Flow Measurement and Instrumentation 50 (2016) 90–101

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Liquid low-flow calibration rig using syringe pump and weighing tank system

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ARTICLE INFO

Article history:
Received 29 November 2015
Received in revised form
18 May 2016
Accepted 15 June 2016
Available online 16 June 2016

Keywords:
Flowmeter
Flowrate
Calibration
Uncertainty
Liquid low flow

ABSTRACT

A calibration rig consisting of a syringe pump and a weighing tank system that can operate in the flow rate range of 0.02–60 L/h was developed in this study. This paper discusses the design considerations of the calibration methods, the development of the rig, the calibration results, and the uncertainty analysis conducted on the rig. A weighing tank system that minimizes the effects of outlet tube contact and evaporation was developed. The syringe pump system was designed using a servomotor, a precise ball screw, and a linear encoder, and it was calibrated using the developed weighing tank system via the standing start and stop method over the target range of flow rates with light oil and industrial gasoline. Several flowmeters were calibrated using the syringe pump via the flying start and finish method. During the flowmeter calibration stage, the effect of the evaporation error was eliminated because the calibration rig can form a closed pipeline system. The influence of dissolved gas and the position dependence of the syringe pulse factor on the calibration accuracy were investigated experimentally. As a result, all obtained syringe pulse factors were found to be within $\pm 0.02\%$ of each other. The preliminary expanded uncertainties ($k=2$) of the calibration rig were estimated to be 0.066% and 0.070% for mass and volumetric flows, respectively.

1. Introduction

The primary goal of the present study was the calibration of flowmeters used in the automotive industry. A wide range of flow rates (0.02–200 L/h) are used in fuel consumption measurements in automobile engine test benches, and the main working liquids are gasoline and light oil. A piston-type positive displacement flowmeter [1] used for such a measurement has a high turndown ratio exceeding 1000:1.

Liquid flows with low flow rates are measured for various purposes not only in the automobile industry but also in semiconductor manufacturing equipment, medical drug delivery systems, analytical instruments, and many other devices [2]. Many types of liquid are measured in such systems, including water, alcohols, solvents, solutions, and oils. Some of these liquids are strongly volatile and/or toxic, and various temperatures and pressures can be encountered in measurement tasks. Although flowmeters can be calibrated using a liquid in a calibration facility under laboratory conditions, the flowmeter may then be used to measure different liquids under various pressure and temperature conditions, which affect the output of the flowmeter. In some cases, theoretical correction, which has a relatively large uncertainty, is needed. Ideally, flowmeters should be calibrated with a real working liquid under actual on-site conditions. These factors necessitate the development of an advanced calibration system that can be applied even to highly volatile or toxic liquids, can operate under a wide temperature range and at extremely high pressures, and is explosion-proof and portable. With a similar goal, an ultrahigh-pressure test rig with exchangeable liquids of three different viscosities was constructed in a previous study [3].

A prototype calibration rig that can calibrate small fuel consumption flowmeters, which have flow rates ranging from 0.02 L/h to 60 L/h, was developed in this study. A prototype calibration rig that may be used under various conditions in the future was constructed. A suitable calibration rig design was considered with the goal of achieving high accuracy. This paper discusses the design considerations for the calibration methods and the development of the rig and presents the results of the calibration and uncertainty analysis.

2. General design considerations for calibration rig

2.1. Target specifications

The primary objective of the present study was to develop a prototype calibration rig that can be used for various working

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http://dx.doi.org/10.1016/j.flowmeasinst.2016.06.014
0955-5986/

liquids under a low flow rate range with a small uncertainty.

The target specifications are as follows.

- Flow rate range: 0.02–60 L/h (High turndown ratio, 1:3000)
- Uncertainty: $<0.1\%$ ($k=2$)
- Exchangeable working liquid
- Highly stable flow rate and temperature
- Automatic operation
- Clear and simple traceability chain

The following points should be considered for future improvements to this measurement principle.

- Applicable to volatile liquids
- Wide temperature range
- High-pressure operation
- Compact and portable
- Explosion-proof

2.2. Considered calibration method for low flow rate

The measurement method used in the calibration rig was selected to allow calibration with volatile liquids at low flow rates. The advantages and disadvantages of the calibration techniques considered for use in the proposed rig are described in this section.

Gravimetric methods are advantageous in terms of their accuracy but produce evaporation errors with volatile liquids at low flow rates. Several approaches can be used to reduce the evaporation effect, including trapping evaporation with a saturated vapor atmosphere [4,5] and applying a cover layer of a lower-density liquid [6,7], such as oil, which has a low vapor pressure. Evaporation trapping was applied to the present calibration rig to ensure the exchangeability of the working liquid.

The flying start and finish method, which employs a diverter system, is advantageous in terms of flow and temperature stability. To minimize the diversion uncertainty in this method, double-wing diverters have been developed in previous studies [8–10]. However, at low flow rates, it is difficult to maintain a continuous liquid jet. Moreover, the sustained amount of liquid wetting on the diverter wing is not necessarily negligible compared with the volume of the collected liquid. Thus, a double-wing diverter was not adopted in the present calibration rig.

