EXPERIMENTAL STUDY OF PISTON ROTATION RATE EFFECT

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Abstract:
The effect of the piston rotation rate on the gauge pressure measured by deadweight pressure balances was experimentally studied. Experiments were performed with a PTB twin primary gas pressure balance and several commercial gas and oil operated pressure balances with different configurations and size of rotating weights. It was found out that the piston rotation effect significantly depends on the distance between the horizontal surface of the rotating weights and the nearest fixed surface of the pressure balance.

Keywords: pressure measurement; pressure balance; piston rotation; gauge pressure

1. INTRODUCTION

Operation of foremost deadweight pressure balances requires the piston being rotating in relation to the cylinder. The piston rotation rate is not present in the pressure equation of a pressure balance but can affect the measurement result when the pressure balance is operated in gauge mode, which is caused by a counteraction of the rotating weights with the surrounding air. For a pressure balance with a piston rotating at up to 1000 rotations per minute (rpm), a relative change in pressure of up to $5 \cdot 10^{-4}$ was observed [1] when it was operated with or without a bell-jar. Measurements with the same type of pressure balance operated at 180 to 600 rpm showed that the error of the measured pressure increases with the square of the rotation frequency and trends to a correct value, within 5 parts per million (ppm), when extrapolating it to zero rotation speed [2]. Modern gas pressure balances are operated at essentially lower rotation speeds, typically lying between 20 and 40 rpm, thus the effect of the rotation being minimised. With state-of-the-art pressure balances developed in the last 15 years, it became possible to measure absolute pressures with a relative standard uncertainty below 1 ppm [3]. To achieve a similar uncertainty of gauge pressure measurements, attention must be paid to the piston rotation effect even at low rotation frequencies. In [4], the rotational dependence of the effective area of a primary pressure balance was determined experimentally, and a respective correction was included in the equation of the effective area.

The purpose of the present work was to systematically study the effect of the piston rotation to define critical parameters and finally to increase accuracy of gauge pressure measurements.

2. PROBLEM STATEMENT

The effect of the piston rotation was analysed theoretically and studied experimentally. Details of the theoretical analysis will be published somewhere else, just reporting here its main results as relating to the experimental study.

Generally, a rotating load disk counteracts with the surrounding air, which produces additional vertical forces acting on the upper and lower faces of the disk. The existence of the rotational dependence expresses the fact that, due to different boundary conditions above and below the disk, the total of these forces is not zero. In [2], a spiral airflow induced by the rotating load carrier and masses and directed downwards on to the top of the pressure balance was visualised and made responsible for the additional force on the piston. In contrast to this suggestion, our theoretical analysis has shown the force due to the downward air flow to the upper surface of the weights to be negligibly small. Instead, the air confined between the lower surface of the disk and the plane of the pressure balance platform and being involved in rotational movement produces a negative gauge pressure below the disk. This pressure acts on the lower side of the disk and causes an additional force directed downwards. Following to this result, the rotational effect is expected to be dependent, among others, on the distance between the rotating disks and the conjugate, non-movable surface. For classical, manually operated pressure balances the additional force always acts on the piston downwards and thus increases the pressure below the piston. However, in the case of a pressure balance equipped with an automatic mass handling system (AMH), in which another fixed weight disk is kept on a short distance above the rotating disk, a negative gauge pressure emerges above the rotating disk, and an additional upwardly directed force is generated, which reduces the measurement pressure.

3. EFFECT OF DISTANCE

To verify these findings, experiments were carried out in which a fixed plate was placed parallel to the plane of the rotating disks at different distances below and above them. The measurements were performed with a special-design twin pressure balance which has been used at PTB since 1991 as primary gauge pressure standard [5], see Figure 1. This twin pressure balance is equipped with two piston-cylinder assemblies (PCA) of 10 cm^2 effective area made of tungsten carbide, manufactured by Desgranges et Huot, France, identified by serial numbers 288 and 290, and operable in the pressure range of (0.05 to 1) MPa. Note: the use of any product in the present research does not mean that it is the best suitable or recommendable product for the use.

