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APPLICATION OF GENETIC ALGORITHMS TO DESIGN OF AN INTERNAL TURBINE COOLING SYSTEM

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ABSTRACT

This paper deals with the development of an optimizing technique based on Genetic Algorithms (*GA*), which can be applied to the optimization of an internal cooling system of turbine nozzles. An impingement cooling system with pins and air-discharging holes is selected as target cooling system to be optimized using a single-objective *GA* code developed in this study. The optimization is performed for several design parameters such as the impingement and discharging hole diameters, pin diameter and pin height. The computational grid is automatically generated and boundary conditions prescribed. A commercial *CFD* code is used to evaluate the target function, which is in the present case simply defined as the ratio between the averaged heat transfer coefficient multiplied by the wetted area and the pressure loss. A hybrid *FORTRAN*/*UNIX* shell script program controls the whole process of the optimization, leading to the successful achievement for finding an optimum configuration of the cooling system concerned.

INTRODUCTION

Thanks to the state-of-the art of cooling technologies such as impingement cooling or film cooling, turbine inlet temperature (*TIT*) of modern gas turbines has exceeded more than 1773K. The next target of turbine cooling designers is to drastically reduce cooling air consumption because thermal efficiency of the gas turbines are now saturating due to the large amount of cooling air mainly used in the turbine section. To meet this goal, countless number of studies are devoted to the investigation of impingement cooling system [1-5]. One of the present authors also investigated heat transfer characteristics of a cooling device that simply combines impingement cooling system with pins in order not only to disturb the impingement jets on target plate but also to enhance the internal surface area (Funazaki et al. [6][7]). Very recently, Funazaki and Hachiya [8] have carried out detailed numerical simulations on this integrated cooling device to clarify effects of several dominating geometrical parameters of the device upon its heat transfer characteristics and pressure loss. Their approach has simply changed pin-height, pin pitches and off-set of the pin location. Although some information useful for developing more effective cooling systems is obtained from this study, it is also clear that more systematic methods should be pursued in order to maximize attainable average heat transfer inside the device or to minimize the coolant mass flow rate maintaining the heat transfer level constant. The present study has adopted Generic Algorithms (*GA*) as an optimizing tool.

The use of *GA* for multi-parameter optimization has become a popular technique in many engineering fields, such as aerodynamic design of blade profiles or wings [9-11] and, more recently, gas turbine related applications [12-16]. The reason for adopting such technique is found by the fact that it is robust, simple to implement and innovative. Conventional optimization methods such as “hill climbing” algorithms search in one direction of the domain only and are strongly limited to well behaved target functions. The *GA*, on the other hand, can handle complex non-linear target functions and provides a multi-directional search, avoiding premature convergence at local peaks, which may not represent the global maximum of the search domain.

The simplicity in translating the *GA* method into a computational code is also one of its great advantages. A *GA* code consists of basic mathematical operations which can be parallelized in a very straightforward manner. Among many authors, Goldberg [17] described the basics about *GA*, including sample program lists.

The aim of the present paper is to show the development of an optimization tool based on *GA*. The authors believe that this study is one of the first attempts to apply *GA*, which takes advantage of a commercial CFD code with an automated grid generation system, to the optimization of internal cooling system for turbine nozzles

NOMENCLATURE

Abbreviations

AMG		algebraic multi-grid

Symbols

A	[m^2]	area
c_p	[kJ/kgK]	specific heat at constant pressure
H	[mm]	height
h	[W/m^{2}K]	heat transfer coefficient
k	[W/mK]	thermal conductivity
k	[m^2/s^2]	turbulent kinetic energy
P	[Pa]	static pressure
R	[mm]	radius
T	[K]	temperature
Tu		turbulence intensity
Δ		variation
η		efficiency
ρ	[kg/m^3]	density

