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Experimental investigation on thermal performance of kerosene–graphene nanofluid

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ABSTRACT

Current study experimentally investigates the thermal performance of kerosene based nanofluid containing graphene nanoplatelets (GNP) for its potential use in regenerative cooling of semi-cryogenic rocket thrust chamber. Stable kerosene–GNP nanofluids at 0.005, 0.02, 0.05, 0.1, 0.2 weight percentage (wt%) and 300, 500, 750 m^2/g, specific surface area (SSA) are prepared using ultrasonication and steric stabilization technique. Oleylamine is found to be the suitable surfactant with an optimum oleylamine to GNP mass ratio of 0.6, for maximum stability of nanofluid. Dynamic Light Scattering (DLS) technique along with thermal conductivity measurements are used to identify the stability of nanofluid with time. 23% enhancement in thermal conductivity and 8% increase in viscosity at room temperature are observed for 750 SSA, 0.2 wt% kerosene–GNP nanofluid. Lower enhancement in thermal conductivity and viscosity are noticed for nanofluid that is prepared with lower SSA GNPs. The study shows less significant effect of temperature on the thermal conductivity of kerosene–GNP nanofluid compared to kerosene–alumina nanofluid. The behaviour observed is collaborated due to the combined effect of Brownian motion in smaller size sheets and thermal conduction in longer chain structure. Maximum effect of temperature on thermal conductivity is observed for 750 SSA nanofluid as compared to other sizes of GNPs. Experimental study on convective heat transfer performance of the nanofluids at turbulent flow regime show significant improvement in heat transfer performance of kerosene–GNP nanofluid as compared to pure kerosene. 49% enhancement in convective heat transfer coefficient is noticed for 750 SSA, 0.2 wt% kerosene–GNP nanofluids. A correlation for friction factor based on the experimental data is also determined. Merit number, used to determine the total heat transfer performance shows the utility of these nanofluids as heat transfer fluids.

1. Introduction

In rocket engines, the increased thrust requirement lead to increased heat flux on the thrust chamber walls and therefore needs to be regeneratively cooled by circulating one of the propellants along the outer surface of the nozzle wall through cooling channels. The cooling efficiency of any fluids depends upon its thermo-physical properties and flow velocity. The increase in flow velocity increases the pressure drop in the system which in turn increases requirement of pumping power. Kerosene is used as a fuel in semi cryogenic engine. Regenerative cooling is used to protect the thrust chamber wall from the hot combustion products. Kerosene is used as coolant in the regenerative passage before admitting it into the combustion chamber. Kerosene with low thermal conductivity is also susceptible to coking if the fluid temperature through the regenerative passage increases beyond a certain limit. Therefore, to enhance the applicability limit of semi cryogenic engine at higher thrust levels and reusability of the thrust chamber, it is pertinent to increase the thermal conductivity of its fuel. Thermo-physical properties of kerosene can be enhanced by addition of small amount of nanoparticles in it. Choi and Eastman [1] in 1995 at the Agronne National Laboratory, Chicago has carried out the pioneering work of dispersing nano-sized particle in a base fluid and named this colloidal solution as "Nanofluid". Nanoparticles used in nanofluids are a class of materials that exhibit unique physical and chemical properties compared to those of larger particles of the same materials. The presence of nanoparticles with large surface area is expected to enhance the heat transfer and also stability of the nanofluid. This property of nanoparticle

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Nomenclature

Cp	specific heat (J/kg K)
Di	diameter of test section, (m)
D	hydrodynamic diameter (nm)
f	friction factor
h	heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity (W/m K)
L	length of test section (m)
Le	equivalent length of graphene sheet (nm)
N	particle count
Nu	Nusselt number
Pr	Prandtl number
Q	heat energy (W)
Re	Reynolds number
T	temperature (°C)
V	voltage (V)
$\tilde{V}$	volume flow rate (m^3/s)
X	axial distance along the test section (m)

Greek symbol

Φ	nanoparticle mass concentration (%)
φ	nanoparticle volume concentration (%)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)
δ	thermal boundary layer thickness
ΔP	pressure drop (Pa)

Subscripts

bf	base fluid
c	current value
f	fluid
i	initial value
nf	nanofluid
np	nanoparticle
s	surface

is utilised to develop nanofluids with an unprecedented combination of two features that are highly desirable for heat transfer systems; extreme stability and very high thermal conductivity.

