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Experimental characterization of laminar forced convection of hBN-water nanofluid in circular pipe

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ABSTRACT

Recently developed hexagonal boron nitride (hBN) containing nanofluids are relatively new class of materials, and increase in their thermal conductivity with respect to base fluid is relatively higher than that of viscosity. This study focuses on convective heat transfer characteristics of hBN-water nanofluids, and thermally developing laminar forced convection of hBN nanofluids in a horizontal copper pipe, subjected to constant heat flux boundary condition, is investigated experimentally. hBN-water nanofluids, with a particle volume concentration range of 0.1–1% are considered for a Reynolds numbers' range of 800–1700. Measured thermophysical properties of hBN-water based nanofluids are used in predicting the heat transfer behavior based on measurements. It is observed that the enhancement in the convective heat transfer coefficient of hBN-water nanofluids is proportional to the observed thermal conductivity enhancement. Therefore, there is no abnormal enhancement in the measured Nusselt number, and measured values are in good agreement with predictions by standard laminar thermally developing flow correlations.

1. Introduction

During the progress of applications of thermal sciences, many efforts and improvements have been devoted to heat transfer area not only for designing high efficiency systems, but also for sustaining safe operation of devices and systems. One way of enhancing heat transfer is to design and develop advanced materials that exhibit improved heat transfer behavior. Developing advanced heat transfer fluids have been a research interest for decades and employing solid additives to conventional heat transfer fluids such as water, mineral oil, ethylene glycol, is often considered to improve the base fluid properties. While initial studies considered heat transfer fluids with millimeter or micrometer sized particles [1,2], these suspensions have significant problems. The micro or millimeter sized particulate suspensions exhibit very poor stability leading to rapid sedimentation of particles, and their use may arise problems related to poor thermal performance, significant increase in pressure drop due to clogging, agile wearing of materials due to abrasion [3].

In recent years, colloidal suspensions of nanometer sized particles, that are also known as nanofluids, are introduced by Choi [4] and they have attracted great interest of scientists and engineers. Nanofluids are considered as the next generation heat transfer fluids by many as the observed increase in their thermophysical properties exceed that of predicted by effective medium theories [5,6]. Colloidal suspensions of nanoparticles are believed to have superior characteristics compared to micro or millimeter sized suspensions due to their greater thermophysical properties, including minimizing the pumping penalty, better long term stability and shelf life [6,7]. Predominant method of producing nanofluids is the two-step method, in which the dry nanoparticles are introduced into base fluids with additional sedimentation and agglomeration preventing treatments such as ultrasonic mixing, pH adjustment and surfactant usage [8,9].

Over the last two decades, the thermal conductivity and viscosity change of nanofluids have been investigated by many studies of various research groups [3,6]. While some studies reported anomalous increase in thermal conductivity beyond the predictions of effective medium theories, such as those predicted by correlations proposed by Maxwell, Bruggeman or Hamilton and Crosser [10], there are other studies reporting thermal conductivity increase similar to or less than these predictions [6,10]. Several theories have been proposed for explaining the observed anomalous conductivity enhancement. According to one, Brownian motion of nanoparticles within the fluid creates micro-convection effects, enhancing the energy transfer [11,12]. Therefore, thermal conductivity predictions relying on the correlations based on this theory

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such as those by or Koo and Kleinstreuer [13] tend to exceed those based on effective medium theories for relatively lower viscosity base fluids where effects of Brownian motion is more effective. One of the main drawbacks of such correlations is that they are mostly semi-empirical, relying on constants estimated from experimental data, and they are valid for limited nanoparticle-base fluid combinations. According to another, there exists a highly-ordered liquid layer with relatively higher conductivity, referred as the nano-layer, surrounding nanoparticles increasing the overall energy transfer rate. Correlations that consider the existence of the nanolayer are developed by modifying effective medium theories based on theoretically estimated nanolayer thickness to match experimental data [14,15]. Another theory suggests that nanoparticle aggregations can create paths for efficient energy transport due to percolation and the anomalous increase can be attributed to cluster effective paths, enabling enhanced heat conduction [16]. Xuan et al. [17] claimed that fractal dimension is a suitable parameter to quantify the aggregate structures and they developed a new correlation. While correlations based on different mechanisms, and various particle-base fluid combinations exits, there exists no generalized theory and expression that is valid for all types of fluid-particle combinations. Therefore, experimental studies are still considered as essential for understanding behavior of different types of nanofluids.

