Exploring Thermal Properties Measurement of Natural & Engineered Materials

HEAT PULSE

2008

Fluid in motion: Movement complicates measurement in nanofluids.

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How Cool are Nanofluids?

An Accurate Way to Measure Thermal Conductivity in Liquid

Nanofluids are the next big thing in cooling everything from engines to supercomputers. Before they can be commercially interesting, however, they need to be better understood. So far, research results have been anything but consistent.

Searching for "Experimental Reality"

Some studies have reported astonishing thermal conductivities for nanofluids; others have found much more modest numbers. The high end numbers fall way outside values that current "effective medium theory" would predict. Some people have speculated that a whole new theory is needed to understand these super fluids.

Dr. Samuel Sprunt, a physicist at Kent State University, was asked to look into the "experimental reality" of these surprisingly high thermal conductivities and, if he could replicate them, to propose a theory that explained them.

Measuring Liquids: A Challenge

Measuring the thermal conductivity of any liquid can be tricky. The technique is simple, but thanks to the effects of convection it's hard to do properly.

Many investigators use the hot-wire technique, in which a super thin heating wire approximates the "infinite line heat source" required by the theory behind a popular thermal properties measurement method. Dr. Sprunt was concerned about transient effects, however, so he initially planned to use the parallel plate method, in which you heat one plate and measure temperature changes at the other.

A Quick and Accurate Way

According to Dr. Sprunt, this method has a lot of theoretical advantages, but in practice, it proved difficult. "While we were able to find a vendor and try some samples, the results we got were not satisfactory," he says. "We tried just ordinary pure fluids whose thermal conductivities are well tabulated, and those numbers were not consistent or accurate." Dr. Sprunt speculates that readings were distorted by fluid convection or invalidated by an air pocket between the plates.

Needing to come up with a "quick and hopefully accurate way" to measure thermal conductivity in fluids, Dr. Sprunt and his colleagues found Decagon's KD-2 Pro on the internet. "The price was surprisingly good," says Dr. Sprunt, "so we figured if this didn't work, it wasn't that much of an outlay." He was surprised and pleased to see that measurements on the pure fluids correlated well with known values.

"Pretty Phenomenal Results"

"We discovered that there are some limitations to the probe…it doesn't work terribly well above about 60 or 70 °C. But at lower temperatures, we were getting some pretty phenomenal results," says Dr. Sprunt, "And Doug [Cobos, Decagon Research Scientist] has been giving us some ideas about how to lower the heat pulse in the unit further."

When Dr. Sprunt and his colleagues tested the nanofluids, they found no extraordinary thermal conductivities. In fact, says Dr. Sprunt, it was just "what you would expect if you substituted

*EV Timofeeva, AN Gavrilov, JM McCloskey, YV Tolmachev, S Sprunt, LM Lopatina, JV Selinger. Thermal conductivity and particle agglomeration in alumina nanofluids: experiment and theory.

volume for volume a higher conducting substance for a lower conducting substance. That's the basic conclusion of our paper*."

Of course, these results don't constitute a definitive answer. They have to be checked, double checked, and rechecked. Nanofluids researchers are setting up a consortium to exchange samples and correlate results, and Kent State University plans to participate in that consortium.

New Challenges

Even while participating in the consortium, however, the Kent State researchers are ready to move on to new challenges. Dr. Sprunt expects that real advances in the thermal properties of these liquids will come not through discovering a nanofluid with extraordinary properties, but through "using existing, well understood, simple, boring, dull effective medium theory" to create better thermal enhancements.

