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An experimental investigation of turbulent forced convection heat transfer by a multi-walled carbon-nanotube nanofluid ☆

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A B S T R A C T

In this work, a nanofluid based on multi-walled carbon nanotubes was formulated, and its heat transfer characteristics experimentally examined for turbulent flow in a straight tube. The experiments found that using the nanofluid resulted in an increase in pumping power and also a decrease in the observed convective heat transfer characteristics. This suggests that multi-walled carbon nanotube nanofluids in turbulent flows will actually impair heat transfer rather than improve it, and so may not be an appropriate heat transfer media in forced turbulent flows.

1. Introduction

Introducing small particles into heat transfer fluids in order to increase the thermal performance of the fluid is not a new idea. More than a century ago, Maxwell [1] published a theoretical work that showed the effective thermal properties of fluids could be improved by the addition of highly thermally conductive particles dispersed in a base fluid. However, until recently these studies were limited to solid particles at millimetre or micrometre scale dispersed in a liquid media, the stability of such fluids is very poor and the particles tend to coagulate. However, in recent years, modern technologies have facilitated the manufacture of the particles down to nanometre scale. As such, it is possible make nanoparticle dispersions in a base fluid that exhibits increased dispersion quality and stability [2]. In this regard, the term nanofluid was coined in the mid-1990s to describe a solid–liquid two-phase mixture consisting of engineered nanometre-sized metallic, non-metallic or oxide particles suspended in a base liquid [3].

In an early study, Choi et al. [3] presented a theoretical analysis of copper metallic particle-based nanofluids and concluded that it increased the effective thermal conductivity of the solutions significantly. Furthermore, during the past two decades, numerous research works have examined the thermal properties of these nanofluids in the hope of improving the thermal characteristics of cooling liquids. Many of them concluded by showing the thermal conductivity of a base liquid increased by adding small particles in suspension [4].

However, limited work has been undertaken on forced convection heat transfer using nanofluids [5]. Pak et al. [6] studied the forced heat convection heat transfer coefficient of nanofluids containing Al_2O_3 and TiO_2 nanoparticles under turbulent flow. They found that Nusselt number increased with an increase in the volume fraction of nanoparticles and Reynolds number. Subsequently, Eastman et al. [7] reported an improvement in heat transfer coefficients with a CuO based nanofluid. In 2008, Williams [8] observed a considerable increase in heat transfer coefficient when ZrO_2-based nanoparticles were used.

Additionally, many experimental studies have reported very high thermal conductivity for carbon nanotubes (CNT) [9,10]; therefore, one might expect that a fluid suspension consisting of CNT would deliver better thermal properties than conventional liquids. In this respect, Yousefi et al. [11] applied a multi-walled carbon nanotube (MWCNT)-based nanofluid to enhance the efficiency of a flat plate solar collector. However, there is very limited work on forced convection heat transfer of MWCNT-based nanofluids in turbulent flow [12]. Moreover, the improvements reported by Choi et al. [13] could not be reproduced by subsequent studies on MWCNT-based nanofluids [14].

In summary, there are a number of studies that have reported inconsistent results [6,15–18] and also some studies showing a decrease in heat transfer coefficient after adding nanoparticles to the base fluids [16,19]. As such, where previous studies concentrated on laminar flow or various formulations of nanofluids, for this study, it was decided to investigate the forced convection heat transfer of an MWCNT nanofluid under turbulent flow conditions.

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2. Experimental method

To determine convective heat transfer from the MWCNT nanofluid, a copper tube-in-tube heat exchanger was built with an inner and outer tube diameter of 1/4 in. and 1 in., respectively, as shown in Fig. 1. An entrance length of approximately 20 diameters of the inner tube was left outside the outer shell of the heat exchanger to ensure fully developed turbulent flow through the inner pipe. Saturated steam, at approximately 4-bar, was condensed in the outer tube to provide a constant wall temperature to the nanofluid circulating through the smaller inner tube. A control valve at the pump was used to control the flow rate of the fluid by allowing fluid to be recirculated into the supply tank. Additionally, the temperature of the steam and the inlet and outlet temperatures of the heated inner tube were measured using T-type thermocouples (±0.3 °C). The flow rate was measured by recording the time taken for a measured mass to be accumulated in a collection container.

2.1. Validation of experimental apparatus

In order to ensure that the experimental setup was able to accurately determine the convective heat transfer coefficients for turbulent flow in a tube, a preliminary experiment was conducted in which water was used as the heat transfer medium. From the inlet and outlet fluid temperature readings, as well as knowledge of the mass flow rate and specific heat of water, the heat transferred from the steam to the fluid (Q) can be calculated. Now because the wall resistance of the copper inner tube is relatively small, it was assumed to be negligible, hence the overall forced convection heat transfer coefficient, h_{fc} can be calculated according to Newton's law of cooling as given in Eq. (1).

$$h_{fc} = \frac{Q}{(A * \Delta T_{ln})} \tag{1}$$

where ΔT_{ln} is the log-mean temperature difference.

