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Determining the thermal conductivity of liquids using the transient hot disk method. Part I: Establishing transient thermal-fluid constraints

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ABSTRACT

Methods to determine the thermal conductivity of liquids have come under increased scrutiny recently due to their relative importance in determining the precise physical mechanisms responsible for heat flow in different materials and at multiple length scales. In transient-based systems, one important but often overlooked parameter is the onset of natural convection. In the first part of this study, the transient effects of natural convection are analyzed numerically for a relatively new transient thermal characterization system (transient hot disk) in order to determine when they begin to affect the calculation of a surrounding fluid's thermal conductivity. A comprehensive analysis of the effect of a fluid's pertinent thermophysical properties, Rayleigh number and Prandtl number on the sensor temperature response during testing is completed. Subsequently, a correlation is developed to determine the onset of natural convection during testing for fluids having a wide range of Prandtl numbers. The solution is verified using experimentation with multiple fluids having known, temperature-dependent volumetric heat capacities. The correlation is used as part of a new method to accurately calculate the thermal conductivity of different Newtonian fluids in Part II of this study, which is published separately.

1. Introduction

Measuring the thermal conductivity of fluids is critically important for the development of novel thermal management systems [1–3] and for understanding the physics of complex fluids, such as nanofluids [4–6]. However, the reported thermal conductivities of these fluids vary widely among research groups using different thermal characterization techniques. This is particularly troublesome in the area of nanofluids [7–10], where an inaccurate measurement can result in a significant misrepresentation of the dominant thermophysics at different length scales within the fluid.

In order to illustrate the difficulty in measuring the thermal properties of fluids, it is useful to discuss the current state of research within the subject of nanofluids. In this area, the variation among reported values of effective thermal conductivity is significant and may be due to a variety of factors, including: the surface conditions of the nanostructures suspended in each fluid [11–15], the fluid's pH [16–19], the differences among measurement techniques [20–22] and liquid layering at the nanostructure interface [23]. A recent study attempted to establish a benchmark of the thermal conductivity of different types of nanofluids in an effort to definitively explain the thermophysical mechanisms that dominate heat transfer in homogenously distributed suspensions [24]. In this study, nearly 20 research groups evaluated the thermal conductivity of nanofluids that were synthesized in the same facility, thereby eliminating the differences between the physical, chemical and geometrical conditions of the nanoparticles used. Consequently, the only remaining difference among the measurements of thermal conductivity is the thermal characterization technique used. In the aforementioned study, the guarded hot plate, transient hot wire and transient hot disk techniques were used to measure the thermal conductivity of the nanofluid samples. Results suggest that there is a statistically significant deviation between the data obtained using each of the different measurement techniques, with considerable outliers in nearly all sample sets. The authors did not report the conditions (i.e. experimental run times, equipment geometries, etc.) used to determine the thermal conductivity in each case. One possible cause for this discrepancy, then, is that the onset of natural convection occurred at a time prior to the end of the test in one or more of the transient systems. Though some studies do exist to provide guidelines for avoiding natural convection in some transient-based systems [25–27], none allow the user to quantify when convection occurs based on pertinent fluid and system parameters, and thus users are currently unable to avoid its influence during experiment with great certainty. A number of other studies have confirmed that natural convection plays a significant role in the accuracy of different transient-based thermal characterization systems and have determined this to be one of the major factors that has fueled the ongoing debate over

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the influence of nanoparticles on the thermal enhancement of common heat transfer fluids [20–22]. The results of the work done in these studies [20–22] suggest that natural convection, which is encountered when experimental run times are ‘too long’ or sensor power levels are ‘too high’, results in artificially high thermal conductivities. However, no criteria for the determination of this time as a function of pertinent experimental parameters (such as the fluid’s Prandtl number) currently exist. Thus, in order to establish an accurate and repeatable solution method to use for measuring liquid thermal conductivity with transient thermal characterization techniques, it is critical to determine the maximum allowable experimental run time for each type of test as a function of all relevant experimental parameters.

The transient hot disk method is emerging as a primary tool for the measurement of the thermal conductivity of novel materials [16,17,28–33] due to its multiple advantages over other transient thermal characterization techniques. In fact, the transient hot disk method is represented in approximately 8% of the studies on the thermal conductivity of nanofluids as of 2010 [20], while less than 5% used steady-state techniques. Steady-state techniques, while simple and cost-effective to implement, require extremely careful preparation in order to avoid high measurement uncertainties, require very long run times and do not have the ability to maintain a precise fluid temperature. Transient techniques, on the other hand, have fast measurement times and can maintain a constant fluid temperature during testing. The most commonly used method, the transient hot-wire technique, is also cost-effective and has been well studied since its inception in 1931 [34]. However, its measurement capabilities are also limited. The platinum hot wire, for instance, is both expensive and brittle. Thus, it is extremely difficult to measure the thermal conductivity of adhesives, fluids with large Prandtl numbers, fluids in extreme temperature environments and nanofluids without risk of damage to the sensor during sample handling and testing. In order to measure the thermal conductivity of these types of materials without risk of damage to the equipment, research groups have increasingly turned to the transient hot disk system. In addition to being a robust and rapid thermal characterization method, the transient hot disk apparatus is able to determine both the thermal diffusivity and thermal conductivity of fluids and solids, which are important to characterize for materials used in transient applications (such as thermal energy storage materials [35–37]).