Dynamic weighing methods have been adopted in many ultralow-flow calibration facilities [5–7]. The flow impact effect on the weighing scale might be a significant error source for the higher flow rates in the target flow rate range. When an outlet tube touches the liquid surface in a weighing tank, complicated interactive forces arise between the tube and the weighing scale.

The main problem with standing start and stop methods based on static weighing is that the meter must accurately follow the changing flow rate [11,12]. Some flowmeters cannot follow flow rate transitions, which could be problematic for flowmeters with significantly nonlinear characteristics or with slow flow rate damping factors. Furthermore, if the total number of pulses from the flowmeter is insufficient, the pulse counting error may be significant. Some flowmeters output overestimated pulses because of fluctuations in the pressure and the flow when the flow is stopped quickly [12]. However, the standing method can be adopted when a device under test (DUT) has linear characteristics and a sufficient number of pulses without the overestimation.

Volumetric standards, such as piston provers, have been adopted in many calibration facilities for oil (including real gasoline) because they can be used in closed pipeline systems. When a linear encoder is connected to the piston, many pulses are output while the piston moves [13]. The characteristics of piston provers are expected to be essentially linear with respect to the flow rate.

A syringe pump is a volumetric flow generator with an ultralow flow rate. However, commercial syringe pumps are still being improved with regard to flow stability to eliminate unpredictable flow fluctuations [5]. Takamoto et al. [14] developed a volumetric flow generator combined with a gravimetric standard as a calibration rig for use at low flow rates. This rig uses a servomotor and a precise ball screw to reduce flow fluctuation. A linear encoder is linked to the plunger rods in the rig. The high potential of the prover system could not be shown because it was calibrated using a simple dynamic weighing method. Similar methods have also been proposed in other studies [6,15,16].

Considering the target specifications, a combination of the volumetric flow generator (syringe pump) and a weighing tank system was adopted in this study to overcome issues related to the low flow range. The syringe pump was calibrated using the weighing tank system via the standing method. The DUT flowmeter was then calibrated using the syringe pump via the flying method. At the DUT calibration stage, the effect of the evaporation error was eliminated because the calibration rig can form a closed pipeline system. The details of the calibration method are described in Sections 3.2 and 3.3.

2.3. Considered methods of feeding liquid to weighing tank

When the outlet tube does not come into contact with the working liquid inside the weighing tank, droplets are formed at the tip of the outlet tube. Although there is no force between the outlet tube and the weighing scale, a change in the liquid mass remaining on the tip of the outlet tube could be a significant source of uncertainty. This change in the liquid mass could be over 8 mg depending on the nozzle diameter [16].

When the outlet tube is inserted into the liquid, the forces between the outlet tube and the weighing tank, such as the capillary effect, the buoyancy due to the displacement of the working liquid by the outlet tube material, and the mass of the liquid inside the outlet tube below the atmospheric pressure level, must be considered, as shown in Fig. 1. The weighing scale measurement is affected by these forces. However, the impact on the scale at a higher flow rate does not affect the scale reading because static weighing is performed in which the weight is measured after the flow is stopped. The difference $\Delta m_{\mathrm{Insertion}}$ (kg) between the actual and measured masses caused by inserting the outlet tube into the liquid is given by

$$\Delta m_{\mathrm{Insertion}} = -E_{\mathrm{Capillary}} + E_{\mathrm{Buoyancy}} + m_{\mathrm{AL}}, \quad (1)$$

where $E_{\mathrm{Capillary}}$ (kg) is the capillary effect, E_{Buoyancy} (kg) is the buoyancy effect due to the displacement of the working liquid by

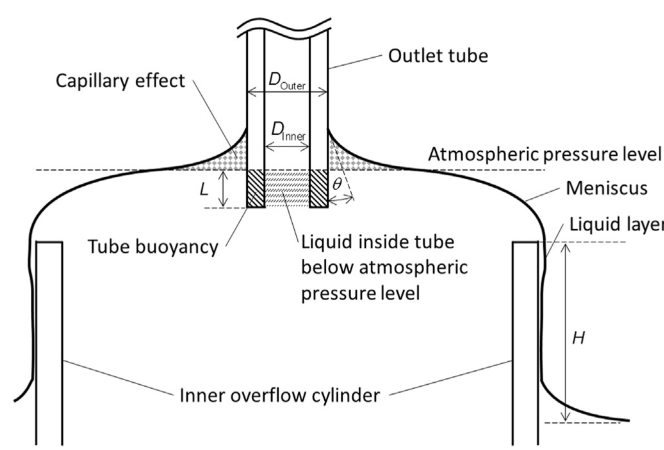

Fig. 1. Schematic of the outlet tube inserted into the working liquid at the top of the inner overflow cylinder.