Helmholtz-Rayleigh Interdisciplinary Silver Medal
in
Physical Acoustics and Engineering Acoustics

Michael R. Moldover

2021

The Silver Medal is presented to individuals, without age limitation, for contributions to the advancement of science, engineering, or human welfare through the application of acoustic principles, or through research accomplishment in acoustics.

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Helmholtz-Rayleigh Interdisciplinary Silver Medal

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David Lubman	2004	Armen Sarvazyan	2016
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Interdisciplinary Silver Medal

Eugen J. Skudrzyk	1983
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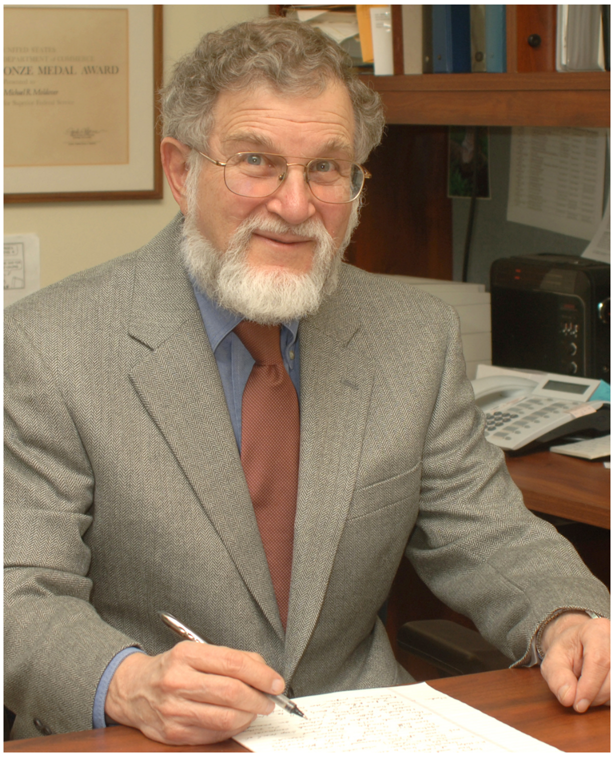

CITATION FOR MICHAEL MOLDOVER

…for establishing spherical acoustic resonators as the foundation of the kelvin in the International System of Units

ACOUSTICS IN FOCUS • 4 JUNE 2021

The standardization of weights and measures has been central to the progress of civilization, commerce, and science since antiquity. Early length standards were based on body parts; next came length and weight standards based on objects kept by authorities and standards based on particular materials. Beginning in 1954, the temperature scale was defined by the triple point of water, with the isotopic variations of water from place to place making this a small insult to the concept of "universal" standardization, as well as a practical nuisance. Today, the kelvin stands firmly on acoustics, thanks to Michael Moldover's development of acoustic resonance techniques of unprecedented accuracy for the measurement of thermodynamic properties of fluids, and thanks to his persistent advocacy for this practical and aesthetic foundation for the kelvin.

Thirteen years after his Ph.D. in physics from Stanford University, and early in his lifelong career at the National Institute of Standards and Technology (originally the National Bureau of Standards) in Gaithersburg, Mike appeared on the ASA scene with papers and talks describing the use of radial resonances in spherical resonators to measure fluid properties such as specific heats and virial coefficients. Resonance measurements rely on frequency measurements, where accuracy is easy; and the radial resonances in spheres avoid viscous boundary-layer damping (but retain thermal boundary-layer damping). In these early stages of Mike's work, one powerful insight was that volume-preserving shape uncertainties in spherical cavities generate no first-order shifts in resonance frequency, so the imperfections of ordinary machine-shop fabrication techniques were unimportant—only the volume of the sphere needed accurate measurement. A second powerful insight was that measuring the ratio of acoustic resonance frequencies to microwave resonance frequencies in such cavities would tie a measurement of the universal gas constant R directly to the speed of light.

In a 1988 article in the *Journal of Research of the National Bureau of Standards*, Mike reported measuring R at the triple point of water, using acoustic resonance in argon, obtaining $R = 8.314471$ J/mol-K with an uncertainty of only 1.7 ppm, a factor of 5 reduction in uncertainty from any previous work. Mike's value of R was soon accepted by the global metrology community as the "best" value. We remember this line of work as one of the most exciting developments in acoustics in the 1980s and early 1990s. His careful attention to detail was inspirational. So was his confidence: That 1988 paper closes with "…we are willing to bet our own money at even odds that our reported value is correct to 5 parts in 10^6, and if by any chance our value is shown to be in error by more than 10 parts in 10^6, we are prepared to eat the apparatus, drink the mercury, and breathe the argon!"

Beginning in 1986, Mike's papers also included the prescient proposal that the International System of Units (SI) temperature scale could be elegantly redefined, by abandoning the triple point of water as a fixed point, replacing it with a *definition* of either R or the Boltzmann constant k_B to be an exact fixed value, and using resonant acoustic thermometry in ideal gases to build a "thermodynamic" temperature scale from that definition, over the broad range of temperatures at which ideal gases exist.

The most basic physics of these ideas is simple. In the low-pressure limit, over a broad range of temperatures, a monatomic gas such as helium or argon is accurately ideal, having a sound speed c given by

$$c^2 = 5RT/3M = 5k_BT/3m \tag{1}$$

Where T is the absolute temperature, M is the molar mass, and m is the atomic mass. Using microwave and acoustic resonances in a single cavity allows an extremely accurate measurement of the sound speed with $c/c_{light} = (f_{\text{acoust}}/f_{\text{em}})/(z_{\text{acoust}}/z_{\text{em}})$, where f is a measured frequency, z is a modal eigenvalue, and em denotes electromagnetic. Then Eq. (1) can be used in either of two ways: First, if the triple-point temperature of water is taken to be known exactly, Eq. (1) yields R or k_B. Second, if R or k_B is defined exactly, Eq. (1) provides a way to measure the temperature without reference to the triple point of water.

Even with such clean physics as a foundation, getting ppm accuracy with this method demands extraordinary efforts. In the acoustics realm, these efforts include corrections for the thermal boundary layer in the gas touching the solid resonator surface, for the breathing motion of the solid resonator, and for the acoustics of the transducers and the fill tube; and accounting for a deliberate non-sphericity needed to break degeneracy in the microwave resonances---in addition to assessing the purity of the gas, ensuring the accuracy and spatial uniformity of the temperature at ppm levels, accounting for the index of refraction of the gas, and, in the case of argon, accounting for the relative abundances of its isotopes.

Mike persisted year after year, and a growing subset of the global metrology community adopted his techniques and his vision, working toward lower uncertainties and a consensus that acoustics should indeed form the basis of the kelvin. By 2017, still using acoustic resonance in a nearly spherical cavity, the community had reduced the uncertainty in R and k_B from 1.7 ppm to 0.6 ppm, the new "best" value falling well within the uncertainty interval in Mike's 1988 paper.

The climax of this 40-year quest came on November 16, 2018, when the Comité International des Poids et Mesures announced that a defined value for k_B has been chosen, based on those acoustical measurements, and that the kelvin is henceforth a derived unit, based on the new definition of k_B. These changes came into force on May 20, 2019. Acoustic gas thermometry is now the key method for ppm measurement of temperature over a broad range of temperatures.

What a thrilling, historic development, with Mike Moldover's research and vision front and center, showing the world a beautiful exemplar of physical and engineering acoustics!

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