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Application and Uncertainty Analysis of a New Balance used in Natural Gas Primary Standard up to 60bar

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Abstract

A new 3-ton electromagnetic balance system was designed and built up for a high level mass-time primary standard of natural gas up to 60bar in CVB. The system is composed of a 3-ton electromagnetic balance, two tanks with thermal isolation, two platforms, two roller guide rails and two big weights which are used for special test. To achieve a lower uncertainty and the security application in natural gas measurement, several special methods were used in the system. Firstly, the tanks and platforms can be moved together steadily on the roller guide rail to be connected with pipeline system or to be weighted by the balance which also reduces the pipeline length between tanks and pipeline system. Secondly, the substitute weighing method is used for high accurate weighting. Finally, the whole system is located in a thermal isolated room with temperature and humidity controlling. Technical details, performance tests, uncertainty analysis and the future improvement ideas of the balance system are presented in the paper. The uncertainty analysis shows that the mass measurement uncertainty of gas can achieve less than 1.0g and the relative standard uncertainty of natural gas mass measurement can achieve less than 0.02%.

1.Introduction

Large tonnage balances are used as the mechanics instruments with high accuracy for weights traceability, mass measurement of gas or liquid as well as torque or tension pressure measurement. Gyroscopes and electromagnetic balances are the most common devices used for mass measurement in mass-time gas facility in the world. Relatively electromagnetic balances are more accurate than gyroscope, so they are popularly used in mass-time natural gas primary facility(see figure 1) over low to medium pressure.

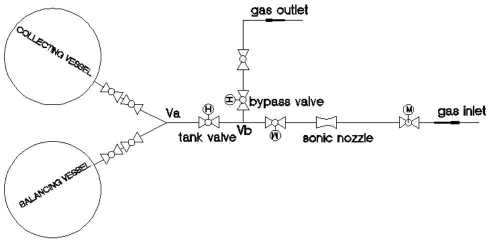


Figure 1: Sketch of the mass-time primary test rig

In 1996, CVB set up a 3-ton balance weighting system and updated the electronic controlling system to improve measurement accuracy in 2003[1].This system was used for mass measurement in a natural gas primary standard facility which was operated under 4bar to 38bar with the maximum flow rate of 2.63kg/s.And the calibration uncertainty of sonic nozzles was 0.22%(k=2). The weighting range of this balance was from 10kg to 110kg, the electromagnetic weighting range was from 0g-500g, the sensitive quantity was 1g, the actual scale interval was 0.1g and the repeatability of weighting is about 2g. The structure of this balance was unequal-armed which was efficient to reduce the balance weights on another side. However there were three main disadvantages in this weighting system. Firstly, it was possible that uneven change of the arms occurred because of this special structure. So the measurement accuracy would be affected. Secondly, direct weighting method was used which meant the reference weights were on the opposite side to the gas collecting vessel. Then the measurement accuracy would decline because of the difference of arm length between two sides caused by the change of temperature and humidity. Thirdly, there were risks of beam shifting which would cause the position change of the coil and magnetic steel even scratching. The reason was that the position of the beaming system was achieved by the groove cutter bearings which were not capable for horizontal position. Then the accuracy of weighting system was declined.

To improve the measurement performance and capability, CVB started to set up a new mass and time primary standard facility for （4-60） bar natural gas with maximum mass flow rate of 5.4kg/s in 2014.So a new 3-ton balance weighting was designed for this standard (see figure 2). The new electromagnetic balance is completely equal-armed. The weighting range is from 4kg to 132.1kg, the electromagnetic weighting range was from 0g-300g, the sensitive quantity was 1g, the actual scale interval was 0.1g and the repeatability of weighting is about 0.5g. Based on this new weighting system, mass measurement uncertainty of the balance achieves less than 1g and the calibration uncertainty of sonic nozzles also improves a lot.

