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Research Paper

Nanofluid flow and heat transfer in a microchannel with longitudinal vortex generators: Two-phase numerical simulation

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HIGHLIGHTS

- Two-phase model for the simulation of nanofluid flow in microchannels with LVG is utilized.
- Local heat transfer coefficient along microchannel with LVG is presented.
- Adding LVG to microchannel with nanofluid flow boosts heat transfer.
- Efficiency of using nanoparticle and/or LVG in microchannel is discussed.

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ABSTRACT

Here we report a comprehensive numerical procedure based on the two-phase approach to simulate a rectangular microchannel consisting of six longitudinal vortex generators (LVGs). Nanofluids are used to remove heat generated within the microchannel. The simulations performed in this paper are based on the newest version of the two-phase Eulerian–Eulerian approach. The TiO_2-based nanofluids with different base-fluids of water, ethylene glycol and water mixture (EG:W (60:40 by mass)) and transformer oil are considered for simulations. The nanoparticles are 21, 40 and 60 nanometers in diameter with the volume concentrations of 1.0, 1.6 and 2.3%. We found that nanofluids together with LVGs can remarkably enhance the heat exchange rates inside the microchannel. The heat transfer coefficient was shown to improve under increasing nanoparticle (TiO_2) concentrations and Reynolds number, whereas the opposite trends were observed for friction factor. Results of this study indicate that using the mixture of EG:W (60:40 ethylene glycol and water) instead of pure water as a base-fluid leads to the increase of heat transfer in the microchannel. Finally, the maximum normalized efficiency of the LVG-enhanced microchannel, compared to the plain channel, is around 14%. Furthermore, using nanofluid can improve the normalized efficiency by 27%.

1. Introduction

Heat exchangers are prominent components of many industrial applications responsible for the transfer of heat between fluids. Their applications could include air conditioning systems, cooling of gas turbines, and electrical circuits in electronic chipsets. Among numerous types of heat exchangers, microchannel heat exchangers have received great attention in recent years as noted in several review papers [1–8]. In terms of definition of the microchannels, Kandlikar and Grande [9] and Mehendale et al. [10] proposed classifications for small channels; however, the former is more common in the literature [11]. Kandlikar and Grande [9] suggested that a channel with hydraulic diameter between 10 μm and 200 μm could be considered as microchannel. Many researchers have conducted experimental, theoretical, and computational investigations with the focus of developing microchannel heat exchangers that are much more efficient with regard to their heat transfer gains and pressure drop losses. Tuckerman and Pease [12] were pioneers in the concept of microchannel heat sink forced convection. They pinpointed the benefits associated with the exploitation of microchannel heat sinks in cooling of the electrical components.

Several studies are concerned with the geometrical characteristics of microchannel heat exchangers and their effects on thermal performance [13–16]. Xu et al. [17] investigated the performance of three various microchannel heat exchangers under both wet and frosting conditions. Their results illustrated that using sample microchannel with wavy fins, in comparison to the sample with a louver fin, enhances the heat transfer rate by 25.8% under wet condition, whereas its pressure drop decreases by 35%. In another work, Glazar et al. [18] studied heat transfer and fluid flow in compact

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heat exchangers. They concluded that heat transfer capabilities are diminished with the rise in the inlet fluid temperature. Furthermore, they found that, among the various types of microchannel they studied, diamond and hexagonal microchannels lead to the highest heat transfer rates, whereas using rectangular microchannels generates the lowest pressure drop. Arie et al. [19] carried out a computational optimization analysis on a full-scale manifold-microchannel heat exchanger. They showed that manifold microchannel provides superior performance in terms of friction factor and Nusselt number.

An innovative method to enhance the efficiency of microchannel heat exchangers is the application of vortex generators inside such heat exchangers. This topic has been the focus of some studies [20–22]. In a more recent study, Ebrahimi et al. [23] performed a numerical simulation on the liquid flow and heat transfer in a rectangular microchannel with longitudinal vortex generators (LVGs). The study was done with the single-phase fluid; nevertheless, they found that adding LVGs in a microchannel can remarkably improve its thermal performance and overall efficiency.

Improving thermal characteristics of the heat transfer fluid is another factor that can significantly improve the performance of heat exchangers. One of the innovative methods to address this challenge is to introduce nanofluids as the heat transfer medium [24–32]. The combination of microchannel with nanofluid could result in a much more efficient heat exchanger. Mohammed et al. [33] numerically modeled a rectangular microchannel heat exchanger when several different nanofluids namely Ag/water, CuO/water, Al_2O_3/water, SiO_2/water, and TiO_2/water were applied. Yue et al. [34] simulated a manifold microchannel heat sink employing nanofluids as heat transfer medium. Their results showed that increasing the volume concentration of nanofluids leads to an increase in Nusselt number and pumping power while entropy generation plummets. Adham et al. [7] reviewed different aspects of microchannel heat sinks such as shapes, materials and heat transfer fluids. They indicated that many studies must be undertaken to clarify which nanofluids and microchannel shapes must be considered for microchannel heat sink.

