Advances in Engineering Research (AER), volume 105
3rd Annual International Conference on Mechanics and Mechanical Engineering (MME 2016)

Research on the Influence of Air Pressure to High Accuracy Mass Measurement

Chang-Qing CAI, Man-Hong HU*, Jian WANG, Yue ZHANG, Tao HUANG, Rui-Lin ZHONG and Kai JIAO

Division of Mechanics and Acoustics, National Institute of Metrology, 100029, Beijing, China

*hmh@nim.ac.cn

Keywords: Mass determination, Air density measurement, Uncertainty evaluation.

Abstract. This paper analyses the influence of air pressure regarding the precise mass measuring process. The stability of air pressure to the mass determination process is discussed experimentally using the new M-one mass comparator. Due to the change of air pressure, air flow and vibration with regard to the weighing hanger can be arisen. The vibration of weighing hanger is from both the base and the air flow. Under air pressure control, the standard deviation of weighing process can be reduced to 0.39 μg.

Introduction

Mass is a physical quantity that can only be determined with indirectly measurement technologies, such as measurement of forces. During the weighing process, the weight will be surrounded with air, and balanced by three kinds of force, which are supporting force from the weighing pan, gravity force and air buoyancy force. According to OIML R111 (Organisation Internationale de Metrologie Legale, Recommendation 111, Weights), altitude and corresponding changes in air density can affect the measurement process when using the conventional mass of weights, in which air pressure is a major parameter to the air density.[1]

For high precise mass measurement, accurate instruments should be used to determine the temperature, pressure, relative humidity and CO_2 content in air. [2-4]The air buoyancy correction shall be used, which requires the density of the weight to be known.[5,6] Usually the weighing process will be ABBA, which means that the reference weight will be weighed two times as A, test weight will be weighed two times as B. The air pressure can not only cause the change of air density and air buoyancy force, but also will influence the weighing process itself.

To evaluate the influences of air pressure to the mass determination process, this paper experimentally investigates two mass determination processes at both the air pressure controlled condition and the air pressure non-controlled condition. And the uncertainty contribution of air pressure is also evaluated.

Experimental Set-Ups

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.

M-one mass comparator is used for mass determination below 1 kg. It has 6 weighing positions. Its 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 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 :

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

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]

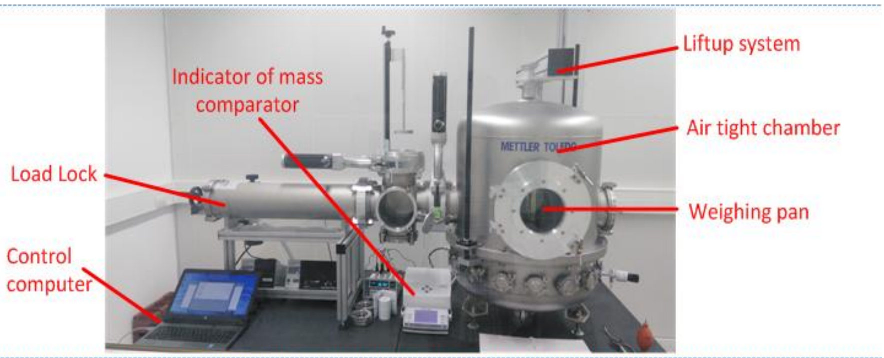

Figure 1. Picture of new M-one prototype mass standard comparator

(a) (b)

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

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

Results and Discussion

For the M-one weighing system, the air pressure is controlled by closing the airtight chamber. The M-one weighing system will be surrounded by certain amount of air. There is no air exchange between inner and outside the chamber. The temperature and relative humidity of whole laboratory are controlled to maintain good measuring condition, that is, the weighing process is not affected by two parameters of air density.

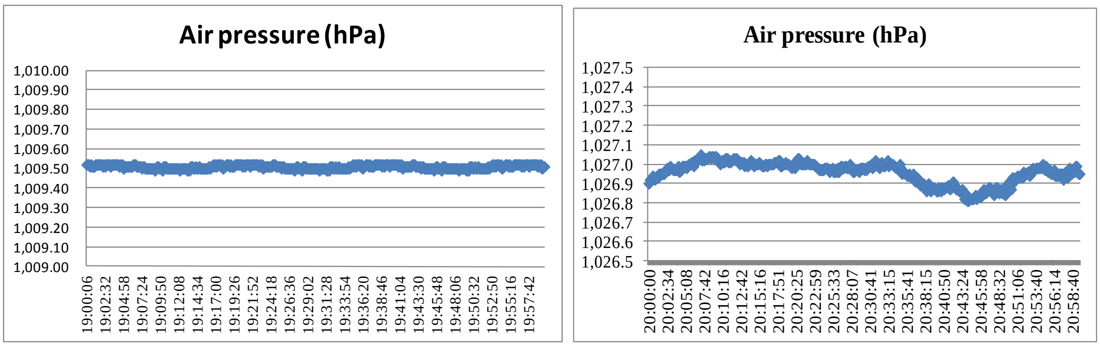

Figure 3. The air pressure change with (a) and (b) without air pressure control

Air pressure is measured continually for 1 hour to monitor the air pressure change inside the airtight chamber. The comparision 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. Figure 5 shows the measuring results when keeping the airtight chamber opened and closed. When the air pressure deviation is low, the standard deviation of measuring process can be reduced from 1.39 µg to 0.41 µg.

