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Laminar convective heat transfer of shear-thinning liquids in rectangular channels with longitudinal vortex generators

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HIGHLIGHTS

- Non-Newtonian fluid flow in a rectangular channel equipped with LVGs is studied.
- The heat transfer performance is enhanced compared with a plain channel.
- The overall performance is improved vis-à-vis water for CMC aqueous solutions.
- The shear-thinning behaviour and the VG positioning notably influence the overall performance.

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ABSTRACT

Heat and fluid flow in a rectangular channel heat sink equipped with longitudinal vortex generators have been numerically investigated in the range of Reynolds numbers between 25 and 200. Aqueous solutions of carboxymethyl cellulose (CMC) with different concentrations (200–2000 ppm), which are shear-thinning non-Newtonian liquids, have been utilised as working fluid. Three-dimensional simulations have been performed on a plain channel and a channel with five pairs of vortex generators. The channels have a hydraulic diameter of 8 mm and are heated by constant wall temperature. The vortex generators have been mounted at different angles of attack and locations inside the channel. The shear-thinning liquid flow in rectangular channels with longitudinal vortex generators are described and the mechanisms of heat transfer enhancement are discussed. The results demonstrate a heat transfer enhancement of 39–188% using CMC aqueous solutions in rectangular channels with LVGs with respect to a Newtonian liquid flow (*i.e.* water). Additionally, it is shown that equipping rectangular channels with LVGs results in an enhancement of 24–135% in heat transfer performance vis-à-vis plain channel. However, this heat transfer enhancement is associated with larger pressure losses. For the range of parameters studied in this paper, increasing the CMC concentration, the angle of attack of vortex generators and their lateral distances leads to an increase in heat transfer performance. Additionally, heat transfer performance of rectangular channels with longitudinal vortex generators enhances with increasing the Reynolds number in the laminar flow regime.

1. Introduction

Enhancing the thermal efficiency of heat exchangers is a challenging task to meet the heat removal capability needed for development of new devices with better performances. A number of designs and approaches have been proposed to passively enhance the heat transfer performance of cooling devices (Hong and Cheng, 2009; Sui et al., 2010; Bi et al., 2013; Chuan et al., 2015; Xie et al., 2015, 2016; Amani et al., 2017; Mahian et al., 2017; Yang et al., 2017). Equipping rectangular channels with vortex generators (VGs) has been demonstrated to be a promising method to passively augment the heat transfer performance (Fiebig et al., 1991; Fiebig, 1998; Ferrouillat et al., 2006; Wu and Tao, 2012; Ebrahimi et al., 2015). Vortex generators with various shapes such as wing (Gentry and Jacobi, 1997), winglet (Ebrahimi and Kheradmand, 2012), rib (Ahmed, 2016; Chai et al., 2016), pin fin (Peles et al., 2005) and surface protrusions (Lan et al., 2011; Ebrahimi and Naranjani, 2016; Marschewski et al., 2016; Passos et al., 2016) have been utilised for heat transfer enhancement applications. The pressure difference between two sides of VGs leads to flow separation from the side edges, which generates longitudinal, transverse and

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Nomenclature

A_h	the surface area of heated walls, m^2
c_p	specific heat capacity, $J\,kg^{-1}\,K^{-1}$
D_h	hydraulic diameter, m
f	fanning friction factor, –
h	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
k	thermal conductivity, $J\,m^{-1}\,K^{-1}$
K	consistency index, $kg\,m^{-1}\,s^{2-n}$
n	power-law index, –
Nu	Nusselt number, –
p	static pressure, Pa
P_{pump}	pumping power, W
Q	volumetric flow rate, $m^3\,s^{-1}$
Re	Reynolds number, –
T	temperature, K
u, v, w	velocity vector components
x, y, z	Cartesian coordinates
α	angle of attack, °
η	overall performance, –
μ	dynamic viscosity, Pa s
ρ	density, $kg\,m^{-3}$
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
$\dot{\gamma}$	strain rate, s^{-1}

Acronyms

CMC	carboxymethyl cellulose
VG	vortex generator
LVG	longitudinal vortex generator

Subscripts

in	inlet
out	outlet
wall	wall
m	mean
s	plain channel

horseshoe vortices (Ahmed et al., 2012). Formation of vortices intensifies fluid mixing and disrupts thermal boundary layer growth, which enhances the heat transfer performance (Fiebig, 1998; Jacobi and Shah, 1995; Biswas et al., 1996). Enhancing the heat removal capability of thermal systems is critical for developing new high-performance devices.

