

IMECE2010-' , % +

DESIGN OF A STEADY-STATE, PARALLEL-PLATE THERMAL CONDUCTIVITY APPARATUS FOR NANOFLUIDS AND COMPARATIVE MEASUREMENTS WITH TRANSIENT HWTC APPARATUS

Milivoje M. Kostic and Casey J. Walleck

Northern Illinois University
Department of Mechanical Engineering
DeKalb, IL 60115, U.S.A.

+1(815)753-9975; kostic@niu.edu * www.kostic.niu.edu

ABSTRACT

A steady-state, parallel-plate thermal conductivity (PPTC) apparatus has been developed and used for comparative measurements of complex POLY-nanofluids, in order to compare results with the corresponding measurements using the transient, hot-wire thermal conductivity (HWTC) apparatus. The related measurements in the literature, mostly with HWTC method, have been inconsistent and with measured thermal conductivities far beyond prediction using the well-known mixture theory. The objective was to check out if existing and well-established HWTC method might have some unknown issues while measuring TC of complex nano-mixture suspensions, like electro-magnetic phenomena, undetectable hot-wire vibrations, and others. These initial and limited measurements have shown considerable difference between the two methods, where the TC enhancements measured with PPTC apparatus were about three times smaller than with HWTC apparatus, the former data being much closer to the mixture theory prediction. However, the influence of measurement method is not conclusive since it has been observed that the complex nano-mixture suspensions were very unstable during the lengthy steady-state measurements as compared to rather quick transient HWTC method. The nanofluid suspension instability might be the main reason for very inconsistent results in the literature. It is necessary to expend investigation with more stable nano-mixture suspensions.

Keywords: - Bias error, data acquisition, measurement uncertainty, nanofluids, nano-suspension, parallel-plate, platinum hot-wire, precision error, steady-state method, thermal conductivity, transient method.

INTRODUCTION

There has been a vast interest and even 'hype' about using nanofluids to meet new challenges in cooling and thermal management due to a number of experimental studies which demonstrated 'anomalous' enhancement of thermal conductivity when small amount of nanoparticles or nanofibers are suspended in common fluids [1]. However, much of the current literature is either incomplete or inconsistent. Theoretical work, developing in the absence of a reliable experimental framework, has resulted in an awkward situation of having a larger number of competing theoretical hypotheses than systematic experimental results to prove, apparently anomalous phenomena [1,2]. Nanomaterials are intrinsically unstable, since they possess a very large fraction of surface atoms and thus tend to oxidize and/or stick together, driven by the reduction of surface energy and other inter-particle and interfacial surface forces. Regardless of ever-increasing number of research studies in this area, the basic research remains in the initial stage, the promising results are still to be experimentally re-confirmed and established, and possibly enhanced.

The potential use of nanofluids in thermal systems has been well documented throughout the scientific communities. The addition of carbon, metal, metal oxide and other nanoparticles to common base fluids has been shown to increase the thermal conductivity and heat transfer capabilities of these fluids. While these nanofluids can be used in a wide array of thermal system applications, they can be further improved with the addition of polymers and other surfactants. Hypothetically, these polymer-enhanced nanofluids, dubbed here POLY-nanofluids [2], should maintain the enhanced thermal properties observed in common (standard) nanofluids while enhancing suspension stability and possibly reduce frictional drag in

turbulent flow, as is the case in the so called drag-reducing fluids [3]. With additional qualities, these POLY-nanofluids are expected to be suitable for use in a wider spectrum of industrial and the cutting-edge applications.

A steady-state, parallel-plate thermal conductivity (PPTC) apparatus has been developed, fabricated, calibrated and used for comparative measurements of complex POLY-nanofluids [4], in order to compare results with the corresponding measurements using the transient, hot-wire thermal conductivity (HWTC) apparatus [5,6]. The related available measurements in the literature, mostly with HWTC method, have been inconsistent and with measured thermal conductivities far beyond prediction using the well-known mixture theory [7]. The objective was to use quite different, concomitant method and check out if existing and well-established HWTC method might have some unknown issues while measuring TC of complex nano-mixture suspensions, like electro-magnetic phenomena, undetectable hot-wire vibrations, and others.

PARALLEL-PLATE APPARATUS DESIGN AND METHOD

The schematic of the PPTC apparatus with all components labeled and relevant nomenclatures is presented in Fig. 1. The objective was to provide controlled one-dimensional heating by conduction through a stationary test fluid specimen and accurate

measurements of relevant temperatures in order to simply and accurately measure the fluid thermal conductivity. The main components are described next.

