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Behavior of commercial spinning rotor gages in the transition regime

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We have investigated the accuracy of commercial Spinning Rotor Gages (SRG) in the transitional regime between 0.1 and 133 Pa. We have found that commerical SRGs which have been calibrated at low pressure (10^{-2} Pa) are in good agreement with our standard for pressures up to 1.0 Pa. Above 1.0 Pa, we found that the SRG readings are systematically in error and are gas and rotor diameter dependent. The best performance was found with the lighter gases, H_2 and He. Errors as large as a factor of 2 were observed for the heavier gases, Ar and N_2. We also have found that different linearization schemes have been implemented in the two brands of SRGs. For one brand of SRG controller, the best performance with the heavier gases was for Ar and 4.76 mm rotors without temperature compensating for gage heating effects. For the other brand of SRG, errors are significantly reduced by temperature compensating for gage heating effects.

1. Introduction

In a commercial molecular drag or Spinning Rotor Gage (SRG), a steel ball (rotor) is magnetically levitated and inductively driven to a specified rotational frequency between 400 and 415 Hz and then allowed to rotate freely. The gas pressure is determined by the rate at which the rotor's rotational motion slows. This slowing is due to the rotor losing some of its angular momentum to the surrounding gas through gas collisions with the rotor surface. The deceleration rate (DCR) of a rotor, the fundamental measurable quantity, is determined by the SRG controller and is then used to compute the pressure. For pressures below 0.1 Pa the SRG DCR is linear with pressure[1–3]. For pressures above 0.1 Pa, the DCR becomes increasingly nonlinear with pressure due to gas viscosity effects[1,3–5]. Commercial SRG controllers use a linearization algorithm to compensate for gas viscosity effects. In this paper we report the results of a study aimed at determining the accuracy of the linearization algorithm implemented in the commercial SRGs at pressures between 0.1 and 133 Pa. In this study we used controllers from the two vendors: Type A and Type B, for two common rotor diameters, 4.5 mm and 4.76 mm, and for the widely-used gases N_2, Ar, He and H_2. We have found, in part, that the linearization algorithm is not the same in Type A and Type B controllers, the most accurate results were found for the lightest gases, that the Type B controller response can be substantially improved using temperature compensation and that both controllers use a piece-wise linear algorithm which introduces significant errors.

2. SRG linearization procedure

2.1. Low pressure behavior. For an SRG operating in the low pressure or molecular regime, the relation between the gas pressure and the DCR can be derived from classical mechanics and kinetic gas theory to be[2,3]

$$\mathrm{DCR}\ (\mathrm{s}^{-1}) = \frac{10\sigma}{\pi\rho a\langle v\rangle}P. \tag{1}$$

Here, P is the pressure, σ is an effective tangential momentum accommodation coefficient, ρ is the density of the rotor, a is the radius of the rotor, $\langle v\rangle$ is the average molecular speed of the gas. Equation (1) is found to be valid for pressures up to about 0.1 Pa[2,3].

2.2. High pressure behavior. Above about 0.1 Pa, the DCR becomes an increasingly nonlinear function of the pressure. At still higher pressures, above about 50 Pa, the rotor DCR approaches a saturation level, DCR_{sat}, where the deceleration rate becomes virtually independent of the gas pressure. The saturation value of the DCR is given by[1,4]

$$\mathrm{DCR}_{sat} = \frac{15C_g\sigma}{a^2\rho}\eta. \tag{2}$$

Here, η is the gas viscosity and C_g is a constant which depends on the rotor/thimble geometry. If the SRG DCR were strictly linear with pressure, then the saturation of the DCR would occur at a pressure of

$$P_{sat} = \frac{3\pi C_g}{2a}\eta\langle v\rangle \tag{3}$$

which is called the saturation pressure and is on the order 10 Pa for the systems considered here. For pressures well above P_{sat}, pressures of several 100 Pa, an additional pressure dependence of the gas friction is found[4] to be due to changes in the nature of the gas flow around the ball. In this paper we do not consider these effects and restrict our discussion to pressures around P_{sat}.