Fifteen sets of readings were taken under steady state conditions for each flow condition, and the mean fluid temperature value was used to determine the physical properties of the heat transfer fluid for each flow condition. This allowed the Nusselt number and Reynolds number values to be determined for the experiment.

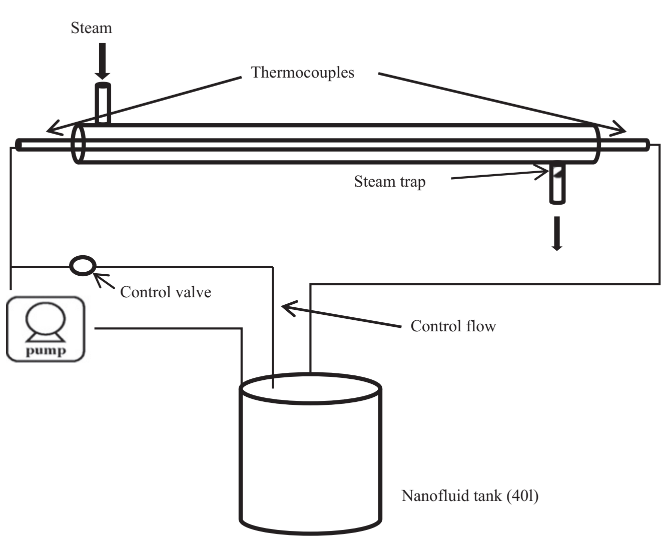

Fig. 1. Experimental setup.

Now to validate the experimental apparatus, the experimental values of Nusselt number were compared to those predicted by the Gnielinski empirical correlation [20] shown in Eq. (2).

$$\mathrm{Nu} = \frac{\frac{f}{8}(Re - 1000) * Pr}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr^{2/3} - 1\right)} \tag{2}$$

For $0.7 < Pr < 2000$ and $3000 < Re < 5*10^6$ where the friction factor (f) is given by Petukhov's correlation [21], as shown in Eq. (3).

$$f = \frac{1}{\left(1.8 \log_{10} \frac{Re}{6.9}\right)^2} \tag{3}$$

In Fig. 2, it can be seen that the Nusselt numbers obtained from the experiment compare favourably with those computed by Gnielinski's empirical correlation. As such, the experimental apparatus should be able to accurately determine the heat transfer characteristics of the nanofluid.

2.2. Nanofluid pre-preparation

Nanofluids are not simply liquid–solid mixtures, but have special requirements. In this regard, stability, homogenous suspension, durability of the suspensions, and agglomeration effects should be considered while making such fluids.

As MWCNT particles are hydrophobic in nature, their dispersability in water is expected to be poor. However, adding a surfactant that has hydrophobic and hydrophilic functional groups may improve the stability of the liquid [22]. Hence, it was decided to investigate the stability and the dispersion of the MWCNT nanoparticles in the water using a surfactant. Rastogi et al. [22] compared the dispersion of MWCNT particles in water using four different surfactants: Triton X-100, Tween 20, Tween 80 and sodium dodecyl sulphate, and found that Triton X-100 had the greatest ability to disperse MWCNT nanoparticles. In addition to that, sonication of the mixture appears to improve the dispersion ability of the particle in the fluid [23,24].

In order to minimize the agglomeration of nanoparticles and to study the stability of the MWCNT nanofluid, it was decided to use Triton X-100 surfactant in conjunction with sonication to prepare the MWCNT nanofluid. In undertaking this analysis, different compositions, as shown in Table 1, and different sonication times were tested.

Four portions of each sample (MWCNT with an average diameter, 10–40 nm; length, 1–25 μm; purity by weight, 93% min and specific surface area, 150–250 m^2/g) [25] were sonicated for 10, 20, 30 and

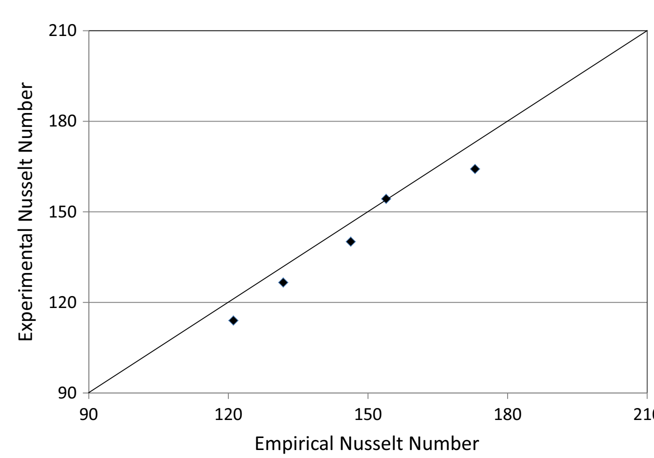

Fig. 2. Experimental versus empirical Nusselt number values.