Test Fluid Specimen Cavity: The test fluid specimen cavity (highlighted yellow on Fig. 1) is a critical component of the PPTC apparatus that houses the test fluid sample for measurement of thermal conductivity. The top and bottom of the test fluid cavity are formed by the parallel plates described later. The faces of the parallel plates in contact with the test fluid specimen have a high level of planarity and mirror-polished finish to minimize measurement errors due to surface geometry imperfections of the parallel plates. The side edge of the test fluid specimen cavity is centered by the upper and lower lips located on both the upper and lower Teflon shells, as detailed below. In order to accurately measure the thermal conductivity of the test fluid specimen, a well-defined heat transfer mechanism consisting virtually of conduction only must be provided. This is accomplished by two major design parameters. First, the heater is above and the chiller is below the test fluid (the heat transfer is in the gravity direction) thus suppressing the convection effects due to buoyancy. The second major design parameter is a very small thickness of the test fluid specimen cavity, $L_F = 1.21 \text{ mm}$. This rather small thickness, similar to that used in a successful apparatus [8], prevents the convection from developing within the test fluid specimen. Another important design

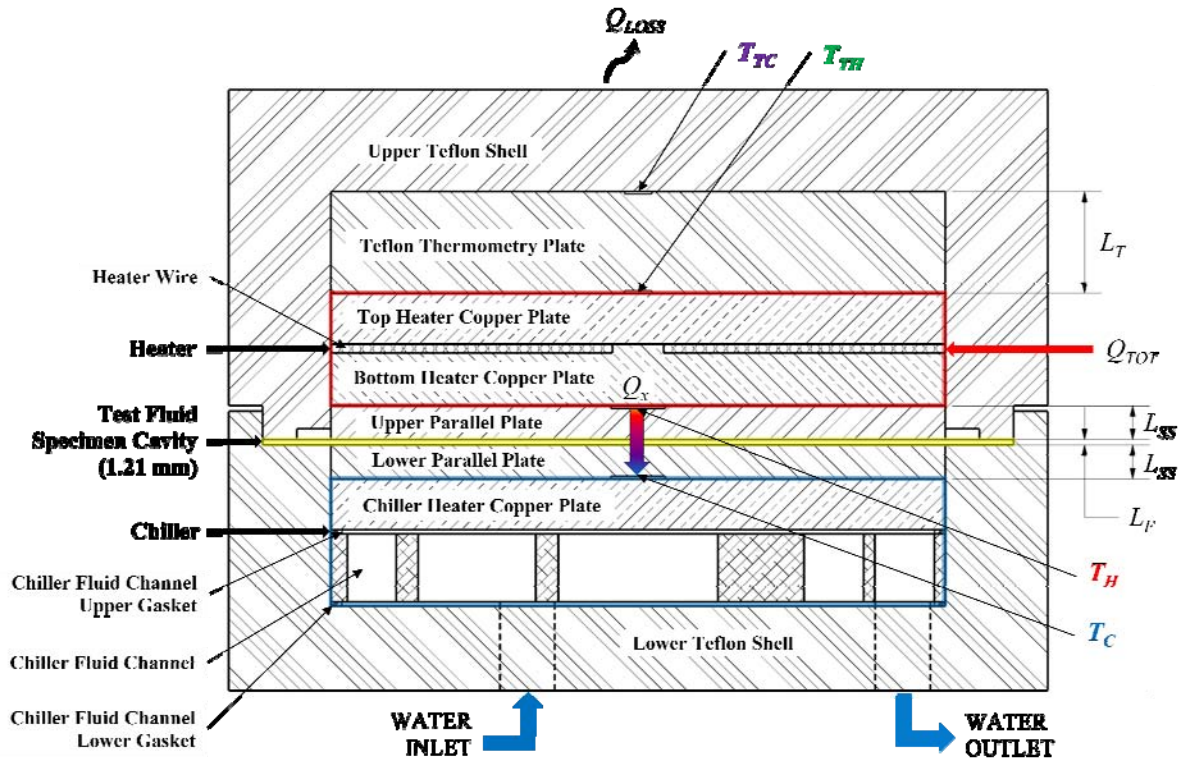


Fig. 1: Schematic of the PPTC apparatus with relevant nomenclatures.

aspect is the method used to establish a gap with accurately calibrated, very small size cylindrical glass-spacers (1.21 ± 0.01 mm thick and 2.0 mm diameter) placed between the upper and lower parallel plate assemblies. The glass spacers have been chosen due to their dimensional stability and thermal conductivity being the same order-of-magnitude as that of the measured test specimens'. Three glass spacers were evenly displaced circumferentially close to the outer edge of the bottom parallel plate. Once the test fluid specimen is added to the test fluid specimen cavity, the upper assembly is carefully rested on the spacers.

The final design aspect of the test fluid specimen cavity is the bull's-eye leveling mechanism mounted on an adjustable stand on which the lower assembly rests. It is important for the lower assembly and the upper assembly to be leveled when the test fluid specimen is loaded to provide an even test fluid specimen thickness and minimize convection effect due to gravity.

