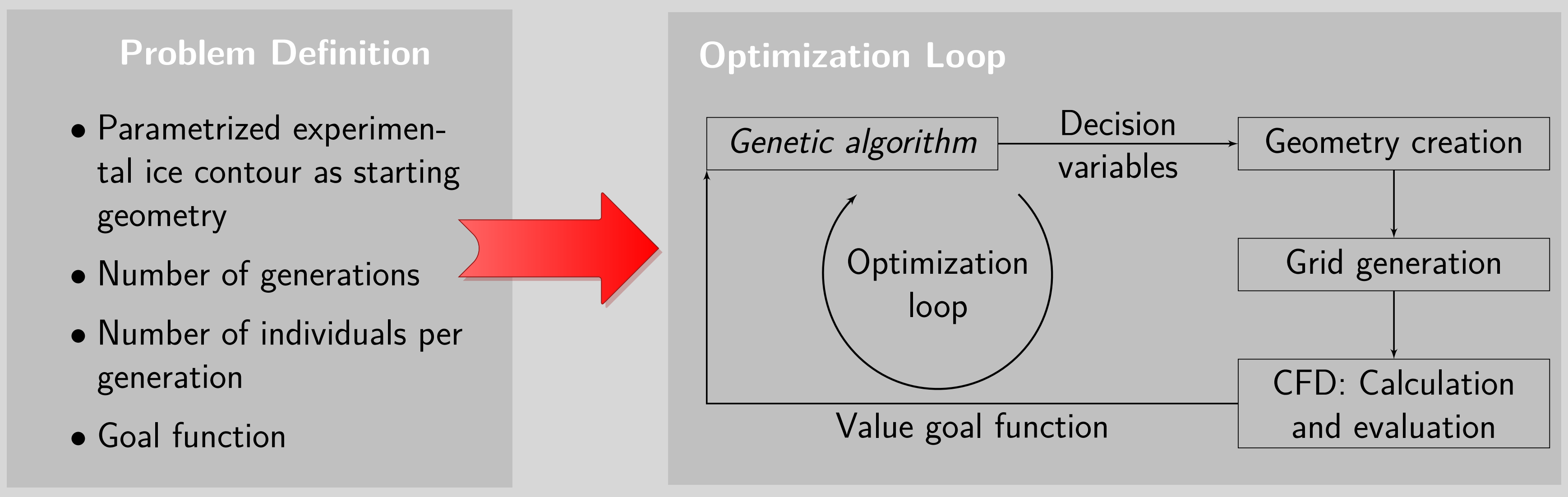


Figure 3: Parametrized ice-contour

5 Numerical Optimization

On the basis of the problem definition, the **optimization loop (NSGA-II [1]) is launched**, starting with the genetic algorithm which creates, based on the initial digitized ice contour, values for the control points of the Bézier splines which constitute the decision variables for the optimization. From these decision variables, new endwall contours are generated using the above parametrization, one contour for each individual per generation. After generating grids for these endwall contours CFD simulations are performed and results evaluated with respect to the goal function of endwall heat transfer. These information is passed back to the genetic algorithm, which deduces new decision variables from these information by simulated genetic processes of selection, recombination and mutation of different individuals. These updated decision variables are then used in the next generation of the optimization loop to create new endwall contours. The optimization loop continues until the prescribed number of generations and therefore convergence is reached.



Problem Definition

- Parametrized experimental ice contour as starting geometry
- Number of generations
- Number of individuals per generation
- Goal function

Optimization Loop

Results and Discussion

Digitized Ice-Contours

To provide starting contours for the numerical optimization, endwall ice-contours were created in the experimental water channel for three values of each of the two parameters Reynolds number Re_C and temperature ratio Θ_C. CFD simulations were conducted for these geometries and for the reference case of a flat endwall at the corresponding Reynolds numbers and results evaluated using the Stanton number.

Stanton Number St

$$St = \frac{Nu}{Re Pr} = \frac{q''_w}{\Delta T \, c_p \, \rho \, u_{ex}} \quad (3)$$

q''_w - specific wall heat flux
ΔT - temperature gradient hot gas - endwall
c_p - specific heat
ρ - mass density

Area-averaged Stanton Numbers

Θ	*Reynolds Number*		
	$34,000$	$49,900$	$71,400$
6.5	$2.98e^{-3}(-7.7\%)$	$2.48e^{-3}(-7.3\%)$	$2.21e^{-3}(-7.6\%)$
8.5	$2.95e^{-3}(-8.9\%)$	$2.46e^{-3}(-8.1\%)$	$2.21e^{-3}(-7.6\%)$
12.2	$2.88e^{-3}(-10.9\%)$	$2.36e^{-3}(-11.8\%)$	$2.17e^{-3}(-9.4\%)$
$flat$	$3.24e^{-3}$	$2.67e^{-3}$	$2.39e^{-3}$

Table 1: Area-averaged Stanton numbers for CFD simulations with digitized experimental ice-contours

Table 1 holds the Stanton numbers, area-averaged over the entire endwall, for the digitized ice-contours and for the reference case of the flat endwall. The values in brackets denote the difference to this reference. The results shown confirm the experimental method's high capability for finding pre-optimized contours with decreased endwall heat transfer. All investigated contours exhibit a reduction of endwall heat transfer from 7.3% up to 11.8%.

