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Research Paper

Thermal performance of compound heat transfer enhancement method using angled ribs and auxiliary fins

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HIGHLIGHTS

- Compound ribs and in-line auxiliary fins are newly devised to boost HTE effect.
- Detailed *Nu* of parallelogram ribbed channels with auxiliary fins are measured.
- *f* and TPF performances are comparatively examined.
- *Nu* and *f* correlations for ribbed channels with/without fin are devised.

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ABSTRACT

Detailed Nusselt number (*Nu*) distributions over two opposite endwalls of two parallelogram channels roughened by 45° ribs without/with in-line auxiliary fins are measured using steady-state infrared thermography method at $5000 \leqslant Re \leqslant 15{,}000$. Pressure drop measurements are individually performed at isothermal conditions to detect the Fanning friction factors (*f*) for thermal performance factors (TPF) evaluations. Relative heat transfer and *f* augmentations for this type of passive compound heat transfer enhancement (HTE) method are assessed by comparing with the Nusselt numbers (Nu_∞) and *f* factors (f_∞) of smooth plain tube references at the same Reynolds number (*Re*). With present in-lined auxiliary fins on two opposite ribbed endwalls, the channel averaged HTE ratios fall between 4.43 and 4.21 with the corresponding f/f_∞ ratios in the range of 6.5–3.35; giving rise to the TPF values between 2.37 and 2.81. As the comparative HTE ratios, f/f_∞ values and TPF values for the similar ribbed channels without auxiliary fins are in the respective ranges of 3.93–3.61, 1.63–1.53 and 2.41–2.35, the present compound HTE method further elevates the Nu/Nu_∞ ratios with the associated *f* amplifications but can still improves the TPF values in general. It is concluded that the present compound HTE method using angled ribs and auxiliary fins is applicable for improving thermal performances of turbulent channel flow.

1. Introduction

Passive heat transfer enhancement (HTE) methods pursue heat transfer enhancements but usually are subject to the accompanying augmentations of pressure drops. Artificial roughness taking various configurations such as ribs, dents/grooves, corrugations, winglets, pin-fillets and their combinations are widely deployed in channels as common passive HTE methods for single phase flows. Relevant HTE mechanisms include the improved mixings in viscous sub-layer, the promotion of turbulent activities, the periodical boundary layer diminishments and/or the swirl/vortice/separations. Inevitably, these HTE flow mechanisms also amplify the flow drags to raise Fanning friction factors (*f*). As an efficiency index to counteractively assess both Nusselt number (*Nu*) and *f* augmentations, the thermal performance factor (TPF) under the criterion of constant pumping power consumption was derived as the ratio between the normalized Stanton numbers (St/St_∞) and $(f/f_\infty)^{1/3}$ as $(St/St_\infty)/(f/f_\infty)^{1/3}$ [1], which is equivalent to $(Nu/Nu_\infty)/(f/f_\infty)^{1/3}$ at the same Reynolds number (*Re*) and Prandtl number (*Pr*). The referenced Stanton number (St_∞), Nusselt number (Nu_∞) and Fanning friction factor (f_∞) are evaluated as the developed tubular flow levels.

In view of the various passive HTE devices involving surface ribs [2–13], the periodically broken boundary layers acting with the amplified turbulences serve the common HTE flow mechanisms for all types of rib arrangements. With angled ribs on channel walls, the axial swirls with small-scale dynamic vortices tripped

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Nomenclature

BR	channel blockage ratio at ribbed section
C_p	specific heat of fluid, J kg^{-1} K^{-1}
d	hydraulic diameter of test channel, m
e	rib height, m
e_f	fin height, m
f	Fanning friction factor of test channel = $\Delta P/(0.5\rho W_m^2)(d/4L)$
f_∞	Fanning friction factor evaluating from Balsius equation = $0.079Re^{-0.25}$
H	channel height, m
h	convective heat transfer coefficient = $q_f/(T_w-T_b)$, W m^{-2} K^{-1}
k_f	thermal conductivity of fluid, W m^{-1} K^{-1}
j	Colburn factor = $\overline{\overline{Nu}}/(RePr^{1/3})$
L	channel length, m
L_f	fin length, m
l	rib land, m
$\dot{m}$	mass flow rate of coolant, kg s^{-1}
Nu	Nusselt number = $qd/[k(T_w-T_b)]$
Nu_∞	Dittus-Boelter Nusselt number level
$\overline{Nu}$	area-averaged Nusselt number over front or back endwall
$\overline{\overline{Nu}}$	channel averaged Nusselt number = $(\overline{Nu}_{FE}+\overline{Nu}_{BE})/2$
P	rib pitch, m
Pr	Prandtl number = $\mu Cp/k_f$
q_f	convective heat flux, W m^{-2}
Re	Reynolds number = $\rho W_m d/\mu = 2\dot{m}/[(W+H)\mu]$
St	Stanton number = $Nu/(RePr)$
TPF	thermal performance factor = $\overline{\overline{Nu}}/Nu_\infty/(f/f_\infty)^{1/3}$
T_b	fluid bulk temperature, K
T_w	w all temperature of endwall, K
W	channel width, m
W_f	fin width, m
W_m	mean through flow velocity, m s^{-1}
X, Y	dimensionless coordinates = x/d, y/d
x, y	spanwise and streamwise coordinates, m
Greek symbols	
ρ	fluid density, kg/m^3
μ	fluid dynamic viscosity, N·s/m^2
Subscripts	
FE	refers to front endwall
F	refers to rib floor with fins
BE	refers to back endwall
R	refers to rib floor without fin

