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Trailing edge cooling of a gas turbine blade with perforated blockages with inclined holes

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ABSTRACT

An improved hole array to enhance the cooling performance of a perforated blockage was proposed in this paper. The internal passage in the trailing region of the blade was modeled as a wide square channel with three parallel blockages. Various configurations of perforated blockages were tested with a fixed Reynolds number based on the channel hydraulic diameter. The baseline design had holes positioned along the centerline of the blockage in the lateral direction, and the array pattern, hole size, and hole direction were manipulated to enhance the cooling performance. Experiments were performed to obtain information on heat transfer and pressure loss. A naphthalene sublimation method was adopted to obtain detailed heat transfer distributions on the surfaces, using the correlation between heat and mass transfer. The pressure was measured at several points to evaluate the pressure loss. The proposed inclined hole array showed noticeably improved cooling performance, as much as 50% higher than the conventional configuration.

1. Introduction

Most modern gas turbines employ internal cooling. The cooling air removes heat from the airfoil flow inside the internal passage and is finally discharged through film cooling holes or trailing-edge slots. To improve the cooling performance as much as possible within the limited space available, various geometric obstacles are employed for internal passage cooling. In particular, close attention must be paid to maintaining effective cooling in the narrow space on the trailing side of the airfoil [1]. Therefore, the use of complicated cooling methods is limited, and ribs and pin–fins are typically adopted as heat transfer promoters for internal cooling of that region. Over the years, ribs [2–6] and pin–fins [7–10] have been extensively investigated by numerous researchers.

Another internal cooling configuration, known as perforated blockage, has also been frequently suggested for cooling the trailing side of the blade, as illustrated in Fig. 1. Two or three blockages are installed in a parallel configuration at the end of the internal passage, and cooling air is forced to pass through holes in the blockages before being discharged through the trailing edge slots. After passing through the holes, the cooling air impinges on the next blockage and generates a highly turbulent flow, which increases the heat transfer rate significantly. There have been relatively few studies of the heat transfer characteristics between consecutive perforated blockages, compared to other heat transfer promoters, such as ribs and pin–fins. Moon and Lau [11] performed experiments to obtain the local heat transfer distributions on one of the channel walls between blockages with round holes, using a thermochromic liquid–crystal method. Ahn et al. [12] conducted naphthalene sublimation experiments to study the effect of hole shape on heat transfer. They compared the results for round holes and elongated holes and reported that large round holes exhibited better thermal performance. A more detailed investigation was carried out by Lau et a1. [13]. They performed naphthalene sublimation experiments in a realistic geometry, which included a right-angle turn and decreasing channel height along the main flow direction.

In the conventional blockage cooling technique, the perforations are directed parallel to the main coolant flow, so that the coolant jet is always heading toward the next blockage. Because the jet impinges on the blockage, rather than on the pressure-side and suction-side surfaces (which are directly exposed to hot gas), the cooling performance is not as high as expected. To overcome this disadvantage of the conventional blockage design, several perforation configurations were examined and the arrangement

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Nomenclature

D_1	hole diameter in Cases 1 and 2
D_2	hole diameter in Cases 3 and 4
D_h	hydraulic diameter of the test channel
D_{naph}	mass diffusion coefficient of naphthalene vapor in air
f	friction factor
f_0	friction factor of fully developed turbulent flow in a smooth pipe
H	height of the test channel
k	thermal conductivity of air
L	length of the test channel
Nu	Nusselt number (hD_h/k)
P_{naph}	naphthalene vapor pressure
Pr	Prandtl number ($\mu C_p/k$)
$\mathrm{Re}_{\mathrm{Dh}}$	Reynolds number based on hydraulic diameter (UD_h/υ)
R_{naph}	Naphthalene gas constant
Sc	Schmidt number (υ/D_{naph})
Sh	Sherwood number ($h_m D_h/D_{naph}$)
Sh_0	Sherwood number, Eq. (5)
$\overline{Sh}$	spanwise averaged Sherwood number
$\overline{\overline{Sh}}$	area averaged Sherwood number
T	thickness of blockage
T_w	wall temperature
U	Test section inlet velocity
W	width of the test channel
P_1	hole-to-hole pitch in Cases 1 and 2
P_2	hole-to-hole pitch in Cases 3 and 4
x	coordinate and distance in the streamwise direction
y	coordinate and distance in the lateral direction
z	coordinate and distance in the vertical direction
h_m	mass transfer coefficient
$\dot{m}$	local naphthalene mass transfer rate per unit area
Δz	sublimation depth of the naphthalene surface
Δt	running time
$\dot{Q}_{air}$	volume flow rate of air
$Z_{sub}\|_x$	average sublimation depth of the naphthalene surface at position x