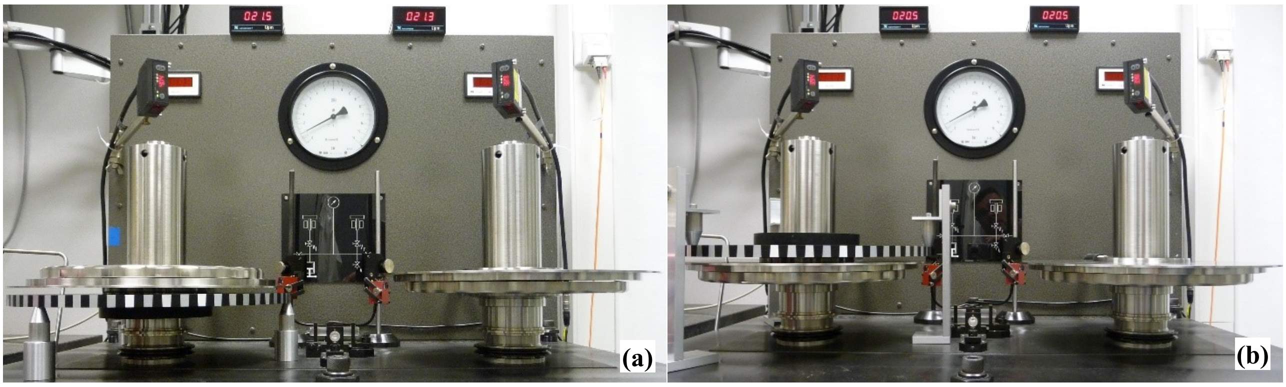

Figure 1: 1 MPa gas twin pressure balance with its left part operated in presence of a fixed plate placed at variable distances below (a) and above (b) rotating disks

The two PCAs were compared with each other by the cross-float method using a differential capacitance diaphragm gauge type 698A11TRC with ±5 Torr range manufactured by MKS Instruments, USA. In this configuration, the determination of the effective area in the full pressure range was possible with a standard deviation of about 0.1 ppm. In the experiments, PCA 290, placed on the right side, was used as a reference (REF), and PCA 288, placed on the left side, as a device under test (DUT), with all measurements having been performed at the same nominal pressure of 100 kPa. The reference PCA was rotating with its regular rotation speed (Ω) of (20 to 25) rpm. The regular position of the pressure balance plate is -93.3 mm below the lower face of the rotating weight disk. It was shown that at such a relatively high distance and $\Omega \leq 25$ rpm, the pressure is practically independent of rotation rate. The DUT PCA was operated once in its regular mode, with the pressure balance plate being -93.3 mm below the weight disk, and then with an additional plate fixed at (-7, -15 and -45) mm below and at (7, 15 and 45) mm above the horizontal surfaces of the rotating loads, all distances being measured and kept during the measurements within ±0.1 mm. In each DUT configuration, the measurements were repeated 5 times at Ω = 10, 20, 30, 40 rpm with the results given in terms of the effective area (A_0) of the DUT as presented in Figure 2.

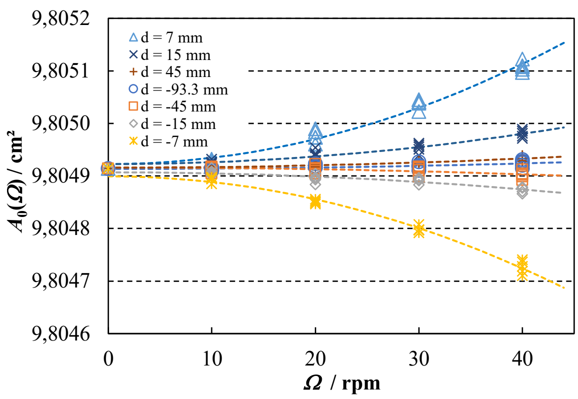

Figure 2: Experimental effective area of PCA 288 in dependence on rotation speed at different distances (d) of the fixed surface from the rotating surface at pressure 100 kPa. Dashed lines show fits of the data using (1).

