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UNCERTAINTY ESTIMATION OF A LIQUID FLOW STANDARD SYSTEM WITH SMALL FLOW RATES IN KRISS

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Abstract: A liquid flow standard system has been used to calibrate liquid volume at a specific flow rate. However, liquid flow rate has not been considered as a calibration item due to lack of flow diversion mechanism. To enable the liquid flow rate calibration service, uncertainty due to flow diversion was estimated. Diversion timing error as well as temperature dependence on the flow rate was considered. Uncertainty contributions by the two factors were largest more than 40 % of the total uncertainty. On the while, the uncertainty contributions due to other factors were less than 5 %.

Keywords: diverter; liquid flow; metrology; uncertainty

1. INTRODUCTION

There are many concerns of calibrating fuel-oil flow meters below 1,000 L/h in applications for automobile or aeronautical industry. The fuel-oil flow meters can estimate fuel volume by measuring elapsed time of flow metering 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 an important factor in estimating the uncertainty of the fuel-oil flow meters. In KRISS, a liquid flow rate standard system (hereafter, the LFSS) can cover the flow rate ranges between 50 L/h and 700 L/h. The main purpose of the LFSS is to calibrate *K*-factors of the fuel-oil flow meters in units of pulses/L, which can estimate the liquid volume by counting the number of pulses during calibration period. However, the LFSS cannot provide flow rate calibration service, because the LFSS is missing one important element for flow rate metrology, i.e., a flow diverter.

The flow diverter is composed of a flow nozzle in conjunction with a diverting mechanism, which can select one of two flow paths for flow sensing [1, 2]. The diverting mechanism can be classified into a swivel, a rotary, and a linear type [1, 3, 4]. Among the three types of the diverting mechanism, the linear type has a simple design concept which makes use of a pneumatic cylinder as an operating medium. Therefore, the linear type can be appropriate for small flow rate measurement. In this case, flow nozzle design becomes important, because the flow exiting the flow nozzle should maintain high flow velocity to reduce flow diversion timing error [1]. This can be attained by manufacturing the outlet of flow nozzle in a rectangular shape with a large aspect ratio [3-6].

In the present study, the LFSS was re-built to provide flow rate calibration service by using a linear-type flow diverter. Toward this end, the flow rate range of the LFSS was extended from (50 – 700) L/h to (50 – 1,000) L/h by replacing the pump and the conduits with larger capacities than the previous system. Uncertainty of the LFSS was estimated by considering timing error of the flow diverter as a main uncertainty factor according to the ISO 4185 and its related work [1, 2]. Temperature increase in the conduit due to pump work was also considered as another uncertainty factor. From the uncertainty analysis, it was found that adjustment of the location of a dove-tail switch for flow diversion was important in determining the overall uncertainty level of the LFSS.

2. EXPERIMENTAL APPARATUS AND METHODS

The experimental setup for the LFSS is displayed as shown in Fig. 1. Main test line was composed of conduits with diameter of 20 mm. 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 between 50 L/h and 1,000 L/h in the main test line. An air vent valve was installed downstream of the needle valves to remove air bubbles within the working fluid in the test line. A pneumatic ball valve (Kitz C-1 3/4" UTE) was located downstream of the air vent valve to calibrate the liquid volume. A diverter valve (Jeongsang Engineering Inc.) with a pneumatic cylinder (SMC CJ2WB16-35 by) was installed downstream of a U-shaped tube. Either the pneumatic ball valve (Kitz C-1 3/4" UTE) or the flow diverter valve was selected to operate the LFSS in either the liquid volume or the flow rate modes, respectively. An electro-magnetic flow meter (E+H Promag W53H08) was used to calibrate *K*-factors by adjusting timing error of the diverter valve [1, 2, 5]. The electro-magnetic flow meter (hereafter, the DUT) generated a train of pulses with respect to flow rate, i.e., 5,000 pulses/s at 1,000 L/h.

