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Uncertainty estimation of a liquid flow standard system with small flow rates

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ABSTRACT

A liquid flow standard system is used to calibrate liquid volume of fuel–oil flow meters at small flow rates between 50 L/h and 700 L/h. However, the system has not been used to calibrate volume flow rate because the system is only operated with the standing-start-and-finish mode. In this study, the liquid flow standard system was rebuilt to provide a calibration service of volume flow rate by attaching two flow diverters, which can operate the system with the flying-start-and-finish mode. To evaluate its performance for volume flow metering, several techniques were introduced. First, diverter timing errors were estimated by linear regression. Second, covariance between buoyancy correction factor and water density was obtained to consider interdependency between the two measurands. Third, calibration and measurement capability (CMC) was evaluated by setting a fixed value of collected weight or elapsed time for flow diversion. Finally, several CMCs were compared to find the best measurement condition. As a result of the above approach, the CMC of the liquid flow standard system was found to be (0.10–0.52)% (k = 2) for (50–700) L/h with a minimum collected weight at 10 kg.

1. Introduction

There are many concerns of calibrating a fuel–oil flow meter below 1000 L/h in applications for automobile or aeronautical industry. The fuel–oil flow meter can estimate liquid volume by measuring elapsed time of steady flows in a pipe at a certain flow rate. Because the elapsed time can be measured in order of 10^{-3} s, the accuracy of flow rate measurement becomes important in determining the measurement uncertainty of the fuel–oil flow meter. KRISS has a liquid flow standard system (hereafter, LFSS), which can cover flow rates between 50 L/h and 700 L/h. The purpose of the LFSS is to determine the K-factor of the fuel–oil flow meter in units of (pulse/L). Nevertheless, the LFSS has not been used to calibrate volume flow rate because it requires a flow diverter to run the LFSS with the flying-start-and-finish mode [1].

There are three types of flow diverters, i.e., a swivel, a rotary, and a linear type diverter [2–5]. The swivel type diverter is a traditional one which has a hinge to switch the flow path from one side to the other side in a LFSS. The rotary type diverter has an advantage to reduce timing errors by rotating the flow diverter in one direction. The linear type diverter has a simpler design than the swivel and the rotary type diverters. Hence, the operation of the linear type diverter becomes easier and its performance can be placed between those of the swivel and the rotary type diverters. A disadvantage of the linear diverter is that the location of an optical sensor to trigger signals should be adjusted precisely to balance the amount of liquid into and out of a weighing tank during flow diversion. The shape of a flow nozzle used in the diverter is also important. Area ratio between the inlet and the outlet, the divergence angle of the nozzle and the aspect ratio between the width and the depth of the rectangular shape of the nozzle outlet should be considered to obtain suitable flow profile at the outlet of the nozzle.

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For the optimal operation of LFSS, a lot of researchers provided experimental works with different perspectives. Cheong et al. fabricated a hydrocarbon flow standard system with flow range between 10 L/h and 100 L/h [6]. They improved the measurement of volume flow rate less than 0.064% (k = 2) [7]. Later, they expanded flow ranges down to 1 L/h and attained reasonable agreements by comparing between the hydrocarbon flow standard system and a water flow standard system [8]. Johnson et al. developed another type of hydrocarbon flow standard system by means of volumetric flow metering, i.e., a piston prover [9]. They implemented hydrocarbon flow metering with a range of (66–9060) L/h. The measurement uncertainty was within 0.074% (k = 2). For estimating diverter timing errors, another researchers gave critical reviews by comparing their experimental results with the well-known method according to ISO 4185 [1]. Cordova and Lederer suggested some formulas for diverter timing errors to improve the two methods regarding static weighing in ISO 4185 [10]. Engel and Baade gave different approaches for estimating the diverter timing errors by considering flow rate fluctuations due to dynamic impacts [11].

