FLOMEKO2019
18th International Flow Measurement Conference
Portugal | Lisbon | LNEC | 26-28 june 2019

Molten salt flow calibration facility by dynamic weighing method base on argon pressure balance principle

Chao Chen[1], Jin Song[2], Yiping Liu[3], Jinchuan Wu[4]

[1]Shanghai Institute of Measurement and Testing Technology, No1500 Zhangheng Rd., Shanghai, China
[2]Shanghai Institute of Measurement and Testing Technology, Shanghai, China
[3]Shanghai Institute of Measurement and Testing Technology, Shanghai, China
[4]Shanghai Institute of Measurement and Testing Technology, Shanghai, China
E-mail:chenc@simt.com.cn

Abstract

Thorium-based molten salt has the characteristics of high temperature, low pressure, high chemical stability and high heat capacity, which can be used as coolant for the molten salt reactor. The high-temperature molten salt flow meters need to measure, display and record the flow parameters in the reactor of molten salt circuit, and monitor the operating conditions of the molten salt reactor equipment, ensuring the safe and reliable operation of the reactor. However, there is no good calibration method for the high-temperature molten salt flow meter in China.

We have established high-temperature molten salt flow calibration facility by dynamic weighing method base on argon pressure balance principle. The flow range is (1～30) m^3/h, and the operating temperature range is from 600°C to 650 °C. The expanded uncertainty is U_{rel}=1.3% (k=2). The calibration facility has the characteristics of using less amount of molten salt, fast response and stable temperature. The configuration of the facility, working principle, main technical specification, data processing methods and uncertainty evaluation are described in this paper. High-temperature molten salt flowmeter of DN25-DN50 can be calibrated in the facility, the traceability problem of the high-temperature molten salt flowmeters can be solved.

1. Introduction

Molten Salt Reactor (MSR) is one of the six candidate nuclear energy systems selected by the Fourth Generation Nuclear Energy International Forum (GIF). MSR has many advantages in radioactive waste treatment, inherent safety and nuclear proliferation prevention. It is the development trend of nuclear energy in various countries. Through the comprehensive utilization of nuclear energy, it can alleviate the problems of carbon emissions and environmental pollution.

In order to ensure safe and reliable operation of the reactor, the high-temperature molten salt flowmeters are used in the molten salt reactor. Therefore, it is necessary to calibrate the high-temperature molten salt flowmeters. The liquid flow standard facility can be divided into three types, volumetric method, gravimetric method and master meter method. At present, the majority of liquid flow standard facility's working medium is oil or water, and the operating temperature of the facility is usually normal temperature. If the high-temperature molten salt flowmeters with medium temperature higher than 600 °C is calibrated with normal liquid flow standard facility, it will cause the problem that the calibration condition is inconsistent with the actual working conditions, so the flowmeters cannot be calibrated accurately.

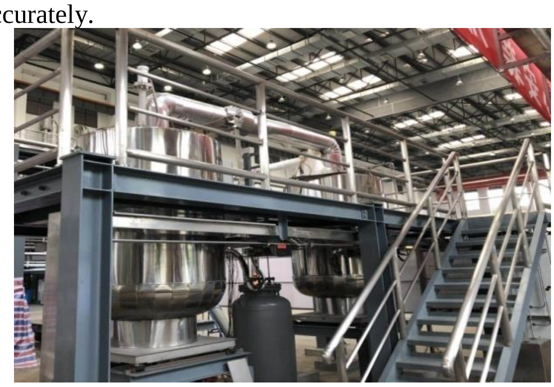

Figure 1: The photograph of molten salt flow calibration facility

Moreover, most of high-temperature molten salt flowmeters are ultrasonic flowmeters, the velocity of ultrasonic in the high-temperature molten salt is different from the velocity of ultrasonic in water or oil, which will also cause greater impact for the high-temperature molten salt flowmeters.

In order to solve the calibration problem of high-temperature molten salt flowmeters, molten salt flow calibration facility is established in China, calibration facility is shown in Figure 1，which is based on argon pressure balance principle. The calibration facility has the characteristics of using less amount of molten salt, fast response and stable temperature.

