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Spatially-resolved heat transfer characteristics in channels with pin fin and pin fin-dimple arrays

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ABSTRACT

A comparative study has been conducted to investigate the spatially-resolved heat transfer characteristics of air turbulent flow in rectangular channels with pin fin and pin fin-dimple arrays. A combined method of experiments and numerical computation was adopted to obtain the spatially-resolved Nusselt numbers on the endwall surface of the pin fin and pin fin-dimple channels. Compared with the pin fin channel, the pin fin-dimple channel shows distinctive local heat transfer characteristics on the endwall beneath the main flow and the wake flow region. Due to the presence of the dimples in the pin fin arrays, extra strong vortex flows are generated near the wall beneath the main flow region downstream the dimples, which distinctively increase the turbulent mixing there and enhance the heat transfer rates; however the turbulent mixing in the wake of the pin fins is reduced appreciably, which leads to decreased heat transfer rates in the wake especially at relatively low Reynolds number. Overall, the dimples in the pin fin arrays increase not only the averaged heat transfer coefficient, but also the heat transfer area on the endwall.

1. Introduction

Short pin fins (pin fin height-to-diameter ratio $H/D = 0.5–4$) are commonly used in the internal cooling passage of gas turbine blades, particularly in the trailing edge where there exist narrow cooling channels [1,2]. In the pin fin channel, the pin fins increase the internal wetted (cooled) surface area. On the other hand, when the fluid flows across the pin fin arrays, the pin fins create accelerated flow between pins, separated highly disturbed wake regions behind each pin, horseshoe vortices from interaction with the endwall, and the unsteady vortical shedding induced from the pin. These mechanisms serve to produce a high turbulence level in the flow and significantly enhance the convective heat transfer performance.

Previously, numerous investigations have been done focusing on the effects of geometrical parameters on the flow friction and heat transfer in the pin fin channel. Zukauskas [3], Van Fossen [4], Metzger et al. [5–7] and Chyu et al. [8,9] revealed that the pin height-to-diameter ratio, array orientation (in-line or staggered) and fin cross-sectional shape, etc. are crucial parameters in determining the heat transfer and friction facto. Lau et al. [10], and McMillin and Lau [11] considered the effects of bleed ejection on heat transfer, and on streamwise pressure variations in a pin fin channel. More recently, Won et al. [12] studied the spatially-resolved Nusselt number and flow structure in a pin fin channel, and their study revealed the underlying mechanisms of heat transfer enhancement in the pin fin channel.

It is noted that, even though the pin fin channel has a significantly improved heat transfer performance, however it pays a penalty of considerably increased flow resistance in the channel. Metzger et al. [5–7] and Chyu et al. [8,9] indicated that, compared to the smooth channel, the channel with pin fin arrays with the streamwise and spanwise spacings of 2.5 can achieve a heat transfer enhancement of 2–4 times, and an increase in the friction factor by 20–30 times in the Reynolds number range of 10,000–100,000.

Dimples on the heat transfer surface can significantly enhance the convective heat transfer, but do not increase the pressure loss appreciably. Chyu et al. [13], Moon et al. [14], Mahmood et al. [15,16] and Ligrani et al. [17] investigated the flow and heat transfer performance in a channel with dimples. Their studies showed that, compared with the smooth channel, the dimpled channel surface can improve the Nusselt number by a factor of 1.8–2.8, with an increase in the friction factor by 1.3–2.9 times. Mahmood et al. [15] stated that the outward shedding or ejection of fluid from the dimples produces the heat transfer augmentation mainly by the periodicity and unsteadiness of the vortical fluid.

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Nomenclature

D	pin fin diameter, m
D_h	channel hydraulic diameter, $2HW/(H+W)$, m
f	friction factor, see Eq. (2)
h	local heat transfer coefficient, $\dot{q}/(T_w - T_m)$, $Wm^{-2}K^{-1}$
H	pin fin or channel height, m
k	fluid thermal conductivity, W m^{-1} K^{-1}
L	length of the pin fin-dimple/pin fin channel, m
Nu	local Nusselt number, hD_h/k
Nu_{ave}	average Nusselt number, see Eq. (1)
Nu_0	Nusselt number of the smooth rectangular channel
ΔP	the pressure drop of the airflow across the test channel, Pa
$\dot{Q}_{net}$	the net heating power, W
$\dot{q}$	local heat flux on the endwall surface, W m^{-2}
Re	Reynolds number based on hydraulic diameter, $\rho u D_h/\mu$
S	spanwise spacing between pin fin centers, m
T_{in}	inlet mean fluid temperature, °C
T_m	local mean temperature of the airflow, °C
T_{out}	outlet mean fluid temperature, °C
T_w	local wall temperature, °C
u	bulk mean channel velocity over the channel cross section, m/s
W	width of the channel, m
X	streamwise spacing between pin fin centers, m