"We're probably not going to continue the search for this mysterious 'enhanced conductivity.' [Instead,] we're going to look at deliberately making structures that within the effective medium theory will give large enhancements, not anomalous or mysterious, but enhancements that can be understood and exploited. One way to do that is to make anisotropic particles. If you get those lined up along the temperature gradient, you can get quite a boost in conductivity, but within well understood principles, and not from speculative mechanisms that nobody's been able to demonstrate consistently." ■

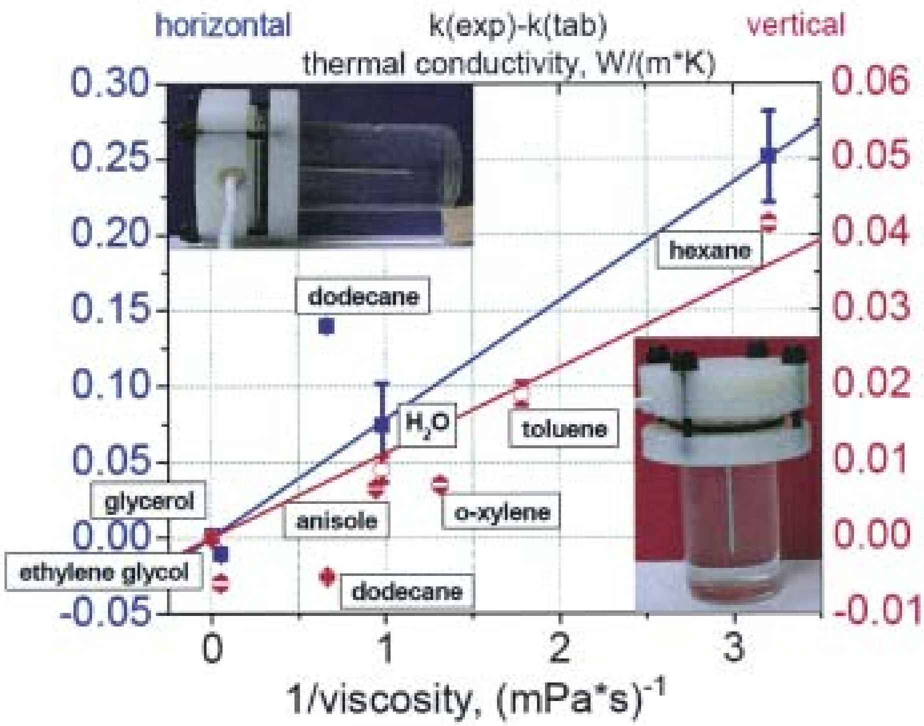

Fig. 2. Difference between measured heat conductivity and reference values for pure solvents as a function of inverse viscosity. [Credit Dr. Samuel Sprunt]

▲ Managing Errors Created by Convection

Dr. Sprunt and his colleagues found that even in the isothermal cell they designed for their experiment convection could not be completely prevented. Still, this graph they created shows that their experimental setup "does work pretty well at ambient temperatures at a wide range of pretty low viscosities."

Convection increases measured thermal conductivity; the error is smaller when the probe is vertical and the fluid is highly viscous.

"We suggest checking for the convection contribution by comparing results in the horizontal and in vertical cell," says Dr. Sprunt. "If the difference is too large for your accuracy, then convection contribution is not negligible for your application."

*Physical review. E, Statistical, nonlinear, and soft matter physics. 2007 Dec;76(6 Pt 1):061203

The KD-2 Pro on the Barbecue

Solving kitchen problems with higher math

The temperature distribution and heat flow in a steak cooking on a grill is pretty complex. It could be modeled on a computer, but we can also approximate it with a solution to a highly idealized steak cooking situation. Assume you have a thick slab of meat initially at temperature To. At time 0 one surface of the meat is placed in contact with the grill surface at temperature Tg. For this simple condition the temperature of the meat for any time, t and any depth, z beneath the heated surface can be computed from

$$\frac{T(z,t)-T_o}{T_g - T_o} = erfc\left(\frac{z}{2\sqrt{Dt}}\right) \qquad (1)$$

Here D is the thermal diffusivity of the meat and erfc is the complementary error function which can be found in tables or approximated numerically (Press et al. 1989).

We want to know the time it will take to bring the center of the steak to the desired temperature. We can therefore take z to be the half thickness of the steak, T(z,t) as the temperature from Table 1, To as the initial temperature of the steak, and Tg as the grill temperature.

Probing for Diffusivity

The only way to get D (thermal diffusivity) is to measure it. Thermal diffusivity is the ratio of thermal conductivity to volumetric specific heat of a substance. The KD2-Pro thermal properties analyzer measures both thermal conductivity and volumetric specific heat using two needles, one with a heater and the other with a temperature sensor. A heat pulse applied to the needle is sensed by the sensor in the adjacent needle. By analyzing the temperature response the thermal properties of the material can be determined.