Optimization

The pre-optimized ice-contours at $Re_C = 49,900$ were used as starting geometries for numerical optimizations. These were conducted with 8 individuals per generation and 10 generations using the averaged endwall heat flux as goal function to be minimized. Figure 4 shows the normalized goal function for each individual of the optimization's 10 generations. These values clearly decline with increasing number of generations until convergence is reached and the optimized endwall contour with least possible heat transfer is found. Figure 4 shows such an optimized contour.

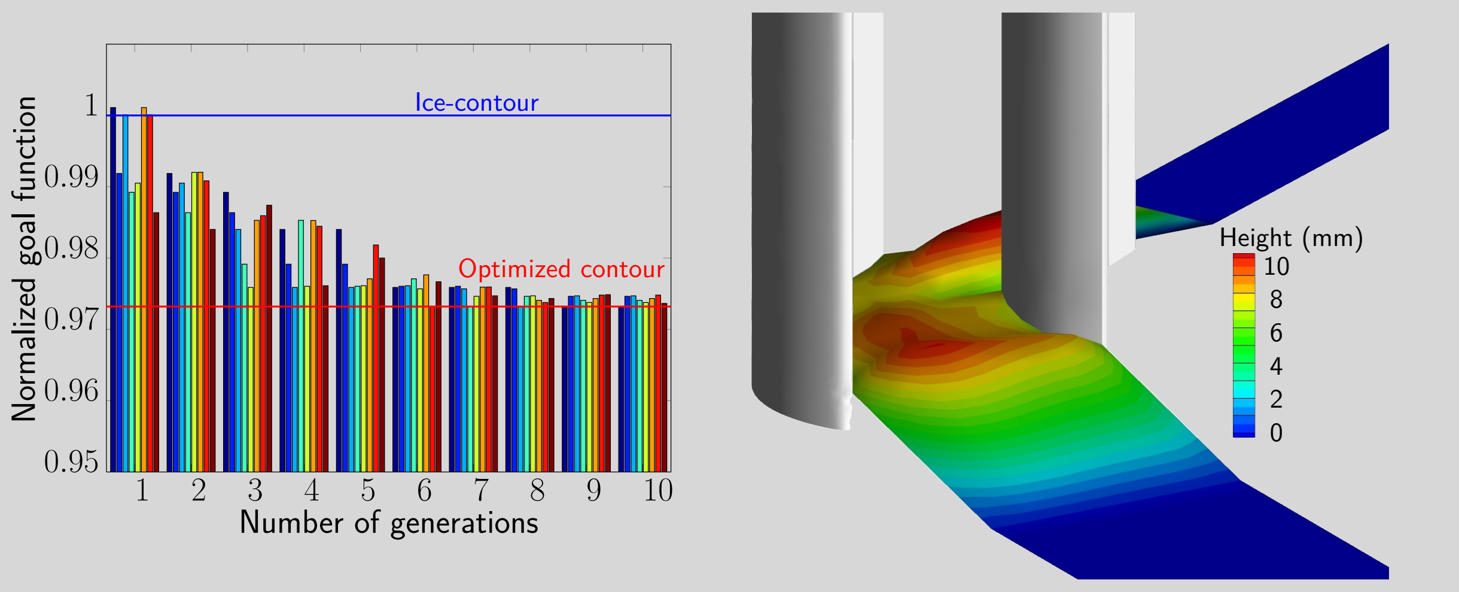


Figure 4: Progress of goal function in optimization and optimized endwall contour

Stanton Number Reduction

Θ	*Ice-contour*	*Flat EW*
6.5	-5.2%	-12.1%
8.5	-5.1%	-12.8%
12.2	-0.6%	-12.3%

Table 2: Averaged Stanton numbers after optimization

Table 2 shows the averaged Stanton numbers of the optimized endwall contours and their difference with respect to the initial ice-contours and the flat endwall. The optimizations further decreased endwall heat transfer, yielding contours which exhibit reductions of more than 12% compared to a flat endwall. These reductions are nearly the same for all initial ice-contours, indicating that the optimized geometries constitute endwall contours with a global minimum in heat transfer. The ice-contour with the highest temperature ratio ($\Theta = 12.2$) is already close to that global minimum and thus constitutes an excellent starting geometry for the numerical optimization.