A weighing tank, of which dimension was 200 mm × 200 m × 200 mm (height × width × depth), was located downstream of the flow diverter to measure the liquid weight. A precision balance (Satorius LP6200S) was used to measure both the liquid weight and the weight of the weighing tank. As for the maximum elapsed time of flow diversion, the capacity of the precision balance (6,200 g) and the weight of the storage tank (2,800 g) were considered.

Figure 1. Experimental setup of the LFSS.

Therefore, there were limitations in testing flow rates greater than 1,000 L/h. A thermometer (Fluke 2180A) and a pressure sensor (Sensys PSHD0030PGPG) were installed upstream of the needle valves to monitor the temperature and the pressure in the main test line, because the temperature was gradually increased as heat was generated by a pump (LG PW-S354SMA). A bypass line was also constructed to maintain the pump performance with a stable condition. A counter/timer (Agilent 53131A) was connected with a triggering cable for the dove-tail switch to measure the elapsed time of collecting liquid in the weighing tank [3, 4, 6]. In-house software (LabVIEW 2010) was programmed to operate the LFSS by measuring flow quantities such as the temperature, the pressure, the liquid weight, and the elapsed time for flow diversion. In the present study, water was used as the flow medium to facilitate testing of the LFSS. Fuel-oil was planned to be used after completing the evaluation of measurement uncertainty as a future work.

3. RESULTS AND DISCUSSION

The location of a dove-tail switch was adjusted to determine the timing error of the flow diverter [1, 2]. A linear curve fitting was performed with a dataset consisting of the *K*-factor of the DUT with respect to diversion time t after ten consecutive measurements. The flow rate was fixed at 400 L/h. When the dove-tail switch was located at x = 7 mm, the slope of the linear fitting curve was 0.6455 [pulses/L/s]. When the dove-tail switch was located at x = 11 mm, the slope of the linear fitting curve was decreased to -1.4853 [pulses/L/s]. At x = 8 mm, the slope became -0.0799 [pulses/L/s] closest to the zero slope within the measured dataset. To estimate the timing error of the flow diverter δt, an equation, as suggested in the previous studies, was modified to consider the effect of *K*-factor of the DUT, as follows [1, 2].

$$\delta t_i = \left(\frac{\varepsilon W_i K_i}{\rho N_i} - 1 \right) t_i \quad (1)$$

Here, δt_i is the diversion timing error [s] during the flow diversion time t_i [s], ε is the buoyancy correction factor, W_i is the liquid weight [g], K_i is the *K*-factor of the DUT for t_i [pulses/L], ρ is the liquid density [kg/m^3], and N_i is the number of pulses of the DUT for t_i [pulses]. It is assumed that K_i has the same value of K, which represents the *K*-factor to be determined with very long time for flow diversion [2]. A linear curve fitting to Eqn. (1) gives an estimated value of flow diversion timing error, $\overline{\delta t_i}$, necessary for correcting t_i. The standard uncertainty for $\overline{\delta t_i}$ can be determined by the statistical estimate of error (SEE), as in the following equation [7].

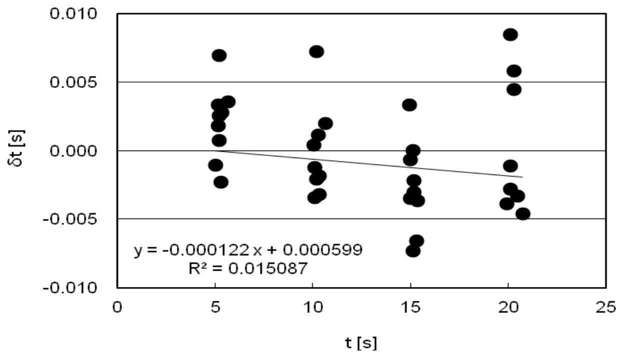

Figure 2. Flow diverter timing error at 400 L/h.

$$SEE = \sqrt{\frac{\sum \left(\delta t_i - \overline{\delta t_i} \right)^2}{N_{meas}}} \quad (2)$$

Here, N_{meas} is the number of measurements for flow diversion experiments. At Q = 400 L/h, $\overline{\delta t_i}$ was estimated to be -0.0019 s at t_i = 20 s, and its standard uncertainty was 0.0055 s, as shown in Fig. 2. This means an appropriate realization of the flow diverter, considering that the flow diversion timing error is should be less than 0.1 s [1].

