Accurate Flow Meter and Viscometer for Gases

Integrated circuits are made in reaction chambers, or process "tools", each of which receives gases from several mass flow controllers at rates which can be as small as 1 cubic centimeter per minute at atmospheric pressure. The uncertainties of the mass flow controllers are typically 1 %, but improvements to 0.5 % are desired. To help the semiconductor industry with this improvement, NIST created a primary standard for small gas flows whose uncertainty is only 0.02 %. NIST then created a portable transfer standard with an uncertainty of 0.04 %.

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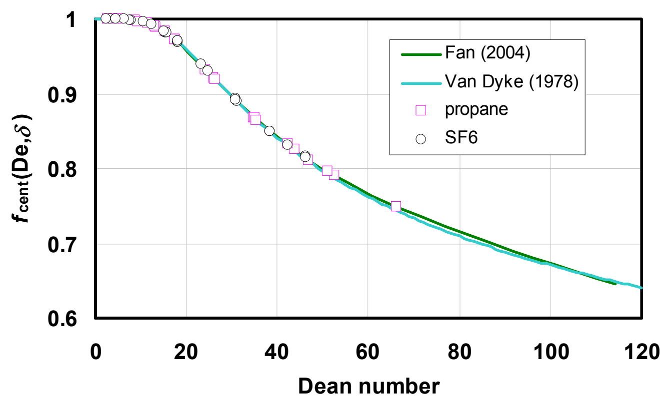
NIST's portable transfer standard has an unprecedented uncertainty of 0.04 %. Achieving such small uncertainties was important because the primary and transfer standards are the first links in a chain of comparisons from NIST to manufacturers of mass flow controllers, and each link increases the uncertainty. The manufacturer either extends the chain to the calibration of the installed mass flow controller, or uses it to verify the performance of its independent primary standard.

The NIST portable transfer standard can serve as either a flow meter or viscometer. Its heart is a coil of quartz capillary of the sort ordinarily made to careful tolerances for gas chromatography. Gas flows through the capillary, transducers measure the pressures at the input and output, and a hydrodynamic model converts the pressure measurements to a flow rate.

The NIST hydrodynamic model achieves good accuracy because it incorporates the six most important corrections to the Hagen-Poiseuille equation for capillary gas flow, and the smooth (laminar) flow through the capillary's simple geometry made the corrections unambiguous. The largest correction was for the centrifugal effects due to coiling the capillary. Measurements with a variety of gases initially disagreed by as much as 0.7 % with the best analytical model for centrifugal effects, but they later were shown to be accurate because they agreed with recent results from a numerical flow model calculated in toroidal coordinates. [Y. Fan, private comm. (2004); Y. Fan, R.I. Tanner, & N. Phan-Thien, *J. Fluid Mech.* **440**, 327 (2001)]

Careful measurements of the capillary's length and radius turned the transfer standard into a primary viscometer. The length was measured by laying out the capillary on a laser interferometric bench, and the radius was measured by weighing the capillary before and after filling it with mercury. The small uncertainty was verified by comparing the result for the viscosity of helium to recent calculations using quantum mechanics and statistical mechanics. Helium is the only fluid for which calculations of the required accuracy are possible.

Centrifugal effects at moderate Dean number decreased the rate of flow through the coiled capillary by more than 20%. Measurements with propane and sulfur hexafluoride agreed with a numerical flow model calculated in toroidal coordinates [Fan (2004)]. (Centrifugal effects scale with Dean number; a value of 60 corresponds here to a Reynolds number of 1500.)



The publications (listed below) that describe the transfer standard, its hydrodynamic model, and the supporting measurements will allow other laboratories to construct and confidently use similar viscometers and flow meters for gases. We are planning to build and test a flow meter for smaller gas flows (0.1 cm^3/min at atmospheric pressure) that will be used to calibrate medium-range vacuum gauges. This work relied on primary standards for gas flow developed recently at NIST, and was funded by the NIST Office of Microelectronic Programs.

The NIST Pressure & Vacuum Group is testing an improved transfer standard that is shoe-box sized and easier to use, but has comparable accuracy.

References:

Berg, R.F., ***"Quartz capillary flow meter for gases,"*** Rev. Sci. Instrum. **75**, 772-779 (2004).

Berg, R.F., ***"Simple flow meter and viscometer of high accuracy for gases,"*** Metrologia **42**, 11-23 (2005).