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Nanofluids Suppress Secondary Flow in Laminar Pipe Flow

Laura Colla, Laura Fedele
National Research Council - Institute of Construction Technologies
Corso Stati Uniti 4, 35127 Padova, Italy
laura.colla@itc.it; laura.fedele@itc.cnr.it

Matthias H. Buschmann
Institut für Luft- und Kältetechnik Dresden gGmbH
Bertolt-Brecht Allee 20, 01309 Dresden, Germany
Matthias.Buschmann@web.de

Abstract **–**For the first time it is experimentally shown that free convection in laminar pipe flow with constant heat flux is significantly suppressed by nanoparticles. Moreover, for nanofluid flow with high heating power, an increase above the analytical solution for pure forced convection is lowered by increasing inlet temperature. It is argued that an explanation for the observed effects can only be found if nanofluids are strictly understood as two-phase media. Especially Brownian diffusion is seen as one of the players equalising thermal gradients necessary for thermal instabilities to grow.

Keywords**:** pipe flow, nanofluid, secondary flow, free convection.

1. Introduction

Facing limited energy and material resources and undesirable man-made climate changes, science is searching for new and innovative strategies to save, transfer, and store thermal energy. One of the currently most intensively investigated options are the so-called nanofluids. Nanofluids are suspensions consisting of a liquid basefluid and solid particles having a size ranging from 10 nm to 100 nm. Nanoparticles are much larger than water molecules, which have a size of about 0.1 nm. However, they are significantly smaller than the characteristic length scales of thermodynamical apparatus. The number of publications with respect to nanofluids has grown exponentially since the beginning of this millennium. However, many publications indicate controversial results. A lack of theoretical understanding is obvious and hampers successful technical applications.

One of the standard tests to investigate nanofluid behaviour is the horizontal laminar pipe flow with constant heat flux. A most recent study (Utomo et al., 2014) indicates that if properly presented, nanofluids cause the same heat transfer in laminar pipe flow with constant heat flux as any other liquid heat carrier having the same thermodynamic properties. The presented research uses once again a laminar pipe flow experiment to study nanofluids. However, this time the focus is on the development of secondary flow. Known from rotating or bended pipes, the radial oriented centrifugal force generates two counter rotating vortices. These vortices are superposed on the mean flow so that in steady state flow streamlines become spirals. In laminar horizontal pipe flow such secondary vortices are generated by thermal instabilities following from radial temperature gradients.

In this study, a fully developed isothermal laminar pipe flow profile entering a heated pipe section is considered. Right at the beginning of the test section the temperature is constant over the entire flow. Further downstream a radial temperature gradient develops. Fluid parcels close to the wall have a higher temperature as that in the core region. Similar as with Rayleigh-Bérnard convection, secondary flow starts when a critical Rayleigh number is exceeded. The following mixed convection consists of a forced convection resulting from mean flow supported by a free convection caused by secondary flow.

2. Nanofluid and Test Rig

The used titania (TiO_2) water-based nanofluid is purchased from Sigma Aldrich at 35 % by mass. Bidistilled water is employed to dilute this commercial nanofluid to obtain desired concentrations of 1.0 wt. % and 2.5 wt. %. The supplier declares the size of the primary nanoparticles as 21 nm. In order to verify the tendency of the nanoparticles in suspension to settle over time, samples are measured several times over 18 days employing DLS technique. It is found that the nanofluids at the concentrations here analysed are stable in the long term and can be employed in thermodynamic devices without aggregation problems. Thermal conductivity is measured in a temperature range between 10°C and 60°C, employing a TPS 2500 S (Hot Disk®), an instrument based on the hot disk technique. It is found that nanofluids and pure water have nearly identical thermal conductivities in the temperature range between 10°C and 40°C. Increasing the temperature further, thermal conductivity of nanofluids becomes slightly higher than that of water. A rotational rheometer (AR-G2, TA Instruments) is employed to determine viscosity (10°C to 40°C). The rheological behaviour of nanofluids is Newtonian. Dynamic viscosity of nanofluid and basefluid water is compared at temperatures between 10°C and 40°C and found to be very similar. Additional information about the experimental apparatus and procedures is given in Colla et al. (2015).

Figure 1 shows the apparatus used to measure the heat transfer coefficient. The entrance length to ensure a fully developed velocity profile of the test rig is 375 mm. The measurement section is a straight copper pipe with 8 mm inner diameter and a length of 2 m. The test section is divided into 8 subsections each 0.25 m long. In each subsection four thermocouples are placed circumferentially. Two platinum resistance thermometers Pt100 measure fluid bulk temperatures at inlet and outlet of the measurement section. Heating electrical resistance wires wound continuously around the pipe impose uniform heat flux.

Local heat transfer coefficient h_i and local Nusselt number Nu_i are predicted according to:

$$h_i = q/\left(T_{w,i} - T_{b,i}\right) \qquad \text{and} \qquad Nu_i = h_i\, d_i/k \tag{1}$$

Here q denotes specific heat flux and subscripts w,i and b,i stand for wall and for bulk in subsection i.