2.3. Transitional behavior. As the value of DCR_{sat} [equation (2)] and the low pressure response [equation (1)] are dependent on gas species, so too is the SRG response. A re-normalization scheme which allows one single linearizing algorithm to be used for all gas species has been proposed[1,4] in which the DCR is simply replaced with a normalized or dimensionless DCR, called D_n, which is given by

$$D_n = \mathrm{DCR}/\mathrm{DCR}_{sat}. \tag{4}$$

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In a similar manner then, the normalized pressure is also written

$$P_n = P/P_{sat}. \quad (5)$$

The relation between D_n and P_n then is written as

$$P_n = D_n CF(D_n) \quad (6)$$

where CF is a viscosity correction function and has the limiting values of $CF \to 1$ for $D_n \to 0$ and $CF \to \infty$ for $D_n \to 1$. Analytic expressions for CF have been proposed in the literature[1,3–5], unfortunately, neither vendor states the actual functional form which has been used in the commercial SRGs. By testing the controllers, it appears that Type B controllers use a functional form which is very close to the form proposed by Lindenau and Fremerey[4] and that both of the commercial SRG controllers use a piece-wise linear representation of CF instead of an analytic form. As CF is a very steep function for large D_n, a piece-wise linear approximation to CF introduces significant systematic errors (see Section 4).

Due to the saturation of the DCR an SRG loses sensitivity at high pressures. This implies that near DCR_{sat}, any small change in D_n results in a large change in P_n, and in turn, the displayed pressure. SRG controllers measure DCR accurately, however, and so a critical factor is the accuracy of the numerical constants used in computing DCR_{sat}. The constants which could yield the largest potential errors in DCR_{sat} are the geometric constant and the gas viscosity, or, changes in the gas viscosity due to gage heating effects. The exact value of the geometric constant needed will depend upon the particular rotor/thimble combination and, perhaps even on the suspension head used, and are not accounted for in the controllers. At high DCR values, SRG controllers use the inductive drive motor to re-accelerate the rotor every few seconds. Due to the eddy currents induced in the rotor and thimble by the drive, the local temperature is raised. As a result of this heating, the local gas viscosity can be substantially changed and large errors in the pressure determination results if this effect is not properly compensated for[4].

3. Experiments

Pressure measurements were performed on the NIST Primary Transition Range Standard. The uncertainty of a pressure generated with this standard is estimated to be 1% or less (3-σ or 99% confidence level) over the entire working pressure range of 10^{-2} to 100 Pa.

Measurements were made with a group of six SRG controllers. Three of Type A and three of Type B. Six chrome steel rotors were used; two 4.5 mm in diameter, the other four 4.76 mm. The thimbles were all made at NIST from 316L stainless steel, have an inside diameter of 8.00 mm and are nominally identical to the thimbles provided by the commercial vendors. Thimble temperatures were measured using 0.05 mm diameter 'Type-K' chromel–alumel thermocouples affixed to the thimble near the location of the center of the suspension head.

The base pressure of this vacuum system was on the order of 10^{-6} Pa after baking. The residual drag for each of the rotors was monitored for several days prior to the beginning of these experiments and an average value and its frequency dependence was determined for each rotor, which is used to correct the lowest pressure data for proper determination of the tangential accommodation coefficient. The residual drag was also monitored on nights and weekends and no changes greater than 10^{-7} s^{-1} in any rotor residual drag was observed during the four-month duration of this study.

