Friction and Heat Transfer Characteristics of Silica and CNT Nanofluids in a Tube Flow

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Abstract: - An apparatus for exploring friction and heat transfer characteristics of nanofluids in tube flow has been developed, instrumented and computerized. It has been calibrated using distilled water for which the results are well established and correlated for both laminar and turbulent flow. Initial turbulent friction and heat transfer measurements for silica and carbon nanotube (CNT) nanofluids show peculiar results with substantial friction drag reduction and heat transfer enhancement for lower Reynolds numbers, but heat transfer reduction for higher Reynolds numbers. The apparently anomalous flow and heat transfer behaviors are hypothesized to be due to the conflicting influence of nanoparticle heat transfer enhancement but reduction due to additives used to stabilize inherently unstable nanoparticle suspensions in base fluid. More research is needed to establish conclusive results and development of innovative nanofluids with optimized nanoparticles and additives for improved flow and heat transfer characteristics for existing critical and novel applications.

Keywords: - nanofluids, nano-suspensions, flow friction, convective heat transfer, thermal conductivity, friction drag reduction, heat transfer reduction.

1 Introduction

There has been a vast interest and even ‘hype’ about using nanofluids to meet new challenges in cooling and thermal management, due to a number of experimental studies which demonstrated ‘anomalous’ enhancement of thermal conductivity and heat-transfer characteristics when small amount of nanoparticles or nanofibers are suspended in common fluids [1-9]. However, much of the current literature is either incomplete or inconsistent. Theoretical work, developing in the absence of a reliable experimental framework, has resulted in an awkward situation of having a larger number of competing theoretical hypotheses than systematic experimental results to prove, apparently anomalous phenomena [10-12]. Nanomaterials are intrinsically unstable, since they possess a very large fraction of surface atoms per unit volume and thus tend to oxidize and/or stick together, driven by the reduction of surface energy and other inter-particle and interfacial surface forces.

Regardless of ever-increasing number of research studies in this area, the basic research of convenience (repetition of similar experimentation with unstable nanofluids) remains in the initial stage; the promising nanofluids are still to be developed and results are still to be experimentally re-confirmed and established.

There are many important variables and issues related to making and using nanofluids, which is confirmed by significant discrepancy in the reported experimental data [1-12]. Type of nanoparticles, their size, shape and distribution are important but not easily measured and usually not well-defined nor properly reported in the publications. Type of base fluids used, method of nanofluid production, use of surfactants and stabilization additives, including pH adjusters, etc. Conglomeration and clustering of nanoparticles in the nanofluid mixture is taking place before and after the nanofluid is made and during its use, and depends on many factors, especially on additives used. Two nanofluid samples with all of the parameters appearing the same but different type and amount of surfactants and/or pH adjusters used, may result in quite different thermo-physical properties and flow and heat-transfer characteristics of apparently the same nanofluids. These and other unknown factors may explain anomalous and controversial results obtained by different researches. Furthermore, ultrasonic vibration (ultrasonication) is commonly...
utilized to enhance dispersion and breaking the clusters of nanoparticles. It is obvious that the duration and the intensity of the ultrasonication will affect the dispersion characteristics, however, the clusters will form again and their size will increase in time after ultrasonication [13]. Therefore, by using apparently the same samples, different results could be obtained just by varying the time between the ultrasonication and measurement of nanofluid characteristics.

There are many other issues to be addressed and resolved. For example, nanofluid thermal conductivity may be a function of temperature gradient (thus heat flux), in addition to temperature level dependence, the way non-Newtonian fluid viscosity is dependent on shearing rate, i.e., velocity gradient (thus flow rate).

The potential use of nanofluids in thermal systems has been well documented throughout the scientific communities, including a review paper regarding convective heat transfer research [7]. The addition of carbon, metal, metal oxide and other nanoparticles to common base fluids has been shown to increase the thermal conductivity and heat transfer capabilities of these fluids. While these nanofluids can be used in a wide array of thermal system applications, they can be further improved with the addition of polymers and other surfactants. Hypothetically, these polymer-enhanced nanofluids, dubbed POLY-nanofluids [12], should maintain the enhanced thermal properties observed in common (standard) nanofluids while enhancing suspension stability and possibly reducing frictional drag in turbulent flow, as is the case in the so-called drag-reducing fluids [14]. With additional qualities, these POLY-nanofluids are expected to be suitable for use in a wider spectrum of industrial and the cutting-edge applications, as well as environmental applications.

In the advanced electronics and new emerging industries there is a great need for efficient thermal management and cooling. In many other industries such as energy production and utilization, manufacturing, transportation and commercial and residential buildings, thermal management is critical and novel nanofluids could yield significant benefits.

2 Flow and Heat-Transfer Apparatus, Instrumentation and Data Acquisition Method

The schematic of the flow and heat-transfer apparatus (with all components labeled) is presented in Fig. 1, while details of the apparatus design are described elsewhere [15]. The apparatus has
been developed to investigate the flow friction and convective heat transfer characteristics of nanofluids. Instead of a usual closed-loop system where pumps and after-cooling units are required, the developed apparatus utilizes nitrogen pressure-driven flow to test a single batch of fluid. This reduces the complexity of the system while improving its reliability and accuracy.