Optimization Using Root Mean Square Averaging

Figure 5 shows local heat transfer reductions on the endwall as Stanton number ratios of optimized to flat endwall. Heat transfer reductions are evident in the front part of the vane passage and especially downstream of the vanes' trailing edges with Stanton numbers reduced to one-fifth of the flat endwall's value. These high reductions are caused by a weakening of the passage vortex by the endwall contouring, which prevents impinging flow in this region and thus yields the low heat transfer.

Root Mean Square Averaging

$$q''_{r.m.s.} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} q''^2_n} \quad (4)$$

$r.m.s.$ - root mean square
n - number of endwall points

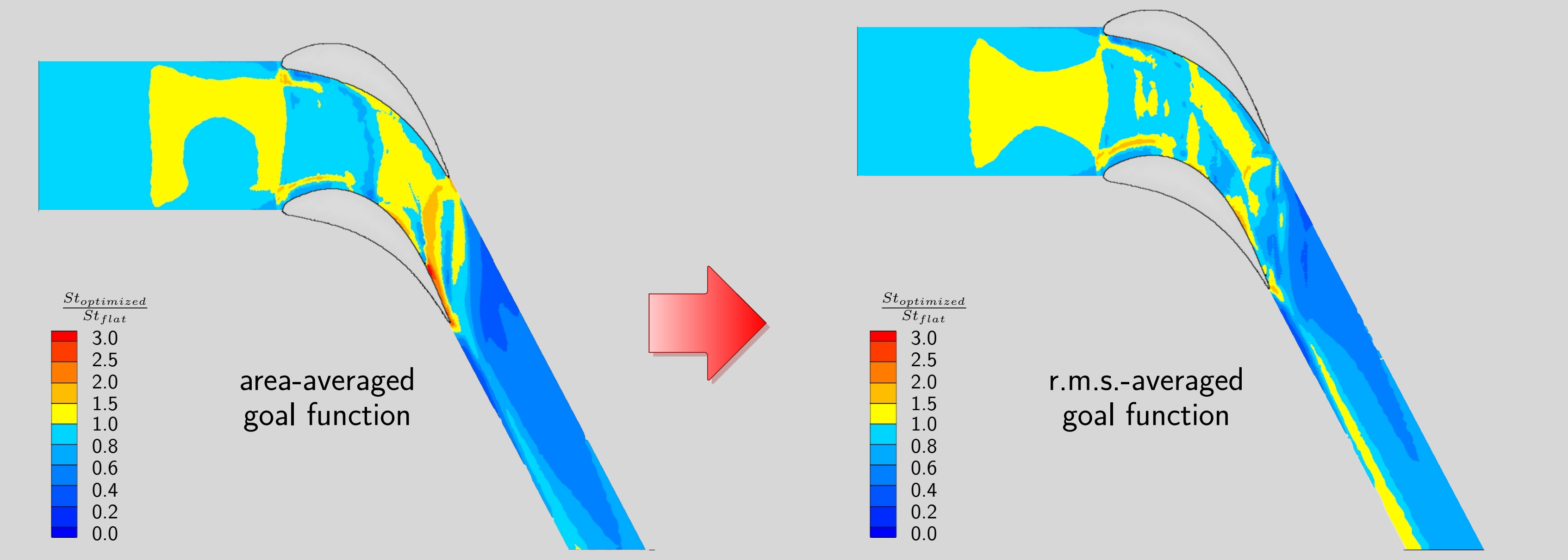


Figure 5: Stanton number ratios for optimized endwalls with area-averaging (left) and root mean square averaging (right)

However, the left contour plot also shows heat transfer locally increased up to three times compared to the flat endwall. To avoid such local peaks in heat transfer, the averaging of the endwall heat flux as goal function of the optimization was changed from area averaging to root mean square averaging which gives stronger weighting to high local heat fluxes. This yields endwall contours with both decreased averaged endwall heat transfer and eased hot spots, as can be seen from the right plot in Figure 5.

Conclusions

Novel turbine endwall contours for the reduction of heat transfer were created using numerical optimization in combination with the ice formation method. Experimentally created ice-contours yielded heat transfer reductions of at most 11.8% compared to a flat endwall. Numerical optimizations with these initial contours could further reduce endwall heat transfer up to 12.8%. By using root mean square averaging of the endwall's local heat flux values, local peaks in heat transfer could also be reduced.

References

[1] Deb K., Pratap A., Agarwal S. and Meyarivan T.: A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II; *IEEE Transactions on Evolutionary Computation, Vol. 6, No.2, April 2002*

[2] Haase K., Winkler S., Weigand B., Neumann S.O.: Novel Turbine Endwall Contours for the Reduction of Heat Transfer Generated Using the Ice Formation Method; *ASME International Mechanical Engineering Congress & Exposition, (ASME paper IMECE2012-87430)*

University of Stuttgart
Germany

Institute of Aerospace Thermodynamics