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Research Paper

Flow and heat transfer characteristics in rectangular channels using combination of convex-dimples with grooves

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HIGHLIGHTS

- We study the turbulent flows in different protrusion-grooved channels.
- The combined effects of convex dimples and grooves have been addressed.
- The effects of spanwise arrangements and number of convex dimples have been studied.
- The convex-dimple-grooves show better thermal performance than transverse-rib-grooves.

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ABSTRACT

In this paper, the main objective is to reveal the usefulness of placing convex dimples upstream of grooves on the improvement of the thermal performance and to address the effects of convex dimple spanwise arrangements and its number on the heat transfer and friction characteristics in the convex-dimple-grooved channel. Additionally, a study on the transverse-protrusion-grooved channel is conducted to serve as a contrast, and three spanwise positions of the convex dimple as well as two convex dimple numbers are considered. The results indicate that compared with transverse protrusions, placing convex dimples upstream of grooves can produce counter-rotating vortex pairs which cause an upstream movement of the flow reattachment. In addition, vortexes shedding from convex dimples can transport the cooler central core flows to the near-wall region and wash up the hotter flows trapped inside the groove region in upward and spanwise directions, which causes significantly higher streamwise, spanwise and downward velocities. Replacing transverse protrusions with convex dimples can enhance heat transfer rate, except the case with convex dimples which are too close to side walls. All cases with convex dimples provide the significantly lower friction loss but higher thermal performance factor than that of the case with transverse protrusions. Additionally, for the convex dimple number studied here, increasing the number of convex dimples leads to a significant increase in Nusselt number as well as thermal performance factor but a slight increase in friction factor. Besides that, the spanwise shift of convex dimples shows complex results.

1. Introduction

Techniques for enhancing heat transfer rate are urgently required by many industrial and engineering applications, including the cooling of gas turbine blades and electronic components, as well as enhancement of heat transfer in nuclear reactors and solar air heaters. Especially in recent years, the higher cost in energy and material causes more and more focus and effort aimed at the development of more efficient heat transfer techniques. A commonly used technique for enhancing heat transfer rate on the surface is to set up periodic turbulators, such as ribs, pin-fins, dimples and grooves, along the streamwise direction, which can trip viscous and thermal boundary layers and enhance the flow turbulence. However, this technique also induces an increase in friction loss penalty, which causes more power cost. Consequently, a desired technique should balance the heat transfer enhancement and power cost. This means that an effective technique should achieve a high heat transfer rate at an economic power cost. Thus, an insight into the flow dynamics, heat transfer and friction characteristics in turbulator-roughed channels should be conducted.

Many researchers have investigated the effects of various turbulators on the heat transfer and friction characteristics of turbulent flows in turbulator-roughed channels. For decades, the rib is

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Nomenclature

A	area of heated wall, m^2
d	the distance between protrusions and grooves, m
D_d	print diameter of protrusion, m
D_h	hydraulic diameter of channel, m
D_p	print diameter of groove, m
e	protrusion height, m
f	friction factor
f_0	friction factor for the smooth channel
H	channel height, m
L_1	length of the unheated starting part, m
L_2	length of the heated part, m
L_3	length of the unheated exit part, m
Nu	area-average Nusselt number
Nu_x	local Nusselt number
Nu_0	Nusselt number for the smooth channel
p	protrusion/groove pitch, m
p_z	distance between convex dimple and side wall, m
P	pressure, Pa
P_{out}	channel outlet pressure, Pa
Pr	Prandtl number
q_w	wall heat flux, W/m^2
Re	Reynolds number based on hydraulic diameter
$T_{w,x}$	local wall temperature, K
T_f	the mass-weighted average temperature between the inlet and outlet of heated part, K
T_{in}	channel inlet temperature, K
TKE	turbulence kinetic energy, m^2/s^2
u_{in}	mean velocity at the inlet, m/s
u_x	streamwise velocity, m/s
u_y	normal velocity, m/s
u_z	spanwise velocity, m/s
W	channel width, m
x	streamwise distance from entrance of heated section, m
z	spanwsie distance from middle plane of channel, z