The experimental effective areas were fitted by equation

$$A_0(\Omega) = A_0(0) + a \cdot \Omega^2 \,, \tag{1}$$

with the results of the fits shown in Figure 2 by the dashed lines. The experimental data well follow to (1), which agrees with the findings of the former works [2], [4] and theoretical predictions. Beside the rotation frequency, the distance to the fixed surface has a strong effect on the additional force. At the regular rotation speed of 20 rpm, the distances between the rotating and fixed surfaces of (±7, ±15 and ±45) mm caused relative errors in the measured pressure of about (4.7, 1.2 and 0.4) ppm, respectively.

4. COMMERCIAL PRESSURE BALANCES

Further, the rotational effect was measured for commercial gas pressure balances models PG7601 and PG7601-AMH operable without and with AMH, respectively, and an oil pressure balance model PG7302-M, all manufactured by Fluke Calibration, USA. Each of these pressure balances in its configuration was operated at a fixed load and rotation speeds varying between (10 and 40) rpm.

PG7601

The PG7601 piston was loaded with one main weight of nominally 2 kg. The same measurements were performed with PCAs of (10, 2 and 0.5) cm^2 nominal effective areas, installed in the PG7601. The cross-float measurements against a REF, which was the same type PG7601 equipped with a PCA of the same size as the DUT and identified by serial numbers 1919, 2278 and 0302, the latter described in [6], were performed at DUT piston rotation speeds of (10, 20, 30 and 40) rpm and repeated five times.

PG7601-AMH

The experiments were performed in two configurations with a 2 cm^2 PCA. Once, the piston was loaded by one main weight of 6.2 kg, in addition to the piston and weights carrier bell load. In the second case, this main weight was removed, and the piston was loaded by a group of the binary weights of (3.2, 1.6, 0.8, 0.4, 0.2) kg, producing nearly the same load as that of the main weight. The total piston load in the first and the second case was almost the same, 6.93 kg and 6.92 kg, respectively, which allowed a comparison of the rotational effect in these two configurations. In both cases, the distance of the rotating loads from the lower fixed surface was the same, but the diameters of the rotating weights, with 31 cm and 13.3 cm, were essentially different, which should allow the effect of the load size to be studied. As a REF, the same PG7601 with a 2 cm^2 PCA serial number 2278 was used as in the measurements with the DUT PG7601. Also here, the cross-float measurements were performed with DUT in each configuration at Ω = (10, 20, 30 and 40) rpm and repeated five times.

PG7302-M

This pressure balance was chosen to study the rotational effect in the case of hydraulic pressure balance. In addition, this pressure balance is characterised by an essentially bigger distance between the rotating disk and the platform compared with that in PG7601 and PG7601-AMH. The PCA used was of 0.2 cm^2 effective area. Two main weights of 5 kg and 4 kg were applied producing totally a 10 kg load of the piston. As a REF, a special design 100 MPa pressure balance equipped with a 0.84 cm^2 PCA serial number 701/2 manufactured by Ruska, USA, and described in [7], [8]. The cross-float measurements were performed at Ω = (10, 15, 20, 25, 30, 35 and 40) rpm and repeated five times.

In all cross-float experiments, the rotational speed of all pressure balances used as a REF was kept constant at 20 rpm.

4.1. RESULTS AND DISCUSSION

For each cross-float measurement point, the effective area of DUT was calculated and corrected to the zero-pressure effective area using DUT pressure distortion coefficients as known. Dependences of A_0 on Ω were fitted by equation (1). The relative changes of $A_0(\Omega)$ related to $A_0(0)$ are shown in Figure 3 .