Figure 2: Picture of the weighting system

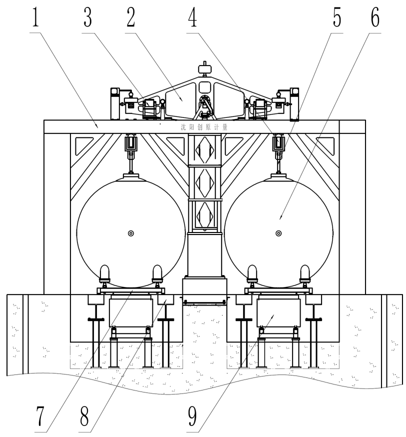
The structure, operation principle, technical details and uncertainty evaluation have been presented in this paper.

2.Structure and the principle

2.1 The structure of the new weighting system

For high pressure natural gas mass measurement, the thick-walled collecting vessels with massive weight up to several tons must be used. So the practical gas mass measurement of the balance is relatively limited. This means a big challenge to achieve high accuracy and lower uncertainty for the heavy-loaded balance which used in natural gas mass measurement.

The new electromagnetic balance is based on the theory of lever equilibrium and electromagnetic force equilibrium(see figure 3).On this way, the mass of the thick-walled collecting vessel can be balanced by the beam system which can bear heavy loads and balance the main weights as well as the imbalance value can be measured accurately by electromagnetic force system.



1-supporting system 2-beam system 3-measuring system
4-automatic weighting system 5-hanging system 6-weighting tank
7-movable platform 8-roller rail 9-precision positioning platform

Figure 3: diagram of the weighting system

The beam system is equal-armed (see figure 4) and is made of high speed tool steel. The high and low temperature aging and natural aging are applied to eliminate the inner stress and the supporting points of the beam system are quenched to ensure a good toughness as well as high hardness. So the supporting points can be very sharp lines.

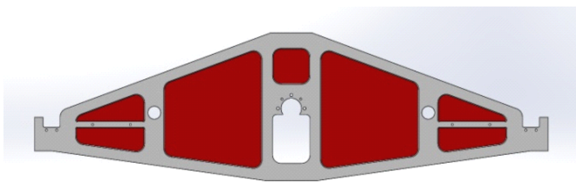


Figure 4: Picture of the beam

By optimizing the structure, the deformation of the beam system under heavy loads can be minimized. In addition, the left and right part of the beam would keep in equal when the environmental temperature and humidity change because of the totally symmetrical structure which could avoid the inaccuracy measurement caused by uneven change of two sides.

As shown in figure 5, two equal vessels are located in each side of the balance. One is for gas collection and another is for balance weight. The difference of air buoyancy of two vessels, which cause by the change of environmental temperature and humidity, can be minimized to achieve high accurate mass measurement.

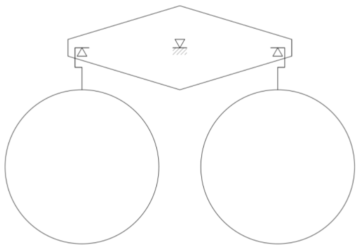


Figure 4: Digram of beam and vessels

2.2 The weighting method

According to the state of the art in mass measurement, substitution weighing method is the most accurate one for mass measurement of high pressure natural gas which can minimize the effect of arm difference.[2]

Natural gas is a kind of inflammable and explosive greenhouse gas which can't be vented directly to atmosphere, so the weighting method is as following.

Firstly, load all reference weights on two sides of balance while the natural gas has been vented properly. Turn on the balance and get I_0 as the initial measurement result without gas filing. Secondly, fill the collecting vessel with expectant quantity of natural gas and unload the relevant reference weights as $m_{weights}$ on the same side. Turn on the balance and get I_p as the final measurement result. Finally, the mass of natural gas m_{gas} in the vessel can be calculated by equation 1.

$$m_{gas} = m_{weights} - (I_0 - I_p) \qquad (1)$$

Figure 6 shows the pneumatic system which loads or unloads reference weights automatically. The system is explosion-proof which achieves the accurate loading of unloading of different weights from 100g to 132.1kg.

