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# Thermo-hydraulic transport characteristics of non-Newtonian fluid flows through corrugated channels

Shubham[a], Anubrata Saikia[a], Amaresh Dalal[a], Sukumar Pati[b,*]

[a] Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India
[b] Department of Mechanical Engineering, National Institute of Technology Silchar, Silchar 788010, India

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ABSTRACT

The present study investigates numerically the thermo-hydraulic transport characteristics of non-Newtonian fluids in corrugated channels. The power-law model is used to describe the constitutive behavior of the non-Newtonian fluid. The results indicate that the enhancement in heat transfer for corrugated channels over equivalent straight channel is not significant for smaller amplitude of the wall waviness of the channel, while there is a significant enhancement for the higher amplitude. The rate of enhancement with respect to equivalent straight channel decreases with increase in power law index and the decrement is more prominent for shear thinning fluids and for higher values of Reynolds number. Furthermore, an estimation of pressure drop for flow through the corrugated and equivalent straight channels has been made to compare the values against the enhancement in heat transfer rate. It reveals that the ratio of pressure drop ($\Delta p/\Delta p_{straight}$) is more as compared to the enhancement in heat transfer ($\overline{Nu}/\overline{Nu}_{straight}$) for all the parameters considered in the present work. It further reveals that the use of shear thinning fluids is more suitable for the purpose of maximum heat transfer augmentation with minimum pressure drop. The results obtained from our studies may have significant consequences on the selection of wavy channel geometry configuration for compact heat exchanger handling non-Newtonian fluids towards a cost effective process of heat transfer.

## 1. Introduction

In the recent years, due to increase in heating load, there is a faster growing demand for compact thermal systems and devices capable of transferring heat in an efficient and cost effective manner by various industries such as chemical, aerospace, process, cryogenics, food and beverages, to name a few. Although, two methods, namely passive and active are used in this regard, the former methods are preferred over later ones [1,2]. The use of special surface geometry, such as corrugated wall channel is one such passive method commonly employed in compact thermal systems because of their enhanced heat transfer characteristics and higher compactness. Appreciating the relevance of corrugated channels in thermal systems, the study of thermo-fluidic transport characteristics through corrugated channels has been a hot topic of research in the past few decades.

A host of articles [3–25] pertaining to numerical and experimental investigations on fluid flow and heat transfer characteristics for flow through corrugated channels is available in the literature. Wang and Vanka [3] numerically investigated the heat transfer characteristics for flow through a periodic array of wavy passages and found that the flow is steady upto Reynolds number of 180 and thereafter flow becomes oscillatory. Rush et al. [4] experimentally studied the fluid flow and heat transfer characteristics in a sinusoidal wavy passage for different wave length, wall amplitude and phase angle between wall using visualization method. They observed that at low Reynolds number, fluid mixing occurs towards the end of the channel whereas at high Reynolds number instability in flow has started from the entrance, which in turn enhances the heat transfer. Wang and Chen [5] numerically investigated the effects of wavy geometry, Reynolds number and Prandtl number on the rate of heat transfer for flow through a sinusoidal curved converging-diverging channel using simple coordinate transformation method. They found that there is an increase in both Nusselt number and skin-friction coefficient with the increase in Reynolds number and amplitude-wavelength. Metwally and Mangik [6] numerically studied laminar forced convection in a sinusoidal corrugated-plate channel maintained at uniform wall temperature for a wide range of channel corrugation aspect ratio and for three different Prandtl numbers (Pr = 5, 35, 150). They observed that there is a strong influence of both the Reynolds number and corrugation aspect ratio on heat transfer enhancement. They also reported that the optimum corrugation aspect

* Corresponding author.
*E-mail addresses:* amaresh@iitg.ernet.in (A. Dalal), sukumarpati@gmail.com, sukumar@mech.nits.ac.in (S. Pati).

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**Nomenclature**

| | |
|---|---|
| $A$ | amplitude of the wavy wall, m |
| $A_w$ | dimensionless amplitude of the wavy wall ($=A/L$) |
| $c_p$ | specific heat of the fluid, $\text{Jkg}^{-1}\text{K}^{-1}$ |
| $I$ | second invariant of rate of strain tensor |
| $k$ | Thermal conductivity, $\text{Wm}^{-1}\text{K}^{-1}$ |
| $L$ | Half separation distance between wavy walls, m |
| $m$ | Flow consistency index |
| $n$ | Power law index |
| $Nu$ | Local Nusselt number |
| $\overline{Nu}$ | Average Nusselt number |
| $p$ | Pressure, $\text{Nm}^{-2}$ |
| Pr | Prandtl number |
| Re | Reynolds number |
| $S$ | Profile of the wavy wall |
| $T$ | Temperature, K |
| $\mathbf{u}$ | Velocity vector |
| $u$, $v$ | $x$ and $y$ velocity components, respectively, $\text{ms}^{-1}$ |
| $x$, $y$ | axial and transverse coordinates, respectively, m |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density of fluid, $\text{kgm}^{-3}$ |
| $\lambda$ | wavelength of the sinusoidal wall |
| $\boldsymbol{\varepsilon}$ | strain rate tensor |
| $\mu_e$ | apparent viscosity |
| $\dot{\boldsymbol{\gamma}}$ | Shear rate |
| $\xi$ | performance factor, defined in Eq. (15) |