For 3 PCAs of (10, 2 and 0.5) cm^2 effective area operated in PG7601, the rotational dependences of A_0 are similar, which confirms that the effect is produced by a disk-air counteraction and is independent of the PCA. The main differences in the PCAs behaviour are a bigger scatter of the results for the 0.5 cm^2 PCA, which is due to its poorer performance, and a slightly lower rotational dependence for the 10 cm^2 PCA compared with the 2 smaller sizes' PCAs. The latter deals, among others, with the fact that the total load of the 10 cm^2 piston is by 300 g bigger, because of its own weight, than the load of the two other pistons. Consequently, the contribution of the rotationally induced force is, in relative units, smaller.

The results obtained for PG7601-AMH operated with a big mass and, alternatively, with binary masses are significantly different. The rotational dependence for the big mass configuration is rather strong, whereas the operation with the binary masses shows a negligible rotational dependence. These very different dependences evidently deal with the different diameters of the big mass and the binary masses.

For the hydraulic PG7302-M, the rotational dependence of the effective area is moderate. This is explained by a relatively big distance between the rotating and fixed surfaces in this pressure balance compared with the distances in PG7601 and PG7601-AMH, which will be discussed later. Another aspect of the PG7302-M results is a relatively big and rather unsystematic deviation of the experimental $A_0(\Omega)$ data from the model equation (1). This can deal with a lower performance of this hydraulic pressure balance, i.e. higher experimental standard deviation, compared with the pneumatic pressure balances.

In the case of the PTB primary gauge gas pressure standard, there is no notable rotational dependence, which is explained by big distance between the rotating disks and the pressure balance table. The experimental $A_0(\Omega)$ data shows a very small increase of A_0 with Ω, but it is statistically insignificant.