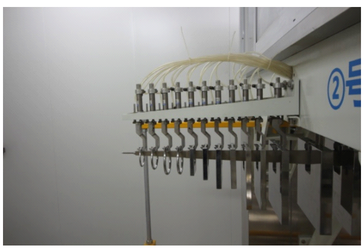


Figure 6: Picture of automatic loading and unloading system

2.3 The moving and positioning of collecting vessel

In general, the installing and uninstalling point between collecting vessel and test pipeline is located outside of the weighting room to avoid the change of environmental temperature and air turbulence in the room. So collecting vessel is movable to minimize the "line-pack" volume between the collecting vessel and under test meter.

Swing of the collecting vessel causes adverse effect for weighting. It would lead to unstable reading and inaccurate measurement because of centrifugal force which causes force difference on each side of supporting point of bearing. So it is critical to minimize the swing while the collecting vessel is hanging on the beam system of balance after gas filling. There are several accurate locating devices to achieve this.

Firstly, there are mechanical positioning between the collecting vessel and the movable platform which loads the vessel and moves together on the roller rail system stably and quickly. Secondly, there are electrical positioning between the movable platform, the roller rail system and the docking system which can guide the vessel to connect with the test pipeline automatically. Thirdly, there is a precision positioning platform combined with the roller guide and located under the balance (see figure 6).When the vessel and movable platform moves underneath the balance where the precision positioning platform also locates, the precision positioning platform raises up the vessel and movable platform together referring to the left part of figure 2, and makes the vessel match with the hanging system properly and stably. Then the precision positioning platform goes down with the movable platform. Then the vessel can be weighted by the balance separately.

Additionally, the docking system is specially designed to be adjusted on 6 different directions (see figure 7) to adapt the deviation caused by installation stress etc. Then the collecting vessel can connect to test pipeline properly for long term.

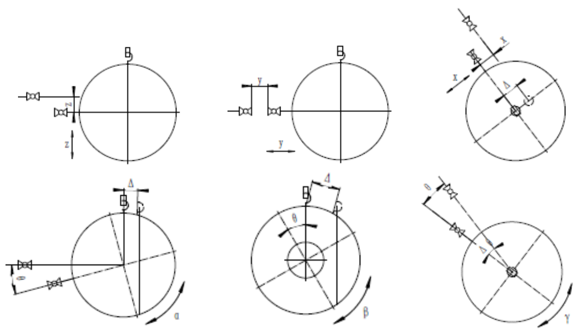


Figure 7: Diagram of 6 directions adjusting

2.4 The controlling and security system
The weighting system is operated automatically by PLC (see figure 8). So staffs can operate the whole system on the touch panel including moving, docking, hanging and weighting of the vessel before gas filling and after gas filling in the controlling room as well as data acquisition and processing which minimize the manual operation uncertainty.

Figure 8: Diagram of weighting controlling principle

The sensors in the security unit are independent from the measurement system. When the mechanical actuators or driving system go wrong and the vessel or platform is not in the correct position, the security system would send alarm signals to PLC and PLC would stop the whole system and remind operators check the specific part of the system.

2.5 Temperature and humidity controlling system

It very important to achieve stable temperature and humidity, turbulence free around the balance to minimize the effect of air buoyancy. For the new weighting system, thermal isolation walls, explosion-proof air-conditioning and micro-hole plates are applied to ensure the temperature stability and turbulence free. The test data shows the fluctuation of temperature is less than 0.5℃ over two weighting runs.