by the angled/broken ribs can further boost the HTE benefits. Nevertheless, the considerable f augmentations accompanying with the HTE benefits limit the combinations of surface ribs with other types of HTE devices for further HTE elevations. However, the compound rib-dimple HTE methods have showed the further HTE elevations with increased TPF values from the rib or dimple only cases [14,15]. Nevertheless, due to the unique feature of micro gas flows with considerable rarefaction, the dominant heat transfer physics for macro-scale continuum phenomena could transit from convection to conduction [16]. Using Knudsen number (Kn) defined as the ratio of the molecular mean free path to the characteristic length of the flow system to define the flow regime, the classical Navier-Stokes equations with the no-slip boundary condition were applicable in the continuum regime of Kn $\leqslant$ 0.01. With the Knudsen layer adjacent to the wall and of one to two mean free paths thick reached 0.1 < Kn $\leqslant$ 10 for the transition regime, the gas kinetic scheme [17] to solve the multiple temperature kinetic model (MTKM) for the study of non-equilibrium flows had shown promising success. With the micro thermal fluid systems, such as the gaseous heat transfer for MEMS, the heat transferred from the micro heater was mainly dependant on Kn and the wall accommodation coefficient due to the decreasing intermolecular collisions relative to the gas–wall collisions. The significances of the geometry for the heated surface on heat transfer properties [16] and thus on the heat transfer enhancements in the high-Knudsen regime were amplified from those for the macro thermal fluid systems governed by the Navier–Stokes equations (NSE). Heat transfer enhancements for the slip regime of 0.1 < Kn $\leqslant$ 10 and the free molecular regime of Kn > 10 are worth of future HTE investigations.

As an attempt to boost HTE elevations from the angled rib scenarios while remaining TPF benefits for NSE based continuum phenomena, this study proposes a newly devised compound HTE methods using angled ribs and three dimensional tilted fins of 1/2 rib height to trip the rib-wise flows with less pressure-drop penalties for thermal performance improvements. As parallelogram channels have found applications for gas turbine blade cooling, this experimental work adopts a parallelogram channel roughened by in-lined angled ribs with/without auxiliary fins to comparatively examine the Nu, f and TPF properties. This study also serves as the first attempt to reveal the differential thermal performances between two opposite endwalls of a parallelogram ribbed channel without/with auxiliary fins. For generating the Nu, f and TPF references against which the data collected from present parallelogram ribbed channel with auxiliary fins are compared, the detailed Nu distributions over two opposite ribbed endwalls of the parallelogram channel without fin; along with the f factors and TPF values are initially detected. Subsequently, the Nu, f and TPF performances for the parallelogram ribbed channel with the present auxiliary fins are measured and comparatively examined to assess the thermal performances of the newly devised compound HTE method for various cooling applications.

2. Experimental details

2.1. Test facilities

Fig. 1 depicts (a) parallelogram test module with two opposite endwalls roughened by in-lined 45° ribs and in-lined 45° ribs with in-lined auxiliary fins (b) rib and fin configurations (c) flow configurations through the present test channel. Prior to entering the test section (1), the cooling air flows through a dehumidifier (2), regulating unit of filter, pressure regulator and digital pressure gauge (3), needle valve (4), mass flow meter (5) and a entry plenum chamber (6). Entry abrupt area ratio is 9.82. An unheated parallelogram section of 30 mm long (7) is installed at the flow exit. The channel hydraulic diameter (d) of the parallelogram test section with the width-to-height (W/H) ratio of 2 and the include angle of 60° is 41.87 mm, which is selected as the characteristic length for present study. Two Teflon channel sidewalls (8), a thick Teflon back wall (9) and the roughened stainless steel heating foil (10) construct the 380 mm long test section. Opposite to the heating foil (10) between the Teflon frame (11) and the channel sidewalls (8), the Infrared Radiometer (IR) (12) is adopted to measure the detailed wall temperature (T_w) distributions for the ribbed or/and finned stainless steel heating foil (13). The precisions of mass flow