Solving the Equation

Equation (1) can be solved to determine the time required for the meat to reach the desired temperature:

$$t = \frac{z^2}{4D\left[erfc^{-1}\left(\frac{T(z,t)-T_o}{T_g - T_o}\right)\right]^2} \qquad (2)$$

The only hard part of this equation is finding values for the inverse complimentary error function. Values are given in Table 2 for the range of temperatures likely to be encountered in cooking steaks on a grill. ■

TRY THIS EXAMPLE

How long will it take to cook a refrigerated 1" cut steak (about 35°F) to medium rare (130°F) if the grill temperature is 500°F?

The diffusivity is easiest to deal with in metric units, so let's measure the meat thickness in metric. Half the thickness of a 1" steak is about 12 mm.

Let's say we measure the diffusivity of the meat and find it to be 0.2 mm²/s.

Table 2 shows that the corresponding inverse complementary error function value is 0.9.

$$\frac{T(z,t)-T_o}{T_g - T_o} = \frac{130 - 35}{500 - 35} = 0.20$$

Solve for t, then grab a stopwatch. This steak should stay on the grill for 14 minutes and 49 seconds.

Decagon Thermal Properties Sensor on Mars

On May 25, NASA's Phoenix Scout Lander reached Mars, opened a soils lab, and started looking for water. Phoenix uses a robotic scoop arm to deliver regolith samples to the suite of instruments aboard the Lander--with one exception. The thermal and electrical conductivity probe (TECP) designed by a team of research scientists at Decagon Devices, Inc. is actually mounted on the robotic arm and makes direct contact with the regolith. It measures thermal conductivity, thermal diffusivity, electrical conductivity, and dielectric permittivity of the regolith, as well as vapor pressure of the air.

Produce precisely the steak your guests ordered using thermal properties and pure math.

Finding Water, Building Climate Models

Phoenix used the TECP to look for evidence of water on Mars and to determine thermal properties of the regolith for use in climate models. The data collected so far await analysis, but the numbers look intriguing and promising not just for Mars study but here on earth.

Earthside Benefits

The results of the Mars project go beyond the data, though. Ideas that made the Mars mission possible benefit all of Decagon's thermal properties instruments. "We don't use conical needles in our commercial thermal properties sensors, but the mathematical models we developed for Mars make those sensors much more accurate and effective," says Dr. Colin Campbell, another member of the team. "The Mars project has expanded both the depth of our understanding and the breadth of our perspective." ■

x	$erfc^{-1}(x)$
0.1	1.16
0.2	0.90
0.3	0.73
0.4	0.60
0.5	0.47
0.6	0.38

Table 2. Inverse complementary error function for values of the temperature ratio likely to be encountered in grilling meat.

The Phoenix Mission has been gathering soil and climate data in the Martian Arctic for five months.

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New ASTM Standard to be Published in 2009