2. Composition and working principle

2.1 Composition of standard facility

Calibration facility is made of electric balances, molten tanks, measuring pipeline, argon pressure control system, heating and insulation system, level meters, pressure transmitter, temperature transmitter, data acquisition system and control system. Because of strong corrosion and toxicity of the high temperature molten salt, the standard facility adopts a closed loop structure to ensure the safe operation. The schematic diagram of standard facility is shown in Figure 2. Two measuring pipelines are connected to the bottom of the molten salt tanks respectively, argon pressure control pipeline are connected to the upper part of the molten salt tank, and the level meters are installed the top of molten salt tank to monitor the molten salt level. The pressure transmitter and temperature transmitter are installed on two molten salt tanks to measure the temperature and pressure in the molten salt tank. The high temperature molten salt flow meter under test is installed on the horizontal measuring pipeline.

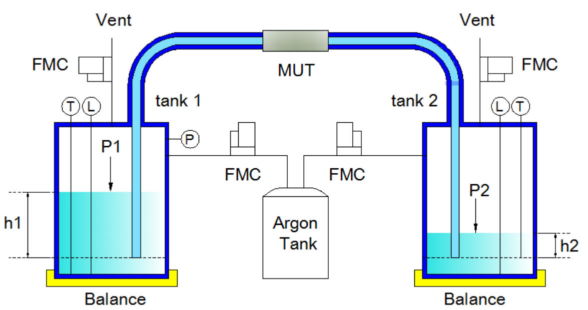

Figure 2: The schematic diagram of standard facility

In order to minimize to use the amount of molten salt and ensure the temperature stability of the medium, the standard facility uses argon pressure as the water head for the medium in the molten salt tank rather than using the conventional pump. The differential pressure in the two molten salt tanks will realize the flow of the high-temperature molten salt by controlling the pressure of the two molten salt tanks. The siphon phenomenon is generated in the measuring pipeline, so the measuring pipe is in fully charged in the molten salt. The different calibration flow can be controlled by adjusting the differential pressure between the molten salt tanks.

2.2 Working principle

Before operating, the high temperature molten salt is heated to the required working temperature, adjusting the pressure in the tank 2 is a little bit higher than the pressure of the tank1, so that the molten salt is completely back to the tank 1.

At the beginning of the calibration, the pressure control system fills the tank 1 with argon quickly, and simultaneously opens the tank 2 exhaust valve to release the argon pressure of the tank 2. At this time, a differential pressure is generated between the two tanks. Then the molten salt in the tank 1 flows through the meter under test， and flows into the tank 2. The pressure control system adjusts the differential pressure continuously between the two tanks to make the flowrate stable, and the data acquisition system records the initial mass M0 of the molten salt in the tank 1, meanwhile system recording the output signal of the meter under test. During the measurement, the parameter of mass, temperature, pressure and liquid level in the two molten salt tanks are monitored. The pressure of the argon in the two molten salt tanks is controlled by the mass flow controller to maintain molten salt flow stability. When the measurement time is up, the finishing mass M1 of the molten salt in the tank 1 is recorded, meanwhile stoping recording the output signal of the meter under test, and the first time of calibration is completed.

Closing the intake valve of the tank 1, and opening the exhaust valve to release the pressure in the tank 1 to reduce the pressure of the tank 1, then opening the intake valve of tank 2 to refill the argon, increasing the pressure in the tank 2 to make the all molten salt back to tank 1, and waiting for the next measurement.

3. Mathematical model of flow controlling

Since the molten salt is an incompressible fluid, it conforms to the Bernoulli equation:

$$\frac{P_1}{\rho g}+\frac{v^2}{2g}+h_1=\frac{P_2}{\rho g}+\frac{v^2}{2g}+h_2+\sum\lambda\frac{Lv^2}{2dg}+\sum\xi\frac{v^2}{2g} \qquad (1)$$

Where P_1 is the pressure of tank 1, P_2 is the pressure of tank 2, ρ is the density of molten salt, g is the gravity acceleration, v is the velocity of measuring pipe, h_1 is the molten salt level of the tank 1, h_2 is the molten salt level of the tank 2, λ is coefficient of friction losses, L is the length of pipe , d is diameter of pipe ,and ξ is coefficient of local losses.

After deforming the formula (1)：

$$(P_1 - P_2) + \rho g(h_1 - h_2) = (\sum \lambda \rho \frac{L}{d} + \sum \xi \rho)\frac{v^2}{2}$$

Assuming：

$$\Delta P = (P_1 - P_2) + \rho g(h_1 - h_2)$$

ΔP includes two items, the first item（$P_1 - P_2$） is the pressure difference between the two tanks; the second item is the pressure difference caused by the difference in the level of the molten salt in the two tanks. Under the action of argon pressure, the molten salt flows from the tank 1 to the tank 2 continuously, h_1 will continue to decrease the molten salt level in tank 1, while h_2 increase continuously. To maintain ΔP stability, the pressure P_1 in tank 1 needs continue to increase, and the pressure P_2 in tank 2 needs to decrease constantly, and the pressure difference （$P_1 - P_2$） between the two tanks varies with the liquid level of the molten salt.