Greek symbols

μ	dynamic viscosity of air
η	thermal performance, Eq. (9)
ν	kinematic viscosity of air
ρ_s	density of solid naphthalene
$\rho_{v,w}$	vapor density of naphthalene on the surface
$\rho_{v,b}$	vapor density of bulk air

shown in Fig. 2(b) is suggested to increase the heat transfer rate on the suction-side and pressure-side surfaces. The purpose of the present research is to investigate this improved blockage configuration for internal cooling of the trailing-edge side of the blade. The thermal performances of four different blockage configurations were tested experimentally, utilizing the conventional configuration as the baseline design.

2. Research method

2.1. Experimental setup and test section

Fig. 3 shows a schematic overview of the experimental setup. The experiment was performed in an indoor laboratory, where a constant air temperature was maintained during the experiment. Room air flowed from a blower to the test section, passing through a heat exchanger, which regulated the inflow temperature. An orifice flow meter was connected to the heat exchanger outlet to monitor the flow rate. Incoming air to the test section first stagnated in a plenum chamber and then flowed through guide vanes and a honeycomb with a screen mesh, to provide flow uniformity in the lateral direction. *J*-type thermocouples were employed for temperature measurements. The thermocouples were installed at three points: inside the orifice, at the duct inlet, and inside the naphthalene plate. The driving potential for mass transfer was the vapor pressure of the naphthalene. Note that the sublimation rate of naphthalene varies by approximately 10% per 1 °C. Because vapor pressure is a temperature-sensitive property, the temperature was carefully monitored and kept constant during the experiment. The pressure difference was monitored with a digital differential pressure transmitter to maintain the mass flow rate

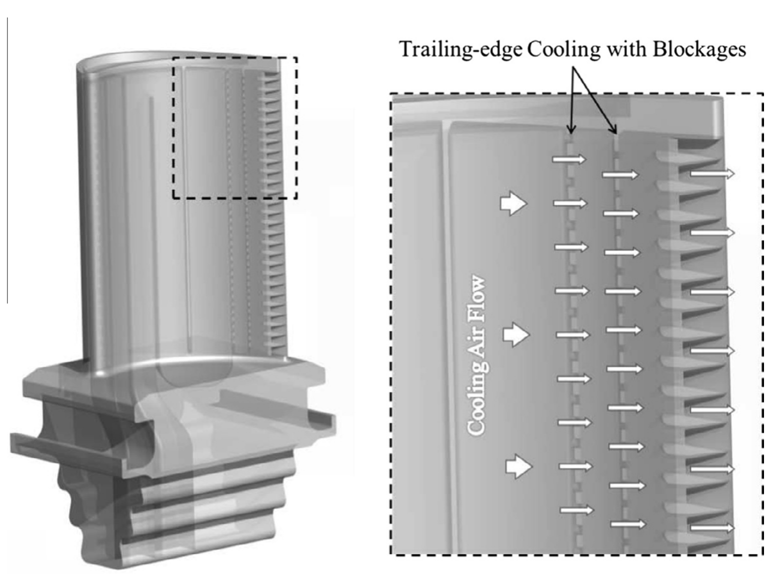

Fig. 1. Internal cooling of the trailing-edge side of the blade.