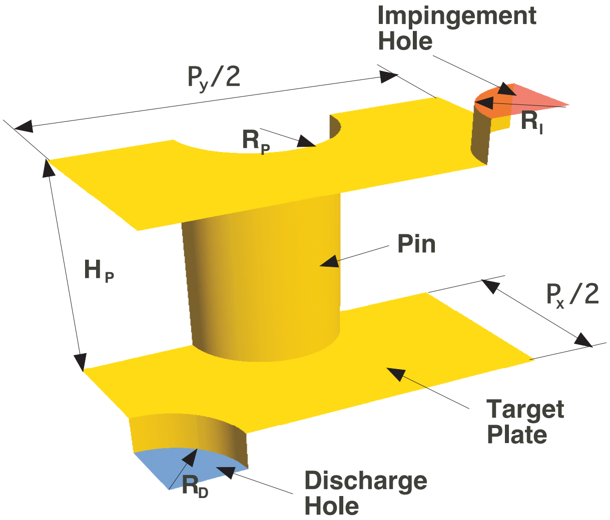


Figure1 Internal cooling system diagram

μ	[kg/sm]	molecular viscosity

Subscripts

D	discharge (hole)
I	impingement (hole)
P	pin
W	wetted (area)

Superscripts

—	area average

PROBLEM DESCRIPTION

The model for the current study (Fig. 1) consisted of one half of the actual cooling system, assuming that symmetry condition was valid for the side boundaries. The flow was injected from the impingement hole, encountered the target plate and pin surface, partially convected through the symmetric boundaries and partially exits the domain at the discharge hole.

The design parameters for this particular optimization problem were the pin height (H_P), the pin radius (R_P), and impingement and discharge hole radii (R_I and R_D respectively). Table 1 presents the constraints adopted for H_P, R_P, R_I and R_D. For the present study, R_I and R_D were considered as one design variable.

The optimization problem had only one target function, which could be generally defined by Eq. 1 as an efficiency of the cooling system,

$$\eta = h(A_W)^a / (\Delta P)^b \ , \quad (1)$$

where h was the area averaged heat transfer coefficient over the the wetted area (pin surface and target plate) A_w and ΔP was the pressure difference between the impingement and discharge holes. The indices a and b were both unity, only for the sake of simplicity. The objective was then to maximize the efficiency within the constraints prescribed for the design variables. The coolant mass flow rate was kept constant through the optimization.

OPTIMIZATION TOOL

Genetic Algorithms

The *GA* is a powerful optimization tool based on the theory of evolution, which means that the "best fit" individuals in one generation survive. The "fitness" in *GA* is the function to be optimized (target function) and the parameter set or problem variables are denominated a "chromosome". In the present study, the real value of each design parameter is encoded as a string of binary digits. For instance, string 111000 refers to $R_I = R_D = 18.80$ mm, string 000001 to $R_P = 10.15$ mm and string 001100 to $H_P = 23.33$ mm. The strings for each one of the parameters are blended into a large string, forming the chromosome 111000000001001100. The *GA* works with a number of chromosomes for each iteration or generation, providing a search in multiple directions of the domain simultaneously. Preliminary tests with *GA* code here described showed that a constant population size of 30 chromosomes was suitable for the optimization task.

Table 1 Constraints adopted for the design parameters (all dimensions in millimeters)

Parameter	Range
Impingement, discharge hole radius	$10 \le R_I = R_D \le 20$
Pin radius	$10 \le R_P \le 20$
Pin height	$10 \le H_P \le 80$

The starting point for an optimization using *GA* is a process called *initialization*. The initial population of chromosomes can be generated automatically by invoking a pseudo-random number subroutine, usually available in computer language compilers. The *GA* converges to the same result independent of the starting population. According to Trigg et al. [11], a given start with specified values for the chromosomes does not seem to be an important feature since initial convergence is rapid.

