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Recommended practices for the use of spinning rotor gauges in inter-laboratory comparisons

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ABSTRACT

The spinning rotor gauge (SRG) is a common transfer standard in key comparisons (KCs) and other intercomparisons for pressures in the range of 1.0×10^{-4} Pa to 1.0 Pa. To make absolute pressure measurements using a SRG, a calibration factor, known as the accommodation coefficient, must be determined. Comparisons which utilize SRGs require each participant to determine the accommodation coefficient. The accommodation coefficient of an SRG is known to have excellent long-term stability ($\leqslant$0.1% over 1 year; $k = 1$) in a laboratory environment where the rotor remains undisturbed and attached to a vacuum standard, but the long-term stability of SRGs used in comparisons is often worse than what is observed in the participants own laboratory. Recently, the Bureau International des Poids et Mesures Consultative Committee for Mass and Related Quantities Working Group on Low Pressures held a workshop to discuss the stability of the accommodation coefficient in inter-laboratory comparisons. Here we summarize the data presented during the workshop and the ensuing discussions and give a list of recommended practices derived from the workshop.

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1. Introduction

On February 24, 2014, the Bureau International des Poids et Mesures (BIPM) Consultative Committee for Mass and Related Quantities (CCM) Working Group on Low Pressures (WGLP) held a workshop on the "Experiences on the stability of the accommodation coefficient of the spinning rotor gauge". One of the recommendations that came out of the workshop was that a "Recommended Practices" document be written for the use of spinning rotor gauges (SRGs) in key comparisons and other inter-laboratory comparisons. The present paper is the result of the recommendation. Four national metrology institutes (NMIs) gave presentations at the workshop which included SRG data from their laboratories: National Institute of Standards and Technology (NIST), USA; Physikalisch-Technische Bundesanstalt (PTB), Germany; National Metrology Institute of Japan (NMIJ); and Institute of Metals and Technology (IMT), Slovenia. Representatives from other NMIs participated in the workshop and contributed to the discussions.

The spinning rotor gauge is a common transfer standard in key comparisons (KCs) and other intercomparisons for pressures $p \leqslant 1$ Pa, and is generally considered to be a useful transfer standard in the range of 1.0×10^{-4} Pa to 1.0 Pa. Below 10^{-4} Pa, ionization gauges are typically used as transfer standards; however, since SRGs are considered to be more stable than ionization gauges, high-vacuum intercomparisons typically include both SRGs and ionization

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gauges as transfer standards, so that the ionization gauge results can be normalized to SRG measurements at a pressure above 1×10^{-4} Pa, as was done in the CCM.P-K3 and other key comparisons [1–3]. The SRG stability desired in KCs is typically <0.5% since many NMIs have standards with expanded uncertainties <0.5% in the pressure range of 1×10^{-4} Pa < p < 1 Pa.

There were several motivations for the workshop and the ensuing report presented here. Protocols in KCs involving SRGs typically require specific procedures for the handling of the SRGs to ensure good stability. Participants may question whether the practices outlined in the protocol are, in some cases, necessary or, in other cases, sufficient to ensure the desired stability of the SRG accommodation coefficient. During a pilot stability study for a CCM.P-K3 follower between NMIJ and PTB, whose new results are yet unpublished upon the preparation of this manuscript, there was some discussion upon the factors and practices that may affect SRG stability, and the few SRG stability tests and studies found in the literature often show results that are non-intuitive, inconclusive, or the relevant conditions of the tests are unclear. One motivation for this report is to elucidate the known factors that affect SRG stability from the literature and from previously unpublished data from the national metrological laboratories (NMIs) that participated in the workshop. Another motivation for this report is to recommend relevant studies that should be carried out to understand and quantify SRG stability in intercomparisons.

