Research on standard device of liquid hydrogen flow driven by air pressure

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Abstract

As an important link in the industry chain of hydrogen energy, liquid hydrogen has great potential in civil aviation, shipping, and urban public transportation, and is a also key component in the future large-scale industrialization of hydrogen energy. The accuracy of liquid hydrogen flow measurement is crucial in its preparation, storage, transportation, application, and trade settlement during the whole industry chain running. The liquid hydrogen flow standard device is the core equipment to check and calibrate the liquid hydrogen flowmeter, which is the key link to ensure the reliable flow measurement of liquid hydrogen. As a low-temperature fluid with ultra-low viscosity and low density, the non-negligible error would be introduced when the flowmeter is calibrated using other fluids instead such as water, especially in the tiny flow range. Therefore, it is necessary to develop a flow standard device for actual-flow calibration of the liquid hydrogen flowmeters. In this paper, based on the existing research of cryogenic fluid standard devices at home and abroad, a liquid hydrogen flow standard device based on the bi-directional dynamic mass method is designed, using helium to drive the liquid hydrogen in the tank, which can provide the standard flow rate in the small flow range for the calibration and verification of the flowmeter under test. The system is designed to take into account the cryogenic temperature, low viscosity, high flammability and explosivity of the liquid hydrogen, as well as the measurement accuracy. Compared with the cryogenic pump, the high-pressure helium source can provide a more stable and smaller flow rate to achieve the higher accuracy and robustness of the calibration and verification of the flowmeters under the small flow rate of the device. The bi-directional dynamic mass method with reverse drive can avoid the influence of additional pipe capacity on the actual error generated during measurement, effectively reduce the measurement uncertainty of the device and improve the measurement system of the liquid hydrogen flow.

1. Introduction

Hydrogen is a clean, efficient, and zero-carbon energy carrier that allows for more economical long-cycle, large-scale storage of electrical or thermal energy and is a key solution to meet future ecological renewable energy needs [1].

Hydrogen in the hydrogen energy industry chain mainly has two states: high-pressure gas hydrogen and low-temperature liquid hydrogen. The volume energy density of liquid hydrogen is much larger than that of high-pressure gas hydrogen, which has obvious advantages in storage and transportation for the large-scale development of hydrogen energy industry. Therefore, liquid hydrogen has great potential for civil aviation, maritime transportation and urban public transportation in the future, and is a breakthrough for the large-scale industrialization of hydrogen energy in the future, which is the main reason why liquid hydrogen has been used as an aviation rocketed propellant fuels from the beginning.

The accuracy of liquid hydrogen flows measurement is crucial to the key segments of liquid hydrogen preparation, storage and transportation, application and trade settlement, which is directly related to the production safety, smooth operation and trade fairness of the whole industry chain. Accurate and reliable liquid hydrogen flow meters and their flow calibration systems are the two key elements to ensure the legitimacy of liquid hydrogen flow measurement.

The overview of the hydrogen energy industry chain is shown in Figure 1. At this stage, research in the hydrogen energy industry mainly focuses on product development of hydrogen equipment such as hydrogen production, hydrogen storage, and hydrogen transmission, as well as fuel cell technology, etc., while less attention is paid to hydrogen product performance testing and quality inspection, etc., and there is a lack of mature hydrogen equipment performance testing and test methods, standards, and infrastructure [2].