Among various nanoparticles, titanium oxide (TiO_2), despite its commercial availability and excellent physical and chemical stability, has received fewer attention especially when it comes to microchannel heat exchangers [35]. Hedayati and Domairry [36] studied the effects of nanoparticle migration and asymmetric heating on mixed convection of TiO_2/water nanofluid inside a vertical microchannel. Ijam and Saidur [37] compared the performance of TiO_2/water and SiC/water nanofluids in cooling of the electronic devices using minichannel heat sink. They reported that TiO_2/water nanofluid produces slightly higher heat transfer rates in the investigated setting.

Water-based nanofluids have been on the spotlight of numerous studies [8,38–40]. While this kind of base-fluid is most convenient to be used for preparation of nanofluids, the effects of other practical and common base-fluids such as ethylene glycol and transformer oil on the microchannel heat transfer are worth studying. Among more recent research, Zhu et al. [41] studied the laminar flow and heat transfer of Al_2O_3/ethylene glycol/water nanofluids in a wavy finned heat sink. Sivakumar et al. [42] experimentally investigated thermal conductivity of CuO and ethylene glycol nanofluid in serpentine shaped microchannel. Studies on the transformer oil-based nanofluids are limited especially regarding their heat transfer capabilities. Most of the available studies on this kind of base-fluid is addressed at their magnetic and electrical characteristics [43–48]. Singh and Kundan [49] conducted an experimental study on thermal conductivity and viscosity of Al_2O_3/transformer oil nanofluid. Ebrahimnia-Bajestan et al. [50] compared the flow and heat transfer of CNT/transformer oil nanofluid in the straight and curved pipes.

As for the numerical modeling, two general approaches are used to simulate the flow and heat transfer of nanofluids. The two-phase approach, as opposed to the single-phase model, solves the governing equations for each phase separately, and the interactions between phases are the basis of the modeling. Hanafizadeh et al. [51] conducted a comprehensive numerical analysis using both single and two-phase models. They concluded that the two-phase model provides more accurate results especially in the fully developed region. In another recent study comparable to that of microchannels, Xu et al. numerically investigated the heat transfer characteristics of nanofluid through metal foams [52]. Owing to their small fluid flow region in both porous media and microchannels, the result of this research can be used for better understanding of the numerical simulation of nanofluids in such mediums. Yari Ghale et al. [53] compared single and two-phase mixture models in a straight microchannel. They observed that the two-phase mixture approach is more precise compared to the single-phase model. Recently, Ebrahimnia-Bajestan et al. [54] modified the common Eulerian–Eulerian two-phase model. Their model is more accurate than the single-phase and the commonly used mixture and Eulerian–Eulerian two-phase models.

In this study, a longitudinal rectangular microchannel with vortex generator (LRMVG) employing TiO_2-based nanofluids as its coolant fluid has been simulated using ANSYS software to find the optimum operating circumstances. According to the literature survey and the best of the authors' knowledge, no similar studies have so far been executed on a longitudinal rectangular microchannel with vortex generator (LRMVG). Results are posed for several consequential parameters, namely TiO_2 nanoparticle diameter, volume concentration and Reynolds number. The effects of water, ethylene glycol and water mixture (60:40 (by mass)) and transformer oil base-fluids are also investigated. Unlike many other research papers that simplify the problem by using the single-phase model, in this investigation, efforts are made to model the discussed problem with the newest formulation of the realistic two-phase approach available in the literature [54].

2. Problem description

The presented problem is a longitudinal rectangular microchannel with vortex generators (LRMVG). To investigate the effects of using nanofluid on conjugated heat transfer and fluid flow behavior within the microchannel, two-phase three-dimensional simulations are carried out in contradistinction to simplify the model to a single-phase two-dimensional (2D) problem. Cartesian coordinate system is used to describe the fluid flow while z axis stands for stream-wise direction. The schematic diagram of the discussed problem is depicted in Fig. 1, while the details of geometrical parameters used to describe the physical model is presented in Table 1. The computational domain comprises three different zones as below:

1. The inlet block representing the flow developing zone that is assumed to have length of L_{in} and adiabatic.
2. The outlet block that provides to eradicate the effects of any possible back flow that could influence the final computational results.
3. In the heated region of the microchannel, six equally spaced pairs of LVGs are located with the dimensions listed in Table 1.

To reduce the computational costs and due to the symmetric arrangement of the microchannel and LVGs, only the hatched region in Fig. 1(a) is deemed for numerical analysis.

Characteristic dimensions of the microchannel and LVGs situated within the microchannel is presented in Table 1.