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Backward-facing step heat transfer of the turbulent regime for functionalized graphene nanoplatelets based water–ethylene glycol nanofluids

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ABSTRACT

Herein, an experimental study on thermo-physical properties of ethylene glycol-functionalized graphene nanoplatelets/water–ethylene glycol nanofluids (EGGNP-WEG) and a numerical study on the convective heat transfer over a backward-facing step are performed. Accordingly, EGGNP was first synthesized covalently to achieve a stable colloidal solution in water–ethylene glycol mixture. Some characterizations were applied to analyze the surface functionality and morphology of EGGNP-flakes. To study the convective heat transfer coefficient in turbulent regime, a numerical study is performed at different weight fractions of EGGNP.

According to the results, a higher weight concentration of EGGNP in basefluid indicates a greater extent of convective heat transfer coefficient and thermal conductivity, implying higher heat transfer rate over a backward-facing step.

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1. Introduction

The thermo-physical phenomena of separation and reattachment e.g. backward-facing step, involving heat transfer, are frequently encountered in many engineering problems like electrical rotating machines. Thus, investigation of the convection heat transfer over a backward facing step is one of the interest topics in many research studies. Heat transfer applications of backward facing step appear in different industrial equipment such as combustors, aircraft, gas turbine engines, and buildings. It is obvious that the separation and reattachment of the flow can change the flow structure and has a direct influence on the heat transfer mechanism as well as thermal performance of equipment [1]. Thus, numerous studies have been investigated to determine the real mechanism of flow separation and reattachment, the best geometry for heat transfer applications, and best type of working fluids in the past decades [2,3]. Although, the flow over a backward-facing step with heat transfer was investigated by some scientists [4,5], a majority of studies considered the isothermal flow, commonly in two dimensional geometry.

A study on the two non-Newtonian liquids was performed in a sudden expansion in the presence of viscoelastic polyacrylamide (PAA) solutions and a purely viscous shear-thinning liquid [6]. According to their results, the reattachment length of non-Newtonian fluid was shorter than that of Newtonian counterparts and surely water. Abu-Nada [7] performed a numerical study on the entropy over a backward facing step for different expansion ratios. Different expansion ratios of 1/4, 1/3, 1/2, 2/3, and 3/4 were selected and the results presented an increase in the Reynolds number with the value of total entropy generation number, which was for the high range of Reynolds number. A numerical study on the laminar regime in a rectangular duct including backward-facing step was performed by Nie and Armaly [8]. They suggested the appearance of the maximum reattachment length at the sidewall. Also, they concluded that as the step height enhances, the amount of Nusselt number increases. Biswas et al. [9] investigated the laminar fluid flow behavior over a three dimensional backward-facing step with various expansion ratios. They concluded that the formation of wall jets at the side wall within the separating shear layer, formed by the spanwise of the velocity moves towards the symmetry channel plane. An experimental study have been done by Armaly et al. [10] for measuring the velocity over a backward-facing step by using two-component laser Doppler velocimeter in laminar regime. In another similar study, Hsieh et al. [11] studied the flow over a backward-facing

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step by the Direct Simulation Monte Carlo method (DSMC). According to their results, the side walls can significantly affect the flow structure and thermal characteristics in the 3-D structure. Bao and Lin [12] also utilized the DSMC approach for investigation of the thermal performance over the microscale backward-facing step in the transition regime. They reported that the streamwise velocity is positive at the Knudsen number of 0.136, indicating the lack of the reversed flow after the step. Also, they concluded that there is a non-linear connection between the mass flow rate and pressure drop ratio in traditional flow.