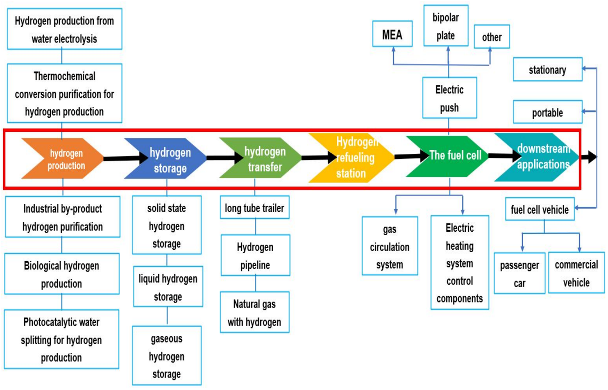

Figure 1: Hydrogen energy industry chain

At present, most of the researchers at home and abroad are devoted to the study of room temperature flows standard devices [3-8], while the study of low temperature flow standard devices is relatively scarce. The liquid hydrogen flow standard device is the core equipment for the calibration and verification of liquid hydrogen flowmeter, which is a key link to the liquid hydrogen flow traceability chain. However, due to the flammable and explosive characteristics of liquid hydrogen, the technical requirements for adiabatic, sealing and safety of liquid hydrogen calibration and verification system are very high [9], and the only sets of liquid hydrogen flow standard devices are concentrated in a few top military research institutions such as NASA [10]. The cryogenic liquid flows standard devices, including liquid hydrogen, are mainly composed of three types: standard meter method, mass method, and volumetric method, among which the mass and volumetric methods are more accurate compared to the standard meter method [11].

Based on the similarity in thermal properties of cryogenic fluids, cryogenic flow standard devices for non-liquid hydrogen are expected to serve as approximate alternative metering equipment for explosive hazards such as liquid hydrogen. The standard device for liquid helium flow based on the volumetric method of the CERN metrology laboratory represents the highest level of cryogenic fluid flowed metering in the world today, which can reach a minimum temperature of 2.5 K [12], but the method is essentially a standard flow meter method, where the standard mass flow rate is obtained from a helium flow meter at room temperature according to the conservation of mass ,which has a small range of calibrated liquid helium flow rates. The experimental setup is shown in Figure 2, where Chorowski et al. reduced the cost and thermal leakage and improved the reliability of the system by reducing the number of components [13].

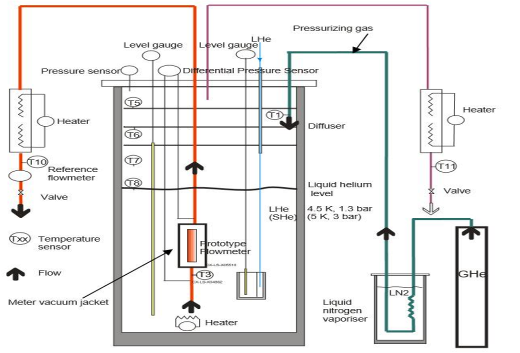

Figure 2: Liquid helium flow verification standard device at CERN[12]

Murakami [14] et al. were the first to study a hot-wire flow meter for liquid hydrogen and designed a preliminary model. Basic performance tests were performed with liquid nitrogen, and the results showed that the higher the speed, the higher the thermostatic rise heating current. The basic performance test was carried out with liquid nitrogen, and the results showed that the higher the speed, the higher the thermostatic rise heating current. On this basis, Kyoto University, Japan, in order to the calibration of the developed liquid hydrogen thermal flowmeter, built the mass method liquid hydrogen flow standard device shown in Figure 3. Unlike the conventional mass method flow standard device, the standard flow rate is taken from the rate of mass drop in the liquid hydrogen tank during the measurement cycle [15]. As shown in Figure 4, to measure the liquid hydrogen flow rate at different flow rates, the results show that the thermal type with the hot wire as the sensing layer has excellent performance in measuring small flow rates of liquid hydrogen, which can compensate for the significantly reduced flow coefficient of the turbine flow meter in the small flow region. Although the calibration system uses liquid hydrogen as the medium, it is still at the stage of highly customized laboratory research and is not commercially available for carrying out the calibration of liquid hydrogen flowmeter.

