Air Density Determination Using 1 kg Buoyancy Mass Comparison(Ⅲ)

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Abstract

In calibration of secondary 1 kg stainless steel mass standard from a platinum-iridium kilogram prototype, a major uncertainty arises from the measurement of air density for the buoyancy correction. This paper is continued to the reference[1]. An experimental determination of air density using buoyancy pairs and a vacuum balance has been carried out and its results were compared with those of the CIPM formula 81/91. The environmental measurement instruments used for this experiment are different from those previously used. Also the true mass difference between buoyancy pairs in vacuum was measured at mass laboratory of NMIJ in Japan and compared with the KRISS result. The disagreement between air density measurements by the 1 kg BA-pair and those by CIPM formula is $5.1\text{x}10^{-4}$ kg/m^3, but the standard deviation of the difference between both methods has been improved, to $5.3\text{x}10^{-5}$ kg/m^3 compared to $1.5\text{x}10^{-4}$ kg/m^3 by the previous experiment.

Keywords : air density, buoyancy, mass

1. Introduction

In case of calibration of secondary 1 kg stainless steel mass standard from a platinum-iridium kilogram prototype, a major uncertainty arises from the measurement of air density due to the buoyancy correction. The CIPM formula-1981/91 used for the calculation of air density itself has a relative uncertainty (k=1) of $1\text{x}10^{-4}$ [2]. Recently the direct determination of air density using a relatively high precision vacuum balance and a buoyancy artifact pair has been shown as a possible method to reduce the uncertainty of air density determination [3].

In this paper, an experimental determination of air density using buoyancy pairs and a vacuum balance has been carried out and its results were compared with those of the CIPM formula.

The buoyancy artifact pair consists of two 1 kg objects which are same in nominal mass, but different in volume. The air density by the artifact weighing, ρ_b, is simply expressed as :

$$\rho_b = (\Delta m_V - \Delta m_a)/ \Delta V \qquad (1)$$

where the Δm_V is the mass difference in vacuum, the Δm_a the apparent mass difference in air, and the ΔV the volume difference of the artifact pair. On the other hand, the CIPM formula is expressed as follows:

$$\rho_{eq} = f(t, h, p, X_{CO2}) \qquad (2)$$

where the t is the temperature, the h the humidity, the p the pressure, and the X_{CO2} the molar fraction of CO_2 in air.

2. Experimental Conditions

The balance used for measuring the apparent mass differences between the 1 kg buoyancy artifacts was a mass comparator with a capacity of 1.001 15 kg, a readability of 1 μg and a standard deviation of about 2 μg (Mettler HK1000). The mass comparator was installed inside an air-tight chamber. However the chamber was not perfect for air-tight. The sensors for measurement of humidity, and temperature are installed inside the balance window, and that for pressure is installed inside the air-tight chamber(Figure 1).

Figure 1. The 1 kg vacuum balance and the environmental condition measurement system.

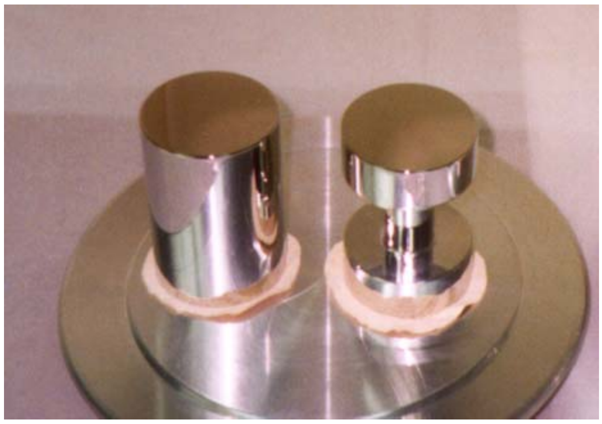

Figure 2. The 1 kg pair buoyancy artifacts from the left : No.1 and No.2.

Table 1. Characteristics of the 1 kg buoyancy artifacts(BA).