The flow rate can be defined by considering the buoyancy correction for liquid weight and the time correction for flow diversion time [1, 2].

$$Q_i = \frac{\varepsilon W_i}{\rho \left(t_i + \delta t_i \right)} \quad (3)$$

Here, Q_i is the flow rate during particular flow diversion time t_i [L/h]. Note that ε is defined as $(1-\rho_a/\rho_w)/(1-\rho_a/\rho)$, where ρ_a is the air density [kg/m^3], and ρ_w is the dead weight density [kg/m^3] [1]. Therefore, the standard uncertainty of flow rate, $u(Q_i)$ can be determined by combining each uncertainty factor (W_i, t_i, δt_i, ρ, ρ_a, ρ_w) with its sensitivity coefficient as in the following equation [8, 9].

$$u(Q) = \left(\sum_{i=1}^{5} c_i^2 u_i^2 + \delta Q^2 \right)^{1/2} \quad (4)$$

Here, c_i is the sensitivity coefficient, and u_i is the standard uncertainty of each uncertainty factor. δQ is introduced to consider the reproducibility and the temperature dependence of the flow rate, determined by the ten consecutive measurements. In this case, the flow rate gradient due to temperature, $\partial Q/\partial T$ is considered, as in the following equation.

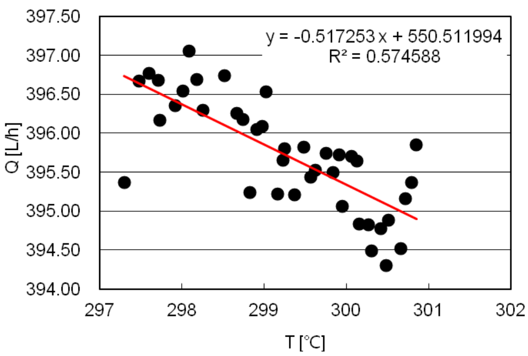

Figure 3. Temperature dependence of flow rate at 400 L/h.

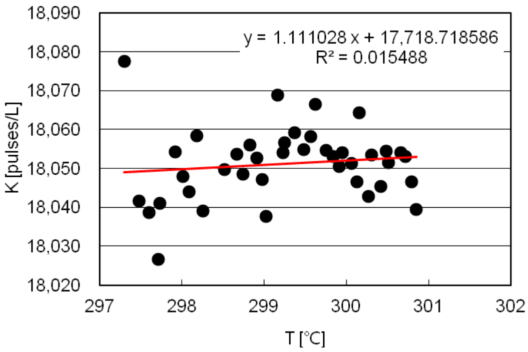

Figure 4. Temperature dependence of *K*-factor at 400 L/h.

$$\delta Q = \left(u_Q{}^2 + \left(\frac{\partial Q}{\partial T} u_T \right)^2 \right)^{1/2} \tag{5}$$

Here, u_Q is the uncertainty contribution of flow rate due to reproducibility [L/h], and u_T is the uncertainty contribution of temperature due to temperature change during one realization of flow rate measurement [K]. As shown in Figs. 3 and 4, both the flow rate and the *K*-factor depend on the temperature change. Therefore, δQ it is necessary to include δQ in Eqn. (4) to compensate the temperature effect during flow metering.

The expanded uncertainty $U(Q)$ can be described as a function of t_i in Fig. 5. $U(Q)$ looks like a decreasing function as t_i increases from 5 s to 20 s. The uncertainty budget, depicted in Fig. 6, indicates that the uncertainty contributions by δt_i and δQ amount to more than 90 % of the total uncertainty. On the contrary, the contributions by other uncertainty factors are less than 5 % of the total uncertainty. Therefore, it can be said that the uncertainties due to flow diversion timing, reproducibility of flow rate, and the temperature dependence of flow metering, can determine the overall measurement accuracy of the LFSS.