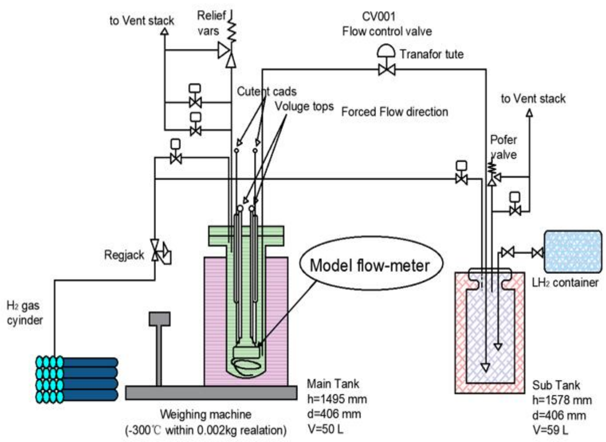

Figure 3: Standard device for calibration and verification of liquid hydrogen flow at Kyoto University, Japan[15]

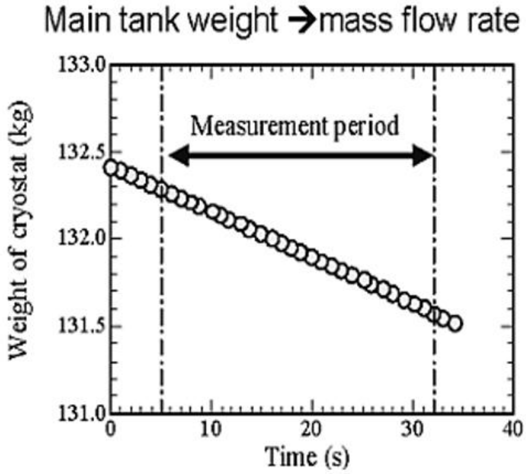

Figure 4: The rate of mass decline in the liquid hydrogen tank during the measurement period[15]

On the domestic side, preliminary research work on the metrological testing of LNG refuellers was carried out by the China Academy of Testing Technology and Shenyang Metrology and Testing Institute. Based on the cryogenic liquid mass method, the latter developed an LNG dispenser calibration device with high metrological accuracy, simple structure, and convenient operation with an extended uncertainty of 0.17% (k=2) [16]. The device is mainly composed of four parts: liquid filling line, gas return line, venting line and data acquisition system. The field trial operation of the calibration device shows that its performance is relatively stable; it can be used for the separate calibration of LNG dispenser and liquid phase flowmeter, as well as for the calibration of LNG flowmeter of the same specification. Recently, Nanjing Emerson Process Control Co., Ltd. has established a deep-freeze flow test station, which can effectively measure the flow of liquid nitrogen at 78K, and has obtained the CMC certification from the National Metrology Institute of the Netherlands. The deep-cooled flow test station of Nanjing Emerson has established two sets of deep-cooled calibration systems, using the mass method and the standard meter method respectively. Mass method uncertainty 0.11% (k = 2), standard meter method flow range 45 ~ 120kg / min, flowmeter size DN15 ~ DN25, flowmeter type LNGM10 / CMF100 / CMF050, etc., process Fluid pressure 0.4 ~ 0.6MPa, standard meter method uncertainty 0.16% (k = 2).

To sum up, liquid hydrogen flow standard device is the core equipment for checking and calibrating liquid hydrogen flowmeter, which is a key link in the liquid hydrogen flow traceability chain. Since liquid hydrogen is a deep cold low density and low viscosity fluid, there will be non-negligible errors when using normal temperature fluid or liquid nitrogen and other low temperature alternative fluids for liquid hydrogen flowmeter calibration, especially in the small flow range. At the same time, how to ensure the stability of liquid hydrogen in the flow process to avoid vaporization is also a serious challenge for the liquid hydrogen flow standard device. Therefore, it is especially necessary and urgent to establish a liquid hydrogen flow standard device that can realize liquid hydrogen real flow verification and calibration to support the healthy and rapid development of hydrogen energy industry chain through independent innovation.

