High-Accuracy Density Measurements: Analysis of Force Transmission Errors in Magnetic Suspension Densimeters

NIST researchers carried out a new analysis of force transmission errors in magnetic suspension densimeters has been carried out, significantly reducing the measurement uncertainties in this type of instrument. Instruments employing the Archimedes (bouyancy) technique in combination with a magnetic suspension coupling for the measurement of fluid density are capable of very high accuracies, but they are subject to systematic uncertainties—known as force transmission errors—due to the effects of magnetic materials, including the magnetic characteristics of the fluid being measured.

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The pressure-density-temperature (p-ρ-T) properties of fluids are key thermophysical property data needed for the development of accurate equations of state. For measurements over wide ranges of temperature, pressure, and density, instruments combining the Archimedes technique with a magnetic suspension coupling have been highly successful in recent years. The Archimedes technique involves weighing a "sinker" of known volume while it is immersed in the fluid of interest; the difference between the apparent mass of the immersed sinker and its true mass yields the fluid. The magnetic suspension coupling transmits the weight of the sinkers to the balance, and separates the fluid, which may be at extremes of temperature and/or pressure, from the balance, which is at ambient conditions. It consists of two magnets on opposite sides of a pressure barrier: an electromagnet hung from the balance and a permanent magnet, from which the sinker is suspended, that is immersed in the fluid.

The efficiency of the force transmission across the magnetic coupling is nearly one, but the coupling will be slightly influenced by nearby magnetic materials, external magnetic fields, and the fluid being measured. These give rise to a "force transmission error" (FTE) that must be accounted for to realize the full accuracy of this technique. The FTE can be divided into two parts. The first arises from the magnetic characteristics of the apparatus itself; it is determined by comparing the known mass of the sinker with a weighing of the sinker using the magnetic coupling. The apparatus effect is well-known, and this correction is routinely made. The magnetic susceptibility of the fluid surrounding the magnets also influences the FTE, but these effects are often ignored. Even when this "fluid specific effect" is included, the details of the correction have, to date, been murky, at best.

In a paper presented at the 16th Symposium on Thermophysical Properties (held August, 2006 in Boulder) and submitted to the *International Journal of Thermophysics*, NIST, together with researchers from Ruhr Universität in Bochum, Germany, has presented a thorough analysis of the force transmission error. The analysis introduces a parameter termed the "coupling factor", which characterizes the efficiency of the force transmission by the magnetic coupling. The NIST densimeter has two sinkers (of similar mass, but different volumes) and two external masses, which are used to calibrate the balance. Thus, a density determination involves four separate weighings. The forces on the balance for each of the weighings are written out in detail to yield a system of four equations in four unknowns that are solved for the fluid density, a balance calibration factor, a parameter related to the balance loads which do not change, and the coupling factor, which is directly realted to the force transmission error. The data from measurements of seven different fluids show that the coupling factor is the sum of an apparatus contribution (which is nearly constant) and a fluid-specific contribution, which is proportional to the fluid density and the magnetic susceptibility of the fluid.

> The NIST densimeter is the only two-sinker densimeter in the world that has the external masses that allow the determination of the force transmission error at each measured density.

There are a handful of other two-sinker densimeters, but these instruments have typically compensated only apparatus effect and have ignored the effects of the fluid. The fluid effect was found to be on the order of 20 ppm for most fluids, but it was as high as 800 ppm for air at high pressures. (While most fluids are weakly diamagnetic, the oxygen in air is strongly paramagnetic.) With the new analysis, the force transmission error is completely compensated for with an uncertainty of about 5 ppm.
The more common type of magnetic suspension densimeter has only a single sinker. This type of instrument does not benefit from some of the error-canceling effects present in two-sinker instruments, and force transmission errors are about an order of magnitude higher. But, the simulataneous analysis of FTE is not possible—there are not enough equations to solve for the unknowns. Our analysis also considered single-sinker instruments. First, data from the NIST two-sinker densimeter were reanalyzed as a vir-

tual one-sinker instrument (*i.e.* the weighing data for one of the sinkers were ignored); by comparing the resulting "single-sinker densities" to the two-sinker results, the magnitude of the force transmission errors were quantified. Then, we demonstrated how an apparatus constant (determined by comparing a set of measurements with a similar set made with a different sinker installed), combined with knowledge of the magnetic susceptibility of the fluid could be used to correct for the FTE in single-sinker densimeters. This allows single-sinker instruments to approach the accuracy of a two-sinker densimeter.

Sinkers and magnetic suspension coupling at the heart of the NIST densimeter. The electromagnet at the top hangs from the balance and levitates the permanent magnet below it. In this photo, the top sinker is being weighed, while the bottom sinker sits on its rest. The permanent magnet and sinkers are normally contained within a pressure vessel.