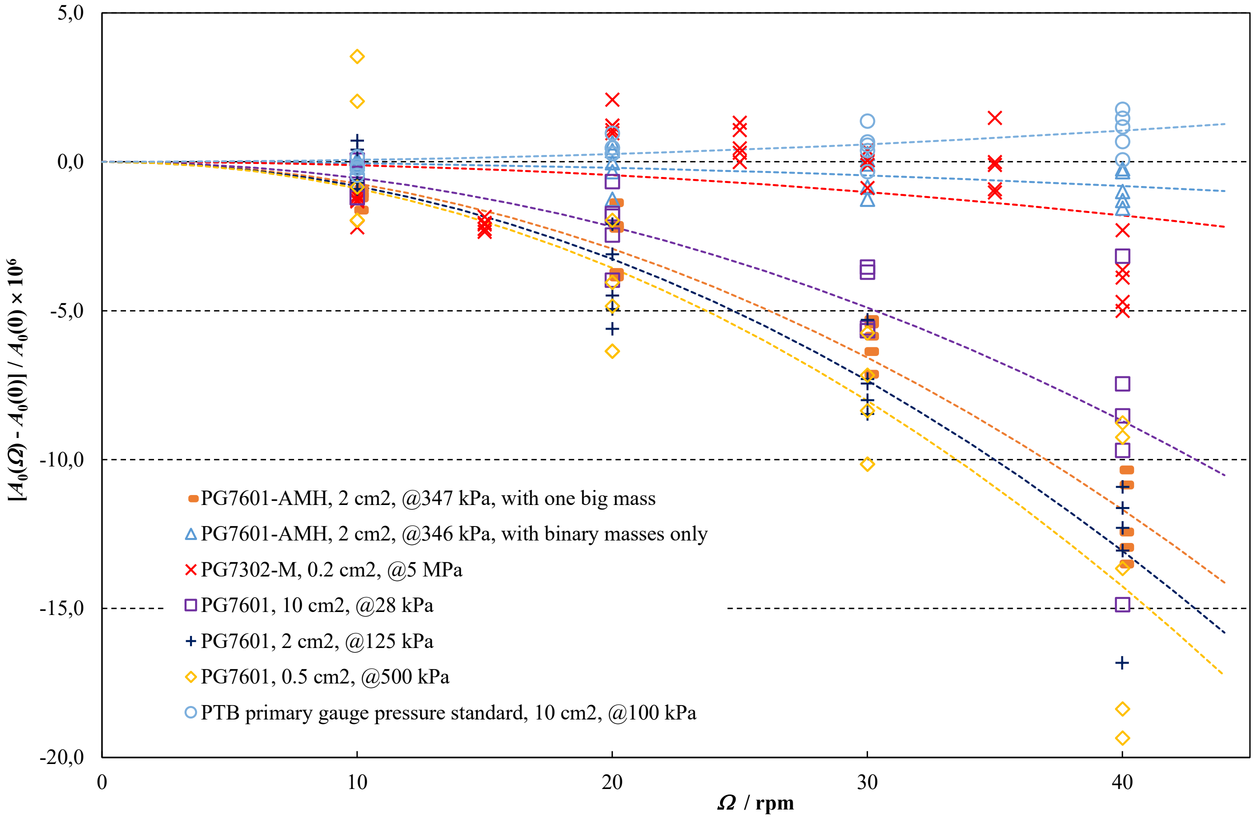

Figure 3: Relative changes in effective areas of PCAs, operated in different pressure balances, vs. on rotation speed. Dashed lines show fits of the data using (1).

Table 1: Pressure balances and their parameters: distance between rotating weights and solid surface (d), weights diameter (D), PCA nominal effective area (A_0), pressure of the experiment (p), maximum pressure (p_{max}), force per squared rotation speed (F) and its standard uncertainty ($u(F)$), apparent nominal additional masses (M) equivalent to the forces induced by the rotation speeds (Ω).

Pressure balance	***d* /mm**	***D* /cm**	**A_0 /cm²**	***p* /MPa**	**p/p_{max} %**	***F* /(N/rpm²)**	**$u(F)$ /(N/rpm²)**	***M* in mg at *Ω*/rpm 20**	**30**	**40**	**50**
PG7601	9.5	23.5	10	0.028	8	$1.5 \cdot 10^{-7}$	$9.7 \cdot 10^{-8}$	6	13	24	37
			2	0.125	7	$2.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$	8	18	32	50
			0.5	0.5	7	$2.2 \cdot 10^{-7}$	$1.4 \cdot 10^{-7}$	9	20	35	55
PG7601-AMH, 1 big mass	5.4	31	2	0.35	18	$5.0 \cdot 10^{-7}$	$3.0 \cdot 10^{-7}$	20	45	79	124
PG7601-AMH, binary masses		13.3				$3.4 \cdot 10^{-8}$	$3.1 \cdot 10^{-8}$	1	3	6	9
PG7302-M	24.5	30	0.2	5	10	$1.1 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$	4	10	18	28
PTB 1 MPa	93.3	34	10	0.1	10	$-6.4 \cdot 10^{-8}$	$3.7 \cdot 10^{-8}$	-3	-6	-10	-16

The properties of the pressure balances, the measurements conditions and the results for the piston rotation speed effect are summarised in Table 1. The distance from the rotating weights to the adjacent solid surface (d) and the load weights diameter (D) are key parameters which define the extent of the piston rotation effect. Using the fit parameter (a) obtained for each experimental data set $A_0(\Omega)$, the force per squared rotation speed (F) was calculated by