2. Air pressure driven standard flow device

2.1 Structure of Air Pressure Driven Standard Flow Device

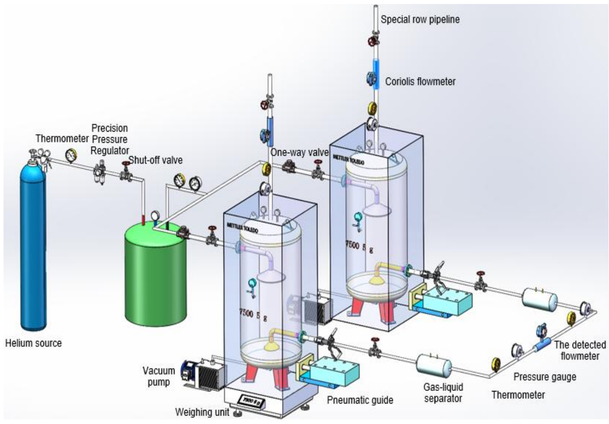

Figure 5: Design drawing of pneumatically driven liquid hydrogen flow standard device

As shown in Figure 5, the system includes a cryogenic high-pressure helium gas source, an adiabatic pre-cooling tank, a supply liquid hydrogen tank, a standard liquid hydrogen tank, a high-precision weighing unit, a liquid hydrogen filling gun, an inspected flow meter, a recovery line, a self-pressurization device, a vacuum pump, an audible and visual alarm gas-liquid separator, and a precision pressure reducing valve, a thermometer, a pressure gauge, a check valve, a Shut-off valve, a pressure reducing valve, a quick coupling, a safety valve, a special discharge pipeline, and a Coriolis flow meter.

2.2 The principle of air pressure driven standard flow device

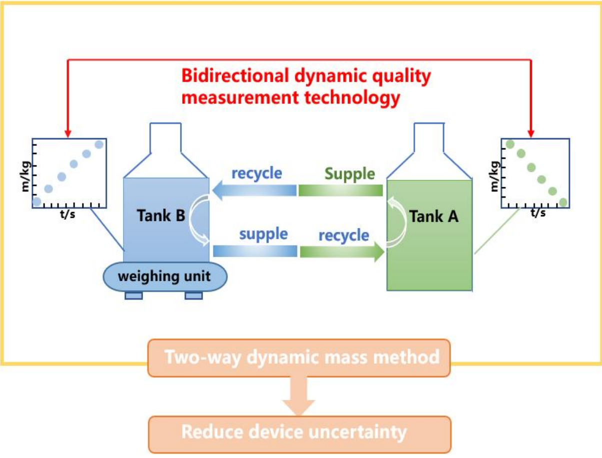

Figure 6: Two-way dynamic mass method pneumatic drive device schematic diagram

As shown in Figure 6, the principle of this air pressure driven standard flow two-way dynamic mass method flow measurement is gas driven with compressed helium as the power source. The main form of supply tank-recovery tank is used to make full use of the similarity of the dual tank structure and mass method structure, and the tank-weigher system can be constructed by adding only one set of weighers. The set of tank-weigher subsystem on the left together with the single tank on the right can realize the free switching of supply/recovery functions. More importantly, the system structure on the left is paired with a high-precision weigher to monitor in real time the decay or increase in mass of this tank during calibration. The design is based on the idea of dynamic mass weighing of liquid hydrogen flow standard devices from Kyoto University, Japan and collects the dynamic mass change signal in real time in the tank-weigher system to obtain more dimensional information about the tank mass change, compare and analyse the correlation and difference between the forward and reverse dynamic mass method weighing results, and provide strong data support for the establishment of two-way dynamic mass weighing intelligent compensation algorithm and additional high-precision tube capacity correction algorithm, and can effectively eliminate the coarse errors and incorrect measurement results caused by improper operation, system failure and other unexpected situations, further reducing the uncertainty of the device.

2.3 Functions of Air Pressure Actuated Standard Flow Devices

The liquid hydrogen flow standard device is used to check and calibrate the liquid hydrogen in the system. Depending on the required calibration flow range, there are two starting methods: compressed helium start and direct start of liquid hydrogen cryogenic pump. When the checked flowmeter is at a small flow rate, the liquid hydrogen cryogenic pump cannot provide a stable small flow rate drive due to its extremely high rate of fluid transfer, while the high-pressure helium source can provide a small steady flow delivery for the checked flowmeter to achieve the accuracy and robustness of calibration and verification of the device at the small flow rates.

