IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference
30 May to 1 June, 2017, Helsinki, Finland

RESEARCH ON THE INFLUENCE OF AIR DENSITY TO HIGH ACCURACY MASS MEASUREMENT

M.H. Hu/Presenter, J. Wang, C.Q. Cai, Y. Zhang, T. Huang, R. L. Zhong and Kai. Jiao

National Institute of Metrology, Beijing, P.R. China, hmh@nim.ac.cn

Abstract: The mass dissemination needs to be conducted in various air density conditions and even vacuum condition after redefinition of kilogram. This paper discussed the influence of temperature, humidity and air pressure to the air density using the CIPM 2007 forum method to the high precise weighing process. The stability of air pressure to the mass determination process is discussed experimentally using the new M-one mass comparator. When the temperature and humidity are well controlled inside the weighing laboratory, the air pressure should also be controlled to achieve precise mass measurement. Due to the change of air pressure, airflow and vibration with regard to the weighing hanger can be arisen. The vibration of weighing hanger is from both the base and the airflow. Under air pressure control, the standard deviation of weighing process can be reduced to 0.39 µg. Experimental results indicate that weights with hollow structure in the middle can reduce the influence of air pressure to the weighing process.

Keywords: Mass determination; Air density measurement; Uncertainty evaluation; Density artefacts;

1. INTRODUCTION

A new definition of the kilogram based on natural constant such as plastics constant is scheduled in 2018, weights as metrology artefacts will be not only used in air condition, but also in vacuum situation or other inactive gas. Mass is usually determined with indirectly measurement technologies, such as measurement of forces. [1]. When weights are surrounded with air during the weighing process, the air buoyancy force will influence the indication of weighing instruments.

The mass of test weight, m_t, can be expressed with the equation 1:

$$m_t = m_r + (V_t - V_r) \times \rho_a + \Delta I \times \frac{m_{cs}}{\Delta I_s} \quad (1)$$

in which m_t and m_r are the mass of test weight and reference weight; V_t and V_r are the volume of test weight and reference weight; ρ_a is density of moist air; ΔI is indication difference of the balance ; m_{cs} is mass of the sensitivity weight; ΔI_s is the indication difference of the balance when put on the sensitivity weight on weighing pan.

According to OIML R111, altitude and corresponding changes in air density can affect the measurement process when using the conventional mass of weights. [2] During high precise mass measurement, the temperature, pressure, relative humidity and CO_2 content in air need to be measured to do the air bouncy correction. [2-6]

Usually the weighing process will be cycle weighing process of ABBA , in which A is the reference weight, and B is test weight, both A and B will be weighed two times. The change of air density will influence to air buoyancy force during the weighing process.

To evaluate the influences of air density to the mass determination process, this paper experimentally investigates air density determination process with sensor method using CIPM 2007 forum. And the temperature, humidity and air pressure to the measuring process are discussed and the uncertainty contributions of air density are also evaluated.

2. EXPERIMENTAL SET-UPS

M-one mass comparator is used for mass determination below 1 kg. With 6 weighing positions, the electronic weighing range is (0~1.5) g and readability is 0.1 µg. As shown in Figure 1, the control computer can program any mass comparison between any two weighing positions referred as P1 to P6. The load lock is used to put the weights into the chamber to be moved on the weighing positions. The M-one is also equipped with an airtight chamber and can be used under vacuum. The chamber can be opened either with the front door or with using the lift-up system. During the mass measuring process, the chamber should be closed to keep the inner air condition as constant as possible. The environment of M-one especially temperature should also be controlled to avoid the energy change between the M-one and the surrounded environment.

According to air density calculation formula of CIPM 2007, the density of moist air ρ_a can be expressed as :

$$\rho_a = \frac{pM_a}{ZRT}[1 - x_v(1 - \frac{M_v}{M_a})] \quad (2)$$

where: p is the air pressure, M_a is the molar mass of dry air; Z is the compressibility; R is the molar gas constant, T is the dynamic temperature using ITS-90, x_v is the mole fraction of water vapor; and M_v is the molar mass of water. [3]

The air density measuring system, developed by NIM, China, can measure the pressure, temperature, relative humidity and carbon dioxide content, as shown in Figure 2. These sensors are mounted in the closed chamber of Mone.