$$F' = a \cdot p, \tag{2}$$

where p is pressure at which a was determined. With the values of F' presented in Table 1, for each pressure balance in the respective configuration it is possible to calculate the additional force due to rotation, to make a respective correction or to estimate the impact of the rotation effect at any pressure. The uncertainty of F' in Table 1, $u(F')$, was calculated from the standard deviation of a. The main quantities which are usually the main uncertainty sources in a cross-float determination of the effective area, such as REF A_0, REF and DUT masses, pressure distortion coefficients, etc., are invariant to the changes of the DUT rotation speed. Other, non-constant quantities, such as ambient conditions, REF und DUT temperatures change with time, but do not have any systematic effect on the F' values, because the measurements were repeated several times at increasing and decreasing Ω, so that all such drift effects are included in the standard deviation of a. The only parameter which might be dependent on the DUT rotation speed is its temperature, but no correlation was observed between the DUT rotation speed and DUT temperature. The last 4 columns in Table 1, show the additional nominal mass which is equivalent to the piston rotation effect at rotation speeds of (20, 30, 40 and 50) rpm. This information is useful when target smallest adjustable masses, in dependence on the expected quality of the cross-float result, are known.

For the 3 PCAs operated in PG7601, the values of F' are consistent within their $u(F')$.

For PG7601-AMH operated with a big mass and with binary masses only, the additional, rotation-induced forces are significantly different, which is due to different diameters of their loads. For the big mass configuration, even $\Omega = 20$ rpm produces a visible effect. In contrast to this, operation with the binary masses only shows no notable effect even at $\Omega = 50$ rpm.

PG7302-M, due to its relatively distance of the rotating loads from the platform, shows a lower rotational dependence than the other PGs.

For all pressure balances studied, except PG7601-AMH operated with main masses, the rotation speed of 20 rpm appears well acceptable without necessity to apply any correction.