Three sets of measurements were collected from the SRG controllers at each calibration point: (i) the rotor DCR; (ii) linearized pressure readings as displayed by the controllers with the average residual drag, room temperature and the gas viscosity at room temperature entered into each controller, i.e. without compensating for gage heating effects (no temperature compensation); and (iii) linearized pressure readings from the controllers with temperature compensation for gage heating effects by entering into each controller the average residual drag, the measured thimble temperature and the appropriate gas viscosity at the measured temperature. In the subsequent data analysis, DCR readings where offset corrected by subtracting the corresponding residual drag (in s^{-1}) from the value obtained from the controller as commercial SRG controllers do not subtract the entered offset (i.e. residual drag) from DCR readings. Also, the low pressure data was corrected for changes in the residual drag due to its frequency dependence.

Four test gases were used: N_2, Ar, He and H_2. We first calibrated the rotors on the standard with all these gases at 10^{-2} Pa to determine the effective accommodation coefficient for each rotor with each gas using the orifice flow technique[6]. We continued to use the orifice flow method for all gases to determine the response of the gages up to 1.0 Pa. For N_2, we continued to use the orifice flow method up to 30 Pa. Above 1.0 Pa, we compared the SRG response with three, 133 Pa full scale, capacitance diaphragm gages (CDG) for all four gases. These CDGs were calibrated *in situ* with the four gases over the entire range 0.1 to 133 Pa using either an Ultrasonic Interferometer Manometer (UIM)[7,8] or the orifice flow technique, depending on the pressure. Using *in situ* calibrated CDGs allows for accurate corrections of the CDG readings for thermal transpiration effects[9]. For N_2, the CDG–SRG comparison data overlapped with direct orifice flow calibrations of the SRGs for pressures up to 30 Pa. The data from these two methods agreed to within $\pm 0.1\%$ of reading over the entire pressure range.

4. Experimental results

4.1. Temperature measurements. The measured thimble temperatures plotted as a function of the DCR are shown in Figure 1. The frequency with which the controller has to re-accelerate a rotor is determined by its deceleration rate and, thus, a linear increase in the thimble temperature with DCR is expected. The time constant to reach equilibrium temperature after a change in pressure was found to be of the order of 10 minutes. From Figure 1 it can be seen that at high DCR values, the temperature deviations for all three Type B SRGs lie close together and are considerably higher than that of Type A. We attribute this difference to the differences in the suspension head design; Type A suspension heads allow for air circulation within the suspension head while Type B do not. The differences among the three Type A SRGs are larger and for one Type A controller we observed multiple and frequent acceleration/deceleration cycles resulting in a larger heat load and hence higher thimble temperature.

4.2. SRG pressure readings. In Figure 2 we plot the ratio of the viscosity-corrected, non-temperature compensated SRG readings to the pressure from the standard versus pressure. Note that all errors increase with increasing pressure (increasing D_n), and

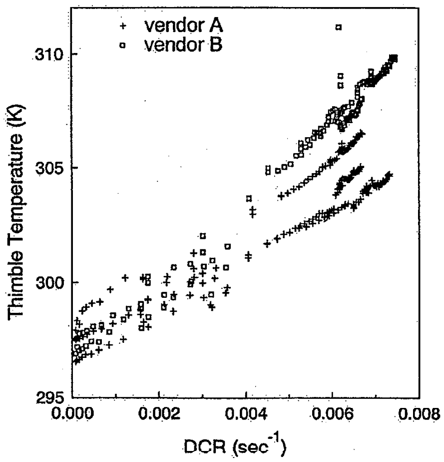

Figure 1. Measured thimble temperatures as a function of the rotor DCR for Type A and Type B SRG controllers.

are gas and rotor diameter dependent, as expected. The differences between data from Type A and B clearly indicate that the controllers from the two vendors have implemented different linearization procedures. The readings from Type A controllers give slightly better results but all read too low a pressure, while Type B all read too high. The best results were found for the lighter gases He and H_2. With the heavier gases, the data for Type A SRGs with 4.76 mm rotors in Ar give reasonable agreement with the standard. We note that the output from Type A exhibits a step discontinuity at about 10 Pa for He, at lower pressures for Ar and N_2, and at higher pressure for H_2, perhaps indicating a programming error in the piece-wise linear approximation to *CF*. The repeating cycloid or 'scallop' shape in both sets of curves is the consequence of the use of the piece-wise linear approximation to *CF*.