Assuming：

$$K = (\sum \lambda \rho \frac{L}{d} + \sum \xi \rho)$$

Then the velocity of the pipe can be expressed as:

$$v = \sqrt{\frac{2\Delta P}{\rho K}} \qquad (2)$$

The flow rate in the pipe can be expressed as：

$$q_v = \frac{\pi d^2}{4} v = \frac{\pi d^2}{4}\sqrt{\frac{2\Delta P}{\rho K}} \qquad (3)$$

During the measurement, the molten salt properties and the pipe characteristics will not change, it can be considered that ρ 、 K and d are constant, so the flowrate will stabilize as long as ΔP is stable.

4. The method of data processing

The standard facility is based on the principle of dynamic gravimetric method, and there is no diverter to start and stop the chronometer. Therefore, there is a certain difference between the actual measuring time and the measuring time of the flowmeter. It is necessary to correct the actual measuring time of the standard facility to the time of meter under test, and then the indication error of the flowmeter can be calculated accurately.

The measured mass of the standard facility at the measurement time is:

$$M_s = M_1 - M_0 \qquad (4)$$

The actual molten salt volume of the standard facility is:

$$V_a = C_f \frac{M_s}{\rho} \qquad (5)$$

Since the measurement time of the actual volume V_a and the indicated volume V_i of the flowmeter are inconsistent, it is necessary to correct the actual volume V_a to the volume of meter under test in t_i. The corrected indication error of the flowmeter is:

$$E_\mathrm{m} = \frac{V_\mathrm{i} - \frac{t_\mathrm{i}}{t_\mathrm{a}} V_\mathrm{a}}{\frac{t_\mathrm{i}}{t_\mathrm{a}} V_\mathrm{a}} \times 100\% = \left(\frac{V_\mathrm{i} \bullet t_\mathrm{a}}{V_\mathrm{a} \bullet t_\mathrm{i}} - 1\right) \times 100\%$$

$$= \left(\frac{V_\mathrm{i} \bullet \rho \bullet t_\mathrm{a}}{\Delta M \bullet C_f \bullet t_\mathrm{i}} - 1\right) \times 100\% \qquad (6)$$

Where t_i is the measurement time of meter under test and t_a is the actual measurement time of the standard facility.

5. Experiments

Flowrate stability is a very important performance of the liquid flow standard facility. It is an important parameter for evaluating the measurement performance of the liquid flow standard facility. The method for evaluating the flowrate stability of the liquid flow standard facility has two methods, flowrate stability between integration interval and flowrate stability within the integration interval, the former mainly considers the long-term stability of the standard facility and it is well known. The high-temperature molten salt flow standard facility is based on argon pressure balance, so using the method of flowrate stability within the integration interval to evaluate flowrate stability is more scientific.

5.1 the method of flowrate stability

The output signal of the flowrate q_{1i} is recorded continuously（i =1,2,3,…., n≥60）.

The average flowrate is :

$$q_1 = \frac{\sum_{i=1}^{n} q_{1i}}{n} \qquad (7)$$

The relative error is :

$$E_i = \frac{q_{1i} - q_1}{q_1} \times 100\% \qquad (8)$$

The autocorrelation function R_j is calculated.

The autocorrelation function：

$$R_j = \frac{\sum_{i=1}^{n-j} E_i \cdot E_{i+j}}{n-j} \qquad (9)$$

Where j=0,1,2,……,n-1 is the succession step, i is the running succession number.

The normalized autocorrelation function, the combination of the coefficients of correlation is determined from :

$$r_j = \frac{R_j}{R_0} \qquad (10)$$

The flowrate within the integration interval is :

$$E_{q1} = k\left[\frac{2}{n}\sum_{j=1}^{j_{\min}}\left|R_j\right|\right]^{1/2} \times 100\% \qquad (11)$$

Where j =0,1..., $j_{\min}$ ($j_{\min}$ is the smallest rank from which r_j is less than or equal to 0.1).

5.2 Measurement datas

According to the method of flowrate stability within the integration interval, the flowrate stability is carried out at maximum flowrate and at minimum flowrate respectively. The flowrate stability test results are shown in Table 1 and Table 2.