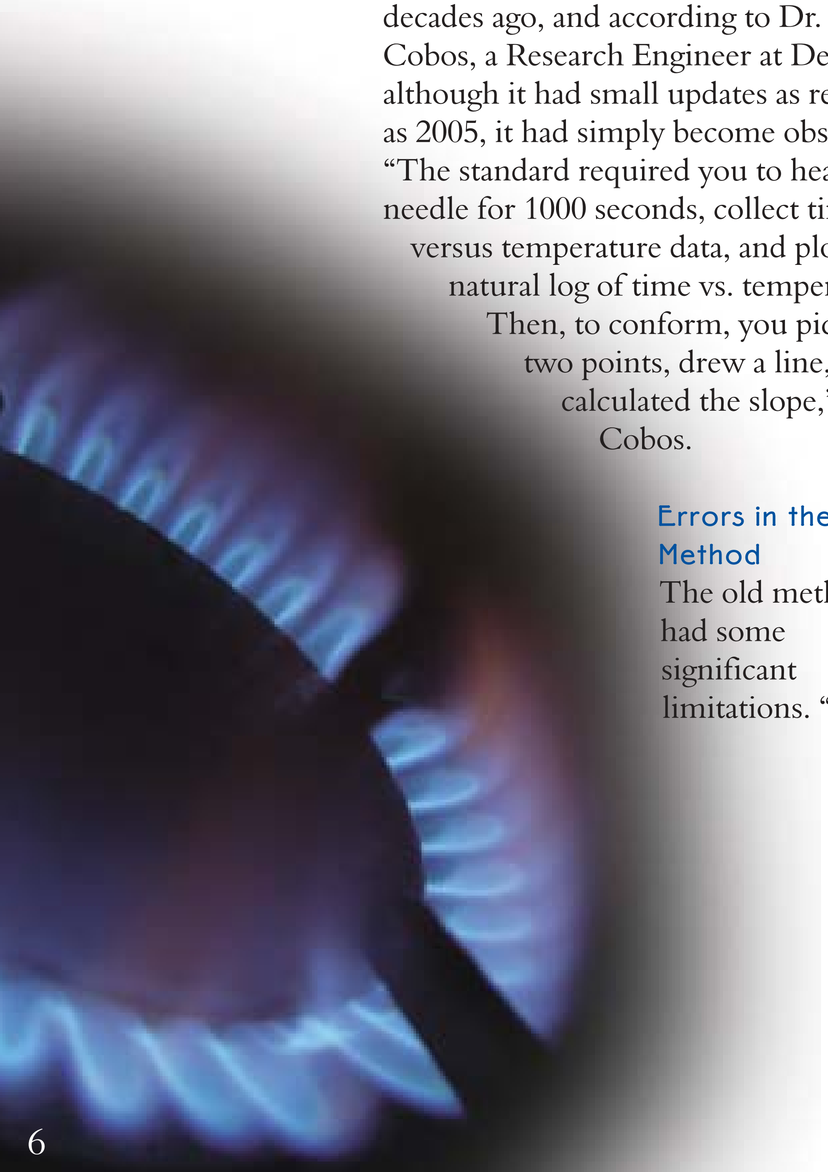
Good News: Put Away the Graph Paper

Use best practices *and* conform to the ASTM standard with the push of one button.

Balloting closed June 10, 2008 on the new ASTM standard D5334-08 for single needle heat pulse probes. You can read the full text of the standard at the ASTM International website (http://www.astm.org). New 2009 ASTM publications will cite the revised standard, but the bottom line for consultants and practicing engineers who use the KD-2 PRO is that at last they can conform to the ASTM standard using the KD-2's sophisticated data analysis software instead of a pencil and graph paper.

Outdated Standard

ASTM D5334-05 was originally written decades ago, and according to Dr. Doug Cobos, a Research Engineer at Decagon, although it had small updates as recently as 2005, it had simply become obsolete. "The standard required you to heat a needle for 1000 seconds, collect time versus temperature data, and plot natural log of time vs. temperature. Then, to conform, you picked two points, drew a line, and calculated the slope," says Cobos.



Errors in the Method

The old method had some significant limitations. "Heat flow is a basic equation when you're calculating heat flow from a plane to a plane." explains Cobos. "Heat flow from a needle is also pretty simple if you keep the needle heated. But as you heat the needle, you cause water to flow away from it, and you get big errors as the water redistributes. You can solve the water redistribution problems by heating the needle in short bursts, but then calculating heat flow is no longer simple—it goes way beyond two points and a line."

KD-2 Uses Complex Numerical Methods

Decagon's KD-2 probe gets its accuracy by using the heat pulse method and calculates thermal conductivity using an intricate mathematical algorithm. "The KD-2 uses complex numerical methods, but it should simplify things for the engineer," says Dr. Cobos. "If you stick the needle in right, you get very accurate thermal conductivity data with one punch of the button."

Conforming With Pencil and Paper

The KD-2 Pro complied with the old ASTM standard, but there was a hitch. "In order to conform completely to standard, our customers had to extract raw data and draw a graph. It created a lot of extra work and degraded the quality of the data," says Cobos. "It ▶

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became clear that we needed to help bring that standard up to date."