In the present study, a LFSS was built to provide calibration service for volume flow rate (flying-start-and-finish) as well as liquid volume (standing-start-and-finish) at small flow rates. Tap water was used as fluid medium for testing purposes prior to using light oil for the calibration service. The LFSS adapted a linear diverter to measure volume flow rate with the flying-start-and-finish mode. Diverter timing errors were estimated by a linear regression based on the Jones method [12,13]. Covariance between buoyancy correction factor and water density was also considered. It is because the volume flow rate is calculated by dividing mass flow rate with the water density. In addition, calibration and measurement capability (hereafter, CMC) of the LFSS was considered as a function of a certain criterion between collected weight and elapsed time which are determined during flow diversion experiments.

This paper focuses on how to estimate the measurement uncertainty of the LFSS at low volume flow rate. Toward this end, an experimental setup for the LFSS is explained first. Mathematical expressions for volume flow rate and its uncertainty are followed. After that, each uncertainty factor determining the uncertainty of volume flow rate is reviewed. Results on the flow diversion experiments are discussed with respect to the collected weight as well as the elapsed time at a given volume flow rate. Finally, the CMC of the LFSS is declared based on the estimated uncertainty of the volume flow rate.

2. Experimental methods

2.1. Liquid flow standard system

An experimental setup for the LFSS is displayed as shown in Fig. 1. A pipeline with diameter of 20 mm was used as a main test line. A pump (Laing E6 vario-25/180 G) was installed to induce water from a reservoir to the main test line with a flow rate between 50 L/h and 700 L/h. Two needle valves with diameters of 19.1 mm (3/4") and 6.4 mm (1/4") were attached as a control unit to adjust the flow rate in the main test line. A bypass line was also constructed to maintain the flow rate in the pipe with a stable condition. An air vent valve was installed to remove air bubbles from the main test line. A ball valve (Kitz C-1 3/4" UTE) was located to operate the LFSS with the standing-start-and-finish mode. Two linear flow diverters (Jeongsang Engineering Inc.) were placed downstream of a U-shaped tube to operate the LFSS with the flying-start-and-finish mode. The flow diverters were designed to operate at different volume flow rates: (50–200) L/h with diameter of 6.4 mm and (150–700) L/h with diameter of 19.1 mm. Both the ball valve and the flow diverters were actuated by pneumatic pressure to make a cost-effective system with fast responses. A weighing tank, which was a rectangular box with 450 mm × 280 mm × 200 mm (height × width × depth), was located on top of a precision balance (Mettler Toledo 64000) with a measuring capacity up to 64 kg.

The operation of the flow diverters is illustrated in Fig. 2. At the initial phase of flow diversion, a signal with negative edge is generated from an optical sensor (Fig. 2a and b). It is because a dove-tail switch which is attached to the splitter plate triggers the optical sensor. This signal starts time measurement by flow diversion. By the time when the dove-tail switch triggers another signal with positive edge, the flow directs from the reservoir to the weighing tank (Fig. 2c). Then, the flow rate is perceived to be constant in view of gravimetry (Fig. 2d). If the flow is to be directed from the weighing tank to the reservoir, the splitter plate moves the opposite direction (Fig. 2e). The dove-tail switch can trigger the signal with the negative edge (Fig. 2f). However, the flow diversion is not finished until the switch triggers the signal with the positive edge (Fig. 2g and h). It is because the dove-tail switch does not return to its original position unless we choose the negative and the positive triggering signals with this configuration. This can be a major difference between the present diverter and the double-wing diverter mentioned in the literature [5]. Therefore, the trigger settings of a counter/timer (Agilent 53131A) were arranged to be a negative edge for starting and a positive edge for finishing the time measurements. Note that the time difference between the negative and the positive edge shown in Fig. 2f and g was 0.01 s. Because the width of the dove-tail switch was 5 mm, moving speed of the splitter plate was 0.5 m/s. The moving speed as well as the time difference could be adjusted by controlling damper settings on the pneumatic cylinder.

In measuring the flow rate in the main test line, water pressure and water temperature in the pipe were monitored by using a pressure transducer (Sensys PSHD0030PGPG) and a thermometer (Fluke 2180A). An electro-magnetic flow meter (E + H Promag W53H08) was used as a reference flow meter when timing errors of the flow diverter were to be found [12]. The flow meter produced pulse signals at a rate of 5000 pulse/s when the flow rate was 1000 L/h.

To determine K-factor of the flow meter in units of (pulse/L), the counter/timer, mentioned earlier, was