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Research Paper

An investigation on thermo-hydraulic performance of a flat-plate channel with pyramidal protrusions

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HIGHLIGHTS

- Pyramidal protrusions are proposed for heat transfer enhancement applications.
- CFD is used to study the hydrothermal performance of the proposed surface pattern.
- The overall performance of a flat-plate channel is enhanced.
- The obtained results are investigated using entropy generation analysis.

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ABSTRACT

In this study, a flat-plate channel configured with pyramidal protrusions are numerically analysed for the first time. Simulations of laminar single-phase fluid flow and heat transfer characteristics are developed using a finite-volume approach under steady-state condition. Pure water is selected as the coolant and its thermo-physical properties are modelled using a set of temperature-dependent functions. Different configurations of the channel, including a plain channel and a channel with nature-inspired protruded surfaces, are studied here for Reynolds numbers ranging from 135 to 1430. The effects of the protrusion shape, size and arrangement on the hydrothermal performance of a flat-plate channel are studied in details. The temperature of the upper and lower surfaces of the channel is kept constant during the simulations. It is observed that utilizing these configurations can boost the heat transfer up to 277.9% and amplify the pressure loss up to 179.4% with a respect to the plain channel. It is found that the overall efficiency of the channels with pyramidal protrusions is improved by 12.0–169.4% compared to the plain channel for the conditions studied here. Furthermore, the thermodynamic performance of the channel is investigated in terms of entropy generation and it is found that equipping the channels with pyramidal protrusions leads to lower irreversibility in the system.

1. Introduction

Compact heat exchangers are very common in different engineering applications such as automotive and aerospace industries, heating and refrigerating, solar collectors, electronic devices, laser technology. In recent decades lots of efforts have been made to improve thermal performance of the compact heat exchangers accompanying a reduction in their size, weight and cost. The heat transfer can be boosted using active and/or passive techniques [1,2]. A variety of passive techniques such as flow additives, swirl flow devices, surface tension devices, rough surfaces, treated surfaces, pin fins, ribbed turbulators and surfaces with dimple and/or protrusions are used for enhancing heat transfer in different applications. The performance of these techniques for enhancing the heat transfer rates are compared to each other by Ligrani et al. [3].

Protruded surfaces are classified as one of the passive heat transfer enhancement methods and can significantly enhance the heat transfer by reducing the thermal resistance of the sublayer adjacent to the solid walls. This is done by generating secondary flows, disrupting the boundary layer growth, flow recirculation and shear-layer reattachment, promoting mixing and increasing the turbulence intensity [4]. In the other hand, using protruded surfaces in thermal systems causes a higher pressure drop due to the losses induced by secondary flow, increasing shear-stresses

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Nomenclature

a	base edge length of pyramids, m
AR	protrusion aspect ratio
c_p	specific heat capacity, J/kg K
D_h	hydraulic diameter, m
f	apparent friction factor
H	height, m
h	convection heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/mK
L	length, m
Nu	Nusselt number
p	pressure, Pa
Q	heat transfer rate, W
q	heat flux, W/m^2
Re	Reynolds number
$S_{G,tot}$	non-dimensional total entropy generation
T	temperature, K
U	fluid velocity, m/s
u, v, w	velocity vector components
V	total volume of the heated zone, m^3
W	width, m
x, y, z	cartezian coordinates
$\dot{m}$	mass flow rate, kg/m^3

Greek symbols

α	attack angle
η	efficiency
μ	dynamic viscosity, kg/m s
ρ	fluid density, kg/m^3

Subscripts

b	between pyramids
f	fluid
ht	heat transfer
i	inlet
m	mean
n	Pyramid's numbers
o	outlet
s	simple channel
w	water

and velocity gradients, and intensive interactions between vortices and the channel walls [5]. Hwang et al. [6] experimentally studied the heat transfer performance of different protrusion/dimple patterned surfaces within a rectangular channel. They reported that for a case with double-side patterned surfaces the overall heat transfer coefficient is much greater than that of a single-side patterned surface thanks to stronger mixing flow. Chen et al. [7] numerically investigated hydro-thermal characteristics of a turbulent channel flow with densely arranged protrusions on its walls. They observed that the higher the height of the protrusions the higher the heat transfer and friction factor. They found an extremum in performance factor curve with increasing the height of the protrusions.

One can find that most of the literature have focused on evaluating the impacts of the hemispherical protrusions on heat transfer characteristics of turbulent channel flows [8–10]; whereas the investigations on flow structure and heat transfer characteristics of protrusions with different shapes inside the channels, especially under laminar flow condition, are scarce. It is well known that the conventional hemispherical protrusions are no longer worthy for increasing demands of heat removal applications; therefore, the researchers are moving towards novel structures and combining different techniques to design more efficient systems in recent years [11–16]. The main objective of this paper is introducing a novel protruded surface to enhance the heat transfer performance of heat exchangers. In order to achieve this goal a novel surface pattern is designed which is inspired from the skin patterns of the desert plants and animals such as cactuses, alligators and thorny dragons. According to the best of the authors' knowledge, it is the first time that pyramidal protrusions are employed for heat transfer augmentation purposes. The effects of utilizing pyramidal protrusions on the laminar flow pattern and heat transfer performance are scrutinized in this paper. Different configurations of the flat-plate channel with pyramidal protrusions, including various alignments (inline and staggered), angle of attacks and sizes, are investigated. Furthermore, the thermodynamic performance of the channel is studied using entropy generation analysis.

2. Model descriptions

2.1. Geometric configurations and computational domain

In this paper, three-dimensional simulations are carried out on different configurations of a flat-plate channel with and without obstacles. Obstacles in the form of protrusions are mounted on both the top and bottom walls of the channel. The schematic diagram of the computational domain and relevant geometrical parameters are illustrated in Fig. 1. The height (H) of the channel is parametrized with the width of the channel (W) and is 3 W/4. The computational domain consists of three zones, namely, inlet zone, main zone and outlet zone. The inlet zone is considered at the entrance of the main zone to ensure the flow uniformity before the protrusions. Furthermore, the outlet zone is embedded after the main zone to ensure that there is no back flow at the outlet boundary. The length of the inlet zone (L_i) and the outlet zone (L_o) are selected to be half of the length of the main zone (L = 20 W) [17–19]. Nineteen equally spaced pyramidal protrusions (L_b = W) are located in the main zone with inline and staggered arrangements. It is worth mentioning that the minimum distance between the main zone entrance and the centroid of the pyramid's base at the first row equals the channel width (W). Protrusions in the form of a square-based right pyramids are defined by the base edge length (a) and apex height (H_v) with different aspect ratios (AR = a/H_v). The flow is described in a three-dimensional Cartesian coordinate system in which x is the span-wise direction, y is the normal direction and z is the stream-wise direction. It should be noted that the origin of the z axis is located at the entrance of the main zone.

2.2. Mathematical methods, governing equations and boundary conditions

Simulations are performed to scrutinize flow pattern and heat transfer characteristics inside a flat-plate channel with protruded surfaces. Pure water is chosen to be the coolant and its thermo-physical properties are modelled using a set of