Greek symbols

ρ	density, kg m^{-3}
μ	dynamic viscosity, kg m^{-1} s^{-1}

The previous research work has showed that a combined structure of pin fins and dimples in a channel can produce greater average heat transfer performance at an even reduced pressure drop penalty compared with the channel with only pin fins [18]. Of interest in the present paper is to investigate the spatially-resolved heat transfer characteristics in a pin fin-dimple channel by comparing with those of the counterpart of a pin fin channel. The research aims to enhance the understanding of how the dimples in the pin fin arrays affecting the local heat transfer distributions on the endwall, which is significantly important for the cooling design for hot components in gas turbines and other thermal systems. In the present paper, experiments combined with computational work have been conducted to obtain the spatially-resolved heat transfer data on the endwalls of the pin fin-dimple channel and the pin fin channel, and characteristics of their local Nusselt number distribution have been revealed.

2. Experimental setup

Fig. 1 shows a schematic diagram of the experimental system for the heat transfer measurements for the pin fin and the pin fin-dimple channels by using a liquid crystal thermography technique. This experimental setup consists of a variable-speed blower, a settling chamber, a nozzle flowmeter, a LabView data acquisition system and a test section.

The air is drawn into the wind tunnel by the blower, and the air mass flow rate is measured by the nozzle flowmeter. After that, the air enters a contraction section, which leads to a rectangular cross section, 124 × 10 mm test channel. The test channel has a length of 645 mm, which is made of 15 mm-thick Plexiglas. The clear Plexiglas channel wall can provide a good thermal insulation and a good optical access to the flow and heat transfer in the channel. The test channel is followed by a diffuser, which exits to the settling chamber. The present experimental configuration has low inlet turbulence levels and a uniform velocity field, which is typical of most pin fin channel heat transfer studies.

The test plate with pin fin/pin fin-dimple arrays mounted on the surface is inserted into the test channel from below, and a 15 mm-thick, Plexiglas-made support plate is used to support the test plate from the bottom by being tightly bolted with the test channel. Above the test plate is a 15 mm-thick cover plate, which is also made of Plexiglas ($k = 0.15$ W m^{-1} K^{-1} at 20 °C). Careful fabrication can ensure that the cover plate is flush with the top wall of the test channel, and the test plate is flush with the bottom wall of the test channel. Upstream the pin fin-dimple/pin fin test plate, there is a 240-mm-long entrance section of the test channel, which is about 13 hydraulic diameters (where hydraulic diameter is 18.5 mm). Immediately upstream and downstream the test plate, there are pressure taps installed in the top wall of the test channel to measure the pressure drop across the pin fin channel. On the other hand, the mixed-mean temperatures of the air entering and leaving the test section are measured respectively by using three calibrated Type-K thermocouples spread across the cross section with an immersion depth of about half of the channel height. Especially, to measure the mixed-mean temperature of the flow leaving the test plate, the thermocouples are mounted approximately 100 mm downstream of the exit of the test plate in order to let the outflow become well mixed. Averaged values of those three thermocouples are obtained as the inlet and outlet mean temperatures respectively. Energy balance validations show deviations of less than 3% for the experiments over the whole Reynolds number range. Therefore the exact experimental inlet and outlet temperatures can be obtained. To reduce the heat loss from the test plate to the environment, the test section was wrapped with a layer of foam insulation.

Fig. 2 shows the geometrical configurations of the pin fin and the pin fin-dimple channels used in the experiments. There is a ten-row staggered array of pin fin/pin fin-dimples in the streamwise direction, and there are five pin fins/dimples each row in the spanwise direction. The pin fin geometrical configurations of the pin fin channel are the same with those of the pin fin-dimple plate. The pin fin diameter $D = 10$ mm, the spanwise spacing-to-diameter ratio $S/D = 2.5$, the streamwise spacing-to-diameter ratio $X/D = 2.5$, and the pin fin height-to-diameter ratio $H/D = 1.0$. The dimples are arranged in-between the pin fins. The dimple print diameter is also 10 mm, and the dimple depth is 2 mm (0.2 D), and the dimple diameter is 14.5 mm. With such dimple configurations, the endwall surface area of the pin fin-dimple channel is about 2.2% more than that of the pin fin channel. The arrangement of the pin fin array with $X/D = 2.5$ and $S/D = 2.5$ is considered to be one of the optimal array arrangement for turbine airfoil cooling. Heat transfer studies in pin fin arrays with such geometrical configurations have also been shown in Refs. [5,8].

The pin fin and the pin fin-dimple arrays are manufactured respectively on the stainless steel plates, which is 245 × 130 mm^2. To measure the spatially-resolved surface temperature of the endwall of the pin fin and pin fin-dimple channels, a micro-encapsulated thermochromic liquid crystal (TLC) combined with thermocouples was used in the experiments. The supplied TLC (Hallcrest SPNR40C20W) has a nominal red start temperature of 40 °C and an active bandwidth of 20 °C. For the specific application of the present experiments, the steady-state liquid crystal