Table 1: The test results at minimum flowrate m^3/h

No. 1-10	No. 11-20	No. 21-30	No. 31-40	No. 41-50	No. 51-60
0.9876	0.9893	0.9788	0.9551	0.9615	0.9886
0.9814	1.0137	0.9494	0.9691	0.9768	0.9798
0.9899	1.0016	0.9836	0.9748	0.9987	0.9781
0.9981	0.9936	0.9550	1.0066	1.0074	0.9489
0.9855	0.9617	0.9929	1.0017	0.9915	0.9719
1.0073	0.9561	0.9519	0.9817	0.9657	0.9649
0.9964	0.9583	0.9924	0.9865	0.9894	0.9656
0.9964	0.9625	0.9924	0.9827	0.9838	0.9727
0.9613	0.9849	0.9898	0.9812	0.9822	0.9638
0.9937	0.9871	0.9900	0.9652	0.9613	0.9644

Table 2: The test results at maximum flowrate m^3/h

No. 1-10	No. 11-20	No. 21-30	No. 31-40	No. 41-50	No. 51-60
18.871	18.851	18.829	18.941	19.000	18.874
18.646	18.909	19.023	19.057	18.969	18.683
18.670	19.080	18.960	18.963	18.907	18.668
18.817	19.096	19.022	18.880	18.830	18.720
18.978	19.080	18.749	18.777	18.912	18.708
19.116	18.978	18.872	18.814	18.742	18.721
18.922	18.853	18.839	18.909	18.896	18.754
18.879	18.790	18.957	18.964	18.936	18.739
18.867	18.750	18.753	18.935	19.078	18.862
18.891	18.785	18.787	19.035	18.917	18.821

5.3The results of flowrate stability

The flowrate is relatively stable at minimum flowrate, However, the flowrate has a little bit decrease within the measuring time. Because the flowrate is small, the flowrate stability duration time can last up to 400s. The minimum flowrate stability of the standard facility is 0.32% can be achieved. Then the control flowrate stable is very difficult at maximum flowrate, the flowrate fluctuation is more obvious than the minimum flowrate, and the duration of the flow stability is relatively short. The maximum flowrate stability of the standard facility is 0.87% can be calculated. The flowrate stability test results at different flowrates are shown in Figure 3 and Figure 4.

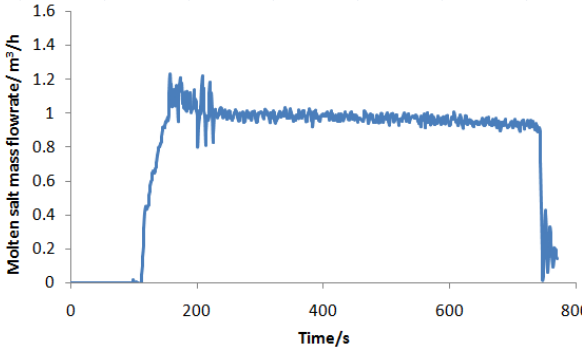

Figure 3 Flowrate stability results of minimum flowrate

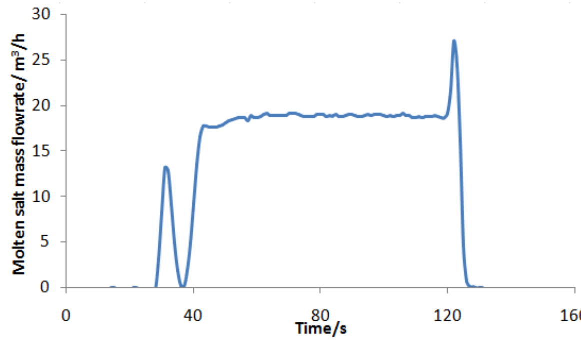

Figure 4 Flowrate stability results of miximum flowrate

6. Uncertainty evaluation

When the high-temperature molten salt flow meters calibrated with molten salt flow calibration facility, it needs to convert display mass of electronic balance to actual volume based on density of molten salt, During the actual working condition, the reference volume is also related to the temperature change of the molten salt and the bubbles in the molten salt. The reference volume of the standard facility at the high temperature molten salt flowmeter is:

$$V_{ref} = \frac{M_s}{\rho} C_f + \Delta V_P + \Delta V_B \qquad (12)$$

Where V_{ref} is the reference volume of the standard pressure at meter under test, M_s is the actual mass of the electrical balance, ρ is the density of molten salt, C_f is the coefficient of buoyancy, ΔV_P is the changeable volume of the measuring pipe, ΔV_B is the volume of the bubble in molten salt.