After the initial population has been created, the *GA* needs to evaluate the fitness for each one of the chromosomes belonging to the initial generation. This means judging how well each chromosome is performing according to their *phenotype* (design parameters). The tool used to evaluate the fitness is transparent to the *GA* code and does not need to embedded in the program. This is a remarkable feature which allows *GA* to be applied in almost any research field. For the present optimization task, the commercial *CFD* code *CFX4.4* (*AEA Technology, Ltd.*) was used for calculating the heat transfer coefficient on the pin surface and pressure drop between the impingement and the discharge holes. These values were then used in Eq. 1 to evaluate the efficiency *h*.

With the fitness values for the chromosomes of the initial generation calculated, the *GA* code must select the candidates for mating. Since in the present work the population size was kept constant, the number of chromosomes to be elected for reproduction is half of the population size. This process is called *selection* and it is directly related to the performance of a *GA* code. Several methods for accomplishing this task are described in the literature [9,10,17,18]. The most common method is called *roulette wheel*, in which all chromosomes of a population share a certain sector of a wheel, proportional to their fitness. The wheel is then spun and the chromosome selected. This method, however, causes premature convergence of the results. The best fit chromosome tends to dominate the others and cause their early extinction. The *GA* will follow one direction, leaving other possible maximum locations behind. Considering these limitations, the *tournament selection* method was chosen instead. This method randomly picks two or more chromosomes (depending on the tournament size) from the population. The chromosomes then compete against each other to decide which one will be on the mating pool. The chromosome with the highest fitness will be the winner in the case of a maximization problem. This process is repeated to elect the other chromosome to join the mating pool. Care must be taken in order to avoid the selection of the same chromosome twice.

After selecting the eligible chromosomes for reproduction, the *recombination* process is performed. The chromosomes mate (parents),

Table 2 Genetic algorithm parameters.

Chromosome length	18
Type of coding	binary
Population size	30 (constant)
Selection method	tournament
Tournament size	2
Recombination method	one-point crossover
Crossover probability	0.6
Mutation probability	0.0333

generating two new chromosomes (children) in order to keep the population size constant. The *genes* or the string bits are exchanged between the children at a probability of 0.6, commonly found in the literature [17]. Like the selection process, there are many ways to perform recombination [10,18]. The one-point crossover was chosen for the present paper. In this recombination method a bit location is randomly chosen. The information from the bit location just after the selected bit to the end of the string is exchanged between child 1 and child 2. For instance, suppose the selected bit location is 12, child 1 = 100100011110001100 and child 2 = 100011111010101101. After crossover, child 1 would become 100100011110101101 and child 2 100011111010001100.

The tournament selection method was found to have one major drawback. It does not guarantee by itself that the best individual in the population will be picked for the tournament. The preliminary part of the tournament is totally random and does not take into account the fitness values. An additional operator was found necessary to be implemented. The *elitism* model was implemented in order to assure that the best individual is maintained from one generation to the other. The best individual is selected, cloned and added to the other children.

In order to keep the search in many directions of the optimization domain, *mutation* was also implemented. The children, except the cloned ones, are selected at random. Mutation occurs in one or more bits of the selected children by replacing 0 for 1 or 1 for 0, with a probability of 0.0333 [17].

After the four main operations (selection, recombination, elitism and mutation) have been completed the children replace the current population of chromosomes. The process is repeated until the convergence criteria has been satisfied.

Table 2 shows a summary of all *GA* parameters adopted in the present paper.

Optimizer Implementation

The *GA* code here described was developed in a hybrid *FORTRAN/UNIX* shell script language. This technique was used so that the *CFX4.4* code could be combined with the optimizer. Figure 2 presents a flowchart describing the mechanism of the code.

One of the critical problems when using a *GA* code is the *CPU* time. The fitness has to be evaluated for all chromosomes belonging to every generation. Thus, for a population of 30 chromosomes, after 30 generations, the flow solver would have been called 900 times. If each one of the solver executions are performed sequentially, the *CPU* time would be 900 multiplied by the time required for each run. In order to provide faster results a simple parallel processing strategy is proposed (Fig. 2, *FITNESS* text box). For each generation the population is divided into three parts. Each one of the parts would be treated as a distinct process, running in parallel. For instance, part I would evaluate the fitness from chromosomes 1 to 10, part II from chromosomes 11 to 20 and part III from 21 to 30. Ideally speaking, this would reduce the *CPU* time required to solve one generation by a factor of 3. A *UNIX* shell script was developed to synchronize the executions.