The copper artefacts and aluminium artefacts as showed in Figure 2 (c) , are used to determine the influence of air density to the weighing process.

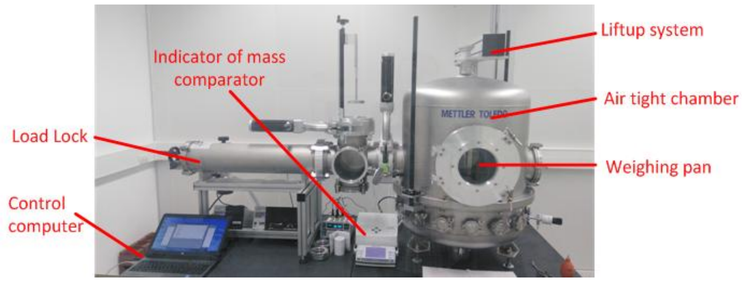


Figure 1. Picture of new M-one prototype mass standard comparator

(a) (b) (c)

Figure 2. Pictures of air density measurement system (a), test samples of 1 kg (b) and the artefacts (c)

3. RESULTS AND DISCUSSION

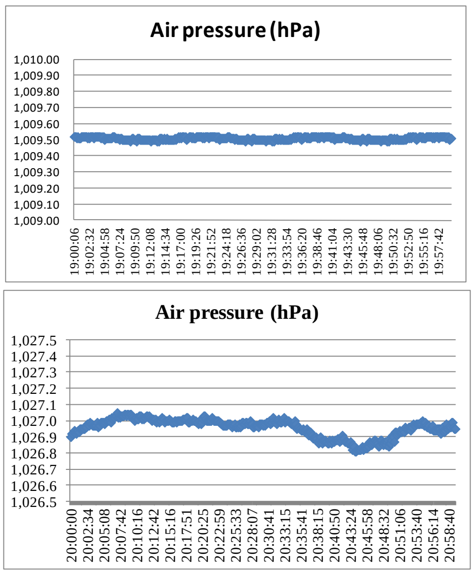
As shown in Figure 1, when closing the airtight chamber of M-one weighing system, certain amount of air will be closed in the chamber, the air pressure inside the chamber will keep constant. There is no air exchange between inner and outside the chamber. The temperature and relative humidity of whole laboratory are also well controlled. The change of temperature, humidity and air pressure inside the chamber are measuring to study the air density's influence to weighing process .

Air pressure is measured continually for 1 hour to monitor the air pressure change inside the airtight chamber. The comparison of air pressure deviation inside the chamber is showed in Figure 3 by keeping the airtight chamber closed or opened. When keeping the airtight chamber opened, the deviation of air pressure inside the chamber is 0.24 hPa. When closing the airtight chamber, the deviation is reduced dramatically to 0.03 hPa.

Figure 4 shows the changes of temperature, relative humidity and CO_2 content when keeping the airtight chamber closed. The other parameters of air are kept as constants with low deviation, which indicate that the mass measuring condition in airtight chamber is stable.

The 6×ABBA cycles of full comparison between any two positions of M-one mass comparator were conducted in both pressure conditions. The measuring results using stainless steel weights are showed in Figure 5(a) when keeping the airtight chamber opened and closed using standard. When the air pressure deviation is low with air pressure control, the standard deviation of measuring process can be reduced from 1.39 µg to 0.41µg.

The measuring results using copper weights and aluminium weights are showed in Figure 5(b). There are no significant standard deviation difference using cooper weights whether control the air pressure or not in weighing position 1 and position 3. Both the cooper weights have hollow structure in the middle of weights.



(a)

(b)

Figure 3. The air pressure change with (a) and (b) without air pressure control

According to equation 2, the uncertainty of air density, μ_{ρ_a}, can be expressed as:

$$\mu_{\rho_a} = \sqrt{\begin{matrix} \mu_F^2 + \left(\frac{\partial \rho_a}{\partial p}\mu_p\right)^2 + \left(\frac{\partial \rho_a}{\partial t}\mu_t\right)^2 \\ +\left(\frac{\partial \rho_a}{\partial hr}\mu_{hr}\right)^2 + \left(\frac{\partial \rho_a}{\partial x_{CO_2}}\mu_{x_{CO_2}}\right)^2 \end{matrix}} \quad (3)$$

in which:

$$\mu_F = 22 \times 10^{-6} \rho_a Pa^{-1}$$

$$\frac{\partial \rho_a}{\partial p} = 10^{-5}\rho_a Pa^{-1}$$

$$\frac{\partial \rho_a}{\partial t} = -3.4 \times 10^{-4}\mathrm{K}^{-1}\rho_a$$

$$\frac{\partial \rho_a}{\partial hr} = -10^{-2}\rho_a$$

$$\frac{\partial \rho_a}{\partial\, x_{\mathrm{CO}_2}} = 0.4\rho_a$$

The uncertainty budget for the density of moist air is showed in Table 1. Although the air pressure is not the biggest contribution to the uncertainty of air density, due to the air buoyancy effects, the air pressure can introduce big influence to the weighing process by causing the air flow and introducing vibration to the weighing hanger of M-one. The vibration of weighing hanger is not only from the base but also from the air flow.

The standard uncertainty of the weighing process, μ_w, is the standard deviation of the mass difference. For n cycles of measurements, it can be expressed as Equation 4:

$$\mu_w = \frac{S(\Delta m)}{\sqrt{n}} \tag{4}$$

For a digital mass comparator with the scale interval, d, the uncertainty due to resolution is :

$$\mu_d = \left(\frac{d/2}{\sqrt{3}}\right) \times \sqrt{2} \tag{5}$$

The uncertainty budgets for mass determination of 1 kg weight using M-one mass comparator are showed in Table 2. The mass of reference weight has the largest uncertainty value. The weighing process can be reduced to small value of 0.065 µg under the air pressure constant controlled in the airtight chamber.

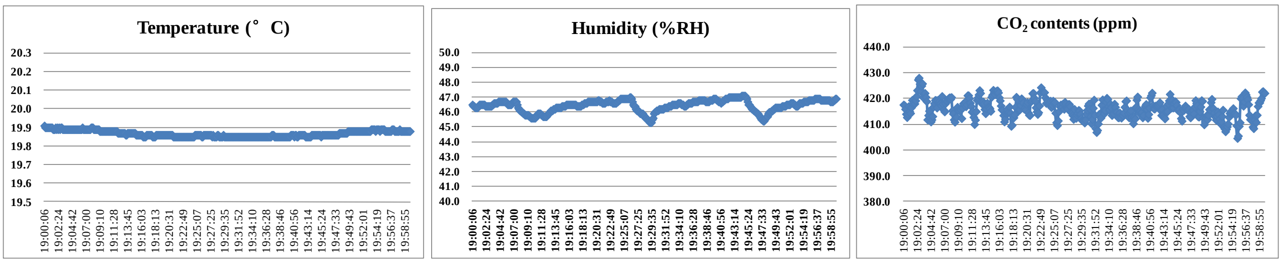
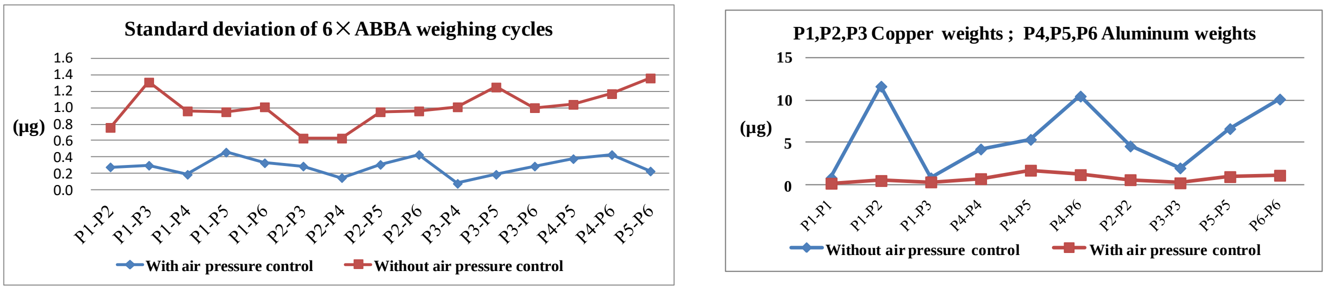


Figure 4. The measuring value change of temperature, humidity and CO_2 content in the closed chamber



(a) (b)