3.Uncertainty evaluation

Uncertainty of gas mass measurement can be written as following equation [3] according to Equation (1).

$$u(m_{gas}) = u^2(m_{weights}) + u^2(I_0) + u^2(I_p) \qquad (2)$$

Because I_0 and I_P is balancing reading before and after gas filling respectively, both of them are related to the performance of the balance. So $u(I_0)$ and $u(I_P)$ are positively strong correlation uncertainty. Then equation (2) can be rewritten as following.

$$u^2(m_{gas}) = 2\times u^2(m_{balance}) + u^2(F_{buoyancy}) \qquad (3)$$

$$u_r(m_{gas}) = \frac{u(m_{gas})}{m_{gas}} \qquad (4)$$

Where $u(m_{balance})$ is the standard uncertainty of mass measurement of balance before gas filling and $u(F_{buoyancy})$ is the standard uncertainty of air buoyancy effect after gas filling.

The mass measurement range of the balance is from 4kg to 132.1kg. So the uncertainty evaluation of 4kg could be representative for mass measurement uncertainty of the balance system.

3.1 $u(m_{balance})$
According to the principle of the balance system, $u(m_{balance})$ is composed of the uncertainty of reference weights $u(m_{weights})$ which are class F_1, measurement repeatability $u(E_r)$, resolution of the balance $u(I)$ and electromagnetic force measurement $u(EM)$ while all the sensitivity coefficient is 1.So $u(m_{balance})$ can be calculated according to equation (5).

$$u(m_{balance}) = \sqrt{u(m_{weights}) + u(E_r) + u(I) + u(EM)} \qquad (5)$$

(1) $u(m_{weights})$
The reference weights for gas measurement are F_1 class weights. Two 2kg reference weights are used for gas weighing, so $u(m_{weights})$ can be calculated as following [4].

$$u(m_{weights}) = |MPE|/3 = 30mg\times\sqrt{2}/3 = 0.006\text{g}$$

(2) $u(E_r)$
From the test data, the maximum repeatability of the balance is 0.5g. Gas weighing would repeat three times, so $u(E_r) = 0.5g/\sqrt{3} = 0.288g$.

(3) $u(I)$
The actual scale interval is 0.1g, so $u(I) = 0.1g/2/\sqrt{3} = 0.029g$.

(4) $u(EM)$
The maximum unbalancing reading of electromagnetic force is 100g which traces to another group of F_1 reference weights. So $u(EM) = 1.6mg/3 = 0.0005g$.

3.2 $u(F_{buoyancy})$
Of course it is necessary to consider the uncertainty component of air buoyancy effect after gas filling which

would raise the temperature of the gas inside the collecting vessel and lead to change of buoyancy of the collecting vessel and mass measurement. It is a tough job to evaluate this uncertainty accurately because there is no mathematical model to calculate the temperature effect of the collecting while gas filling because the thick wall of 24mm. So it is more practical to get $u(F_{buoyancy})$ from the test data which means calculate it according to the measurement results for several times.

3.3 calculation of $u(m_{gas})$ and $u_r(m_{gas})$

The calculated result of $u(m_{gas})$ and $u_r(m_{gas})$ are shown in table 1 referring to equation (2).

Table 1 gas mass measurement uncertainty results of the new balance

name	quantities	Sensitive coefficient	Standard uncertainty component
$u(m_{weights})$	0.06g	1	0.06g
$u(E_r)$	0.288g	1	0.288g
$u(I)$	0.029g	1	0.029g
$u(EM)$	0.005g	1	0.005g
$u(F_{buoyancy})$	0.2g	1	0.2g
$u(m_{gas})$	0.591g		
$u_r(m_{gas})$	0.018%		

4. conclusions

The performance of the new weighting system has achieved a high level because of the application of proper structure, substitution weighting method, precision positioning system etc. The mass measurement of natural gas is no more than 0.6g and the relative uncertainty is less than 0.02%. According to uncertainty evaluation, repeatability of balance and air buoyancy effect after gas filling are the main uncertainty components for mass measurement of natural gas after gas filling. So it is efficient to minimize temperature change around the collecting vessel over gas filling procedure. CVB is doing some further research on it.

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