Optimal Heat Flux Reduction Inside Film Cooled Wall

Nicolay Kortikov and Vladimir Polishuk

Abstract This work is devoted to search for the global extreme of heat flux reduction into the film cooled wall. It was carried out by varying five main system parameters from a combination of the lateral average of both the adiabatic effectiveness and the heat transfer coefficient. The lateral average heat flux reduction is processed according to the *IOSO* technology. It yields a prediction of the heat transfer coefficient from the ejection position to far downstream, including effects of extreme blowing angles and hole spacing. Together with the calculation of the adiabatic effectiveness it provides an immediate determination of the stream wise heat flux reduction distribution of cylindrical hole film cooling configurations.

Keywords Optimization · Reduction heat flux · IOSO technology

1 Introduction

An increase in the initial temperature of the gas at the turbine inlet poses the problem of ensuring the operability of the elements of gas turbine units (GTU), which are exposed to high gas temperatures in combination with high external loads. The vanes and blades of the first stage of the high-temperature turbine [1] have a developed convective-film cooling scheme in which the cooler is fed through rows of perforations to the surface of the blade (Fig. 1a).

To create competitive samples in the field of gas turbine engineering [2], it is necessary to combine mathematical models [3, 4] and software systems [5–7] with search methods [8–10] for the most effective technical solutions within the framework of the optimization environment. Moreover, to solve optimization problems, it is necessary to solve the problem of integrating various programs within the framework of one project.

Figure 1b introduces the following notation: T_G, T_C—hot gas and coolant temperatures, respectively; $T_f = T_{AW}$—gas temperature equality T_f and adiabatic wall T_{AW}

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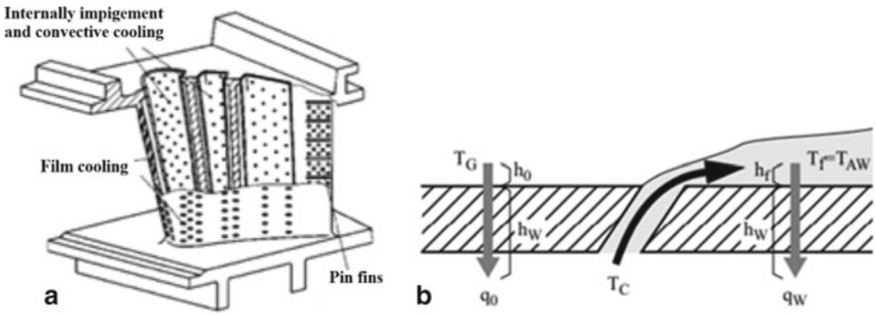

Fig. 1 Nozzle blade with convection-film cooling (**a**); heat transfer through the diabatic wall (**b**)

in the presence of film cooling; h_0 and h_f are heat transfer coefficients before and after the film on the upper surface of the plate; h_W—heat transfer coefficient on the bottom surface.

In papers [11, 12] introduced the concept of the net heat flux reduction (NHFR) to evaluate film cooling in terms of its wall heat flux effect

$$\eta_q = 1 - \frac{q_w}{q_0} \tag{1}$$

Best cooling is achieved for large values of NHFR, indicating maximum reduction of the heat flux into the film cooled wall q_w compared to that without cooling film q_0. Using the definitions of the heat flux into the cooled and the uncooled wall leads to

$$\eta_q = 1 - \frac{h_f}{h_0}(1 - \eta\theta) \tag{2}$$

Given the values of the heat transfer augmentation $\frac{h_f}{h_0}$ and the effectiveness $\eta = \frac{T_G - T_{AW}}{T_G - T_C}$, NHFR is obtained for a preset dimensionless wall temperature $\theta = \frac{T_G - T_C}{T_G - T_W}$:

$$\eta_q = 1 - \frac{2\left({h_f}/{h_0}\right)}{1 + \left({h_f}/{h_0}\right)}(1 - \eta) \tag{3}$$

The heat transfer measurements [13] indicate that configurations causing the highest heat transfer augmentation in general coincide with those configurations yielding the best overall effectiveness. Obviously, it is necessary to combine the measurements of both parameters to determine the wall temperature governing the heat flux reduction. Only a comparison based on the heat flux reduction allows for a final decision for one of several competing ejection configurations.

Currently, a large number of commercial software packages are known that declare the ability to organize a search for a global optimum for functions with a large number of variables. Among the most promising are the algorithms of *IOSO* technology [14]. The *IOSO NX GT 2.0* program is able to find a global extremum for functions with five of independent variables.

In this work, *IOSO NX GT 2.0* verification was carried out on the basis of integration with the adiabatic wall temperature and reduction of the heat flux calculation programs when the curtain was blown onto the plate through perforations (Fig. 1b) in order to increase the reduction of the heat flux of gas turbine blades.