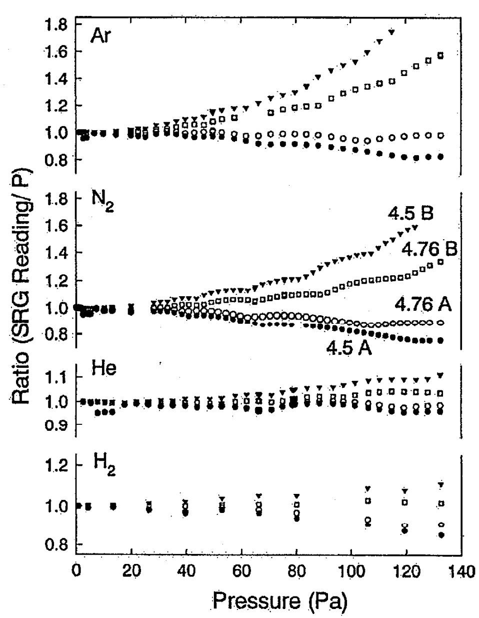

Figure 2. Ratio of displayed SRG reading to pressure from the standard vs pressure without compensating for gage heating effects (see text). The display symbols for the data from vendor A and vendor B SRGs for the two ball diameters are the same for the four gases and are indicated on the N_2 data.

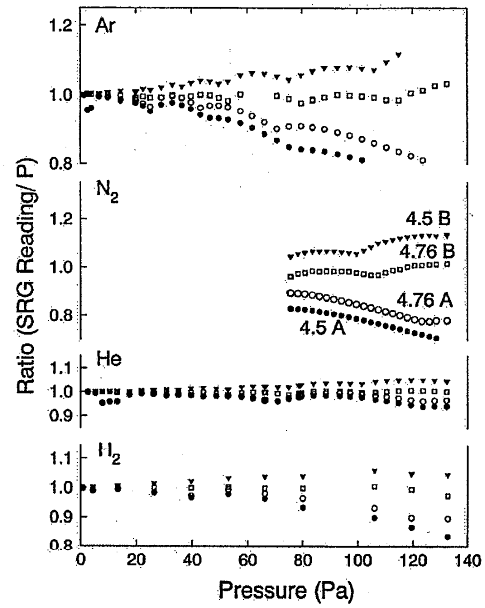

Figure 3. Ratio of displayed SRG reading, compensated for gage heating effects (see text), to pressure from the standard vs pressure. The display symbols are the same as in Figure 2.

In Figure 3, we plot the ratio of the temperature compensated and viscosity-corrected SRG readings to the pressure vs pressure. Basically, temperature compensating for gage heating effects shifts all ratios to lower values (compare with Figure 2). Type B SRG now read closer to the true pressure and the temperature compensated data for 4.76 mm rotors with Type B are in good agreement with the standard for all test gases. The difference between the balls of different diameters is again evident in Figure 3. The geometric constant, C_g, should be different for different ball thimble combinations, and is not accounted for by the controllers. For both types of SRGs, the displayed pressures were in better agreement with true pressures for 4.76 mm diameter balls.

5. Conclusions

While the accuracy of a calibrated SRG is excellent when operating in the molecular regime, due to the poor linearization procedures which has been incorporated into the 'second generation' SRG controllers, the accuracy degrades significantly above 1 Pa where errors as large as a factor of two are observed. However, a detailed analysis of our DCR vs pressure data shows that the accuracy of SRGs in the range 20 to 100 Pa could be as good as $\pm 1\%$ using a new viscosity correction function, a best fit geometric constant, C_g, for each ball/thimble combination, and by compensating for changes in the thimble temperatures.

We shall report on the analysis of our DCR vs pressure data in a separate publication.

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