3. Standard device technical solution

3.1 Forward air drive method

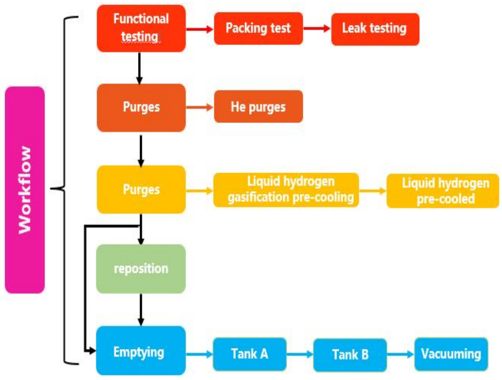

Figure7: Overall flow of the liquid hydrogen flow standard device

As shown in Figure 7, the overall workflow of the liquid hydrogen flow standard device includes functional test, pre-cooling, charging, calibration and emptying. In order to ensure the normal operation of the system, the first functional test of the device is required, which mainly includes pressure-holding test and sealing test.

The device calibration system is preceded by a pre-cooling process of the entire device to prevent measurement errors in the weighing unit caused by the vaporization of liquid hydrogen due to temperature effects during the flow. In the pre-cooling stage, the high-pressure helium source is turned on, and the high-pressure helium gas generated is passed into the adiabatic pre-cooling tank, where the temperature is reduced to the same temperature as the stored liquid hydrogen, and then flows into the tank of the supply liquid hydrogen tank through the helium diffuser. Pre-cooling process. When the cryogenic high-pressure helium is introduced for a period of time, the temperature of the whole system device can reach the temperature value of cryogenic liquid hydrogen before entering the next stage.

In the liquid hydrogen filling stage, the liquid hydrogen filling gun is used to fill the supply liquid hydrogen tank and the standard liquid hydrogen tank respectively, and to complete the liquid hydrogen filling of the supply liquid hydrogen tank and the standard liquid hydrogen tank with the indication of pressure gauge and liquid level meter.

As shown in Figure 8,the flow standard device uses compressed gas forward drive the flow meter under test tiny flow.

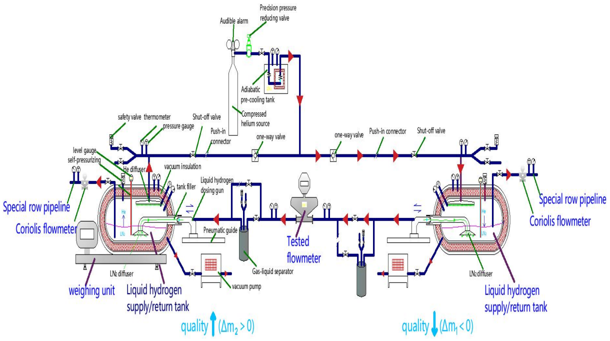

Figure8: Forward drive diagram of cryogenic compressed gas at micro flow rate

When the forward calibration is started, the check valve to the reverse direction is closed and the check valve to the forward direction is opened at the same time, and the cryogenic high-pressure helium source is turned on as the starting point. After passing through the adiabatic pre-cooling tank, the high pressure helium gas enters the helium diffuser and flows into the supply liquid hydrogen tank, which drives the flow of liquid hydrogen from the supply liquid hydrogen tank to the inspected flow meter. The liquid hydrogen flowing through the inspected flow meter steadily adds liquid to the standard liquid hydrogen tank on the high precision weighing unit. Until the flow of liquid hydrogen in the experiment is controlled to stop by shutting off the high pressure helium, at which point the liquid hydrogen filling gun is pulled out as a stopping point for timing. The system satisfies the need for calibration of the flowmeter under test on the test pipeline. The said standard liquid hydrogen flow rate is calculated from the mass difference before and after the liquid addition to the high precision weighing unit and the liquid addition time, thus producing a standard cumulative flow rate of liquid hydrogen. The standard cumulative flow rate of liquid hydrogen is calculated from the mass difference before and after filling the standard liquid hydrogen tank and the filling time. Then the standard cumulative flow rate of liquid hydrogen and the value displayed by the checked flowmeter will be compared and analyzed to achieve the calibration of the checked flowmeter.