2 Problem and Method

The appearance of the maximum value for the Stanton number $\overline{St}$ of cooling the plate with a gas curtain when blowing through perforations (Figs. 2, 3 and 4) is associated

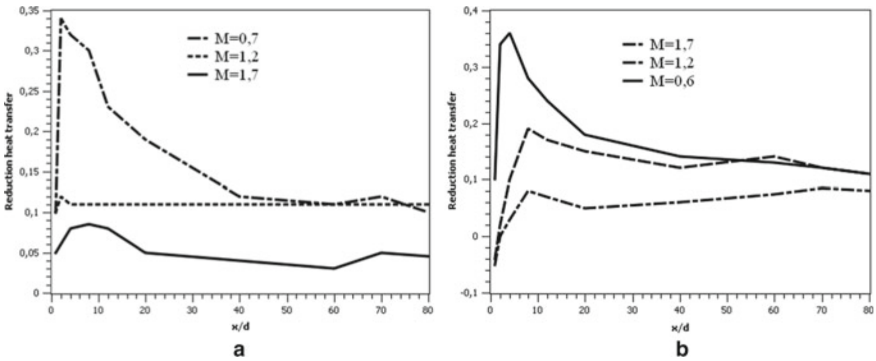

Fig. 2 Effect of the density ratio on the heat flux reduction: $\alpha = 30°$, *P/d* = 3, *DR* = 1.2 (**a**); $\alpha = 30°$, *P/d* = 3, *DR* = 1.8 (**b**)

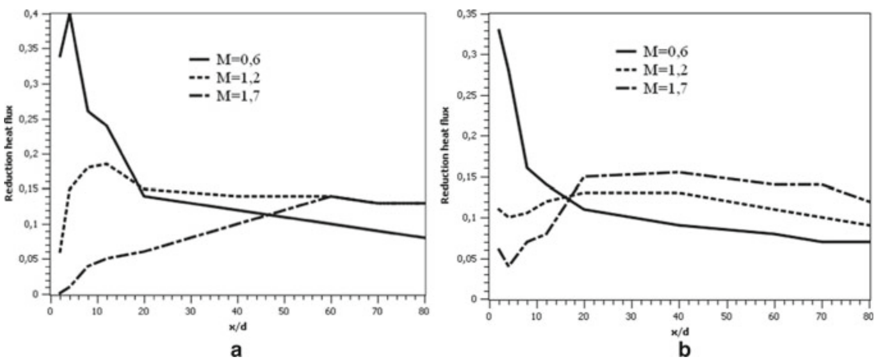

Fig. 3 Effect of the blowing angle on the heat flux reduction: $\alpha = 60°$, *P/d* = 3, *DR* = 1.8 (**a**); $\alpha = 90°$, *P/d* = 3, *DR* = 1.8 (**b**)

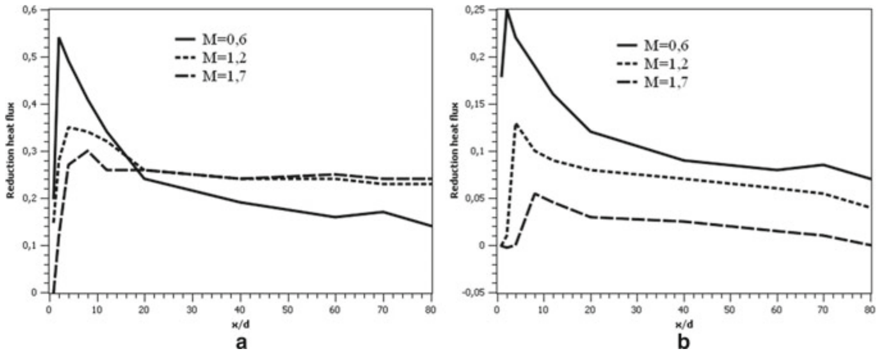

Fig. 4 Effect of the hole spacing on the heat flux reduction: $\alpha = 30°$, *P/d* = 2, *DR* = 1.8 (**a**); $\alpha = 30°$, *P/d* = 5, *DR* = 1.8 (**b**)

the Stanton number with various effects on the flow and heat transfer of the following factors (θ—dimensionless wall temperature, *M* is the injection parameter, *DR* is the ratio of the densities of the main and secondary flows, Tu_1 is the degree of turbulence of the main stream, α is the angle of blowing of the curtain, $\overline{P} = P/d$ is the relative step between the perforation holes (*d* is the diameter of the hole), δ_1/d—the dimensionless displacement thickness, *L/d* is relative cooling tube length, x/d is the dimensionless longitudinal coordinate).