Dimension	Cylindrical artifact / No.1	Bobbin artifact / No.2	Difference / 1-2
Diameter of BA / cm	5.752	5.758, 2.246	
Height of BA / cm	8.527	8.513	
Height of gravity center /cm	4.263	4.256	0.007
Volume at 20 °C / cm^3	221.31705	127.21206	94.1050
Volume coefficient of thermal expansion	$5x10^{-5}$ /K^{-1}		
Magnetic susceptibility	≤0.0049		
Surface area / cm^2	204.497	202.165	2.332
Material	STS310s composition : 24•26 %Cr; 19•22 %Ni; 2.00 %Mn; 1.50 %Ni; 0.08 %C; 0.045 %P; and 0.030 %S		
Surface Roughness Rz /μm	< 0.1		

The uncertainty(k=1) sources are the 1 %RH(Vaisala HMI38, div. 0.1 %RH) for the humidity, the 2 mK(ASL F700, div. 1 mK) for temperature, the 2.3 Pa(Mensor 2104, div. 1 Pa) for pressure, and 50 ppm(Horiba 2000, div. 1 ppm) for CO_2 concentration.

A pair of 1 kg buoyancy artifacts, No.1 (hollow-cylinder) and No.2 (bobbin-cylinder), being approximately same in mass and in surface area, but different in volume, were used for measuring the apparent mass change due to the air buoyancy effects(Figure 2). The dimension of No. 1 was taken after considering that of mass comparator pan. The artifacts were not cleaned and washed since cleaning with ethanol and washing by steam jet of doubly distilled water in 1998.

The dimensions and the physical properties of the artifacts are given in Table 1. The material of the pair artifacts was a stainless steel SUS310S. The pair was fabricated in 1996. The surface roughness for the ten point height of irregularities, Rz, were measured by roughness testers. The magnetic susceptibilities, χ, could be measured by the use of the BIPM type susceptometer and the reference material with a known magnetic susceptibility. The Rz and the χ of the artifacts satisfied the conditions of Organisation Internationale de Metrologie Legale(OIML) Class of E_1 mass standards. The volumes of the BA-pair were measured at KRISS density group in 2002 as shown on the Table 1. The obtained uncertainty is 0.00023 cm^3 for the cylindrical BA and 0.00022 cm^3 for the Bobbin BA with a coverage factor of k=2.

3. Results and Discussions

3.1 Mass Difference in Vacuum

The mass difference, Δm_V, between the No.1 and the No.2 in vacuum was measured by using AT1007 mass comparator at NMIJ (former NRLM) in Japan after evacuating for 7 days on Sep. 1999 with an experimental standard deviation(s.d.) of 0.0001 mg. The degree of vacuum was about 6x10^{-4} Pa for the $\Delta m_{v,1999,\ nmij}$ measurements. The result was compared with those of KRISS. The difference between $\Delta m_{v,1999,\ KRISS}$ and $\Delta m_{v,1999,\ NMIJ}$ is as small as 6.8 μg, but that between $\Delta m_{v,1998,\ KRISS}$ and both $\Delta m_{v,1999,\ NMIJ}$ $\Delta m_{v,1999,\ KRISS}$ is so big. The reason of mass difference can't be explained explicitly but guessed instability of artifacts.

• $m_{v,1998,\ KRISS}$ = 2.634 mg, s.d.=7 μg (3)
• $m_{v,1999,\ KRISS}$ = 2.658 mg, s.d.=7 μg (4)
• $m_{v,1999,\ NMIJ}$ = 2.6652 mg, s.d.=0.1 μg (5)

3.2 Air Density

The air density measurements by the BA-pair weighing and by the internationally recommended CIPM-81/91 formula were carried out simultaneously during 7 days from Mar. 21 to May 6 in 2002 and the data of 425 measurements were obtained. The change of ambient condition during experiments was shown in Figure 3. The apparent mass difference was measured by the substitution weighing(R-T-R) which takes about 5 minutes for the one measurement of mass difference.

The results show that the disagreement between air density measurements by the 1 kg BA-pair and those by CIPM formula is 5.1x10^{-4} kg/m^3, but the standard deviation of experiments, 5.3x10^{-5} kg/m^3 is much better than that of the previous experiment, 1.5x10^{-4} kg/m^3. It requires more accurate calibrations in the related constants of BA-pair, some ambient measuring sensors, and the unknown sources from weighing system.