3.2 reverse pneumatic drive

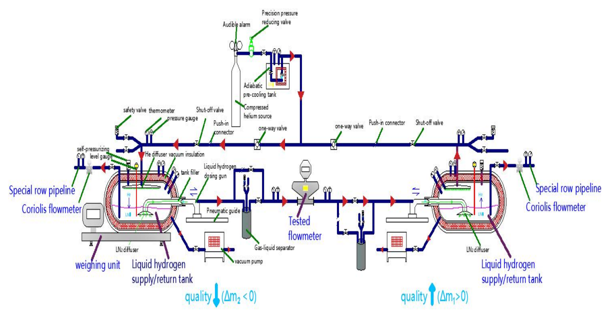

Figure 9: Low-temperature compressed gas drive reverse drive diagram at micro flow rate

The flow standard device can also adopt another compressed gas reverse drive calibration method, as shown in Figure 9. Before the calibration, the standard liquid hydrogen tank is filled with a certain volume of liquid hydrogen, and after the calibration starts, the one-way valve to the forward direction is closed and the one-way valve to the reverse direction is opened at the same time. The standard cumulative flow rate of liquid hydrogen is determined by the mass difference of the standard liquid hydrogen tank before and after the calibration time. In this way, the uncertainty of the device is further reduced in order to reduce the influence of the additional tube capacity on the actual error produced during the calibration and verification of the checked flowmeter. After the system inspection and test, if the device is not used for a long time, the liquid hydrogen in the device needs to be emptied. The liquid hydrogen in the storage tank is vaporized by the tank self-pressurization device, and the supply liquid hydrogen tank, standard liquid hydrogen tank and pipeline are emptied in turn.

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4. Conclusion

To sum up, the research on cryogenic liquid flow standard devices at home and abroad is still in the exploration stage. Only a few special foreign cryogenic flow standard devices are in use in top aerospace and metrology research institutions, and there are no liquid hydrogen calibration devices and standards in China. Based on the similarity of thermal properties, the use of liquid nitrogen, liquid helium and other cryogenic fluids instead of liquid and LNG for approximate real flow calibration of cryogenic flow meters is a solution recognized by international authoritative metrology institutions, which can avoid the real flow testing of liquid hydrogen and LNG. At the same time, to a large extent, reproduce the working fluid properties of liquid hydrogen at deep low temperature, ultra-low density and viscosity.

Among the existing cryogenic flow standard devices, the mass method has the lowest uncertainty and is the most stable. The design of this paper uses a high-pressure helium gas source drive to achieve accurate adjustment of the liquid hydrogen flow, which provides high stability of the standard flow in the small flow range and is less costly than the liquid hydrogen pump drive method. In the inverse mass method pneumatic driven calibration method, the liquid hydrogen in the standard liquid hydrogen tank is pressurized by a high pressure helium source and the liquid hydrogen is discharged to flow through the checked meter in order to calculate the standard cumulative flow of liquid hydrogen , by this way, the influence of additional tube capacity on the measurement results can be reduced. In this way, the influence of additional tube capacity on the measurement results can be reduced. The establishment of this liquid hydrogen flow standard device can realize the liquid hydrogen real flow verification and calibration. The system can provide the liquid hydrogen real flow standard flow required for liquid hydrogen flow meter verification and calibration, which can be directly traceable to the standard weights of the corresponding measurement level to complete the quality traceability. The design of the system adopts the dynamic mass method, taking into account the requirements of low temperature, low viscosity, explosive and measurement accuracy of liquid hydrogen, which is innovative enough to fill the gap of the international deep cryogenic metrology and calibration device and make up for the shortcomings of the liquid hydrogen industry chain.

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