The upper reservoir, made of heavy-gauge 316 stainless-steel, is designed to accommodate up to 1 liter of a test-fluid under regulated nitrogen pressure up to 1500 psi, and instrumented with a pressure and temperature sensors, see Fig. 1. It has two heavy-duty stainless-steel flanges for cleaning and maintenance access with appropriate ports for instrumentation, nitrogen line and test-fluid feed line, the latter also used for release of nitrogen pressure when needed. The 316-stainless-steel test-tube is 36-inch long, with a 0.069-inch inner diameter and 0.125-inch outer diameter, resulting in a dimensionless L/D ratio of 522, long enough to provide fully-developed flow over most of its length. The test tube is mounted in the upper and lower test-tube assemblies by soldering it to the copper connectors wired to a DC low-voltage but high-current power supply with computerized control. Thus the test tube acts as both the flow channel and electrical-resistance heater. Electrical DC current is passed through the test-tube in order to heat up the flowing fluid. To insure minimal heat loss to the surrounding, the test tube is well insulated with thick fiberglass along its entire length, so that virtually all heating power is transferred from the heated stainless-steel test tube (with a thermal conductivity of 13.4 W/mK [15]) to the flowing test fluid inside the tube. A number of Tefon-coated 30 AWG type-T thermocouples are mounted on the outside of the test tube (where radial temperature gradient is negligible) in order to accurately measure the temperature distribution along the tube in the axial direction, and then the corresponding inner wall temperatures are easily

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**Fig. 2:** Flow and Heat-Transfer Apparatus Data Acquisition Algorithm
calculated. A thermal epoxy with low thermal and high electrical resistivity is used to mount the thermocouples on the test tube, as detailed elsewhere [15].

The lower reservoir, open to the atmosphere, is designed to collect the test fluid, exiting the test tube, and instrumented with a thermocouple to measure the fluid exit temperature and with an ultrasound level sensor to measure the fluid level and thus its collected volume in time, needed to calculate the flow rate and cross-sectional average fluid-velocity, see Fig. 1, with full details in [15].

National Instruments’ data acquisition hardware is used (see Fig. 1), and LabVIEW® software is developed to acquire and process the test data, see Figs. 2 and 3. Details are described in [15].

2.1 Experimental and Data Reduction Methods:
An experimental test (or “run”) is conducted by filling in the test fluid in the upper reservoir, and using the developed LabVIEW® program which controls relevant actuators (open the pneumatic valve to start the test fluid flow, turn on heating, etc.) and acquire measured data in time (DC power supply voltage and current, fluid inlet pressure and temperature in the upper reservoir, test tube wall temperatures, and collected test fluid exit temperature and level in the lower reservoir), see Figs. 1, 2 and 3. Full details are described in [15]. Prior to execute the LabVIEW® program to monitor the flow data, the upper reservoir pressure is measured while open to the atmosphere and lower reservoir ultrasonic level is recorded, both to be used to zero out the relevant sensors. Then the upper reservoir has to be closed and pressurized to a desired pressure, measured or known fluid properties and desired heating DC current have to be entered via LabVIEW® Front Panel user interface, see Figs. 2 and 3, and then the program is executed to acquire data at 2 Hz sampling rate (unless otherwise desired) during the flow and heat transfer run, and calculate the results as per algorithm in Fig. 2. Selected data are interactively displayed and all data are stored in a file on a local storage media, as described in [15].

During a sample period the average values of flow rate and heating power are acquired and calculated using the simple correlations for the flow and heat transfer in a steady-state tube flow, since the changes of parameters are negligible during a small sample period (usually 0.5 second). However, the change of flow and heat transfer characteristics in time during the whole batch run is monitored and recorded accordingly, as well as to verify the peace-wise steady-state assumption. The LabVIEW® program automates all measurements and calculations, with very little input from a user.

3 Calibration and Uncertainty Analysis
In order to validate the operation and accuracy of the apparatus, the system was fully calibrated using distilled water for laminar flow with Re<2000 and turbulent flow with up to Re=40,000. The Darcy friction factor was found to be within 4% of the established values, while the Nusselt number was found to be within 5% of the accepted Gnielinski approximation, both with 95% confidence. In addition, a conservative and detailed uncertainty error analysis has been performed for the measurement results using the method of propagation of errors, resulting in a maximum conservative uncertainty of 8% at 95% probability, for heat transfer coefficient [15]. Most contributing
error uncertainties are due to the ultrasonic level sensor (with uncertainty of about 1.5%; calibrated against a lab grade caliper within the operating range of 2 to 14 inches) and thermocouples (with uncertainty of 0.1°C; calibrated against a lab grade RTD sensor). The laminar entry lengths are long and measured water calibration values should be compared with the appropriate entrance region data; however, for turbulent flow data, comparison with the corresponding fully-developed reference data are justified since the entry length is negligible compared to the test tube length of 522 diameters. The turbulent heat transfer results for distilled water are presented on Fig. 4 and compared with the well-established Gnielinski correlation. Those results were used for over-all calibration of the apparatus in the range of current interest. The bias over-all error of 4.2% and precision error of about 2% were observed, both within 95% confidence, resulting to over-all uncertainty within 5% at 95% confidence. However, for comparison measurements under similar conditions the bias error will cancel out thus resulting in comparative uncertainty of about 2%, which is much smaller than the conservative uncertainty estimate using the propagation of elemental errors’ method. The details are presented in [15].