As mentioned above, a majority of studies focused on having novelty in changing design such as expansion ratio, in particular in the laminar regime, and neglected thermo-physical properties of working fluid. Thus, as another novelty for improving heat transfer rate over a backward-facing step is the utilization of nanofluids. A combination of nanofluids with thermal conductivity and backward-facing step can result in an effective approach for enhancing the heat transfer rate. In addition, previous studies [13–16] showed that nanofluids made of the mixture of basefluids and nanoparticles with good thermal conductivity could enhance the thermal performance of the different heat transfer equipment. The main reason for increasing the thermal conductivity of basefluid loaded with nanostructures is attributed to the Brownian motion of the nanostructures suspended in the working fluid [17–23]. Also, the formation of surface nanolayers can be another reason for enhancing the thermal conductivity [17]. The first study on the heat transfer rate of nanofluid in a backward-facing step was performed by Abu-Nada [1]. To reach the purpose, five nanofluids of CuO-, Al_2O_3-, Ag-, Cu- and TiO_2-based water nanofluids were synthesized and convective heat transfer coefficient was investigated. He concluded that there is a direct connection between the Nusselt number and the volume fraction of nanoparticles in basefluids. As an important result, they demonstrated that Nusselt number is significantly dependent of the thermo-physical properties of the nanoparticles inside the recirculation zone. Mohammed et al. [24,25] investigated the influence of different nanofluids (8 nanofluids) on the mixed convective heat transfer over the vertical and horizontal backward-facing step. Their results showed that the nanofluids with secondary recirculation regions have lower Nusselt number and the diamond-based water nanofluid illustrated the maximum Nusselt number in the presence of primary recirculation region. Al-Aswadi et al. [26] showed that nanofluids with low dense nanoparticles demonstrate higher velocity than those with high dense nanoparticles. Kherbeet et al. [27] investigated the heat transfer behaviors of four types of nanofluids (Al_2O_3-, CuO-, SiO_2- and ZnO-based water nanofluid) in the laminar regime over a microscale backward-facing step. The results showed the lack of recirculation region behind the step for all prepared samples at different concentrations. In addition, the results suggested that SiO_2-based water nanofluid has the highest Nusselt number as compared with other nanofluids. In addition, the results showed that the amount of Nusselt number enhances with the increment of the volume fraction of the nanoparticles in the base fluid. Kherbeet et al. [28] performed a numerical study on the laminar mixed convection flow of nanofluids over a horizontal microscale forward-facing step (MFFS) using a finite volume method. Different nanofluids including SiO_2-, Al_2O_3-, CuO-, and ZnO-based ethylene glycol nanofluids at various volume fractions investigated in terms of heat transfer parameters and the results demonstrated that the SiO_2-based ethylene glycol nanofluid had the maximum Nusselt number. They also reported that the Nusselt number increases with decreasing nanoparticle density and diameter as well as increasing volume fraction of nanoparticles.

It is obvious from the above literature review that the terms of thermal conductivity of nanoparticles was neglected. In addition, most of the previous studies on the backward-facing step involved metal- or metal oxide-based water or ethylene glycol as the basefluid and there is no study concentrated on nanofluids including carbon nanostructures. It is known that the thermal conductivity of most carbon particles such as carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) are much higher than that of metal or metal oxide nanoparticles. This implies that the carbon-base nanoparticle have higher potential for enhancing the thermal conductivity of base fluids [29]. Despite some promising thermal properties of graphene nanopleteles in the field of nanofluids, the strong van der Waals interactions have limited their thermal applications. Non-covalent and covalent functionalizations are the effective approaches to improve the dispersibility of GNPs. Also, there is not any study in water–ethylene glycol media over backward-facing step.

Herein, three phases of study have been performed to investigate the heat transfer behavior of EG-treated GNP based water–EG coolants over a backward facing step. First, a promising and potentially industrially scalable functionalization approach is employed to prepare ethylene glycol-functionalized graphene nanoplatelets (EGGNP) and EGGNP based water–EG coolant (EGGNP-WEG). First phase followed by analyzing EG-treated GNP samples in terms of functionality and morphology. Second phase of study comprises of the experimental-evaluation of the thermo-physical, rheological and colloidal properties of EGGNP-WEG. As the three phase of study, a numerical analysis on the heat transfer over a backward-facing step is performed in the presence of EGGNP-WEG at different weight concentrations. The main objective was to investigate the heat transfer enhancement and pressure drop in the presence of EGGNP in basefluid. The latter is obtained by the calculation of the performance index.

2. Material and methods

2.1. Preparation of EGGNP-WEG coolants

To prepare EGGNP-WEG, anhydrous Aluminum Chloride ($AlCl_3$) with purity of 99.999% was prepared from Sigma–Aldrich. All of the other chemicals were also bought from Sigma–Aldrich in analytical grade. Pristine Graphene Nanoplatelets (GNPs) with purity > 90 wt%, and Number of layer < 30 were purchased from Nanostructured & Amorphous Materials, Inc.

The pristine GNP (0.5 g) and $AlCl_3$ (9.27 g) were typically placed in a planetary ball-mill container and agitated with speed of 500 rpm for 1 h. The obtained mixture was poured into a vessel filled with 80 ml of anhydrous EG and then sonicated for 15 min with a probe-sonicator to reach a homogeneous back suspension. The concentrated hydrochloric acid (1 ml) was poured into the vessel over sonication time. After sonication, the suspension was transferred into a microwave (Milestone MicroSYNTH programmable microwave system) and heated for 15 min at 150 °C. The resultant mixture was filtered with a PTFE membrane and subsequently washed with abundant DI water to remove any unreacted materials. Filtration cake was then dried for 48 h at 50 °C and labeled as EGGNP. While the pristine GNP is not soluble in most organic solvents, the EGGNP was significantly soluble in both water and EG. The easily-miscible EG functionalities can explain a significant increase in dispersibility of the functionalized GNP with EG in both media of water and EG.

To synthesize EGGNP-WEG coolants at different weight concentrations, the known amount of EGGNP was poured into a vessel filled with a mixture of water and EG with a volumetric ratio of 40:60 and sonicated with a probe-sonicator for 10 min.

2.2. Experimental equipment

The prepared EGGNP was analyzed in terms of structure, morphology and thermo-physical properties. Fourier transform

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