The effect of the surface area difference, 2.332 cm^2, was estimated by using the method[4] and considered negligible;

$$\Delta m_{ads} = \mu\bullet_{air\text{-}vac} \times \Delta S = (0.35\ \mu g/cm^2) \cdot 2.332\ cm^2 = 0.86\ \mu g \quad (6)$$

with the uncertainty of 0.011 μg/cm^2(k=1) for the μ2and the uncertainty of 0.5 cm^2 (k=1) for the surface difference ΔS.

The uncertainty sources and the combined standard uncertainties are summarized in Table 2. The results of air density measurements by the 1 kg BA-pair within the tentative experiments show the uncertainty level (k=1) of 3.6x10^{-5} kg/m^3 and those by the internationally recommended BIPM air density equation show the uncertainty level (k=1) of 1.1x10^{-4} kg/m^3 . However the disagreement between the both methods shows an amount of 5.1x10^{-4} kg/m^3. It may be assumed that there are some mass instabilities of buoyancy artifacts between in vacuum weighing and air weighing.

4. Uncertainty

Table 2. Uncertainty budget

Source of Uncertainty	$C_i = \delta\rho/\delta_{qi}$	$u(q_i)$	$C_i u(q_i)$, kg/m^3
$u(\rho_{sys})$			1.1x10^{-4}
P	1.2x10^{-5} kg m^{-3} Pa^{-1}	2.3 Pa	2.8x10^{-5}
T	2.8x10^{-3} kg m^{-3}K^{-1}	0.002 K	5.6x10^{-6}
H	1x10^{-2}	0.01	1x10^{-4}
X_{CO2}	0.48	5x10^{-5}	2.4x10^{-5}
$u(\rho_0)$			1.2x10^{-4}
$U(\rho_f)$			1x10^{-4}
$u(\rho_{eq})$ = 1.1x10^{-4} kg/m^3			
Δm_v	0.0106 kg m^{-3} mg^{-1}	1.2x10^{-3} mg	1.3x10^{-5}
Δm_a	0.0106 kg m^{-3} mg^{-1}	3.2x10^{-3} mg	3.4x10^{-5}
μ'	0.0124 kg m^{-3} (mg/cm^{-2})	1.1x10^{-5} (mg/cm^{-2})	1.4x10^{-7}
ΔV	0.0124 kg m^{-3} cm^{-3}	1.1x10^{-4} mg	1.4x10^{-6}
ΔS	3.72x10^{-6} kg m^{-3} cm^{-2}	0.5 cm^{-2}	1.9x10^{-6}
$u(\rho_b)$ = 3.6x10^{-5} kg/m^3			