Measurements employing DI-water and titania nanofluids are carried out in order to compare the behaviour of both working fluids under identical conditions. Particle mass fractions of titania nanofluid are 1.0 wt. % and 2.5 wt. %. Mass flow rate ranges from 2.6 g/s to 10.2 g/s. Temperature of working fluid at the inlet of the test section is either 20°C or 40°C. Power supplied ranges from 50 W to 400 W.

3. Experimental Results

Water data with inlet temperatures of 20 °C (blue) and 40 °C (light blue) for two heating powers are plotted in Fig. 2. Reynolds number is in all cases about 900 to 1000. The general observation is that with increasing inlet temperature the departure of the Nusselt number from the analytical solution for pure forced convection (Jiji, 2009) becomes stronger (red arrows). This effect decays with increasing heating power. For still higher heating powers Nusselt number distributions of different inlet temperatures may collapse. However, it is implausible that 20°C data will generate a higher Nusselt number than 40°C data.

Comparing nanofluid and water data indicates that the onset of free convection and therewith the increase of the Nusselt number above the analytical solution for pure convection is delayed in nanofluid flow. Obviously the nanoparticles suppress thermal instabilities necessary for secondary flow to grow. Such a behaviour was also found for free convection in enclosures (Putra et al., 2003). A theoretical analysis of free convection in nanofluids is given by Nield & Kuznetsov (2015).

For heating power of 50 W the Nusselt number increases with increasing inlet temperature (green arrows left column of Fig. 2). The increase is weaker for higher concentration (lower left plot). Increasing the heating power to 200 W shows that this effect either disappears (1.0 wt. % upper right plot) or reverses (2.5 wt. % lower right plot).

For the lower concentration the situation forecasted for water at high heating power has already arrived. Increase of the Nusselt number above analytical solution of pure convection no longer depends on inlet temperature. More surprising is the situation for the higher concentration, where the increase of inlet temperature lowers the increase of the Nusselt number. Again nanoparticles obviously suppress free convection. The effects described so far are supported by the data taken at 100 W heating power, which are not shown here.

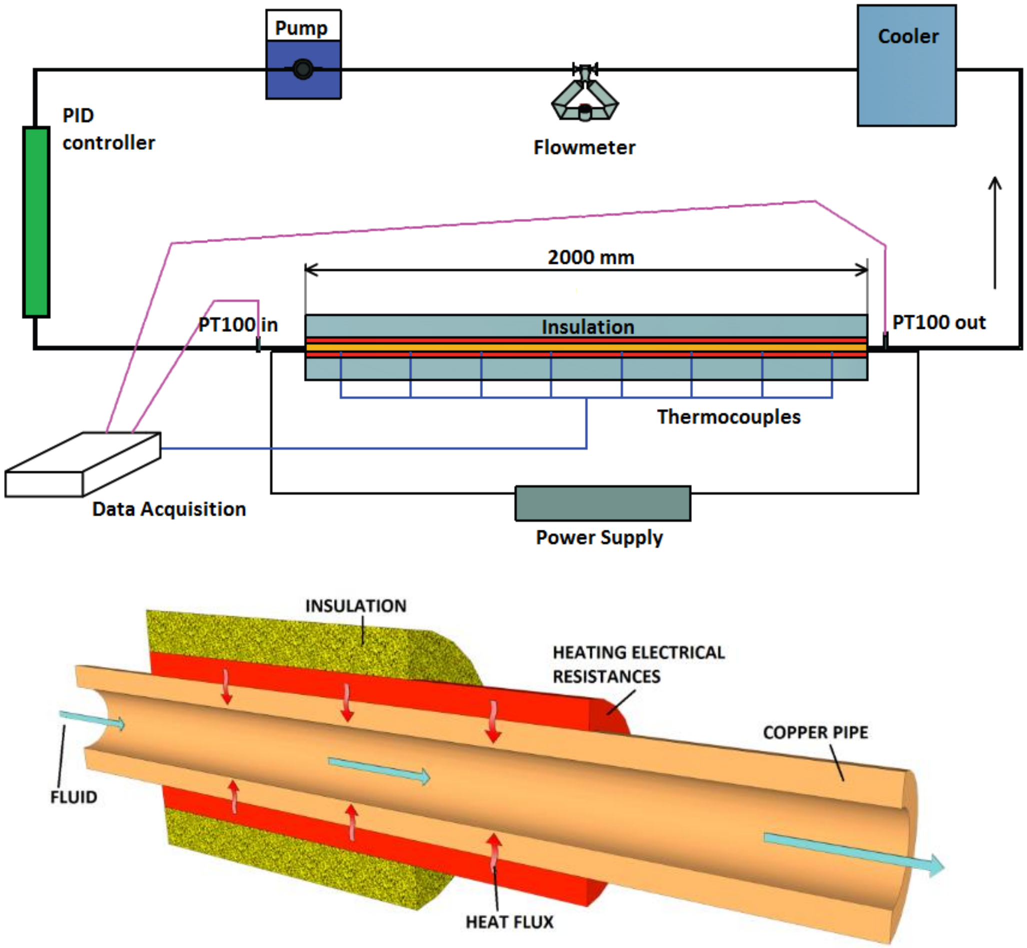

Fig. 1. Sketch of test rig (above) and measurement section (below) (Colla et al. 2015)