Figure 5. Comparison of measuring results of measuring sequence 6×ABBA cycles with and without air pressure controlling using standard stainless steel weights (a) and cooper and aluminium artefacts (b)

Table 1. Uncertainty budgets for the density of moist air

Source(X_i)	**Value Standard uncertainty $u(X_i)$**	**Sensitive coefficient $\|C_i\|$**	**Uncertainty contribution $u_i(\rho_a)$**
Pressure, μ_p	1.2 Pa	1×10^{-5} kg/ (m^3 Pa)	1.2×10^{-5} kg/ m^3
Temprature, μ_t	0.007 K	-4×10^{-3} kg/ (m^3 K)	-2.8×10^{-5} kg/ m^3
Humidity, μ_{hr}	0.008	-9×10^{-3} kg/ m^3	-7.2×10^{-5} kg/ m^3
Carbon dioxide content	0.0000034	0.4 kg/ m^3	1.3×10^{-6} kg/ m^3
CIPM 2007 formula, μ_F			22×10^{-6} kg/m^3
Combined uncertainty of air density $u(\rho_a)$			8.3×10^{-5} kg/m^3
$U(\rho_a)$ (k=2)			1.7×10^{-4} kg/m^3

Table 2. Uncertainty budgets for mass determination of 1 kg using M-one mass comparator

Source(X_i)	**Value Standard uncertainty $u(X_i)$**	**Sensitive coefficient$\|C_i\|$**	**Uncertainty contribution $u_i(m)$ /mg**
Mass of reference weight , $\mu(m_r)$	0.01 mg	1	0.01
Weighing process, μ_w	0.000065 mg	1	0.000065
Air density, μ_{ρ_a}	0.00017 mg cm^{-3}	2.4362 cm^3	0.00042
Volume of reference weight	0.0008 cm^3	1.2134 mg cm^{-3}	0.00098
Volume of test weight	0.0012 cm^3	1.2134 mg cm^{-3}	0.0014
Balance linearity	0.000001 mg	1	0.000001
Balance sensitivity	0.00003 mg	1	0.00003
Balance display resolution	0.000041 mg	1	0.000041
Combined uncertainty of air density $u(m)$			0.011
Extended uncertainty of air density $U(m)$ (k=2)			0.022

4. CONCLUSIONS

In this paper, the influence of air density to precise mass measuring process is discussed. When the temperature and humidity are well controlled inside the weighing laboratory, the air pressure should also be controlled to achieve precise mass measurement. The constant of air pressure can reduce the air movement inside the airtight chamber, decrease the friction at the vertical surface of the weight and pressure force at horizontal surfaces, and lead to less standard deviation of weighing process. When using the airtight chamber to control the air pressure, the standard deviation of mass comparison can be reduced lower to 0.39 µg. The mean standard deviation of mass comparison can be achieved as 0.065 µg. Experimental results also indicate that weights with hollow structure in the middle can reduce the influence of air pressure to the weighing process.

5. ACKNOWLEDGEMENTS

This research is supported in part by natural science foundation of china (NSFC) (Grant No. 51205379), in part by the National Science and Technology Support Program under Grant 2011BAK15B06, in part by the Special-Funded Program through the National Key Scientific Instruments and Equipment Development under Grant 2012YQ090208, and in part by National Key Research and Development Program for National Quality Infrastructure under Grant 2016YFF0200103.

6. REFERENCES

[1] M. Glaser, M. Borys, "Precision mass measurements," Rep. Prog. Phys., vol. 72, pp 1-32 ,2009.

[2] OIML R111, Weights of classes E1, E2, F1, F2, M1, M1-2, M2, M2-3, and M3, OIML Publication, 2004 Edition.

[3] A. Picard, "Revised formula for the density of moist air (CIPM-2007)," Metrologia, vol 45,pp. 149-155, 2008.

[4] M. S. Kim and J. R. Pratt, "SI traceability: current status and future trends for forces below 10 micro newtons," Measurement, vol. 43, pp. 69-82, 2010.

[5] M. Borys, M. Glaser, M. Mecke, "Mass determination of silicon spheres used for the Avogadro project," Measurement, vol. 40, pp. 785–790, 2007.

[6] N. Khelifa, M. Lecollinet, M. Himbert, "Molar mass of dry air in mass metrology," Measurement, vol. 40, pp. 779–784, 2007.