Change "Long Overdue"

Two years ago, Dr. Cobos got involved with ASTM. As you'd expect, standards change is slow and deliberate. The process involves sitting on a subcommittee, proposing changes, authoring them, debating them and responding to all comments. Naturally, every committee member has to agree to the new standard.

It took two years to update ASTM D5334-05. But the result is a modern standard that lets engineers use best practices *and* conform to the ASTM standard with the push of one button.

One Down, One to Go

As one committee member said, "Thanks for stepping up to the plate and revising this standard. It's been badly needed but nobody has been willing to devote the time to update it."

"It was worth it," says Cobos, "but I'm not ready to take on the dual needle standard until I've recovered a little bit." ■

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Thermal Testing Service Available for Tough Samples

Decagon has partnered with a local independent testing laboratory to offer a material thermal properties testing service.

This service specializes in determining thermal resistivity of solid, granular, and liquid materials. For liquids, solids and small grain particles, test methods ASTM D5334-05 and IEEE 442-1981 are used. A specially designed steady state thermal apparatus is used for more difficult large particle samples such as gravels and aggregate materials.

Other thermal properties testing is also available, including thermal conductivity of all sample types, as well as thermal diffusivity and volumetric specific heat of small grained granular materials and liquids. We can evaluate the samples over a wide range of temperature as well, -40 to +100 °C (depending on sample type).

Additionally, in porous media (like soils), thermal properties can be measured at specified water content ranging from oven dry to saturation and at specified material density. Most samples can be analyzed within two weeks of receipt of material at Decagon. Contact Decagon for more information or quotes for specific services. ■

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American Geophysical Union (AGU)
15–19 December 2008
San Francisco, California, USA

European Geosciences Union (EGU)
19–24 April 2009
Vienna, Austria

Thermal Conductivity Short Course 2010
Barcelona, Spain

Experimental Heat Transfer, Fluid Mechanics and Thermodynamics (EXHFT-7)
28 June–03 July 2009
Krakow, Poland

International Thermal Conductivity Conference (ITCC)
29 August–02 September 2009
Pittsburgh, Pennsylvania, USA

Measuring and Modeling Thermal Properties of Soil, Rock and Concrete
Online Virtual Seminar
December 2008

Soil Thermal Properties Seminar

Good soil properties analysis is a critical part of many projects, but it isn't always done or done correctly. Even with the best intentions, project engineers are hampered by:

- **Inaccuracies in the National Electrical Code Annex B:** Numbers are off by a factor of 2 to 4 in a direction and can lead to serious trouble.

- **Meaningless charts:** Soil resistivity is extremely variable in space and time, making a chart of resistivity values almost worthless.

"...and we can save 700 lira by not taking soil tests."

- **Variability:** Changing moisture conditions dramatically affect thermal resistivity/conductivity.

- **Outdated standards:** Following ASTM and IEEE guidelines can lead to almost arbitrary results.

- **Flawed traditional methods:** Using uncalibrated IEEE large thermal resistivity probes results in a consistent 40% error.

- **Temperature drift:** Even when it's almost imperceptible, temperature drift can lead to significant errors.

Dr. Gaylon Campbell addresses these and other issues in a free online Soil Thermal Properties seminar. Dr. Campbell discusses soil thermal properties, how to measure them, and how to model their behavior. The discussion includes details about applications, definitions, behavior, measurement, standards and modeling. To obtain a copy of the archived seminar, contact Decagon. ■

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"A few years ago I participated in a soils field trip. One of the sites visited was in southeastern Washington where hundreds of wind power generators have been installed.

The group asked why some of the generators were not working and were told that the underground cables connecting those generators to the grid had burned out. The operators said the wind blown soil (loess) that makes up that area had especially low thermal conductivity. They claimed that this fact was not known until the problems with burned out cables emerged.

"The thermal properties of this soil are not unusual; in fact, theyíre well understood by soil scientists. The real problem was one that many of you likely have encountered. As depicted in this cartoon, soils information usually isn't sought as part of the design. People only start asking questions when problems arise. That approach, of course, is an expensive one."