Parallel (Thermometry) Plates: The parallel (thermometry) plates provide the plane surfaces that comprise the top and bottom of the test fluid specimen cavity described above. These plates also house the thermocouples used to measure a number of the temperatures at different locations, used to determine the temperature difference across the test fluid specimen, as well as temperature uniformity in the other two directions, see Fig. 2. One parallel plate is press fit into the bottom of the upper assembly and one parallel plate is press fit into the top of the lower assembly, resulting in one parallel plate on either side of the test fluid specimen. The parallel plates are made from ANSI 304 stainless steel and are 4.50 inch

in diameter and have a thickness of 0.25 inch. Stainless steel was chosen as the material for the parallel plates to provide corrosion resistance and for easy cleaning of the test fluid specimen cavity. One surface of each of the parallel plates facing the test specimen has a mirror finish. Before the parallel plates are press fit into place, the faces contacting both the heater assembly copper plate and the chiller assembly copper plate are coated with a thin layer of high thermal conductivity paste to reduce the effects of contact thermal resistance. Each face of the parallel plates facing away from the test fluid specimen has radial thermocouple grooves, see Fig. 2. These grooves provide locations needed to place the thermocouples and clearance for thermocouple wires. There are three radial thermocouple grooves evenly spaced around the circumference of each parallel plate. These grooves extend from the center to the outside edge of the parallel plates, and are 0.20 inch wide and 0.02 inch deep. There are fifteen, 30-gauge *T*-type thermocouples mounted on each parallel plate, with each thermocouple groove containing five thermocouples. The thermocouple grooves are then filled with a high thermal conductivity epoxy that isolates and holds the thermocouples in place.

A large number of thermocouples are utilized in this design for two reasons. Firstly, redundant thermocouples could be used in case of some thermocouple malfunction in the future, since it would be difficult and impractical to disassemble the pressed-fit apparatus in order to repair malfunctioning thermocouples. Secondly, having a large number of evenly spaced thermocouples provides means to verify the radial and circumferential temperature uniformity,

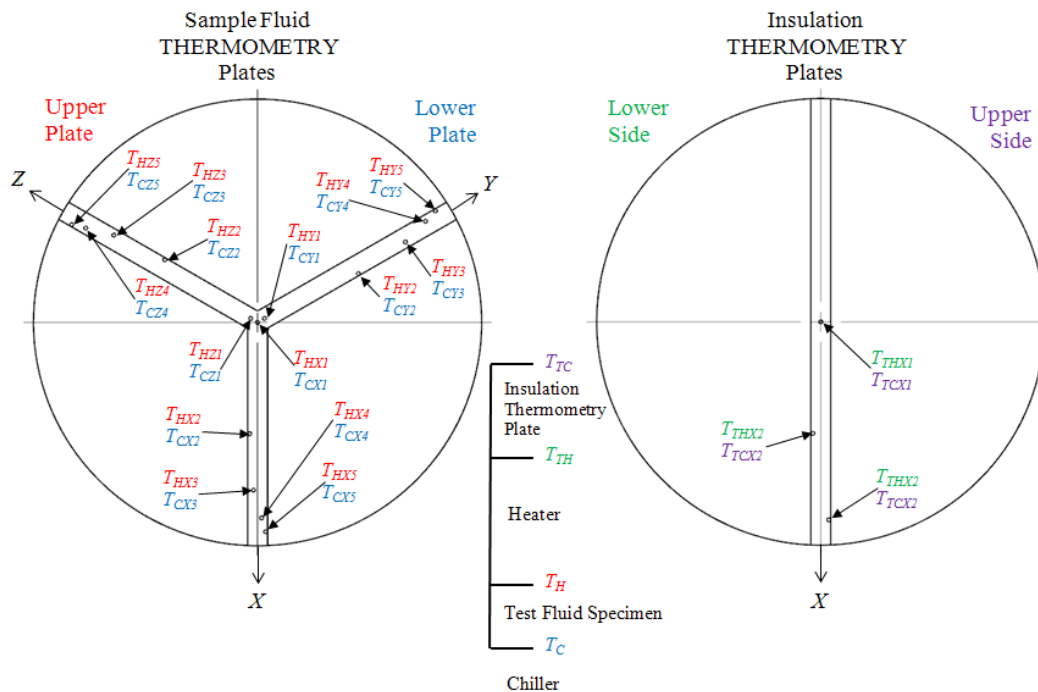


Fig. 2: Parallel (Thermometry) Plate and Teflon (Insulation) thermometry plate with thermocouple placement locations and relevant nomenclature.

needed for evaluation of heat losses, if any, and validation of one-dimensional heat transfer through the thickness of the test specimen, as modeled by the working equation used for evaluation of the thermal conductivity. On Fig. 2, the Teflon (Insulation) thermometry plate for evaluation of heat losses from the top of the apparatus is also presented. The Teflon thermometry plate is located above the heater assembly, see Fig. 1. The purpose of the Teflon thermometry plate is two-fold. First, the low thermal conductivity of the Teflon (0.35 W/m/K) provides extra insulation to the top of the heater assembly. Second, the thermocouples provide a means to calculate the heat loss through the top of the heater assembly. The Teflon thermometry plate is made of virgin electrical grade Teflon. It is 4.50 inch in diameter and has a thickness of 0.75 inch . Thermocouples are attached on both sides of the Teflon thermometry plate and are located in thermocouple grooves that are machined into each face of the Teflon thermometry plate.