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

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

in which:

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

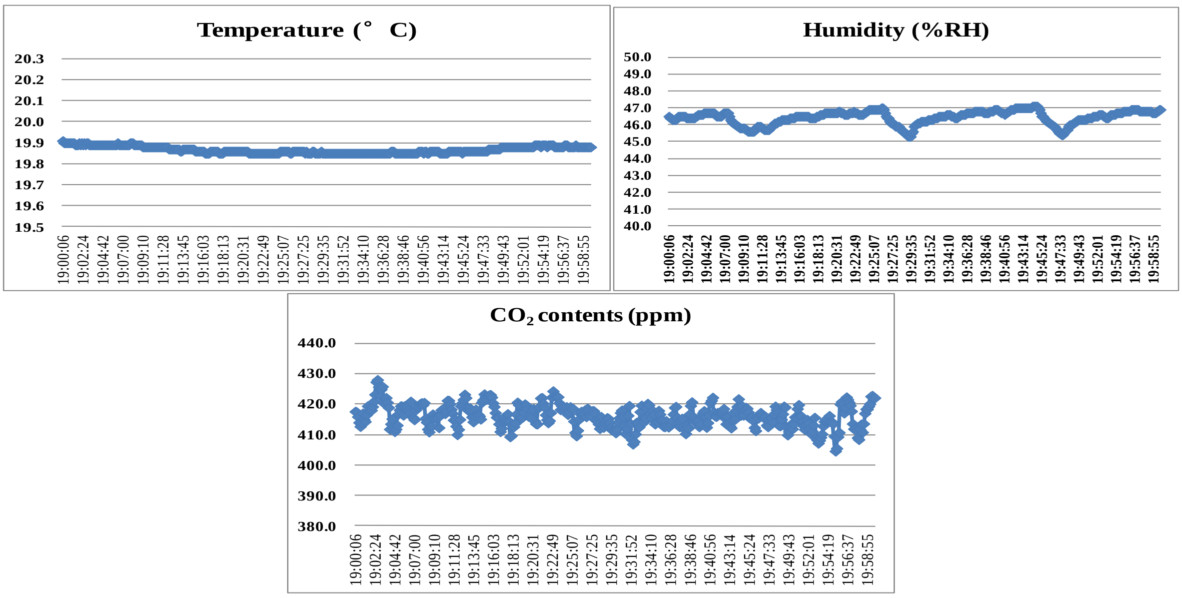

Figure 4. The measuring value change of temperature, humidity and CO_2 content in the closed chamber

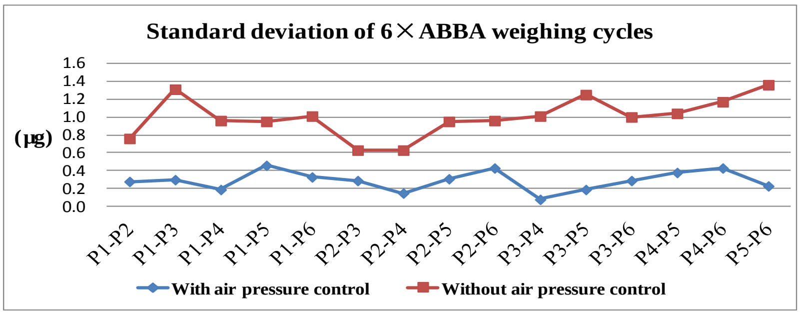

Figure 5. Comparison of measuring results of measuring sequence 6×ABBA cycles with (a) and without (b) air pressure controlling

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

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

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

$$\frac{\partial \rho_a}{\partial\, x_{\mathrm{CO_2}}} = 0.4 \rho_a$$

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.

Table 1. Uncertainty budgets for the density of moiste 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 $\times10^{-6}$ kg/m^3
Combined uncertainty of air density $u(\rho_a)$			8.3 $\times10^{-5}$ kg/m^3
$U(\rho_a)$ (k=2)			1.7 $\times10^{-4}$ 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

Conclusions

In this paper, the influence of air pressure to precise mass measuring process is discussed. 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.

Acknowledgements

This research is supported by natural science foundation of china (NSFC) (Grant No. 51205379).

References

1. M. Glaser, M. Borys, Precision mass measurements. Rep. Prog. Phys. **72**, 1-32 (2009)

2. Weights of classes E1, E2, F1, F2, M1, M1-2, M2, M2-3, and M3. OIML regulation R111. edition 2004 (E)

3. A. Picard, Revised formula for the density of moist air (CIPM-2007). Metrologia. **45**,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. **43**, 69-82(2010)

5. M. Borys, M. Glaser, M. Mecke, Mass determination of silicon spheres used for the Avogadro project. Measurement. **40**, 785–790 (2007)

6. N. Khelifa, M. Lecollinet, M. Himbert, Molar mass of dry air in mass metrology. Measurement. **40,** 779–784 (2007)