Referring to a similarity and sensitivity analysis of the discussed film cooling situation (see [3]), this dependence can be formulated as a functional relation of similarity numbers. Employing the Stanton number as dimensionless heat transfer coefficient yields. In [4], to calculate the Stanton number $\overline{St}$ averaged over the width of the plate, the dependence (4) was proposed:

$$\overline{St} = \overline{St}\,(\theta, M,\ DR,\ Tu_1,\ \alpha,\ P/d,\ \delta_1/d,\ \ L/d,\ x/d) \tag{4}$$

In the presence of film cooling, the influence of the ejection on the heat transfer situation is of particular interest. Therefore, the ratio of the heat transfer coefficients on the surface with and without film ejection is regarded. Since the Stanton numbers of both cases should refer to the hot gas flow properties, the dimensionless augmentation ratio fulfils$h_f/h_0 = \overline{St}/\overline{St_0}$. It was obtained as a result of a generalization of experimental data, and its practical use is associated with the sequential calculation of thirty-one algebraic equations. Figure 2 compares heat flux reduction results of the typical geometry of shallow angle ejection and standard hole spacing for low (Fig. 2a) and high (Fig. 2b) density rations. Optimum overall heat flux reduction is obtained at $M = 0.6$ for low density ratio and $M = 0.85$ at high density ratio. The maximum heat flux reduction obtained is about 35% close to the ejection and 10–12% downstream, gradually increasing with density ratio. Blowing rates of $M = 1.7$ and beyond yield heat flux reductions in the order of 2–5%, indicating that a large amount of coolant is ejected without any beneficial effect.

Along the film cooled surface, the areas of dominating single jet in crossflow mixing and adjacent jet in crossflow interaction downstream can be clearly distinguished. For the steep angle ejection (Fig. 3a), the adverse effect of a rising blowing rate can be observed upstream $x/d = 30$ for lower blowing rates with a shift to $x/d = 50$ for high blowing rates.

For normal ejection, a distinct crossing point of all curves is present at $x/d = 18$. It obviously separates the single jet dominated region close to the ejection from the film flow dominated region downstream (Fig. 3b). The optimum is less pronounced than for shallow angle ejection.

Figure 4 shows the results of small pitch and large pitch ejection at typical shallow ejection angles and engine like high density ratios. At a hole spacing of $P/d = 2$ (Fig. 4a) the heat flux reduction is monotonically increasing with blowing rate over most of the regarded downstream length.

This shows the dominance of the adjacent jet interaction at small pitch resulting in stable cooling films. In contrast to the findings at larger hole spacings, the heat flux reduction is especially high at high blowing rates. The large pitch ejection (Fig. 4b) displays a completely different behavior. The almost purely jet in crossflow structured situation obviously exhibits optimum cooling conditions at a blowing rate of $M = 0.85$.

3 Results

The calculation results are presented in Table 1. The initial version of the film cooling system for the nozzle blade of the first stage of the turbine [2] is characterized by the parameters presented in the first line of Table 1. The search for the reduction heat flux was carried out on the basis of a mathematical model, including a Fortran program for sequential calculation of thirty-one algebraic relations and the *IOSO NX 2.0* package.

The calculation results indicate a small contribution of film cooling to a decrease in the maximum heat flux inside the wall for the initial version of the cooling system: $\eta_q = 0.0217$ at a relative coolant flow rate $\overline{G_c} = \dot{G}_c / \dot{G}_f = 5.8\%$, where $\dot{G}_c$ and $\dot{G}_f$—where mass flow rates of the cooler and hot gas flow.

Table 1 Parameters of the film cooling system of the gas turbine unit [12] before and after optimization

Parameter	P/d	α radian	Tu %	M	DR	$\bar{G}_c$ %	η_q
Before optimization	4.6	0.785	5	3.01	2.35	5.8	0.0217
After optimization: Pressure side of the nozzle blade (Fig. 1a)	3.0	1.5	9.9	1.682	1.5	5.0	0.0928

Optimization results obtained with the *IOSO NX 2.0* package indicate a possible increase in the maximum of reduction heat flux (up to $\eta_q = 0.0928$) with the parameters indicated in the second line of Table 1. These parameters correspond to the trends in the reduction heat flux shown in Figs. 2, 3 and 4.

The search for the maximum reduction heat flux was carried out by varying five independent parameters: $5.0\% \le Tu_1 \le 10\%$; $30° \le \alpha \le 90°$; $1.2 \le DR \le 2.5$; $3 \le \overline{P} \le 5$ and $0.5 \le M \le 3.0$.

These values correspond to the experimental data [3, 4], while the discrepancy of 15% can be explained by some difference in the initial data in the experiment and calculation.

4 Conclusions

It is shown that *IOSO NX GT 2.0* is a reliable tool for finding the optimal solution to one function of the target (the reduction heat flux). This algorithm can be successfully used in combination with various application programs. Only the decay of heat transfer and a simultaneous formation of a closed cooling film due to adjacent jet interaction assists heat flux reduction far downstream. As an example, a search was made for a global maximum of reduction heat flux and optimal parameter values for a film cooling system, as applied to operating conditions of gas turbine blades.

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