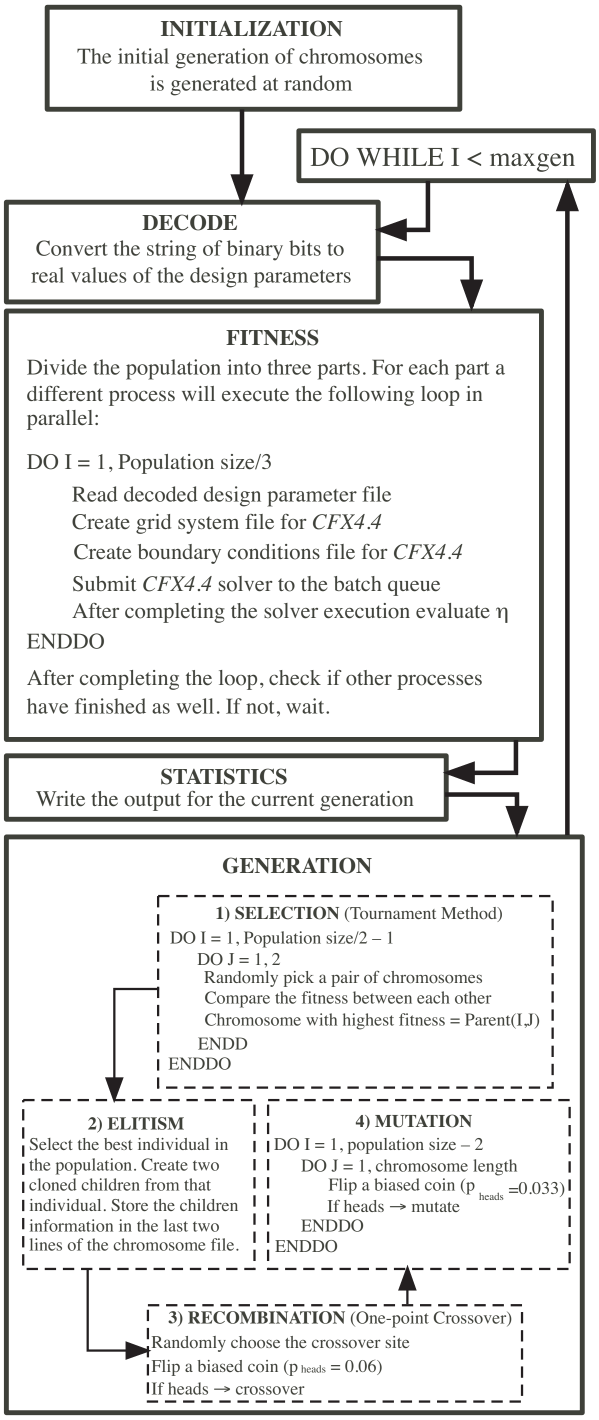


Figure 2 Genetic algorithm optimizer flowchart

Parts I through III should start and finish at the same time so that the other parts of the *GA* code can be correctly performed. If one of the parts finishes before the others it will wait until all parts have been completed. Executions were successfully performed in parallel with minimum overhead.

