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 CO₂ 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:

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

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; \(\rho_a\) is density of moist air; \(\Delta I\) is indication difference of the balance ; \(m_{cs}\) is mass of the sensitivity weight; \(\Delta I_s\) 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
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.
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. 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 0.41µg.

According to equation 2, the uncertainty of air density, $\mu_{p_a}$, can be expressed as:

$$
\mu_{p_a} = \sqrt{\mu_{f}^2 + \left(\frac{\partial p_a}{\partial p} \mu_{p}\right)^2 + \left(\frac{\partial p_a}{\partial t} \mu_{t}\right)^2 + \left(\frac{\partial p_a}{\partial h}\mu_{h}\right)^2 + \left(\frac{\partial p_a}{\partial x_{CO2}} \mu_{x_{CO2}}\right)^2}
$$

in which:

$$\mu_{f} = 22 \times 10^{-6} \rho_{a} Pa^{-1}$$
Figure 5. Comparison of measuring results of measuring sequence 6×ABBA cycles with (a) and without (b) air pressure controlling

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

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

\[
\frac{\partial \rho_a}{\partial h_r} = -10^{-2} \rho_a
\]

\[
\frac{\partial \rho_a}{\partial x_{CO_2}} = 0.4 \rho_a
\]

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, \( \mu_w \), is the standard deviation of the mass difference. For \( n \) cycles of measurements, it can be expressed as Equation 4:

\[
\mu_w = \frac{s(\Delta m)}{\sqrt{n}}
\]

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

\[
\mu_d = \left(\frac{d^2}{\sqrt{3}}\right) \times \sqrt{2}
\]

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 \( \mu g \) under the air pressure constant controlled in the airtight chamber.

Table 1. Uncertainty budgets for the density of moist air

<table>
<thead>
<tr>
<th>Source((X_i))</th>
<th>Value Standard uncertainty (u(X_i))</th>
<th>Sensitive coefficient ([C_i])</th>
<th>Uncertainty contribution (u(\rho_a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure, (\mu_p)</td>
<td>1.2 Pa</td>
<td>(1\times10^{-5}) kg/ (m(^3) Pa)</td>
<td>(1.2\times10^{-5}) kg/ m(^3)</td>
</tr>
<tr>
<td>Temperatue, (\mu_t)</td>
<td>0.007 K</td>
<td>(-4\times10^{-3}) kg/ (m(^3) K)</td>
<td>(-2.8\times10^{-3}) kg/ m(^3)</td>
</tr>
<tr>
<td>Humidity, (\mu_{hr})</td>
<td>0.008</td>
<td>(-9\times10^{-3}) kg/ m(^3)</td>
<td>(-7.2\times10^{-5}) kg/ m(^3)</td>
</tr>
<tr>
<td>Carbon dioxide content</td>
<td>0.0000034</td>
<td>0.4 kg/ m(^3)</td>
<td>1.3\times10^{-6}) kg/ m(^3)</td>
</tr>
<tr>
<td>CIPM 2007 formula, (\mu_F)</td>
<td></td>
<td></td>
<td>22 (\times10^{-6}) kg/m(^3)</td>
</tr>
<tr>
<td>Combined uncertainty of air density (u(\rho_a))</td>
<td></td>
<td></td>
<td>(8.3 \times10^{-5}) kg/m(^3)</td>
</tr>
<tr>
<td>(U(\rho_a)) ((k=2))</td>
<td></td>
<td></td>
<td>(1.7 \times10^{-4}) kg/m(^3)</td>
</tr>
</tbody>
</table>
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 \(u(m) / mg\) |
|-----------------------------------------------------|--------------------------------------|---------------------------------|--------------------------------------|
| Mass of reference weight , \(\mu(m_r)\)              | 0.01 mg                              | 1                               | 0.01                                 |
| Weighing process, \(\mu_w\)                         | 0.000065 mg                          | 1                               | 0.000065                             |
| Air density, \(\mu_{\rho_a}\)                       | 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 \(\mu g\). The mean standard deviation of mass comparison can be achieved as 0.065 \(\mu g\).

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

References
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