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Endwall heat transfer and pressure drop in scale-roughened pin-fin channels

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ABSTRACT

There is a growing requirement for improved heat transfer performance for a number of electronic devices and this dictates a need to further elevate the endwall heat transfer performances for pin-fin channels. Driven by this need, a novel compound heat transfer enhancement (HTE) measure that combines deepened scales and pin-fin array is devised. Characteristics of heat transfer and pressure drop performances in two scale-roughened pin-fin channels with two different pin pitch-to-diameter ratios are compared for both forward and backward flows in the Reynolds Number (*Re*) range of 1000–30000. Comparisons of heat transfer data, pressure drop measurements and thermal performance factors with previous results collected from a variety of single and compound HTE devices demonstrate the significant augmentations in both heat transfer rates and pressure drop coefficients for the present HTE measure. This present compound HTE measure with scales and pin-fin array demonstrates an enhancement on the heat transfer up to of 22 times of the developed flow references in smooth-walled pipe within the *Re* range of 1000–30000. Experimental correlations of heat transfer and pressure-drop coefficients for two scale-roughened pin-fin channels with forward and backward flows are derived to assist design applications.

1. Introduction

As a passive heat transfer enhancement (HTE) measure, pin-fins enhance structure integrity, increase heat transfer areas via fin effects and induce horseshoe vortices at the pin-endwall junctions hence facilitating HTE impacts. These features are widely fitted in the cooling passages at the trailing edge of a gas turbine blade and in the heat sink for cooling of electronic chipsets to enhance the heat transfer. Driven by these cooling applications, a large number of experimental and numerical studies examined heat transfer performances over the pin-fins and endwalls in the pin-fin channels [1–16]. These pin-fins improve heat transfer performances by tripping wakes which enhance fluid mixing but with consequential increase in pressure gradients and friction drag. The pin-to-endwall junctions and each pin-row give rise to a number of complex vortex structures that augment endwall heat transfer rates. In this respect, the horseshoe vortices initiated upstream each pin at the pin-endwall junctions are of the primary importance for regional endwall HTE effects [1]. At locations upstream the leading edges of pin-fins on the endwall, two legs of each horseshoe vortex separate and roll around the adjoining pin that advect downstream to form the pin-fin wakes [2]. These wakes re-circulate the fluids behind each pin and generate low heat transfer regions there. Adverse pressure gradients are simultaneously developed as flows traverse each pin that considerably elevates the pressure drop penalties. The separated shear layers induced by these vortical flows reattach after the recirculation zone and re-elevate local heat transfer rates near the reattachment points. Along with the downstream growth of the HTE mechanisms tripped by pin-fins, the boundary layers develop over each endwall. The endwall heat transfer performances along a pin-fin channel are indicative of the trade-offs between the streamwise enhanced HTE mechanisms tripped by pin-fins against the thickened endwall boundary layers. As a result of such trade-offs, the endwall Nusselt number (*Nu*) increases progressively in the downstream direction over the first 3–4 pin-rows prior to the so-called periodically developed flow region. The different flow conditions generated over the endwall and around the outer surface of each pin-fin generally provide the higher HTE effects on the pin surfaces by 35% [3] or 10–20% [4] over those on the endwall.

While the aforementioned flow physics generalizes the heat transfer characteristics in a pin-fin channel, the detailed HTE effects vary with the height-to-diameter ratio [5,6] and the shape [7–11] of pins, the arrangement [12,13] and the orientation [14] of pin-arrays

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Nomenclature

English Symbols

A,n,E,F,G	Correlation coefficients
Cp	Constant specific heat ($Jkg^{-1}K^{-1}$)
D	Diameter of scale (m)
D_P	Pin diameter (m)
D_S	Diameter of scale (m)
d	Hydraulic diameter of the test channel (m)
e_S	Depth of scale (m)
f	Pressure drop (Fanning friction) factor = $[\Delta P/(0.5\rho W_m^2)]/(d/4L)$
f_∞	Fanning friction factor for developed flow in smooth walled plain tube
H	Channel height (m)
H_P	Pin height (m)
k_f	Thermal conductivity of fluid ($Wm^{-1}K^{-1}$)
L	Channel length (m)
Nu	Local Nusselt number = $qd/k_f(T_w - T_b)$
$\overline{Nu}$	Averaged Nusselt number for developed flow
Nu_∞	Nusselt number value for developed flow in smooth walled plain tube
P_P	x-wise pin-pitch (m)
P_S	Skew-wise pin-pitch (m)
P_r	Prandtl number = $\mu Cp/k_f$
ΔP	Pressure drop across entire test channel (Nm^{-2})
q	Convective heat flux (Wm^{-2})
Re	Reynolds number = $\rho W_m d/\mu$
S	y-wise pin-pitch (m)
S_P	Scale pitch (m)
T_b	Fluid bulk temperature (K)
T_w	Wall temperature (K)
W	Channel width (m)
W_m	Mean flow velocity (ms^{-1})
x, y	Coordinate system referred to midway of flow entry as origin (m)

