Energy optimisation through the use of heat exchangers using nanofluids

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The University of Pretoria has been actively researching thermofluid systems since the early 1980s. The Thermofluids Research Group in the Department of Mechanical and Aeronautical Engineering has launched a project, as part of the University's Institutional Research Theme (IRT) on Energy, to develop advanced measuring setups that can be used to experimentally obtain accurate data and develop design correlations for flow through different types of heat exchangers.

Since the early 1990s, there has generally been a growing emphasis on computational research in the thermoflow field. Applications of thermofluid include electronics cooling and industrial computational fluid dynamics (CFD).

Heat exchangers are critical components of processes that generate energy, such as in concentrated solar, nuclear and fossil fuel power processes. It is also used, for example, in the processing, manufacturing, mining, aerospace, transportation, ventilation and air-conditioning industries.

Normally, two flow streams at different temperatures are involved in a heat exchanger. The function of the heat exchanger is to move heat (energy) from one stream to the other. Usually, the two streams are separated by a thin wall with a high thermal conductivity to allow better heat transfer. To ensure efficient heat transfer between two flows at different temperatures, it must be possible to estimate the heat transfer and pressure drop behaviour. This behaviour is very complex and is influenced by several factors.

The first factor is the development of flow regimes and, specifically, the boundary layer of the flow close to the wall that separates the two streams. The flow associated with the boundary layers may be laminar, transitional or turbulent in nature. All these flows have different flow and heat transfer characteristics.

The second factor that influences heat transfer and pressure drop behaviour is the surface geometry of the channel used in the heat exchanger, as the geometry determines the available heat transfer area. The geometry of the surface and objects in and on the surface can also be used as heat transfer enhancement techniques. Examples are extended surfaces, such as fins, surfaces with dimples and pin fins, swirl-flow devices, and thin, twisted plates.

A third factor is the nature of the flow. A single-phase flow behaves very differently to a flow that changes phase. The temperatures of a single-phase flow change in direct proportion to the heat transfer. This can reduce the temperature, as the fluid potential of heat transfer rates remains high as the fluid flows through the heat exchanger. If the pressure drops are not significant, the temperatures of phase-changing flows (boiling, evaporation and condensation) remain constant and have a significant amount of latent heat. Therefore, these flows ensure more efficient heat transfer. Another technique that can be used to improve heat transfer in a heat exchanger is to use fluids with high thermal conductivity.

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The abovementioned factors contribute to the fact that it is very complicated to design an effective heat exchanger, and it can only be done if accurate design information is available.

Heat transfer correlations have been developed, but because of a poor understanding of the fundamentals and less than accurate instrumentation, the best correlations for single-phase flow have errors of approximately 20%. For flows with phase change, it is about 40%. This is not good enough if heat exchangers have to be as cheap and efficient as possible. Over the past few years, heat transfer coefficients of heat exchangers with errors of less than 10% and empirical equations that can be used by engineers to optimise their designs have been developed. Unfortunately, methods or instrumentation to measure the required data are not commercially available.

During a research project conducted by Kersten Grote, a master's degree student at the University of Pretoria, advanced measuring setups were developed that can be used to experimentally obtain accurate data and to develop design correlations for flow through different types of heat exchangers. These can be used by engineers to design better heat exchangers and optimise their efficiency. Over the past 12 years, several such setups have been designed, built and commissioned under the leadership of the Thermofluids Research Group. A recent example is a setup that has been developed to measure the heat transfer and pressure drops of nanofluids. Nanofluids are liquids that contain suspensions of nanoparticles. These fluids are known for substantially higher thermal conductivity than the effective medium theories anticipate.

The reason for considering nanofluids is that water, as a fluid that is used in most heat exchangers, has a relatively low thermal conductivity of 0.58 W/mK at 25 °C. Many studies have investigated methods of improving the heat transfer conductivity of fluids by using mixtures of micrometre-sized particles in base fluids such as water and oil. The studies found that, although higher conductivity and higher heat transfer capabilities are possible in practice, problems are experienced with clogging, sedimentation and increased potential damage of systems due to abrasion.

During the past 25 years, much research on colloidal dispersions of solid nanoparticles in nanofluids, as a new class of heat transfer fluid, has been conducted. Studies found that a fluid's conductivity could be enhanced by adding nanoparticles, such as aluminium oxide, titanium dioxide or copper oxide. The potential enhancements are high, as the thermal conductivity of aluminium oxide is 30 W/mK and that of carbon 3 000 W/mK. These values are respectively 50 and 5 000 times higher than that of water.

This project focused on the measurement of average heat transfer and pressure drop characteristics in the transitional flow regime. The potential of different concentrations of multi-walled carbon nanotubes was investigated. The researchers also took measurements in both the laminar and turbulent flow regimes.

The concentrations were 0%, 0.33%, 0.75% and 1%, and the nanofluids were multi-walled carbon nanotubes. They were stabilised with gum Arabic powder and were sonicated. The carbon nanotubes had outside diameters of 10 nm to 20 nm, inside diameters of 3 nm to 5 nm, and lengths of 10 μm to 30 μm. Thus, the length-to-diameter ratio of the nanofluids was very long, with an order of magnitude value of approximately 1 000. It was expected that the nanofluids, which became entangled with each other in the water and looked like "spaghetti" when enlarged with a scanning electron microscope (SEM), would significantly disturb the velocity and thermal boundary layers.