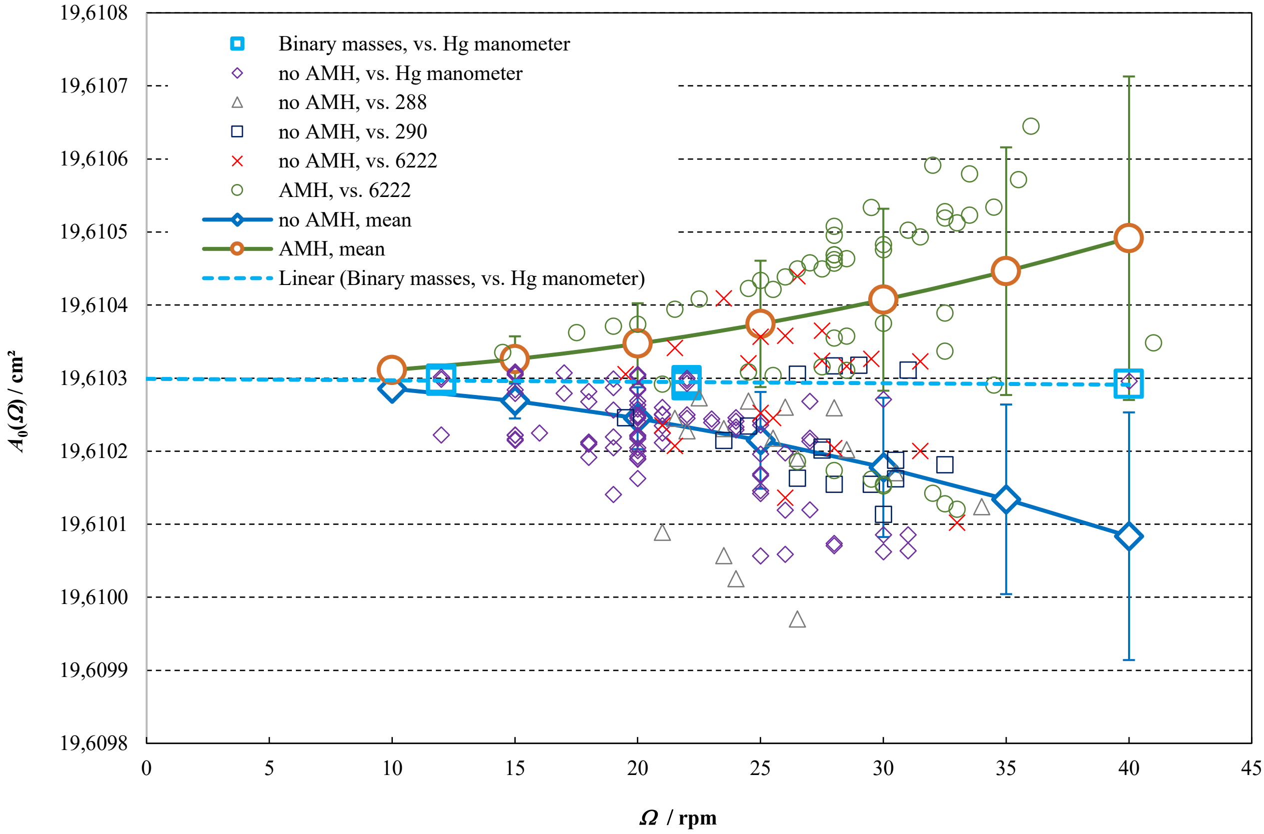

Figure 4: Effective area of PCA 1159 operated in the "Boltzmann constant" pressure balance with binary masses only, with main masses without AMH and with AMH, in dependence on rotation speed, obtained in comparison with different reference standards. Vertical bars of mean results shown indicate their standard uncertainties.

5. "BOLTZMANN CONSTANT" PRESSURE BALANCES

These special pressure balances were developed to measure absolute pressure in helium with a relative standard uncertainty below 1 ppm required redetermination of the Boltzmann constant (k_B) by the dielectric-constant gas thermometry method [3]. Though absolute pressure measurements were required in the k_B experiments, numerous comparison measurements of the k_B pressure balances were also performed, in gauge mode, against primary pressure standards, the twin pressure balance described above [5], against both PCAs 288 and 290, a primary 2 MPa pressure balance operated with a 5 cm^2 PCA manufactured by Desgranges et Huot, France, serial no. 6222 [9],[10], and PTB primary mercury manometer [11]. In those experiments, the k_B pressure balance was operated in different configurations, with main masses without AMH, with main masses with AMH and with binary masses only. Respectively, the configurations were realised in which a gap was present between a rotating load and the platform surface below (operation without AMH), a small gap between the rotating load and not rotating weight kept by the AMH above (operation with AMH), and operation with binary masses only. In Figure 4, $A_0(\Omega)$ of PCA 1159 is shown as obtained in measurements against 4 primary standards, all results rescaled to a pressure of 100 kPa. According to the main masses' configurations, downward and upward directed forces were produced by the rotation, as well as rather low forces when the pressure balance is operated with binary masses.

6. SUMMARY AND OUTLOOK

Rotation of the piston loads in the surrounding air produces an additional force which is nearly proportional to the square of the rotation speed and strongly increases with decreasing distance between the rotating loads and the nearest fixed surface. Moreover, this force increases with the diameter of the load disks. Special analysis and corrections for weights rotation are required to achieve accuracy of gauge pressure measurements on the level of few ppm. The rotational effect is found to be independent of PCA type and the pressure-transmitting medium. For few commercial pressure balances, force corrections depending on the piston rotation speed are determined and can be used to either to apply a respective correction, or to estimate a respective uncertainty contribution or to decide as for reduction of the rotation speed. For all studied cases except PG7601-AMH operated with big masses, rotation speeds below 20 rpm appear to have a negligibly low effect. To predict the additional force produced by the load rotation, a model would be helpful which includes such parameters of pressure balance as the load size, the load position in relation to the non-movable parts of the pressure balance and the rotation speed. Such a model will be presented in the next future.

7. ACKNOWLEDGEMENTS

Experiments with the k_B pressure balances, analysed in the present work, have been performed by Dr. T. Priruenrom, which is much appreciated.

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