Apart from surface modifications, employing efficient coolants are expected to be a reasonable approach to enhance heat transfer performance of thermal systems. Liquid coolants are preferred over gaseous coolants for heat transfer enhancement applications because of their higher heat transfer coefficients (Bergman and Incropera, 2011; Bejan, 2013). Non-Newtonian fluids are of high interest in practical applications since they can be made relatively easily compared with nanofluids (Li et al., 2017). It has been demonstrated that employing shear-thinning non-Newtonian fluids in thermal systems as working fluids can enhance the heat transfer performance of the system (Kurnia et al., 2014; Esmaeilnejad et al., 2014; Li et al., 2016a, 2016b; Poh et al., 2004). Aqueous solutions of carboxymethyl cellulose (CMC) are shear-thinning non-Newtonian liquids (also known as pseudoplastic liquids) that have been used for heat removal applications. Applications of non-Newtonian liquid coolants are usually bounded to the laminar flow regime because of low fluid velocity and high viscosity of the fluid (Li et al., 2016a; Martínez et al., 2014).

Velocity gradients and therefore shear stresses are larger in channels with LVGs in comparison with plain channels (Ebrahimi et al., 2015, 2016). It is known that shear-thinning behaviour influences the structure of vortices generated by VGs (Li et al., 2016b, 2017; Yang et al., 2016). Therefore, the shear-thinning behaviour can result in a change in heat transfer performance of a heat exchanger (Ebrahimi and Kheradmand, 2012; Biswas et al., 1996). According to the best of the author's knowledge and to the reviewed literature, the influence of the non-Newtonian fluid flow behaviour on the thermo-hydraulic performance of rectangular channels equipped with LVGs is not addressed yet. More studies are essential to attain an insight into the effects of non-Newtonian fluid flow behaviour in channels equipped with LVGs and consequently on the heat transfer performance of channels. The primary aim of this study is to understand the influence of shear-thinning behaviour on fluid flow structure and heat transfer characteristics in rectangular channels equipped with LVGs. In the present study, three-dimensional numerical simulations have been performed to explore the shear-thinning power-law fluid flow structure and heat transfer in a rectangular channel with LVGs. To highlight the effect of shear-thinning behaviour on the heat transfer performance of a rectangular channel equipped with LVGs, CMC aqueous solutions with different CMC concentrations are scrutinised. Additionally, the influence of the shear rate on fluid flow structure and heat transfer performance is investigated by changing the angle of attack and the lateral distance of the LVGs. The non-Newtonian fluid flow structure and heat transfer characteristics are compared with a Newtonian fluid (*i.e.* water). The thermo-hydraulic performances of the channels with LVGs are also compared with a plain channel. The results presented in this paper may introduce new perspectives towards novel approaches to heat transfer enhancement in heat exchangers.

2. Model description

2.1. Computational domain

A rectangular channel with five pairs of LVGs was considered in the present study. A schematic diagram of the channel is shown in Fig. 1. Six different configurations with VGs mounted at different angles of attack (*i.e.* $\alpha = 30°$, 45° and 60°) and lateral distances (*i.e.* $d_t = 5$, 2.5 and 1.25 mm) were designed. The thickness of the VGs was idealised and supposed to be zero (Hiravennavar et al., 2007). The geometrical parameters for different configurations are reported in Table 1. The heat and fluid flow were described in a three-dimensional Cartesian coordinate system, in which the mainstream was in the *z*-axis direction. The computational domain consisted of the inlet, main, and outlet zones. The inlet zone with adiabatic walls and the length of L_{in} was defined to ensure the flow uniformity at the main zone entrance. The main zone encompasses five pairs of LVGs that were equally spaced in the mainstream direction. The solid walls were kept at constant temperature of 320 K in the main zone. The main zone was extended by adiabatic walls with the length of L_{out} (*i.e.* outlet zone) to avoid any flow reversal at the outlet boundary.

2.2. Physical model

To highlight the differences between non-Newtonian and Newtonian coolants, aqueous solutions of carboxymethyl cellulose