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Experimental investigation on convective heat transfer of non-Newtonian flows of Xanthan gum solutions in microtubes

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ABSTRACT

Convective heat transfer of thermally developing flows of non-Newtonian Xanthan gum solutions, a potential candidate for cooling and heating applications, was experimentally investigated in a microtube. Xanthan gum solutions of different concentrations (0.1, 0.5, 1 and 4 g/L), whose properties matched with the Carreau-Yasuda model, were tested at different fixed flow rates at constant uniform heat flux. The results revealed that the heat flux was effective at more downstream locations, and the enhancements were attained at low concentrations ($c = 0.1$ g/L) and low flow rates. Therefore, at the same flow rate, Xanthan gum solutions are not very good candidates for enhancement of convective heat transfer unless they are used at both low concentrations and low flow rates.

1. Introduction

The rapid progress in fabrication of miniaturized devices enabled the integration of microchannels to compact systems, which have been utilized in microfluidic systems, chemical reactors, and heat exchangers, where high heat removal rates are sought. In the design of such micro devices, parameters related to the heated area and type of the working fluid play a vital role. Enhancing the heated surface via coatings or growing artificial features on plain surfaces are effective in augmenting the heat transfer performance [1]. Tailoring the properties of the base fluid with additives is another popular method to improve heat transfer characteristics. Nanofluids and polymeric solutions have shown to be potential alternatives for heat transfer fluids and could have the potential of offering a better performance, although some contradictory results were also reported in the literature [2].

Nanofluids are dispersions of nanoparticles (with average diameters of 1–100 nm) with typically higher thermal conductivities than conventional base fluid, such as water, ethylene glycol, engine oil and refrigerants [3]. The addition of metallic (Cu, Al, Fe and Ti) or metal oxides nanoparticles (Al_2O_3, CuO, Fe_3O_4 and TiO_2) to a base fluid increases thermal conductivity and could enhance overall heat transfer [4–9]. However, both enhancement or deterioration in heat transfer were reported, while there were also some studies, where no considerable enhancement was observed [10–12]. In our previous study [13], convective heat transfer characteristics of Al_2O_3 and TiO_2 nanoparticle based nanofluids were investigated in a microtube with an inner diameter of $\sim$500 μm. No significant enhancement was obtained at low Reynolds numbers, whereas enhancement in convective heat transfer became significant at high Reynolds numbers (>1500).

A major issue regarding the use of nanofluids is the clustering and sedimentation of nanoparticles, which should be taken into consideration. Therefore, other types of fluids, which do not have such drawbacks, such as non-Newtonian polymeric solutions, can be alternatively used. There are many studies on the rheology and flow characteristics of non-Newtonian fluids. But convective heat transfer of non-Newtonian fluids has not been adequately investigated in comparison to their rheological characteristics, and the studies on this subject focus on computational [14–20] or analytical [21–27] efforts.

The experimental investigations of non-Newtonian fluids on heat transfer were rather limited in the literature. As an example of an experimental study, Etemad et al. [28] measured Nusselt number of Carbopol 934, which was modeled as a power-law fluid, for flows in a semicircular and triangular minichannel at constant heat flux. Their results demonstrated dependency of Nusselt number on Rayleigh number, and local maxima and minima were found for water at high Rayleigh numbers. Peixinho et al. [29] conducted experiments on Newtonian and non-Newtonian Carbopol aqueous

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Nomenclature

A	area (m^2)
c_p	specific heat (kJ/kg K)
c	concentration (g/L)
D	diameter (m)
f	friction factor
g	gravitational acceleration (m/s^2)
HTC	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	liter (dm^3)
L_h	heated length (m)
L_{tot}	total length (m)
$\dot{m}$	mass flow rate (kg/s)
P	electrical power (W)
Pr	Prantdl number
Q	flow rate (mL/min)
q	heat rate (W)
q''	heat flux (W/m^2)
$\dot{q}$	volumetric heat generation rate (W/m^3)
Ra	Rayleigh number
Re	Reynolds number
T	temperature (K)
U	uncertainty
X	uncertainty variable
x	location (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
ρ	density (kg/m^3)