Greek Symbols

α_S	Scale attack angle (degrees)
ρ	Density of fluid (kgm^{-3})
μ	Fluid dynamic viscosity ($kgm^{-1}s^{-1}$)
η	Thermal performance factor = $(\overline{Nu}/Nu_\infty)/(f/f_\infty)^{1/3}$

and the clearance between endwall and detached pins [15,16]. In view of the endwall heat transfer performance, the staggered diamond pin-fin array with pitch ratios of 1.5–2.5 pin-diameters offers considerable HTE effects; while the elliptical fins provide higher thermal performance factors [13]. Among the various pin-fin geometries, the circular pin-fins are most extensively adopted for cooling of gas turbine blades that offer the endwall Nu elevations in the general ranges between 2 and 3.2 times of the Dittus-Boelter Nusselt number levels (Nu_∞) [2]. The adverse pressure gradients around each pin and the increased friction drag over a pin-fin array have increased the pressure-drop penalties substantially. Therefore previous work utilized the detached pin-fins [16] as an attempt to reduce the pressure drop coefficients in the pin-fin channels by eliminating the adverse pressure gradients at the pin-endwall junctions. The accelerated flow through the small clearance between the endwall and each detached pin replaces the diminished horseshoe vortices as an alternative HTE mechanism. For such detached pin-fin channel with the clearance to pin-diameter ratio of 1/4, the reductions in endwall Nusselt number (Nu) arising from the attached pin-fin references are less than 10%; while the pressure drop coefficients in this detached pin-fin channel fall dramatically to the levels about 40% of those in the attached pin-fin channel and result in the improvements in thermal performance factors [16]. However, when occasions demand for further endwall HTE performances in a pin-fin channel, the combination of other HTE measure(s) with pin-fin array to form the so-called compound HTE device is required. It is worth noting that, unlike the channel enhanced by angled ribs which induce strong cross-plane secondary flows as a major HTE mechanism; these pin-fins can disrupt such rib-induced secondary flows considerably. It is therefore considered to combine the pin-fin array with the deepened scales [17] in order to merge the HTE mechanisms triggered by the pin-fin array and the scale imprints.

With scaled imprints over an enhanced channel wall, the boundary layers are repeatedly broken with the intensified turbulence. Taking the fin effects into account, Nusselt number ratios (Nu/Nu_∞) for a scale-roughened narrow channel can reach about 3 and 4.5 for the backward and forward turbulent flows, respectively [17]. Our recent flow measurements [18] disclose the flow physics associated with such HTE impacts inside a rectangular channel with two opposite walls roughened by deepened scales. In the spanwise direction, each deepened scale triggers a jet-like central flow with a pair of counter-rotating vortices on its two sides complying within the scale. The near-wall counter-rotating vortex pairs serve as the essential HTE mechanism. These vortex pairs roll the heated fluids toward the core region from the wall by the vortex array functioning as the roller and are subsequently convected downstream to merge with the main stream. Above the near-wall vortex array, the unstable and transient large-scale vortices are visualized which affect the turbulent structures. The roller-like vortex arrays, dominant streamwise convective velocities, and the higher turbulent kinetic energy levels are concluded as the main HTE mechanisms for the scale-roughened channel with forward flows [18]. As these secondary vortices are absent for the downward flows, forward flow cases consistently provide higher HTE effects than their downward flow counterparts in scale-roughened channels.

Driven by the needs to further elevate endwall HTE impacts for the pin-fin channel with cooling applications to gas turbine blades and electronic chipsets, the compound HTE measure is devised by combining the deepened surface scales and the pin-fin array. The present experimental study comparatively examines the HTE ratios, pressure drop characteristics and thermal performance factors for roughened pin-fin channels. No previous study is available for this novel compound HTE measure which merges the complex flow features induced by the pin-fin array and the scale imprints over the endwalls.

2. Experimental details

2.1. Test facilities

Fig. 1 depicts (a) schematics of the experimental facility and (b) the pin-fin array and scale-roughened surface. As shown in Fig. 1a, the screw-type compressor (1) and the refrigerating unit (2) supplied the dehumidified and cooled airflow to the test assembly at the ambient temperature level. The test airflow was channeled through a set of pressure regulator and filter (3), a needle valve (4), a mass flow meter (5) and a pressure transducer (6) through which the pressure and the mass flow rate of the test coolant entering the