Heater Design: The heater generates the heat flux and thus the temperature difference across the test fluid specimen. The heater is made of a resistance wire that is formed into a spiral and sandwiched between two copper plates to equalize radial and circumferential temperature distribution. The resistance wire of 55% copper and 45% nickel with a diameter of 0.036 inch (19 AWG) has Teflon insulation. The resistance is approximately 0.227 ohms per foot, resulting in the total of the heater wire resistance of 4.21 ohms . The plates made from 145 tellurium copper alloy (of 400 W/m/K thermal conductivity) are chosen for easy machining and to ensure that the heat generated by the heater wire will be evenly distributed across the entire surface of the test fluid specimen. The top copper plate is a 0.375 inch thick circular disc with a 4.50 inch diameter. The bottom plate has the same dimensions, but it includes a 0.80 inch high post of 0.50 inch diameter. The heater wire is wrapped spirally around the post in the bottom copper plate, providing an evenly distributed heating, and the two plates are screwed together creating a single heater assembly.

The heater assembly and the Teflon thermometry plate are press fit into a Teflon shell, creating the upper assembly of the apparatus. Teflon is used for the heater assembly housing for three reasons. First, the Teflon provides sufficient rigidity for the press fitting of the heater assembly. Second, the low thermal conductivity of Teflon provides insulation, reducing the amount of heat lost to the surroundings. Finally, the Teflon provides for easy cleaning of the apparatus. The upper Teflon shell has an outer diameter of 6.00 inch and an overall height of 2.58 inch . It also has a raised lip (0.25 inch deep and 0.25 inch thick) at the bottom surface. This lip helps to center the upper assembly when it is placed on the lower assembly. It also forms the outer side of the test fluid specimen cavity. Finally, the upper assembly is covered with a polystyrene shell. This shell provides a 0.75 inch thick

layer of insulation around the entire upper assembly. The polystyrene shell has an extremely low thermal conductivity of approximately 0.027 W/m/K , and further minimizes the heat loss to the surrounding.

Chiller Design: The chiller forms the lower assembly of the apparatus and utilizes cold water as its cooling medium, see Fig. 3. A channel made from aluminum is designed to guide the cooling water around the lower assembly and provide even removal of the heat generated by the heater. The basic shape of the fluid channel is a spiral-like, with the water entering the chiller closer to the center and exiting at the outer edge, this enabling more uniform circumferential temperature.

The fluid channel has an outer circumference of 4.50 inch , and a depth of 0.50 inch . The channel walls are 0.08 inch thick, providing sufficient rigidity. The chiller is also comprised of a copper plate that forms the top of the chiller assembly and provides even heat transfer to the chiller fluid. The material and dimensions of the chiller copper plate are identical to

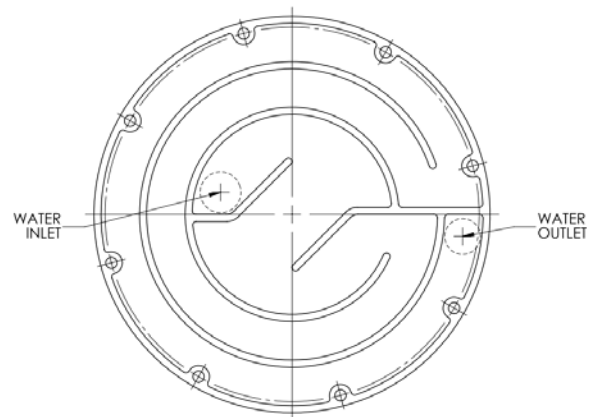


Fig. 3: Water Chiller Design

those of the upper heater copper plate.

The chiller fluid channel and chiller copper plate are press fit into a Teflon shell, creating the lower assembly of the apparatus, nearly identical to the upper Teflon shell.

Method and Mathematical Model: The steady-state, parallel-plate method utilizes the simple mathematical model of one-dimensional heat conduction through a composite three layers of cross-sectional area A : the test-fluid specimen of thickness L_F between two identical stainless-steel, parallel thermometry plates of thickness L_{SS} and known thermal conductivity k_{SS} , see Fig. 1, resulting in the simple equation for calculation of the test fluid thermal conductivity based on known and/or measured quantities [4]:

$$k_F = \frac{L_F}{A \cdot \left(\frac{T_H - T_C}{Q_x} - \frac{2L_{SS}}{k_{SS} A} \right)}$$