NUMERICAL SIMULATION

Grid Generation

A FORTRAN code was developed by the authors in order to auto-

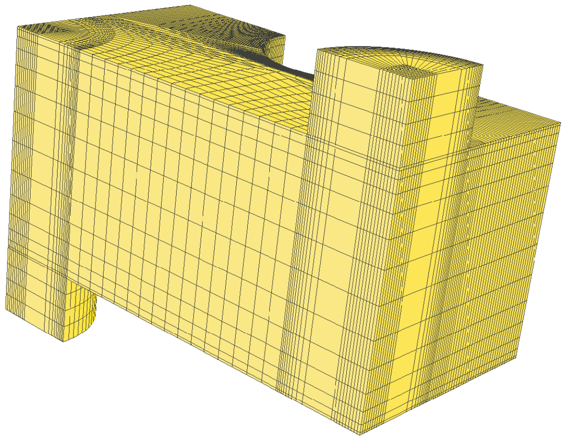


Figure 3 Grid system

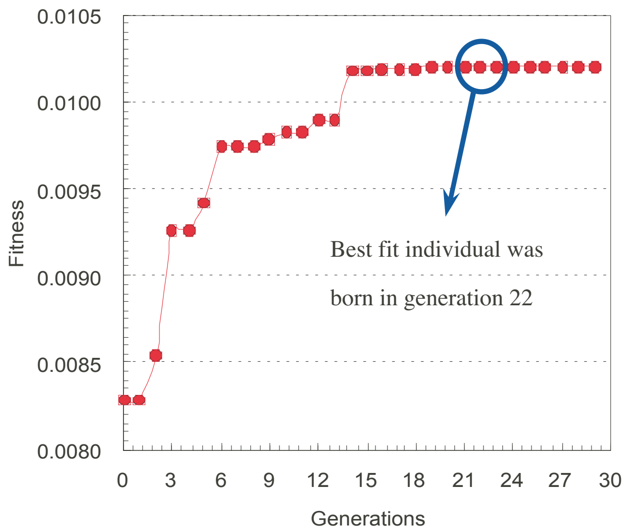


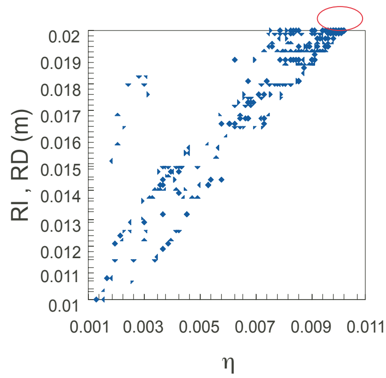
Figure 4 Convergence history (Maximum fitness)

mate the computational grid generation. For every chromosome, the code reads the decoded real values for the design parameters, generates a multi-block grid system and exports it to the *CFX-4.4* solver through an *ASCII* file. Figure 3 shows a mesh for $R_I = R_D = 20$ mm, $R_P = 20$ mm and $H_P = 50$ mm.

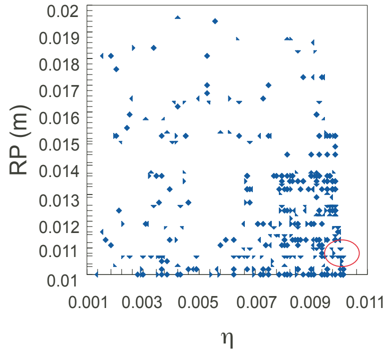
The grid system shown in Fig. 3 was highly optimized in order to reduce the number of nodes. Several coarse grids were run and results were compared to finer grid ones and experiments [6-8]. After a reasonable agreement was found the final configuration was defined. The number of grid points was kept constant (59,520) so that the *CPU* time for one run would be approximately one hour.

Computational Code

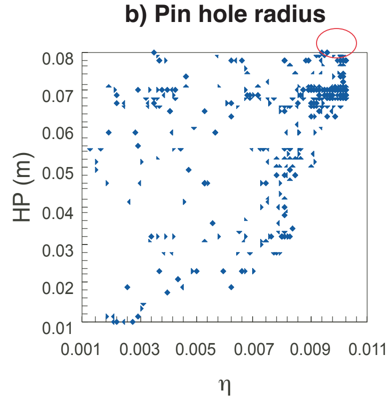
The three-dimensional, steady, Reynolds-averaged, incompressible Navier-Stokes and energy equations were solved with the finite difference *CFX-4.4* computational code. A second-order difference scheme using a body-fitted coordinate system was employed based on the Rhie-Chow algorithm [19]. That is, the code performs curvilinear transformations to map the complex flow domain in physical space to a simple (rectangular) flow domain in computational space. A non-staggered grid is used when solving the velocity components of the momentum equations. Considering the velocity-pressure algorithm, the *SIMPLEC* method was adopted. Thanks to the implementation of