4 Nanofluids Flow and Heat Transfer Results

Two types of nanofluids have been tested and compared with the corresponding distilled water measurements. Several concentrations of silica nanofluids have been prepared by diluting a 40 wt% (by weight) silica dispersion (with effective 50 nm SiO₂ nanoparticles of 1.28 W/mK thermal conductivity in water with 9 pH value, manufactured by Allied High Tech Products, Inc.). The NaOH pallets have been added to distilled water until pH value was increased to 9, and then it was used to dilute the original 40 wt% silica dispersion to obtain desired nanofluid concentrations of 1%, 5%, 10%, and 20% by weight (wt%). After shaking the mixture vigorously, the container was placed in an ultrasonic vibrator for one hour before it is being tested.

First the nanofluids thermal conductivity was measured using HWTC apparatus [16] and dynamic viscosity was measured using a commercial, Brookfield cone-and-plate digital viscometer. The measured thermal conductivities of all silica nanofluids were close to the water value (within the uncertainty of the apparatus), however, the dynamic viscosity has been showing shear-rate dependence at higher silica concentrations, for 20wt% being more than 20 times higher than water’s at 1000 s⁻¹ shear rate.

The second type of nanofluids tested were 1 wt% Carbon multi-walled nanotube (CNT or MW-CNT) suspensions in water with unknown additives (sold under the Nanosolve name from Zyvex Performance Materials Co.). The first test results (CNT-1) were replicated later (CNT-2) under similar conditions since the first obtained results have been “unexpected” and somewhat unstable, probably due to unknown additives (trade secret) used to stabilize, otherwise unstable MW-CNT suspensions in water; also possibly not being mixed/ultrasonicated well enough before testing. The thermal conductivity for the first CNT nanofluids (CNT-1) were measured to be close to water’s (unexpected result) and the second set (CNT-2, with prolonged ultrasonication) exhibited 23% thermal conductivity enhancement (more reasonable result). The measured dynamic viscosity showed shear rate dependency (non-Newtonian effect; increase from 5.5 to 11 cP while decreasing shear rate from 384 to 77 s⁻¹ [15]), probably due to the unknown additives used during manufacturing of the CNT nanofluid.

The limited, flow and heat transfer results for all tested nanofluids are presented on Figs. 5 and
Surprisingly, all test results showed a reduction of friction factor in turbulent flow for all tested nanofluids, suggesting that the latter additives used are more effective friction drag reducers than the silica’s additives. The CNT nanofluid showed strong reduction of friction factor in turbulent flow, being 75% lower than the distilled water value at 30,000 Re number (see Fig. 5). The drag reduction phenomena are not that widely known within the nanofluids’ research community and such anomalous phenomena may introduce further confusion in addition to rather unstable nanofluid structure and disagreement among fluid characteristics, between apparently similar nanofluids, where nanoparticle type and concentration are taken into the account, but type and amount of additives used to stabilize the mixture is often unjustifiably overlooked.

The heat transfer results are presented in Fig. 6. Up to about 20,000 Re number, the silica nanofluids had the convective heat transfer enhancement (compared with water results) for all the concentrations (1 to 20 wt%). The heat transfer increase, with the 20 wt% silica nanofluid at about 5,000 Re, was about 155% of the distilled water value. At about 20,000 Re number all the nanofluids begin a trend of reduced thermal performance, whereas at about 30,000 Re number the 20 wt% silica nanofluid had the lowest performance at 68% of the distilled water values. The second type of tested nanofluids was with 1.0 wt% carbon-nanotube (CNT) nanoparticles. The observed enhancement of the convective heat transfer coefficient was up to 100% larger than the distilled water values at 5000 Re number. At 30,000 Re number the trend of diminished convective heat transfer performance was observed as compared to the distilled water values, which is probably due to the turbulent heat transfer reduction due to additives in CNT nanofluid.
5 Conclusion

The turbulent friction drag reduction was observed for all nanofluids tested. The enhancement of convective heat transfer due to presence of nanoparticles is observed for the smaller values of Re numbers, where turbulent heat transfer reduction due to additives used is not strong enough to neutralize the enhancement. However, for higher values of Re numbers, the turbulent heat transfer reduction is predominant and stronger than the heat transfer enhancement due to nanoparticles, resulting in over-all reduction in convective heat transfer. This hypothetical reasoning based on the two known and opposing phenomena, nanoparticle heat transfer enhancement and additive heat transfer reduction in turbulent flow, may explain many surprising and apparently anomalous behaviors, as well as discrepancies between research results in the literature. However, due to limitation of this initial testing, more measurements are needed with different types of nanoparticles and additives before more conclusive results can be established. It is hoped that these unexpected and inconclusive results will initiate constructive criticism and further investigations, related to many open issues in nanofluids research to date.

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