Greek letter

ΔP	pressure drop, Pa
ρ	flow density, kg/m^3
μ	flow dynamic viscosity, $N\ s/m^2$
λ	thermal conductivity, W/m K
η	thermal performance factor
δ	groove depth, m

one of the most common used turbulators to enhance the heat transfer, and systematical investigations on the effects of the rib spacing, rib angle and channel aspect ratio as well as Reynolds number on the heat transfer enhancement in the ribbed channel have been conducted by Han et al. [1–4] who found that replacing the transverse rib and wide aspect ratio channel with the angled rib and narrow aspect ratio channel can achieve better heat transfer performance. Taslim et al. [5] investigated the rib height effect and pointed out that the heat transfer performance is insensitive to the rib height, while the pressure loss increases remarkably with increasing rib height. The effects of different rib shapes were reported by Gao and Sunden [6], Han et al. [7] as well as Liou et al. [8] in terms of V-shaped ribs, and Wright et al. [9] as well as Kumar et al. [10] in terms of multi V-shaped ribs.

Recently, due to the high heat transfer enhancement with low pressure loss penalty, the dimple has attracted more and more attention. The influences of dimple parameters in terms of the dimple depth, dimple print diameter, dimple spacing and dimple arrangement on heat transfer and pressure loss characteristics in the dimple-roughed channel were reported in the literatures [11–14]. Rao et al. [15] investigated the combined effects of pin-fins and dimples on heat transfer enhancement.

Introducing grooves on the wall is also an effective technique for heat transfer enhancement. Eiamsa-ard, and Promvonge [16] numerically investigated the effects of groove-width to channel-height ratios on heat transfer and friction characteristics in the grooved channel, and their results showed that the highest thermal performance factor can be obtained for the groove-width to channel-height ratio of 0.75. The effects of groove cross-section shapes, in terms of circular ones, rectangular ones, trapezoid ones and triangular ones, on the heat transfer and friction loss in the grooved tubes were reported by Bilen et al. [17] and Ramadhan et al. [18], and their results showed that the triangular groove performed best thermal performance. Moreover, some novel groove geometries in terms of conventional circular groove with rounded transitions to the adjacent flat surfaces and modifications to their bases were presented by Liu et al. [19] who found that adding the rounded transition of the grooves could obtain higher heat transfer rate with lower pressure loss penalty, compared with the circular groove.

Other attempts have been made to enhance the heat transfer rate by using the combination of protrusions and grooves. Many researchers [20–25] investigated the effects of protrusion-grooved turbulators on the heat transfer and friction characteristics in the channel. Jaurker et al. [20] conducted a comparison in the thermal performance between the ribbed surface and rib-grooved surface, and they found that the combination of ribs and grooves yields higher heat transfer coefficient with slightly higher pressure loss penalty. Eiamsa-ard and Promvonge [21] investigated the effects of rib-groove arrangements (rectangular rib-to-triangular groove, triangular rib-to-rectangular groove, and triangular rib-to-triangular groove) on the thermal performance of rib-grooved channels. Additionally, the combined effects of right triangular-ribs with isosceles triangular-grooves are also examined by Aharwal et al. [22]. Skullong et al. [23] adopted the combination of triangular wavy ribs and rectangular grooves to enhance heat transfer rate. Saha et al. [24] paid attention to the angled protrusion-grooves, and experimentally investigated the performance of the combination of transverse or angled ribs with angled grooves, which showed that the angled-rib-grooves performed better thermal performance. Liu et al. [25] focused on the heat transfer enhancement of the combination of V-shaped ribs with V-shaped grooves.

Although there were many investigations on the effects of turbulators in terms of ribs, dimples, pin-fins and grooves on the heat transfer and friction characteristics of turbulent channel flows, to our knowledge, the study on the combination of groves with convex dimples is nonexistent. From above references, it can be known that the idea of combining transverse protrusions with grooves is proposed to make the flows diverted upward by protrusions reattach before or inside the downstream grooves to enhance the heat transfer rate. However, the flows trapped in grooves have low near-wall velocities, especially at groove-corners. Therefore, this paper introduces convex dimples upstream of grooves for the purpose that convex dimples can generate vortex flows which help transport the cooler central core flows to the near-wall region