a) Impingement, discharge hole radius



b) Pin hole radius



b) Pin height

Figure 5 Search domain for each one of the design parameters (red circles indicate the location of the best fit individual

Rhie-Chow algorithm, checkerboard oscillations in the velocity and pressure usually associated with non-staggered grids was eliminated. All equations were solved using the Algebraic Multi-grid (*AMG*) method, described by Lonsdale [20]. This method solves the discretized equations on a series of coarsening meshes, internally produced by *CFX-4.4*. Detailed information on the theoretical basis of the software can be found in the *CFX-4.4 Solver* documentation [21].

Convergence was improved by specifying 6 inner iterations for the energy equation (expressed in terms of enthalpy), 2 iterations for the turbulence equations and one iteration for the other variables. The number of outer iterations was found to be the most critical aspect related to the compromise solution between good accuracy and short computational time. After several trials it was concluded that 500 outer iterations was a good measure.

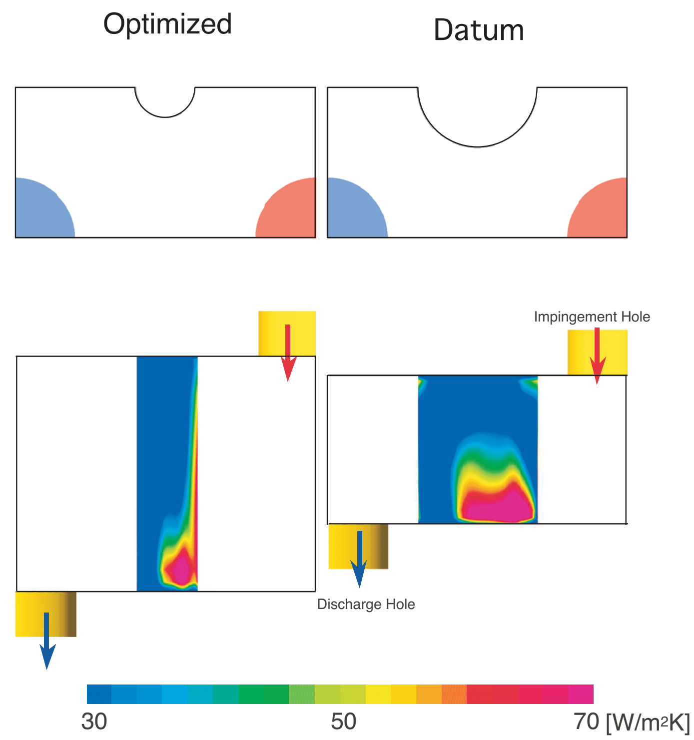


Figure 6 Comparison between the heat transfer Comparison between the heat transfer coefficient for the optimized and datum configuration

Boundary Conditions

For the impingement hole surface, normal velocity was calculated so that the Reynolds number (based on the inlet hydraulic diameter) would equal 10,000. The other quantities prescribed at the inlet were temperature T_I = 323K, turbulence intensity Tu_I = 3.7% and dissipation length scale ε = 0.01, the selection here being based on the previous study [7]. Non-slip boundary conditions were applied to the top wall, the target plate, the pin and the surfaces contouring the impingement and discharge holes (yellow surfaces in Fig. 1). The temperature on these surfaces was assumed as constant and equal to 303K. At the discharge hole, mass flow was prescribed. On all side boundaries (except the pin) symmetry condition was applied. The working fluid used in the calculations was air at a reference temperature of 288 K (molecular viscosity μ =1.969 x 10^{-5} kg/sm, density ρ = 1.088 kg/m^3, thermal conductivity k = 0.02759 W/mK, specific heat at constant pressure c_p = 1.008 x 10^3 kJ/kgK).