Subscripts

amb	ambient
avg	averaged
dev	developing
el	electrical
f	fluid
h	heated
i	inner
in	inlet
o	outer
s	surface
ss	stainless steel
th	thermally
tot	total
w	wall
ww	w/w%

solutions modeled by the Herschel–Bulkley model in a pipe of a diameter of 30 mm under laminar and turbulent flow conditions. They found that the non-Newtonian fluid parameters raised the flow instability and further affected heat transfer characteristics. Joshi and Bergles [30] dealt with laminar flows of water-methocel pseudoplastic solutions in a circular tube at constant heat flux. They compared their experimental results with numerical predictions and also proposed correlations by taking the temperature-dependent rheological characteristics into account. Naimi et al. [31] considered the effect of the temperature-dependent parameters on Nusselt number for Herschel–Bulkley fluids in concentric annuli and proposed a correlation for Nusselt number. Farias et al. [32] performed a study on Carbopol aqueous solutions within concentric annuli at uniform heat flux on the inner wall. Their results indicated a minor effect of the rheological parameters on Nusselt number of the inner wall. In the study of Nouar et al. [33], Herschel–Bulkley fluid flows were investigated inside an annulus of adiabatic and rotating inner tube and stationary outer tube at constant heat flux and focused on the impact of temperature-dependent rheological factors on mixed-convection heat transfer of power-law fluid flows in an annulus at uniform heat flux on both inner and outer walls in their later study [34]. Their experimental data were in good agreement with their performed numerical results. Martínez et al. [35] performed experiments on fluid flow and heat transfer of both Newtonian—propylene glycol—and non-Newtonian fluids—CMC (carboxyl-methyl-cellulose) solution (concentration of 1%) in water—in a smooth tube of a diameter of 18 mm, which was enhanced by two different inserted wire coils. Increases of 3.5 and 4.5 times in the friction factor and Nusselt number were obtained relative to the smooth tube, respectively. Pawar and Sunnapwar [36] conducted a heat transfer study on the flow of Newtonian fluids, water and glycerol-water mixture, and non-Newtonian fluids (dilute aqueous polymer solutions of sodium carboxymethyl cellulose (SCMC) and sodium alginate (SA)) in coils under both laminar and turbulent flow conditions as well as under isothermal steady state and non-isothermal unsteady conditions. Heat transfer deteriorated either by the dissolution of polymeric additives into water or with the increase in helix diameter.

The abovementioned experimental studies on convective heat transfer of non-Newtonian polymeric solutions are related to macro scale channels. To the best knowledge of the authors, convective heat transfer of non-Newtonian fluid flows of Xanthan gum solutions in microchannels has not been experimentally investigated despite some theoretical and numerical attempts. This study presents an experimental investigation on convective heat transfer of non-Newtonian Xanthan gum solutions. The solutions were prepared by the dissolution of Xanthan gum powder into water at different concentrations, whose viscosities are shear-dependent and can be expressed by the Carreau-Yasuda model [37]. The effects of concentration and heat flux on heat transfer characteristics of thermally developing micro flows were examined at different flow rates, and the corresponding results were compared with those of pure water in order to check for enhancement in heat transfer. As a result, the conditions for the enhancement in convective heat transfer with the addition of Xanthan Gum powder were determined.

2. Experimental setup and procedure

The schematic of the experimental setup and test section is displayed in Fig. 1a. The experimental setup consists of a syringe pump (Cole-Parmer 200 Touch Screen Series, USA) with 2 syringes, hypodermic stainless steel tube (Small Parts Inc., USA) as the test section with an inner diameter of 889 μm, an outer diameter of 1087 μm and a heated length of 13.5 cm, a DC power supply (Xantrex Technology Inc., USA) for delivering the desired heat flux, 5 K-type thermocouples (Omega Engineering Inc., USA), and digital thermometers (Uni-Trend Group Limited, China) for measuring outer wall temperatures of the test section. Joule heating was applied to the microtube by attaching two thin alligator clips on the surface. The thermocouple locations along the test section