*Subscripts*

| | |
|---|---|
| avg | average |
| b | bottom |
| e | ending point of wavy part |
| in | inlet |
| s | Starting point of wavy part |
| t | top |
| w | wall |

ratio for maximum augmentation of heat transfer lies in between 0.3 and 0.6. Chen et al. [7] numerically studied fluid flow and heat transfer characteristics for a two dimensional, steady, developing flow through a periodic wavy passage and compared the results with the case of flow through a corresponding parallel plate channel. They found that at low Reynolds number, there is no significant enhancement in heat transfer in wavy channel compared to straight channel, however significant enhancement in heat transfer takes place compared to straight channel at higher Reynolds number. Islamoglu and his group [8–12] investigated both experimentally and numerically the effects of channel configuration and channel type on the heat transfer characteristics and pressure drop for flow of air through corrugated channel for moderately larger values of Reynolds number. They pointed out that the performance of the channel with rounded wavy peak is greater than the channel with sharp wavy peak [12]. Naphon and his colleague [13–16] numerically analyzed the heat transfer and flow distributions in the channel with various geometrical configuration wavy plates under constant heat flux both in laminar and turbulent regime. Pati et al. [17] recently reported a comparison of thermo-hydraulic performance between raccoon and serpentine channel for different values of amplitude and wavelength of the wall waviness. Ferley and Ormiston [18] numerically examined the fluid flow and heat transfer characteristics for steady, two-dimensional, laminar flow through corrugated plate channels with three wall corrugations, namely, sinusoidal-wavy-shaped (SWS), rounded-ellipse-shaped (RES), and rounded-vee-shaped (RVS) and found that the SWS corrugation has, in general, the lowest friction factor and highest average Nusselt number over the ranges of the geometric parameters considered. However, they reported that at an inlet Reynolds number of 300, the RES corrugation has the highest heat transfer per unit pumping power. Song et al. [19], in a recent work, described the conceptual design of a new generation of wavy channel used in a wavy-fin heat exchanger using the principle of constructal theory. They carried out numerical optimization to determine the optimal geometrical parameters of the wavy channel. Liu and Niu [20] numerically investigated the effect of apex angle and aspect ratio on heat transfer, pressure drop and thermo-hydraulic performance of a periodic cross-corrugated channel for the Re range of 200–3000. Chiam et al. [21] investigated both numerically and experimentally the fluid flow and heat transfer characteristics in wavy micro-channels with alternating secondary branches and found that the addition of secondary branches enhances the heat transfer performance. Mills et al. [22] numerically investigated the effects of wall amplitude, period length, driving pressure, and flow regime on the heat transfer characteristics for flow through wavy channels. Singh et al. [23] carried out experiments on cross-corrugated plate heat exchangers to investigate the heat transfer characteristics and pressure drop with different channel inclination angles. Khoshvaght-Aliabadi et al. [24] experimentally analyzed the cooling performance of the sinusoidal–wavy minichannel heat sink having square cross section and correlations for Nusselt number and friction factor are developed as function of Reynolds number, Prandtl number, and geometrical parameters. Ramgadia and Saha [25] numerical investigated fully developed fluid flow and heat transfer characteristics through a horizontal wavy surface for Reynolds number in the range 25–1000. Vasudevaiah and Balamurugan [26] theoretically analyzed the heat transfer characteristics for rarefied gas flows in a corrugated microchannel.

It is important to mention here that several studies have been done by researchers to analyse the stability of flow on different surfaces or channels [27,28]. To explore the physics of stability analysis, a notable work has been done by Floryan [29] in which a linear stability analysis has been carried out in a diverging-converging channel. In this analysis, it is found that in the streamline vortices, the flow in diverging-converging channel may become unstable due to disturbances. In another study, Floryan [30] considered the flow inside two-dimensional channel having distributed surface roughness to analyse the linear stability. It is shown that the structure of the disturbance field is related to the structure of the roughness if the ratio of the respective wave numbers is rational. It is observed that the presence of roughness destabilizes the disturbance in the form of travelling waves. Cabal et al. [31] executed the linear stability analysis of flow in a channel bounded by wavy walls. It is found that an instability increases due to wall waviness which manifests itself through generation of streamwise vortices. In line of this, a temporal linear stability of a pressure-driven flow in a diverging–converging channel with respect to the traveling wave disturbances was analysed by Floryan and Floryan [32]. Gepner and Floryan [33], in a recent work, investigated the dynamics of flows in converging–diverging channels with an objective to identify geometries which result in increased mixing. Firstly, they considered a two-dimensional model and reported that by increasing the corrugation wavelength, there is an appearance of an unsteady separation. In the second part, they considered three-dimensional dynamics and identified the conditions when such dynamics precedes the two-dimensional dynamics. In their work, they showed that the dominant factor for flow dynamics is the centrifugal instability over a large range of geometric parameters, resulting in the formation of streamwise vortices. Furthermore, they demonstrated that the onset of the vortices may lead to