The transient hot disk technique, like the transient hot-wire technique, utilizes a volume element (sensor) that serves as both a heat source and a temperature sensor. The sensor must be fully immersed in a fluid or sandwiched between two solid samples in order to measure thermal conductivity. In principle, when the sensor is powered, its temperature will increase rapidly when immersed or sandwiched between insulating materials and increase slowly for thermally conductive materials. A detailed formulation of the solution for the thermal conductivity of fluids using the transient hot wire technique can be found in [38], while a detailed formulation of the solution for the thermal conductivity of materials using the transient hot disk can be found in [39] and the second part of this study [40]. While many studies have utilized the transient hot disk method to measure the thermal conductivity of solid materials [41–48], fewer have used this method to characterize the thermal conductivity of liquids [49–52]. Some of the studies on liquid phase thermal conductivity with the hot disk technique highlight the difficulty in taking measurements due to the possibility that natural convection occurs during testing [49,50], while others ignore these potential effects altogether [51,52]. In an effort to limit the presence of natural convection during testing, some researchers [49,50] have taken to substantially reducing measurement times and sensor power levels. However, this too can lead to inaccuracies in measurement, as such short sampling times may exaggerate the effects of the interfacial thermal resistance between the sensor and the fluid, and low power levels often lead to high rates of data scattering, resulting in artificially high thermal conductivities. A careful examination of these phenomena is given in the second part of this study [40] in order to determine optimal experimental run times during which natural convection is absent.

Though attempts have been made to avoid natural convection during testing with the transient hot disk system, few groups have compiled any quantitative data that illustrates the potential effect that it may have on calculating thermal conductivity. In a recent study, Nagai et al. [53] compared the measurements of the thermal conductivity of silicone oils using the hot disk method in both a microgravity environment and a ‘ground-based’ environment. Their results indicate that the measurements were greatly affected by the presence or absence of convection during testing, particularly for low Prandtl number fluids. More recently, Boumaza and Redgrove [49] evaluated the effect of natural convection on the calculated thermal conductivity of water and silicone oil when the hot disk sensor face was perpendicular to the direction of gravity. The authors found that Rayleigh–Benard convection currents increased with increasing sensor diameter, indicating that the Rayleigh number has a significant effect on the onset of convection in fluids. However, their work realistically represents a sensitivity study, and no effort was made to determine when convection occurs across the face of the sensor as a function of the thermophysical properties of the fluid and the power loading level of the sensor. In their conclusion, the authors comment that using a smaller sensor size can reduce the onset of significant natural convection, but that “for liquids it is clear that further development of the probe or measurement technique is required to obtain greater accuracy”. Ultimately, no criteria currently exist to determine the time at which convection will occur as a function of sensor size, sensor power level and fluid type.

In an effort to reduce the uncertainty of the transient hot disk thermal characterization technique, a correlation for the onset of natural convection across a conventional hot disk sensor of varying diameter is developed in the first part of this study. This correlation is developed as a function of the surrounding fluid’s thermal expansion coefficient, its Prandtl number, the Rayleigh number and the sensor power load via numerical simulation and experiment. Numerical simulation is performed using FLUENT (v. 12). The effect of sensor temperature rise during the measurement on the calculated thermal conductivity of the fluid is also examined due to the potential for the liquid to heat up rapidly in close proximity to the sensor face. In the second part of this study [40], an iterative solution procedure is developed using the correlation for the onset of natural convection that is established in this portion of the study and is verified using fluids with a wide range of Prandtl numbers.

2. Problem formulation

In this analysis, a thin circular disk is vertically immersed in a fluid with known thermophysical properties at an initial temperature, $T_0 = 303.15$ K. The circular element used in this study has a radius $r = 3.189$ mm and a thickness $t = 0.01$ mm, which represents a standard sensor size available for thermal characterization with the hot disk method. The radius remains unchanged in the numerical simulations. The strength of natural convection as represented by the Rayleigh number (Eq. (1)) is varied by changing the sensor power. In order to determine the effect of Ra, Pr (Eq. (2)) and thermal expansion coefficient (β) on the time to natural convection, each parameter is varied in a parametric analysis. The Prandtl number ranges from 0.7 to 1324 to represent a wide range of heat transfer fluids. Likewise, the coefficient of thermal expansion, β,