The two effects – delay of onset of free convection and lowering of the Nusselt number increase – can only be explained when the two-phase character of nanofluids is considered. Nanofluids are mostly seen as one-phase media characterised by effective thermophysical properties. However, sophisticated numerical investigations (Avramenko et al., 2011) as well as simple sedimentation experiments show the separation of phases. Physical mechanisms causing the separate movement of nanoparticles and basefluid are Brownian and thermophoretic diffusion, gravity, and other imposed forces.

4. Conclusion

Heat transfer water and titania nanofluid in laminar pipe flow with constant heat flux is investigated with respect to onset and intensity of free convection. Two central observations follow: onset of free convection is suppressed by nanoparticles and, for high heating power, Nusselt number increase above the analytical solution may be lowered by increasing inlet temperature. It is concluded that an interpretation of both effects is only possible when nanofluids are strictly understood as two-phase media where nanoparticles may freely move. Especially Brownian diffusion is seen as one of the main reasons for equalizing radial thermal gradients necessary for thermal instabilities to grow and finally to generate secondary flow.

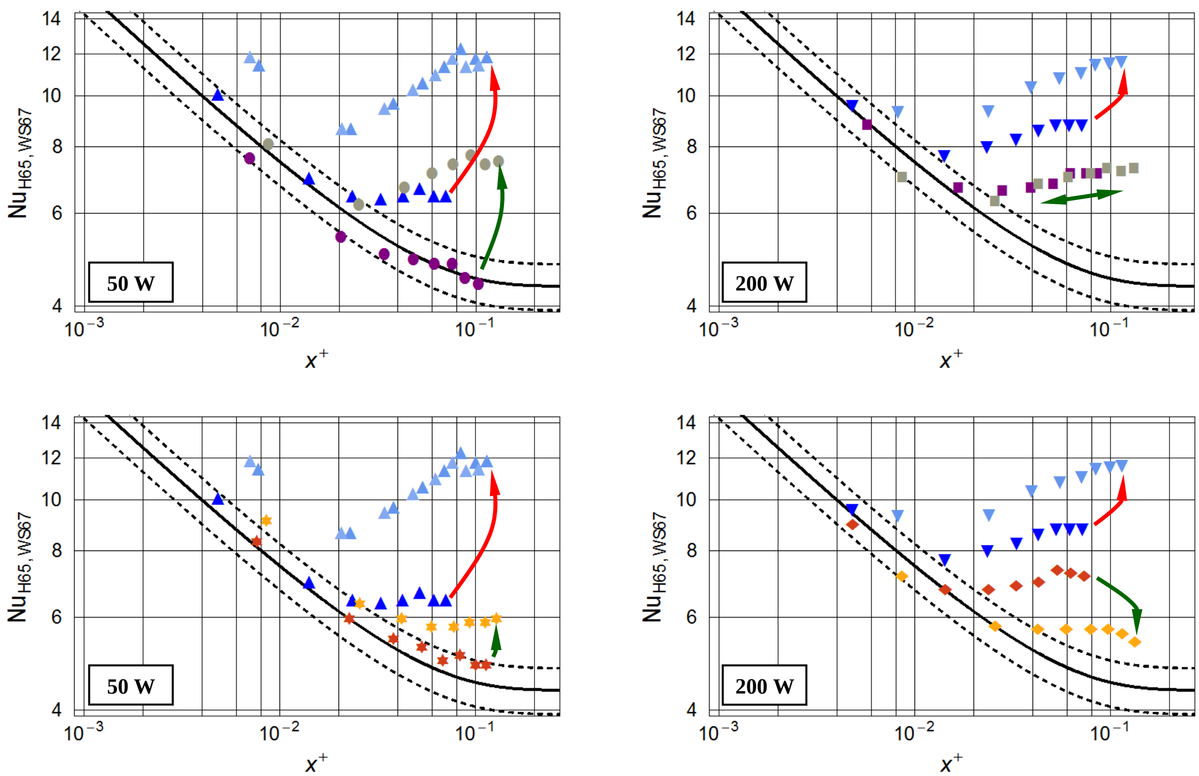

Fig. 2. Nusselt-Graetz plots of laminar Nusselt number. Water data are indicated employing blue (T_{in} = 20 °C) and light blue (T_{in} = 40 °C) symbols. Nanofluid data for 1.0 wt. % (upper row) are indicated by purple (T_{in} = 20 °C) and grey (T_{in} = 40 °C) symbols. Nanofluid data for 2.5 wt. % (lower row) are indicated by red (T_{in} = 20 °C) and orange (T_{in} = 40 °C) symbols. Reynolds number ranges from 900 to 1000. Bandwidth error is ±10%.

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