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Augmented heat transfer with intersecting rib in rectangular channels having different aspect ratios

Heeyoon Chung [a], Jun Su Park [a], Sehjin Park [a], Seok Min Choi [a], Dong-Ho Rhee [b], Hyung Hee Cho [a,*]

[a] Departmentof Mechanical Engineering, Yonsei University, 50, Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea
[b] Korea Aerospace Research Institute, Eoeun-dong, Yuseong-gu, Daejeon 305-380, Republic of Korea

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ABSTRACT

This study was an experimental investigation of the effect of an intersecting rib on heat/mass transfer performance in rectangular channels with angled ribs and different aspect ratios. In a rib-roughened channel with angled ribs, heat/mass transfer performance deteriorates as the channel aspect ratio increases, since the vortices induced by angled ribs diminish with increasing aspect ratio. A longitudinal rib that bisects the angled ribs is suggested to overcome this disadvantage. The heat transfer performance of angled rib configurations with a 60° attack angle were tested with and without an intersecting rib using naphthalene sublimation method. The channel aspect ratio is varied from 1 to 4. When the intersecting rib was present, additional vortices were generated at every point of intersection with the angled ribs. Thus the heat/mass transfer performance was significantly enhanced for all channel aspect ratios when an intersecting rib was added to an ordinary angled rib configuration.

1. Introduction

The operating temperatures of modern gas turbines have been increasing steadily to provide enhanced efficiency and power output. However, metals and other materials have heat resistance temperature limits, and their lifetimes are shortened by higher temperatures. Therefore, the development of cooling techniques for the hot components in a gas turbine is an essential part of gas turbine engine design. The most popular method of cooling the hot components of a turbine (such as nozzle vanes and rotor blades) is internal cooling, which employs internal passages for coolant air to absorb heat from hot components.

In an internal cooling passage, the heat transfer characteristics are mainly dominated by turbulent transport and secondary flow induced by geometrical features. This means that better cooling performance can be obtained by adding to or otherwise modifying the geometry of an internal passage. Certain geometric features, such as ribs [1,2], pin–fins [3–5], protrusions and dimples [6,7], have been investigated as heat transfer intensifiers. In particular, various types of rib configurations have been studied, due to their simplicity and usefulness [8–10].

An ordinary internal passage design is shown in Fig. 1. Serpentine-type multi-passage internal cooling is employed, and rib turbulators are installed on the internal surfaces of the pressure and suction sides. Since blade thickness varies from the leading edge to the trailing edge, the aspect ratios of the internal passages are different. The fluid flow and heat transfer characteristics of an internal passage are dependent not only on the configuration of rib turbulators, but also on the aspect ratio of the channel. There has been extensive research on the heat transfer performance of rib-roughened channels with various aspect ratios [11–13].

Previous researchers have reported that ribs installed at an acute angle provide better heat transfer performance than orthogonally installed ribs [14]. These angled ribs generate strong secondary vortices adjacent to the channel surface as the flow moves in the direction of the ribs. The vortices sweep the surface, and locally intensified heat transfer occurs in these regions. Moreover, parallel ribs installed on opposite channel surfaces generate a rotational flow, which promotes mixing of the fluid [15,16]. Recently developed gas turbine blades have adopted these angled rib turbulators for improved internal cooling performance. The flow patterns induced by angled ribs are illustrated in Fig. 2.

Unfortunately, as the channel aspect ratio increases, the effect of the secondary vortices induced by angled ribs diminishes due to development of a thermal boundary layer between the ribs, so that the heat transfer performance is degraded [17]. To overcome this deficiency, a new idea is suggested for improving the heat transfer performance of angled ribs in a large-aspect-ratio channel by installing an intersecting rib. The intersecting rib is installed to

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* Corresponding author. Tel.: +82 2 2123 2828; fax: +82 2 312 2159.
E-mail address: hhcho@yonsei.ac.kr (H.H. Cho).