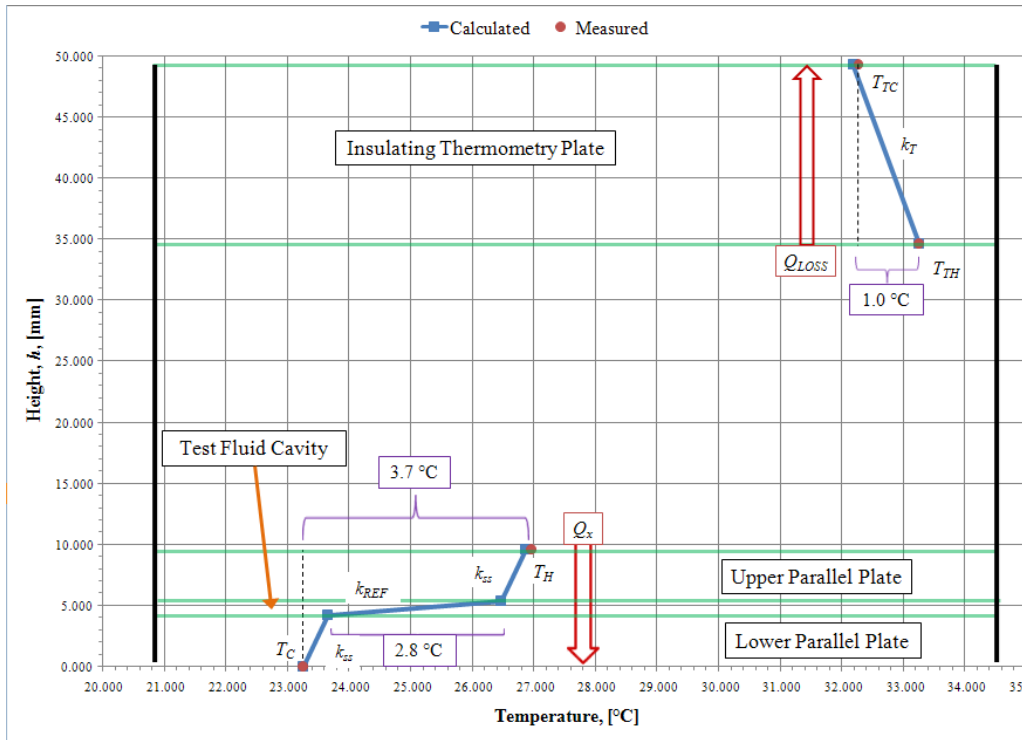


Fig. 4: PPTC apparatus typical measured temperature profile (calibration with distilled water).

The heat rate transferred through the test fluid specimen in the axial-gravity direction,

$$Q_x = Q_{EH} - Q_{top} - Q_{rad} ; \text{ where, } Q_{EH} = \frac{V_{heater}^2}{R_{heater}}$$

rate supplied by the electrical resistance-heater, while the other quantities, Q_{top} and Q_{rad} are the top-surface and radial heat losses through the thermal insulation, respectively. The V_{heater} and R_{heater} are measured voltage across and the calibrated resistance of the heater wire. The T_H and T_C are representative temperatures at upper and lower parallel thermometry plates, respectively, see Figs. 1 and 4. It is verified, based on extensive temperature measurements, that temperature profile is virtually uniform in radial and circumferential direction, justifying the validity of the above 1-D equation and neglecting the radial heat loss above, while the top-surface heat loss is measured using the Teflon thermometric plate described above, and thus accounted for (usually less than 2%). Typical measured temperatures are presented on Fig. 4.

INSTRUMENTATION AND DATA ACQUISITION

The PPTC apparatus, with all instrumentation and computerized data acquisition, is depicted on Fig. 5, while measurement sensors and data acquisition components are presented on Fig. 6. Agilent E3644A DC Power Supply with a range of 0-8V, 8A or 0-20V, 4A was used, since the typical heater requires 8.00 volt, drawing about 1.875 amp electrical current, i.e., about 15 watt power.

All thermocouple temperatures (described in previous section) and the supplied heater voltage were measured frequently throughout the testing process at a rate of five times per minute using National Instruments' data acquisition hardware and LabVIEW® application software, described in details elsewhere [4, 9].

The LabVIEW program automates all measurements and calculations, with very little input from a user; only maximum number of measurements, N_{MAX} , recommended 1500 measurements, and the output data file name and location. This condition is used to stop the program if the steady-state conditions, defined within the LabVIEW® program, are not satisfied within the maximum number of measurements. The output file contains all measurements and calculations performed during a

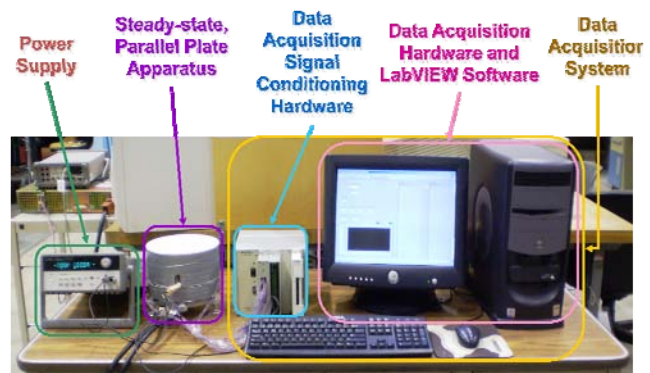


Fig. 5: Lab Setup: PPTC apparatus with all instrumentation and computerized data acquisition.