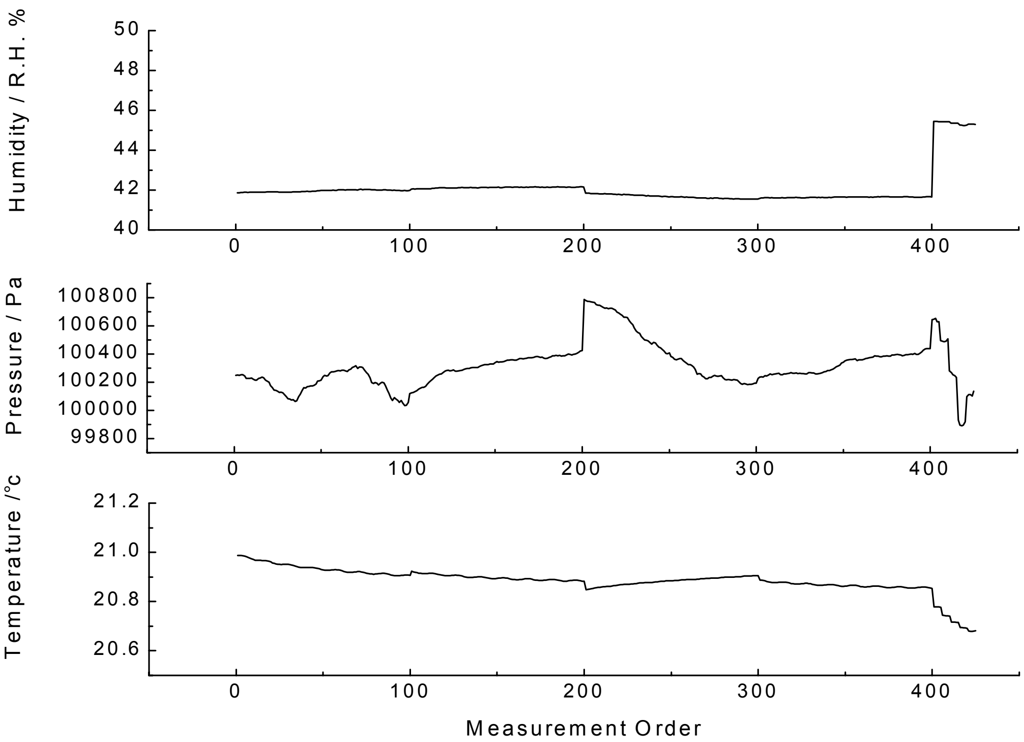

Figure 3. The measured ambient conditions during experiments

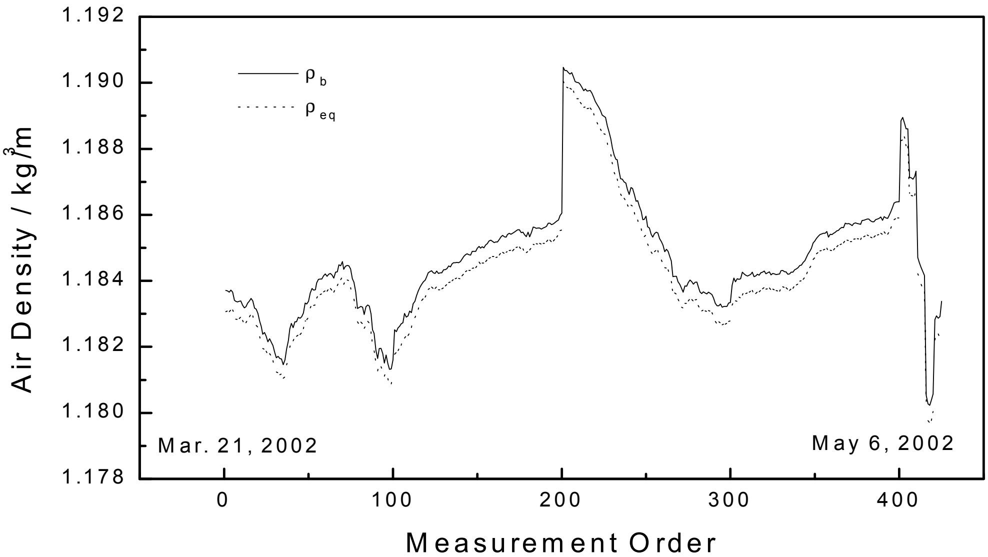

Figure 4. Results of the air density measurements. The solid line is measured by the BA-pair weighing and the broken line is obtained by the internationally recommended CIPM formula 81/91.

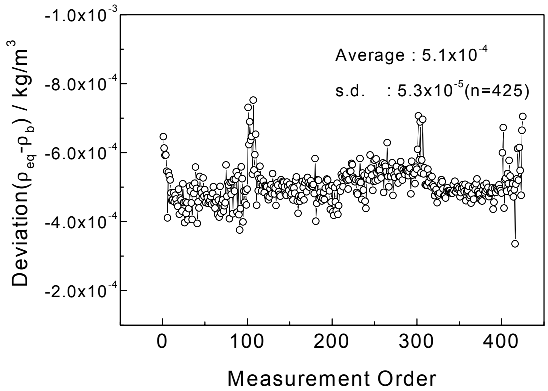

Figure 5. Difference of Eq-BA

5. Conclusions

The results of air density measurements by the 1 kg BA-pair show the uncertainty level (k=1)of $3.6x10^{-5}$ kg/m^3, but the disagreement with those by the internationally recommended CIPM formula 81/91 is significant as much as $5.1x10^{-4}$ kg/m^3. It may be assumed that there are some mass instability of buoyancy artifacts between in vacuum weighing and air weighing and the unstable measurement of ambient condition due to imperfect air-tight chamber. This work will be continued after installation of Mettler-Toledo 1 kg/0.1 μg mass comparator.

References

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