6.1 Standard uncertainty of electrical balance u_{Ms}

6.1.1 Uncertainty of calibrating electrical balance u_{Ms1}

The full scale of the electrical balance is 1500 kg being used in the molten salt flow calibration facility, the electrical balance is used at 3 fixed points, which is 800kg at the maximum flowrate, 400kg at the medium flowrate and 200kg at minimum flowrate respectively.
According to the calibration certification of the electrical balance, the expanded uncertainty is 0.5kg（k=2）at 800kg .
The standard uncertainty caused by the calibration of the electrical balance at maximum flowrate is:

$$u_{Ms1} = \frac{0.5}{2} = 0.25\,\text{kg}$$

6.1.2 Standard uncertainty of deviation of electrical balance u_{Ms2}

According to the calibration certification of the electrical balance, the deviation of electrical balance is 1.0kg,（k=2）at 800kg.
The standard uncertainty caused by the deviation of the electrical balance at maximum flowrate is:

$$u_{Ms2} = \frac{1.0}{\sqrt{3}} = 0.58\,\text{kg}$$

6.1.3 Standard uncertainty caused by resolution of the electrical balance u_{Ms3}

According to the display of the electrical balance, the resolution of electrical balance is 0.5kg.
The standard uncertainty caused by resolution of the electrical balance is:

$$u_{Ms3} = \frac{0.5}{\sqrt{3}} = 0.29\,\text{kg}$$

6.1.4 Standard uncertainty caused by connecting pipe stress u_{Ms4}

Because the high-temperature molten salt flow calibration facility is a sealing system, the connecting pipe will stress the electronic balance when the molten salt flows. The maximum uncertainty caused by connecting pipe stress is 1.2kg. The standard uncertainty caused by the connecting pipe stress at maximum flowrate is:

$$u_{Ms4} = \frac{1.2}{\sqrt{3}} = 0.69\text{kg}$$

6.1.5 The calculation of standard uncertainty of input quantity M_s

The standard uncertainty of M_s is：

$$u_{Ms} = \sqrt{u_{\text{Ms1}}^2 + u_{\text{Ms2}}^2 + u_{\text{Ms3}}^2 + u_{\text{Ms4}}^2} = \sqrt{0.25^2 + 0.58^2 + 0.29^2 + 0.69^2} = 1.0\text{kg}$$

Sensitivity coefficient is：

$$c\ (M_s) = \frac{\partial V_{ref}}{\partial M_s} = \frac{C_f}{\rho} = 0.0005(\text{m}^3/\text{kg})$$

6.2 Standard uncertainty of molten salt density u_ρ

6.2.1 Standard density uncertainty caused by temperature transmitter $u_{\rho 1}$

The range of the temperature transmitter is（0～1000）℃， the maximum permissible error of the temperature transmitter is ±5℃.The maximum deviation of density caused by the temperature is 3.2kg/m³. The standard density uncertainty caused by temperature transmitter is:

$$u_{\rho 1} = \frac{3.2}{\sqrt{3}} = 1.9\ \text{kg/m}^3$$

6.2.2 Standard uncertainty caused by the deviation between the molten salt density function and the actual value of the molten salt $u_{\rho 2}$

Since the molten salt density is calculated by the temperature，and then calculating the density of the molten salt, there is a certain deviation between the calculated density and the actual density.According to the relevant reference information, it is known that the maximum deviation of the molten salt density is16 kg/m³. The standard density uncertainty caused by the deviation between the molten salt density function and the actual value of the molten salt is :

$$u_{\rho 2} = \frac{16}{\sqrt{3}} = 9.2\text{kg/m}^3$$

6.2.3 Standard uncertainty caused by measurement position of the temperature $u_{\rho 3}$

Because the temperature sensor cannot measures the temperature of the medium at the right position of high-temperature molten salt flowmeter, which will cause some difference of the temperature. The maximum temperature deviation that measured in different positions is 3℃, The maximum density deviation 1.9 kg/m³. The standard density uncertainty caused by the measurement location of the temperature is:

$$u_{\rho 1} = \frac{1.9}{\sqrt{3}} = 1.1\ \text{kg/m}^3$$

6.2.4 The calculation of standard uncertainty of input quantity ρ

The standard uncertainty of ρ is：

$$u_\rho = \sqrt{u_{\rho 1}^2 + u_{\rho 2}^2 + u_{\rho 3}^2}$$

$$=\sqrt{1.9^2+9.2^2+1.1^2}=9.5\text{kg/m}^3$$

Sensitivity coefficient at maximum flowrate is:

$$c\ (\rho)=\frac{\partial V_{ref}}{\partial \rho}=-\frac{M_s C_f}{\rho^2}=\text{-0.0002（m³）}^2\text{/kg}$$