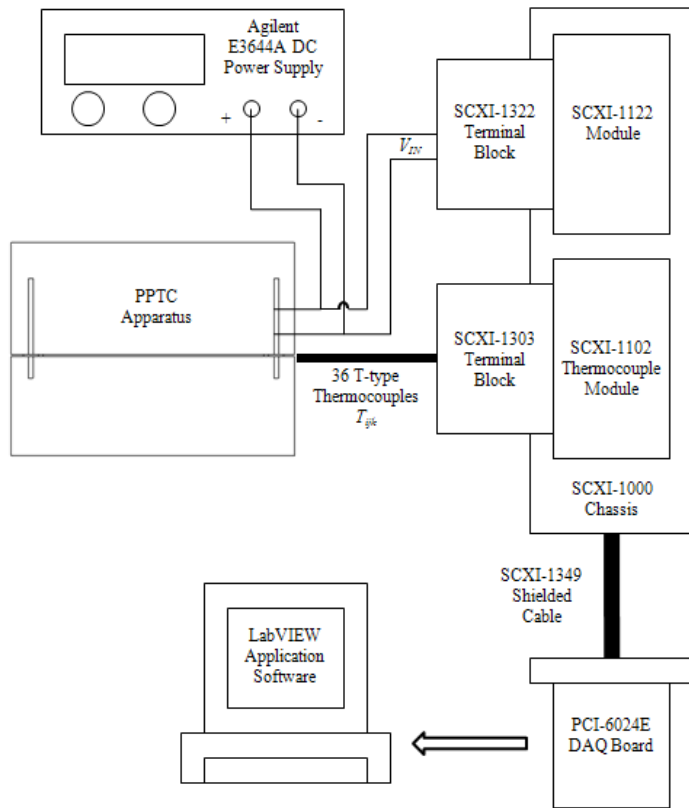


Fig. 6: PPTC apparatus instrumentation and data acquisition components.

single test in text format, convenient for further post-processing if desired. Details are given elsewhere [4, 9].

The instrumentation for all transient thermal conductivity measurements were performed using the Hot-Wire, Thermal Conductivity (HWTC) apparatus developed at Northern Illinois University [5, 6].

CALIBRATION AND UNCERTAINTY ANALYSIS

The PPTC apparatus has been thoroughly calibrated in order to insure accurate measurement results. All thermocouples used have been calibrated against a precise RTD standard, reducing thermocouple uncertainty to 0.1°C . A correction factor has been determined in order to minimize errors occurring in fluid thermal conductivity measurements due to heat loss through the apparatus. A conservative and detailed uncertainty error analysis has been performed for the PPTC apparatus using the method of propagation of errors, resulting in a conservative uncertainty within 8% at 95% probability. The unidirectional heat transfer in the apparatus has also been validated through a radial heat conduction analysis based on detailed temperature measurements. Finally, the consistency and over-all accuracy of the PPTC apparatus has been calibrated with repeatability study using distilled water. The PPTC apparatus exhibits a bias error of approximately -4.5% and a precision error of less than 4% with a 95% confidence. The PPTC apparatus exhibits an overall accuracy of

approximately 6.5%, however, when bias error is accounted for an accuracy of about 4% is achieved. By repeating measurements on the same sample the accuracy of the mean values of measured quantities and the thermal conductivity could be further improved. The details are presented in [4].

NANOFLUID THERMAL CONDUCTIVITY

A polymer- or POLY-nanofluid consists of a common or standard nanofluid with additional polymer additives [1, 2]. The reason for adding polymers to standard nanofluids is two-fold. First, certain polymer additives in extremely small concentrations, usually on an order of tens weight-parts-per-million (*wppm*), have been shown to substantially reduce the turbulent friction drag [3]. The drag reduction in turbulent flow is of importance because it may increase performance of the POLY-nanofluids in many practical applications. Second, it is expected that some of these polymer additives could increase the stability of the nanofluid suspension by preventing agglomeration of the nanoparticles. If the viscosity of the POLY-nanofluid is too high, it will have increased drag in laminar flow, but still may exhibit drag reduction in turbulent flow [3],

the latter being very important since the flows in most thermal systems are turbulent.

Nanofluids containing silica and alumina nanoparticles have been prepared first to satisfy the *zeta*-potential vs. *pH* relationship in order to achieve suspension stability [10, 11]. Then, two different polymers have been added to the 5% by weight silica-nanofluid and the 5% by weight alumina-nanofluids. The first polymer chosen was *polyvinylpyrrolidone*, or PVP, with approximately 9000 *Da* (Daltons) molecular weight, manufactured by BASF under the brand name *Luvitec K17*. This polymer was chosen because it is known to increase the suspension stability of nanofluids [12]. The second polymer chosen is *polyacrylamide*, manufactured by Stockhausen, Inc. under the brand name *Praestol-2273*, since it is known to substantially reduce friction drag in turbulent flows [3].

The polymer concentrations chosen for the POLY-nanofluids are 0.02% and 0.05% PVP by weight and 0.02% and 0.05% *polyacrylamide* by weight (i.e., 100 and 500 *wppm*), for the *silica* POLY-nanofluids; and 0.02% and 0.05% PVP by weight and 0.01% and 0.02% *polyacrylamide* by weight, for the *alumina* POLY-nanofluids. These small concentrations are judged to be sufficient to achieve the desired effects of increased suspension stability and improved frictional drag while maintaining a suitable viscosity. A lower weight concentration of polyacrylamide is necessary for the alumina-nanofluids, as a concentration greater