The pH, thermal conductivity, viscosity of the water and gum Arabic powder, as well as the volume concentrations of carbon nanotubes, were measured separately as a function of temperature. The densities and specific temperatures were

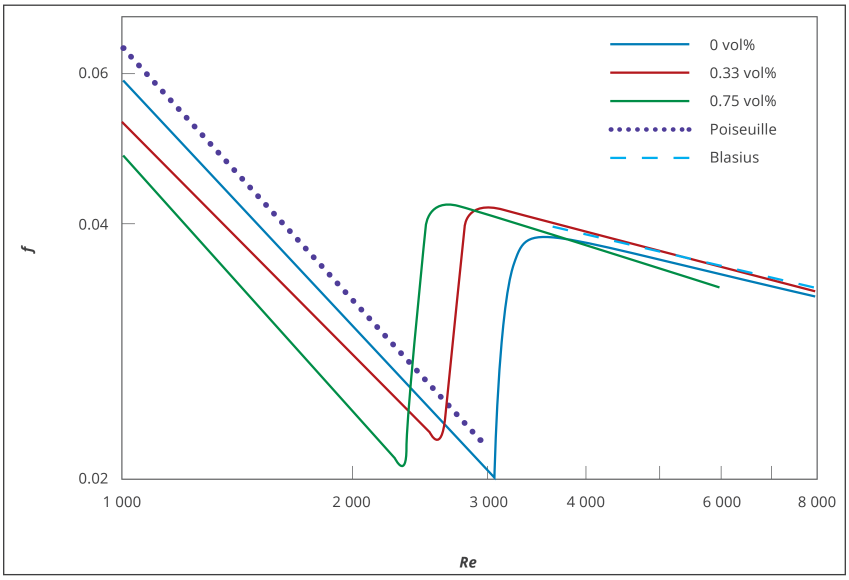

Figure 1: Diabatic friction factors for different concentrations of multi-walled carbon tubes as a function of the Re number. Results for a concentration of 1% could not be taken, as it blocked the pressure ports.

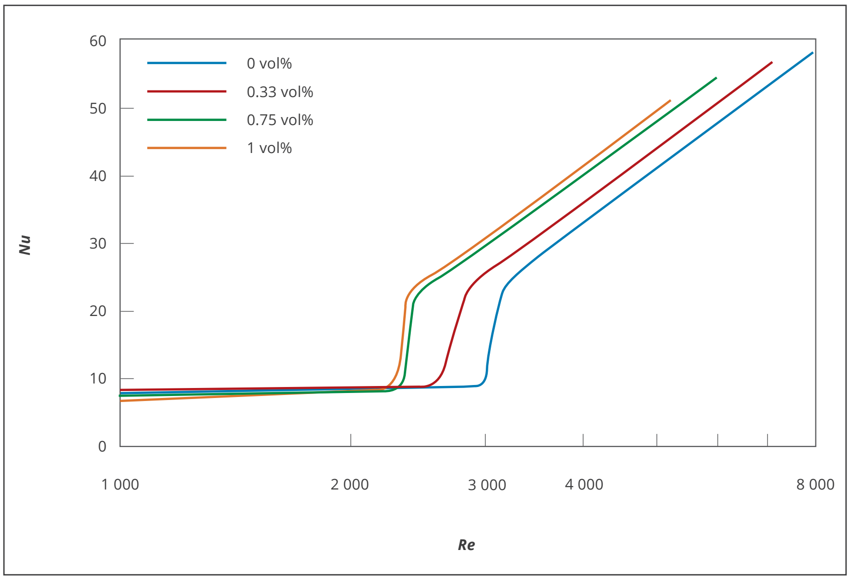

Figure 2: The non-dimensionalised heat transfer (Nu numbers) as a function of the Re number.

determined from well-known correlations. Experiments were conducted in the Rayleigh (Ra) number range, ensuring that forced convection and friction factors, as well as heat transfer coefficients, were determined as functions of the Reynolds (Re) number. The Re number is a dimensionless quantity that is used to help predict similar flow regimes in different fluid flow situations.

The diabatic friction factor results in Figure 1 indicate that, in the turbulent flow regime, the friction factors did not significantly differ from those of water. In the laminar flow regime, however, the friction factors differed significantly. The reason for the decrease was that the addition of nanofluids changed the viscosity of all the fluids significantly. Pressure drop comparisons at the same fluid velocity indicate that the pressure drop will increase when nanofluids are added. The results in Figure 1, however, show how the critical Re number changed significantly as the concentration of nanoparticles increased. The higher the concentration, the sooner transition will occur.

The heat transfer results in Figure 2 show a significant number of (non-dimensionalised heat transfer coefficient) enhancements of approximately 30% in the turbulent flow regime. The enhancement is caused by the increase in the thermal conductivity of the base fluid. This enhancement occurred because of the addition of the nanofluids, which had a high thermal conductivity of 3 000 W/m°C, compared to the water thermal conductivity of approximately 0.61 W/m°C. In the transitional flow regime, the results of the Nusselt (Nu) number (the ratio of convective to conductive heat transfer across the boundary) show that transition as a function of the Re number occurred earlier as the concentration of nanofluids increased.

> Over the past 12 years, several heat exchanger setups have been designed, built and commissioned under the leadership of the Thermofluids Research Group.

It can be concluded that heat exchangers are critical components used in energy production. Normally, two flow streams of nanofluid are used in a heat exchanger. Researchers working on a heat transfer project in the University's Department of Mechanical and Aeronautical Engineering developed advanced measuring setups that can be used to obtain accurate data and develop design correlations for flow through different types of heat exchangers.

The heat transfer results showed significant Nu number enhancements in the turbulent flow regime. The enhancements occur because of the increase in the thermal conductivity of the base fluid, which had a high thermal conductivity compared to the water's thermal conductivity. In the transitional flow regime, the Nu number results showed that transition as a function of the Re number occurred earlier as the concentration of nanofluids increased.

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