Over the past one and half decade, many researchers have investigated the nanofluids for their enhanced heat transfer properties. Researchers have carried out wide range of experimental studies [2] using spherical particles made of oxides, carbide and metal nanoparticles in water or ethylene glycol. Most of these studies clearly indicate higher heat transfer performance for nanofluids as compared to the respective base fluid. The enhanced thermal conductivity of nanofluid made of non-spherical particles, viz; multiwalled carbon nanotube (MWCNT) was first reported by Choi et al. [3]. An increase of 160% in thermal conductivity for 1 vol % MWCNTs dispersed in poly-(αolefin) oil was noticed. The main reason for the selection of carbon nanotubes (CNT) was its very high thermal conductivity. Subsequently, many studies were carried out using MWCNT [4,5] and single walled carbon nanotube SWCNT [6,7] and most of the studies reported significantly higher heat transfer properties for these nanofluids in comparison to spherical particle nanofluids.

Graphene, a single atomic layer of graphite has two-dimensional form of carbon and found to exhibit high crystal quality as it has ballistic electronic transport at room temperature. Graphene attracted much attention since it was discovered by Novoselov et al. [8] in year 2004. Graphene has superior thermal conductivity and therefore would expect to result higher heat transfer performance as a nanofluid. According to Hamilton and Crosser [9], when the particle to liquid thermal conductivity ratio of a suspension is above 100, the particle shape can play a substantial effect on its effective thermal conductivity. More recently Balandin et al. [10] reported very high value of thermal conductivity of 5000 W/m k for single-layer graphene. This has generated increased interest among the scientific community to use this novel material as suspension in base fluid to be used as a heat transfer fluid.

The first study on graphene based nanofluid was simultaneously reported by two researcher groups, Yu et al. [11] and Baby and Ramaprabhu [12]. Yu et al. [11] experimentally determined the thermal conductivity of Graphene Oxide based nanofluid and reported 30.2%, 62.3% and 76.8% enhancement in thermal conductivity for 5 vol% Graphene oxide nanosheets in water, propyl glycol and liquid paraffin respectively. Baby and Ramaprabhu [12] used functionalized thermal exfoliated graphene oxide (f-TEG) in Deionized (DI) water and Ethylene glycol (EG) as nanofluid. They found significant increase in thermal conductivity of water based nanofluid as compared to those with EG. The reported value for 0.056% vol% f-TEG water nanofluid was 14% at 25 °C and 64% at 50 °C. Further, in their study, the authors [13] found 76% enhancement in heat transfer coefficient at 0.01 vol% f-TEG water nanofluid for a Reynolds number of 4500. In their subsequent work [14] the thermal performance of Ag/HEG nanofluid are determined and nanofluids was found to be stable for a period of more than 3 month.

Mehrali et al. [15] prepared water-GNP nanofluids without using surfactant and observed maximum enhancement of 27.64% in thermal conductivity for 0.1 wt% GNP. They determined the rate of sedimentation of GNPs with time and reported the effect of specific surface area (SSA) and concentration of sedimentation rate. They also observed increased viscosity for higher SSA nanofluids.

Effect of temperature on thermal conductivity was first reported by Das et al. [16] for metal oxide based nanofluids. The authors observed 2–4 fold increase in thermal conductivity of nanofluid as the temperature was increased from 21 °C to 51 °C. Subsequently, large number of researchers carried out study in this area and some of them reported significant enhancement of thermal conductivities with temperature [12,17–21] whereas, some have reported none [11,22–24].

Baby and Ramprabhu [12] observed significant effect of temperature on thermal conductivity for water- graphene nanofluid. Ijam et al. [17] prepared GNP – glycerol + water nanofluids and monitored the stability of nanofluids with time. It was found that their nanofluids were stable for more than 5 months. The study also showed significant effect of temperature on the thermal conductivity of nanofluids. Wang et al. [18] prepared stable graphene based nanofluid in ionic liquid without surfactant and reported 15.5% and 18.6% increase in thermal conductivity at 25 °C and 65 °C respectively for 0.06 wt% of graphene. They found decrease in viscosity for graphene based nanofluid as compared to the base fluid. Thermal conductivity of nanofluid at very high temperature is measured by Liu et al. [19] for [HMIMM]BF4-graphene nanofluid. Increase in thermal conductivity from 15.2% at 20 °C to 22.9% at 200 °C for 0.06 wt% GNP nanofluid is observed.

Contrary to above mentioned findings, Yu et al. [11] did not observe any increase in thermal conductivity for graphene oxide