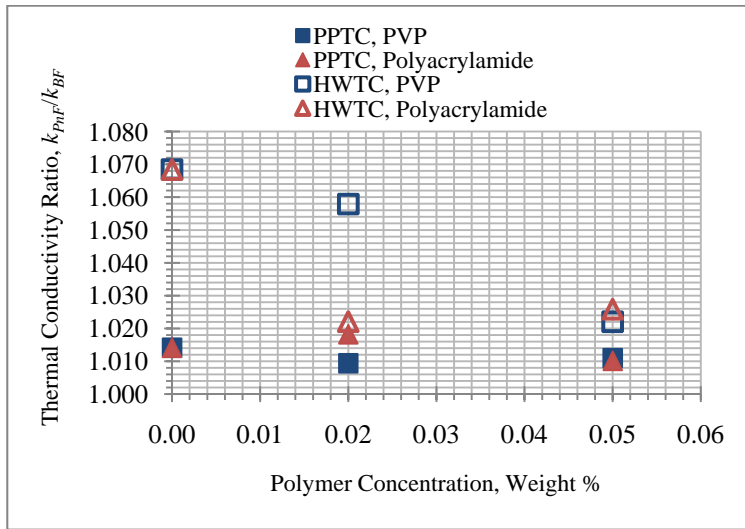


Fig. 7: Thermal conductivity ratio versus polymer concentration for 5% by-weight *silica* POLY-nanofluids (solid symbols with PPTC and open symbols with HWTC apparatus).

than 0.02% by weight leads to severe agglomeration of the nanoparticles. The thermal conductivity of these POLY-nanofluids was then measured using both, an existing transient, hot-wire, HWTC apparatus [5,6] and this new steady-state, parallel-plate PPTC apparatus [4]. Comparative measurements have been made using the two quite different methods and apparatus, in order to explore the possible influence of different measurement techniques on the thermal conductivity results of the complex POLY-nanofluids, since the existing data in the literature are very inconsistent and not well justified.

The results are presented on Fig. 7 for *silica* POLY-nanofluids and on Fig. 8 for *alumina* POLY-nanofluids. The results are expressed as dimensionless thermal conductivity ratio, k_{pnf}/k_{BF} , between POLY-

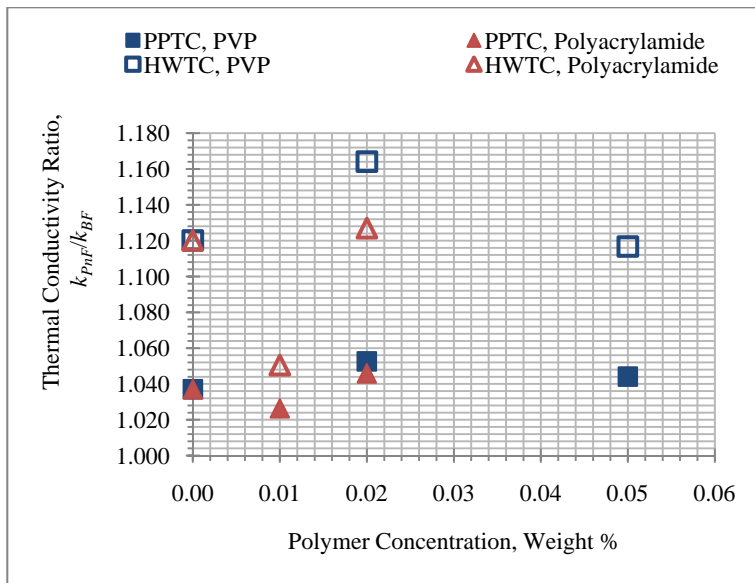


Fig. 8: Thermal conductivity ratio versus polymer concentration for 5% by-weight *alumina* POLY-nanofluids (solid symbols with PPTC and open symbols with HWTC apparatus).

nanofluid thermal conductivity, k_{pnf} , and the base fluid (water) thermal conductivity, k_{BF} , the latter typical value of 0.59 W/m/K.

The average thermal conductivity enhancement over the base fluid exhibited by the *silica* POLY-nanofluids is 1.3% when measured using the PPTC apparatus, and 4.4% when measured using the HWTC apparatus. The average thermal conductivity enhancement over the base fluid exhibited by the *alumina* POLY-nanofluids is 3.8% when measured using the PPTC apparatus, and 11.4% when measured using the HWTC apparatus. The effects of the polymer additives PVP and *polyacrylamide* on the *silica* nanofluids can be classified as statistically insignificant. The thermal conductivity enhancement over the standard *alumina* nanofluid exhibited by the *alumina* POLY-nanofluids suggest that a small concentration of PVP can be beneficial to *alumina* nanofluid thermal conductivity, while a small concentration of *polyacrylamide* can have a negative effect on thermal conductivity. The viscosity of the POLY-nanofluids was also measured and is presented elsewhere [4]. The POLY-nanofluids containing PVP exhibited a slight increase in viscosity when compared to the base fluid, while the POLY-nanofluids containing *polyacrylamide* exhibited a larger increase in viscosity when compared to the base fluid.

Unexpectedly, on average, the differential thermal conductivity enhancements measured by the HWTC apparatus are about three times greater (though with significant scatter) than the corresponding thermal conductivity enhancements measured by the PPTC apparatus. This difference demonstrated that the measurement technique might have a notable impact on the observed thermal conductivity enhancement of both common nanofluids (without, i.e., no/zero polymer additives) and POLY-nanofluids over the base fluid. However, this large difference may be contributed to the suspension instability; namely the POLY-nanofluid suspensions are observed to be degrading during the lengthy steady-state thermal conductivity measurements using the PPTC apparatus (usually takes several hours) as opposed to quick measurements with HWTC apparatus (takes only several seconds). Interestingly, the results obtained using the PPTC apparatus are similar to those predicted by the simple mixture theory [7].