There are also many other experimental studies, focusing not only on the change in thermophysical properties, but also on characterization of the convective heat transfer behavior of nanofluids. Wen and Ding [18] investigated Al_2O_3-water nanofluids under laminar flow and concluded that there is a significant enhancement in the entrance region and the enhancement decreases along the axial direction. Rea et al. [19] studied Al_2O_3 water nanofluids under laminar flow, and reported that enhancement in convective heat transfer coefficient is more distinct at the fully developed region. However, the observed enhancement in the fully developed region cannot be identified as anomalous considering the measurement limits. Convective heat transfer characteristics of propanol nanofluids containing Al_2O_3, was investigated by Sommer and Yerkes [20], within a large Reynolds number range. For Reynolds numbers between the range of 1000–2800, they reported that there is no abnormal enhancement beyond the thermophysical property increase. However, beyond Reynolds number of 2800, they observed decrease in convective heat transfer rate. Ding et al. [21] reported a significant heat transfer coefficient increase, up to 350% at $Re = 800$, for multi walled carbon nanotube (MwCNT)-water nanofluids, in laminar flow regime and claimed that convective heat transfer enhancement was dependent on the axial direction on the test section. Hwang et al. [22] studied Al_2O_3-water nanofluids in laminar flow and reported that the enhancement in convective heat transfer coefficient was beyond the increase in thermal conductivity enhancement and measured quantities cannot be predicted by standard theoretical correlations.

Baby and Ramaprabhu [23] investigated thermophysical properties and convective heat transfer characteristics of the hydrogen exfoliated graphene containing nanofluids with two different base fluids, DI water and ethylene glycol (EG). They observed drastically larger enhancement in convective heat transfer compared to that of thermal conductivity. Wang et al. [24] observed CNT-water nanofluids under laminar flow regime and found that heat transfer enhancement reached up to 190% for a volume concentration of 0.24% at a Reynolds number of 120. They observed that enhancement in convective heat transfer behavior was far more than the increase in thermal conductivity and the increase in pumping power very small, making such nanofluids good candidates for potential applications. Convective heat transfer characteristics of graphene–water nanofluid in laminar flow was investigated by Zanjani et al. [25]. They found 14.2% enhancement in convection heat transfer coefficient, where the thermal conductivity enhancement was 10.3% for a volume concentration of 0.02% at a Reynolds number of 1850. Esfe et al. [26] investigated, double-walled CNT-water nanofluids in turbulent flow in a double tube heat exchanger. They stated that even with the small amount of particle loadings such as 0.4% volume concentration, heat transfer enhancement reached up to 32% with 20% increase in pressure drop. Esmaeilzadeh et al. [27] worked with γ-Al_2O_3–water nanofluids under laminar flow regime. Results showed that heat transfer coefficient increased up to 6.8% and 19.1% for volume concentrations of 0.5% and 1%, respectively. Another notable result they outlined was that heat transfer coefficient increases with increasing heat flux.

While convective heat transfer of nanofluids depends on several different interactions based on many studies in the literature, there is no consensus among the reported results [28–30]. Such discrepancy can be attributed to many factors including; differences in nanoparticles' shape and size, preparation methods of nanofluids under different conditions. Nanofluids containing even the very same nanoparticles have resulted in different characteristics in terms of thermal behavior. Therefore, there is a need for more experimental investigations in regards to convection heat transfer of nanofluids including different materials and nanoparticles.

Boron nitride is a ceramic material with different crystal structures. Hexagonal form of boron nitride (hBN) has versatile properties, such as chemical inertness and high in-plane thermal conductivity which makes it a good candidate for heat transfer applications. Considering the fact that hBN nanofluids are relatively new class of materials, there are limited studies within the literature in terms of characterization of BN nanofluids [31–35]. Existing literature on hBN nanofluids focuses on the stability, thermal conductivity, rheological behavior and lubrication properties of hBN nanofluids. While there are, many studies investigating the convection heat transfer of metal oxide, graphene and CNT [28,30] containing nanofluids, there is no prior study in the literature for hBN nanofluids' forced convective heat transfer behavior. Recently, it was found that the increase in hBN-water nanofluids' thermal conductivity exceeds the increase in viscosity, making them promising heat transfer fluids for various engineering systems [31]. Therefore, there is a certain need for studies investigating the convective heat transfer behavior for hBN nanofluids. This study focuses on laminar forced convection of hBN-water nanofluids in a circular copper pipe and identifies the change in heat transfer coefficient with respect to the base fluid to address this need. As the study is carried out experimentally, a setup is built and validated first, and the convective heat transfer behavior of hBN-water nanofluids is then identified and reported for laminar flow.

2. Experimental set-up and methodology

An experimental test setup is developed and manufactured considering laminar thermally developing flow in a uniformly heated circular copper pipe so that local heat transfer coefficient can be measured. The test setup is first validated by experiments using DI-water. It is then used for testing hBN-water nanofluids with different particle volume concentrations, and flow rates. The nanofluids tested in this study are produced by a two-step method using ultra-sonication and surfactant addition to achieve stability. Thermal conductivity and viscosity of the nanofluids are measured prior to testing their convective behavior. In order to investigate the effects of testing conditions on nanofluid samples, thermophysical properties of hBN nanofluids are also measured right after the conducted laminar flow experiments.