Turbulence Model

The Menter modified low Reynolds number k-ω model was employed. In this model, the equations switch from the standard k-ω model close to the walls to equations equivalent to the k-ε model away from the walls, but for independent variables k and ω.

RESULTS

The *GA* code solved 29 generations in 11.5 days using SGI Origin 3800 at the Supercomputing Center of Iwate University. The convergence history shown in Fig. 4 indicates that the best fit individual was first born in generation 22, with an outstanding performance of h = 0.010946. The optimizer keeps searching in the domain for other possibilities but saturates, as shown in the graph by the straight line from generation 22 to 29.

Table 3 Comparison between the performance of the optimized configuration with the datum

	Optimized	Datum
Efficiency (η)	0.010946	0.007448
h	28.46 W/m^2·K	28.51 W/m^2·K
ΔP	19.46 Pa	27.56 Pa

Figure 5 presents the search domain for each one of the design parameters. These graphs contain all points searched during the whole execution of the code. Thus, Fig. 5 provides a report on how well the search domain was explored by the *GA* and the tendency of the individuals to develop themselves according to the best fit chromosome. The red circles indicate the location of the maximum point. Best fit individual was born in generation 22. The best fit individual corresponds to a cooling system with $R_I = R_D$ = 20 mm, R_P = 10 mm and H_P = 77.7 mm. For the given set of constraints the optimum efficiency would be obtained for a long pin with a small radius and large impingement and discharge holes. The efficiency was defined by correlating the heat transfer coefficient, the wetted area and the pressure drop. Therefore, the geometrical configuration which provides the maximum efficiency will not necessarily have the highest heat transfer coefficient on the pin surface.

Figure 6 presents a comparison between the heat transfer coefficient h for the optimized and datum ($R_I = R_D$ = 20 mm, R_P = 20 mm and H_P = 50 mm) configurations. The surface averaged h indicates a negligible favorable tendency for the datum configuration (Table 3). This trend is overturned when efficiency is calculated, showing an improvement of almost 32% from the original design to the optimized one. It is more clearly understood if one takes into account that the wetted area for the optimized case is almost 20% larger for the optimized case and the pressure drop around 30% smaller than the datum. In both cases, the impingement hole radius is exactly the same, i.e., the magnitude of the velocity prescribed at the inlet does not change. The outstanding performance of the optimized case can be attributed to the small pin radius, which reduces the blockage effect of the pin to the impinging flow. The larger pin height is an attempt of the optimizer to retain the same surface area as the datum, thus maintaining h as high as possible.

The methodology adopted in this study may be applied to many other practical engineering problems. However, the authors acknowledge the necessity of improvements in the code. For example, the *optimum* cooling configuration searched out in the above might not be necessarily the best one that air-cooled turbine designers usually seek for, since the optimum solution obtained from the single-objective *GA* approach adopted in this study strongly depends on the selection of target function. To get rid of this drawback, the present authors have almost developed a multi-objective *GA* approach, which is about to be applied to the problem dealt here or another ones.

CONCLUDING REMARKS

The present study described the development of an optimization tool and its application to the design of an internal cooling system for turbine nozzles. The genetic algorithms have proven to be a useful tool for tackling the challenging design tasks of modern gas turbines. The development of a hybrid *FORTRAN*/*UNIX* shell script program enabled the authors to combine the *GA* code with a commercial software.

The maximum efficiency was obtained for a configuration with large impingement and discharge hole radius, large pin height and small pin radius. The large pin height was an attempt of the optimizer to retain the heat transfer coefficient values from the datum design by increasing the pin area while the small pin radius was beneficial for reducing the pressure drop.

ACKNOWLEDGMENTS

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