CONCLUSION

An apparatus based on steady-state, one-dimensional heat conduction between two parallel plates, has been developed, designed and fabricated with main objective to measure thermal conductivity of fluids, polymer solutions, nanofluids and POLY-nanofluids [1,2,3,4]. The goal was to reduce the overall test sample volume for nanofluids, while maintaining the precision and accuracy of the apparatus. Data acquisition hardware and LabVIEW® application software are optimized to minimize signal noise and enhance acquisition and processing of useful data.

The bias measurement error, based on calibration with distilled water, has been found to be -4.5 %, and precision below 4%. The total uncertainty, after accounting for the bias error in measured thermal conductivity, has been estimated to be within 4 % at 95 % confidence probability.

These initial and limited measurements have shown considerable difference in TC measurements using the two methods, whereby the measured TC increase beyond the base fluid TC by developed PPTC apparatus was about three times smaller than the comparative measurements of apparently the same nano-mixtures using the HWTC apparatus, though with significant scatter, the former data being much closer to the mixture theory prediction [7].

However, the influence of measurement method on the TC results is not conclusive since it has been noticed that the complex nano-mixture suspensions were very unstable during the lengthy steady-state measurements as compared to rather quick transient HWTC method, so the two nano-mixture suspensions were really not the same. The nanofluid suspension instability might be the main reason for very inconsistent results in the literature. It is necessary to expend investigation of the influence of TC measurement methods on the results with more stable nano-mixture suspensions. More testing is necessary to explore the effect of measurement technique on nanofluid thermal conductivity. Also, more testing is necessary to verify the initial POLY-nanofluid thermal conductivity and viscosity results. It is hoped that these unexpected but inconclusive results will initiate constructive criticism and further investigations, related to many open questions.

ACKNOWLEDGMENT

The authors acknowledge support by National Science Foundation (Grant No. CBET-0741078), and additional support by NIU College of Engineering. The authors are also grateful for help in mechanical design and fabrication to Mr. Al Metzger, instrument maker and technician supervisor at NIU Engineering.

REFERENCES

- [1] Kostic, M., 2006, "Critical Issues and Applications Potentials in Nanofluids Research," *ASME-MN2006 Multifunctional Nanocomposites International Conference, Honolulu, Hawaii*, ASME Proceedings, 9 pp.
- [2] POLY-nanofluids (Polymer-nanofluids) & DR-nanofluids (Drag-Reduction-nanofluids): <http://www.kostic.niu.edu/DRnanofluids/>; Accessed in May 2010.
- [3] M. Kostic, 1994, "On Turbulent Drag and Heat Transfer Reduction Phenomena and Laminar Heat Transfer Enhancement in Non-Circular Duct Flow of Certain Non-Newtonian Fluids," *Int. J. Heat & Mass Transfer*, Vol.37, Suppl.1, p.133-147.
- [4] Walleck, C.J., 2009, *Development of Steady-State, Parallel-Plate Thermal Conductivity Apparatus for Poly-Nanofluids And Comparative Measurements with Transient HWTC Apparatus*, M. S. Thesis, Northern Illinois University, DeKalb, IL.
- [5] Simham, K.C., 2008, *Development of Computerized Transient Hot-Wire Thermal Conductivity (HWTC) Apparatus for Nanofluids*, M. S. Thesis, Northern Illinois University, DeKalb, IL.
- [6] Kostic, M., Simham, K.C., 2009, "Computerized, Transient Hot-Wire Thermal Conductivity Apparatus for Nanofluids," Proceedings The 6th WSEAS International Conference On Heat And Mass Transfer (HMT'09), Ningbo, China, January 10-12, 2009. In *Recent Advances in Heat and Mass Transfer* (Editor: Lifeng Xi), ISBN: 978-960-474-039-0, WSEAS Press, p. 71-78.
- [7] Maxwell, J.C., 1873, *Electricity and Magnetism*, Clarendon Press, Oxford, U.K.
- [8] Sengers, J. V. 1962, "Experimental determinations of the thermal conductivity of Fluids," *Thermal Conductivity, Vol. 2.* (Ed. Tye, R.P), Academic Press, London.
- [9] National Instruments Web site: <http://www.ni.com>; Accessed in May 2010.
- [10] Singh, B.P., Menchavez, R., Takai, C., Fuji, M., Takahashi, M.T., 2005, "Stability of dispersions of colloidal alumina particles in aqueous suspensions," *Journal of Colloid and Interface Sciences*, Vol. 291, pp. 181-186.
- [11] Oja, T., 2009. *What is Zeta Potential?* Colloid Measurements Company LLC, Scarsdale, NY.
- [12] Wei, X., Zhu, H., Kong, T., Wanga, L., 2009, "Synthesis and thermal conductivity of Cu₂O nanofluids," *Intern. J. Heat and Mass Transfer*, 52: 4371-4374.