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Nomenclature

AR	aspect ratio of channel
D_h	hydraulic diameter (mm)
D_{naph}	mass diffusion coefficient of naphthalene vapor in air (m^2/s)
e	height of rib (mm)
f	friction factor
f_0	friction factor of fully developed turbulent flow in a smooth pipe
H	channel height (mm)
k	Thermal conductivity (W/m K)
L	channel length (mm)
Nu	Nusselt number (hD_h/k_c)
P_{naph}	naphthalene vapor pressure (N/m^2)
Pr	Prandtl number ($\mu C_p/k$)
Re_{Dh}	Reynolds number based on hydraulic diameter (UD_h/ν)
R_{naph}	naphthalene gas constant (J/mol K)
Sc	Schmidt number (ν_{air}/D_{naph})
Sh	Sherwood number ($h_m D_h/D_{naph}$)
Sh_0	Sherwood number, Eq. (6)
$\overline{\mathrm{Sh}}$	spanwise averaged Sherwood number
$\overline{\overline{\mathrm{Sh}}}$	area averaged Sherwood number
W	duct width (mm)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
P	rib-to-rib pitch (mm)
x	coordinate and distance in the streamwise direction (mm)
y	coordinate and distance in the lateral direction (mm)
z	coordinate and distance in the vertical direction (mm)
h_m	mass transfer coefficient (m/s)
$\dot{m}$	local naphthalene mass transfer rate per unit area (kg/m^2 s)
η	thermal performance, Eq. (8)
ρ_s	density of solid naphthalene (kg/m^3)
$\rho_{(v,w)}$	vapor density of naphthalene on the surface (kg/m^3)
$\rho_{(v,b)}$	vapor density of bulk air (kg/m^3)
Δz	sublimation depth of the naphthalene surface (mil)
Δt	running time (s)

cut across both the flow and the angled ribs. The main purpose of this intersecting rib is to break down the developing thermal boundary layer between the angled ribs. The present study is an experimental investigation of the effect of an intersecting rib on the heat transfer characteristics in a rectangular channel with angled ribs. Two sets of rib configurations and three different channel aspect ratios were investigated at fixed Reynolds numbers representing the fully turbulent flow regime. Detailed heat transfer distributions were determined via mass transfer experiments, utilizing the naphthalene sublimation method, and the overall thermal performance of each case was evaluated considering frictional losses.

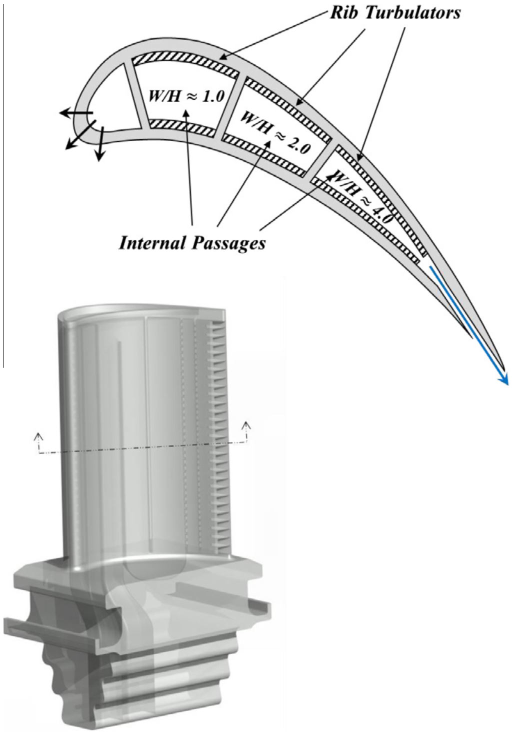

Fig. 1. Blade internal passages of various aspect ratios.

2. Experimental setup and data reduction

2.1. Experimental setup

A schematic overview of the experimental setup used in the present study is shown in Fig. 3. The experiment was carried out in an indoor laboratory, where the air temperature was held constant by the air conditioning system. The test facility was composed of an air blower, a heat exchanger with a constant-temperature water bath, an orifice flow meter, a plenum, a test channel and a monitoring computer. The airflow rate was controlled by the frequency inverter used to regulate the speed of the air blower, and the flow rate was measured by the orifice flow meter. The air discharged from the blower passed through

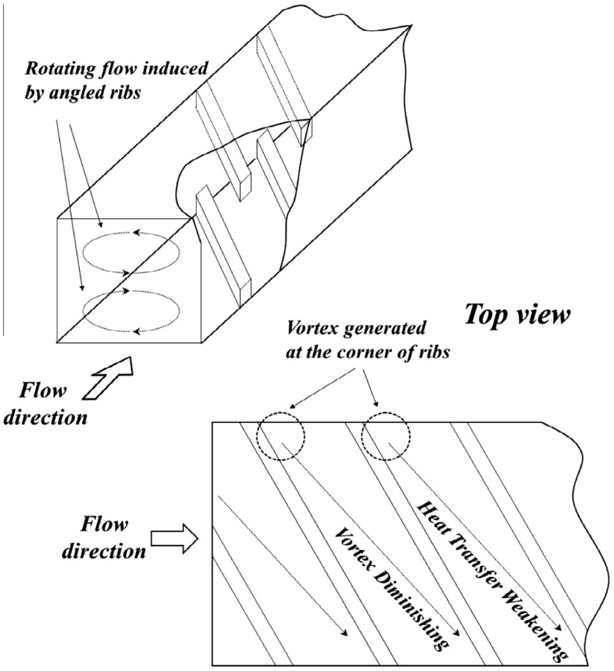

Fig. 2. Flow pattern induced by angled ribs.