6.3 Standard uncertainty of air buoyancy coefficient u_{Cf}

Standard uncertainty of air buoyancy coefficient mainly depends on the density of the molten salt and the density of the air in the laboratory environment, the maximum changeable of the buoyancy correction factor is 0.0001. The standard uncertainty caused by air buoyancy coefficient is:

$$u_{Cf}=\frac{0.0001}{\sqrt{3}}=0.000058$$

Sensitivity coefficient at maximum flowrate is:

$$c\ (C_f)=\frac{\partial V_{ref}}{\partial C_f}=\frac{M_s}{\rho}=0.40\text{m}^3$$

6.4 Standard uncertainty caused by changeable volume of the measuring pipe u_P

The temperature of molten salt will not change more than 5 °C during one measurement, the volume from the molten salt inlet line to the high temperature molten salt flowmeter is 0.1 m³. The volume expansion coefficient of molten salt is 2.6×10^{-4}/℃, The changeable volume is:

$$\Delta V_P=V_p\times\beta_w\times\Delta t$$
$$=0.1\times0.00026\times5=0.00013\text{ m}^3$$

The standard density uncertainty caused by the changeable volume of the measuring pipe is:

$$u_P=\frac{0.00013}{\sqrt{3}}=0.00008\text{ m}^3$$

Sensitivity coefficient is:

$$c\ (V_P)=\frac{\partial V_{ref}}{\partial V_P}=1$$

6.5 Standard uncertainty caused by the bubble in molten salt u_B

Small bubbles may be exist in the molten salt medium during the test, the working pressure of the standard facility is 0.2MPa, The volume of bubbles in the molten salt is 0.06L. The standard uncertainty caused by the bubble in molten salt is:

$$u_B=\frac{0.06\times0.4}{\sqrt{3}}=0.014\text{L}$$

Sensitivity coefficient is:

$$c\ (V_E)=\frac{\partial V_{ref}}{\partial V_E}=1$$

6.6 Calculation of expanded uncertainty

Based on the calculated standard uncertainty of each input quantity, the expanded uncertainty of the uncertainty can be calculated at maximum flowrate, The uncertainty summary is shown in Table 3.

Table 1: The uncertainty summary at minimum flowrate

№	Uncertainty	Source	$u(x_i)$	c_i	$\lvert c_i\rvert u(x_i)$
1	u_{Ms}	Mass	1.0kg	0.0001 m³/kg	0.0005m³
2	u_ρ	density	9.5m³/kg	-0.0002（m³）²/kg	0.0019m³
3	u_{Cf}	Buoyancy	0.000058	0.4 m³	0.000002m³
5	u_P	Pipe volume	0.00008 m³	1	0.00008m³
6	u_B	Bubble	0.000014 L	1	0.000014m³
Combined standard uncertainty: u_c =0.0020m³					

Relative uncertainty at maximum flowrate:

$$u_{rc}=\frac{0.0020\times2022}{800}\times100\%=0.50\%$$

Expanded uncertainty at maximum flowrate:

$$U_{\text{rel}}=ku_{\text{rc}}=2\times0.50\%=1.0\%$$

Using the same method, the expanded uncertainty at minimum flowrate also can be calculated U_{rel} =1.3%（k=2）。

7. Conclusion

High-temperature molten salt flow calibration facility by dynamic weighing method base on argon pressure balance principle is established in China. The unique flowrate driving method is used in the standard facility, The calibration facility has the characteristics of using less amount of molten salt, fast response and stable temperature. Test results show that the flowrate stability is better than 0.9%, which can be meet the requirement of calibrating high-temperature molten salt flowmeters.

References

[1] JIN Yuan,CHENG Jinhui,WANG Kun,*Thermal study several typical molten salt coolant*.Nuclear Technology,2016,39(5) .

[2] Yanxun Su, Guowei Liang. Jian Sheng, *Flow Metrology and Measurement（second edition）*

[3] Chi Wang, *Analysis on uncertainty of flow measurement*, Beijing:China Metrology Publishing House, 2002.

[4] Gill D D,Kolb W J,Briggs R J, *An evaluation of pressure and flow measurement in the molten salt test loop system*.SAND2013-5366,US:Sandia National Laboratories.2013.