It is important to consider that the SRG stability observed in the laboratory is often better than what is observed during intercomparisons. This is investigated in Section 4 by summarizing the stability observed in a few recent key and supplemental comparisons involving rotor gauges. In the range covered by SRGs (10^{-4} Pa to 1 Pa), static expansion standards and dynamic expansion (also known as continuous expansion or orifice-flow) standards are the most common vacuum standards used by NMIs. The relative expanded Type B uncertainty is typically better than 1.0% over this pressure range, and at 10^{-2} Pa the relative Type B uncertainties typically range from 0.2% to 0.5% ($k = 2$). Type A uncertainties can vary considerably depending on lab conditions and the behavior of the SRG; nevertheless, Type A uncertainties $u_A < 0.1\%$ are common in KCs, but they are typically larger than 0.01%. Consider, for example, a rotor with density $\rho = 7.7$ g/cm^3 and diameter $d = 4.5$ mm: a repeatability of 5×10^{-10} s^{-1} in the residual drag translates into a relative uncertainty of 0.01% at 1×10^{-2} Pa and 25 °C. Therefore, in context of this report, SRG stabilities ⩽0.1% over the course of a comparison are considered to be excellent and more than sufficient for the vast majority of comparisons. Stabilities <0.5% are considered to be good and will be sufficient to compare the capabilities of many NMIs to within their stated uncertainties.

2. Background

The working principles of the SRG are discussed in many publications (see Refs. [4–6], for example) and will not be repeated in detail here. Here we offer a brief discussion for clarity in this report. Below about 0.1 Pa, in the free molecular flow regime, the pressure of the SRG is given by

$$p = \frac{\pi v \rho d}{20\sigma}\left(-\frac{\dot{\omega}}{\omega} - RD(\omega) - 2\alpha\frac{dT}{dt}\right). \tag{1}$$

Here d = rotor diameter, v = mean thermal velocity of the gas molecules, ρ = rotor density, α is the thermal expansion coefficient of the rotor and T is the rotor temperature. $RD(\omega)$ is the frequency dependent residual drag (also known as the vacuum decrement) and is mostly due to the slowing of the rotor caused by eddy currents in the rotor and surrounding thimble generated by the spinning rotor. The offset due to residual drag is rather large – in the range of 10^{-5} Pa to 10^{-3} Pa for N_2 gas – but is usually very stable with repeatability typically between 1×10^{-6} Pa and 5×10^{-6} Pa. The decrement is given by $\dot{\omega}/\omega'$, and σ is the accommodation coefficient. For a perfectly smooth ideal spherical rotor, $\sigma = \sigma_t$, where σ_t is the tangential momentum accommodation coefficient representing the fraction of tangential momentum the gas molecule acquires from the rotor during a single collision. Perfect momentum accommodation means that $\sigma = 1$ and the gas molecule leaves the rotor surface with a tangential velocity component identical to the surface velocity of the rotating sphere. Thus, $0 < \sigma_t \leqslant 1$. However, technical materials have surface roughness that affects the angle at which the gas molecules leave the surface. If the surface roughness is taken into account, it can be shown that an effective accommodation coefficient can have a value as high as $\sigma_{eff} = 1.27$ [4]. In calibrations, it is the effective accommodation coefficient, taking into account the surface roughness, which is determined. In addition, nominal values of d and ρ are typically used with no associated uncertainties, and so σ_{eff} also includes the difference between these nominal values and the true values. Above 0.1 Pa the SRG is no longer in the molecular flow regime and viscosity corrections must be applied; however, between about 0.1 Pa and 2 Pa Eq. (1) can still be used if σ_{eff} is replaced by a linear model $a + bp$, with $a = \sigma_{eff}$ ($p \leqslant 0.1$ Pa) [7]. Larger pressures are not a consideration of this report.

The last term in Eq. (1) is relevant for laboratories with poor temperature control or for higher pressures when the rotor heats up due to friction forces. For stainless steel, $\alpha \approx 1.5 \times 10^{-5}$/K; with $\rho = 7.7$ g/cm^3 and $d = 4.5$ mm, a slope of 0.25 K/h of the rotor temperature gives a relative change in pressure of about 0.2% at 1×10^{-2} Pa. In principle, a consistent temperature slope could be accounted for in Eq. (1), if known, but a fluctuating temperature change is more difficult to remove from the data and could, in principle, translate into a larger Type A uncertainty. However, the temperature of the rotor is not directly measured and, for lower pressures, is related to the temperature of the SRG thimble temperature solely by thermal radiation. A temperature instability of 0.1 K/h or smaller is common in many advanced laboratories and so the dT/dt term is not an issue in these environments. Invar rotors have also been used to lessen the effect of temperature changes but, as will be discussed later in this report, to date there is no compelling evidence that these