The same procedure to estimate $U(Q)$ is applicable to flow rates in (50 ~ 800) L/h, as shown in Fig. 7. At 50 L/h, $U(Q)/Q$ is found to be 1.0 %. $U(Q)/Q$ is decreased from 0.57 % at 100 L/h to 0.07 % at 800 L/h, as Q is increased. Adjustment of the dove-tail switch for flow diversion was important to obtain the uncertainty distribution of the LFSS. In the present setup, the adjustment of the dove-tail switch was taken place at 400 L/h. However, if the dove-tail switch had been adjusted at lower flow rate than 400 L/h, the overall uncertainty distribution could have been affected.

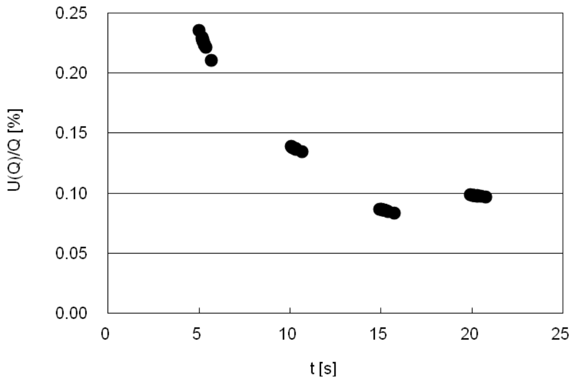

Figure 5. Expanded uncertainty of flow rate at 400 L/h.

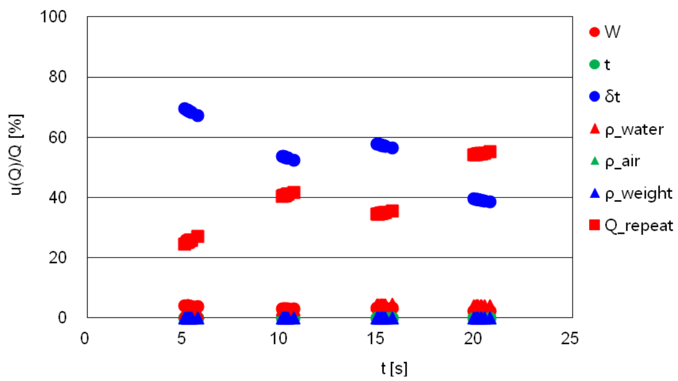

Figure 6. **U**ncertainty budget of flow rate at 400 L/h.

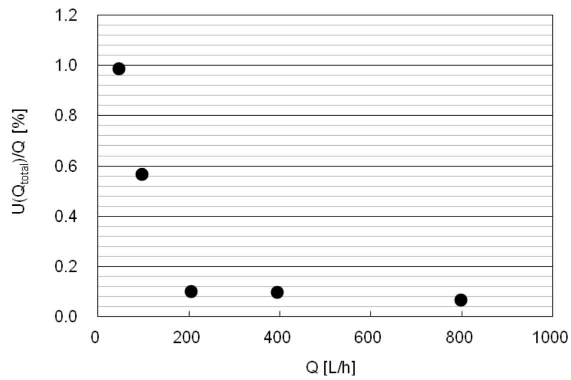

Figure 7. Expanded uncertainty distribution of the LFSS.

Otherwise, another nozzle for flow diversion should have attached to control flow rates lower than 100 L/h. It is because the nominal value for turn-down ratio should be 10 : 1, which means that the current experimental setup is validated in the flow range of (100 ~ 1,000) L/h. However, the uncertainty distribution in Fig. 7 shows that the present turn down ratio is 4:1 with (200 ~ 800) L/h range. Therefore, the design of conduit diameter as well as the size of flow nozzle is important to determine the uncertainty of the LFSS.

4. CONCLUSIONS

The LFSS must provide flow rate range broader than the present flow rate range, i.e. (50 – 700) L/h, to calibrate the fuel-oil flow meters. It is because many fuel-oil flow meters are operating below 1,000 L/h. In the present study, the capacity of the LFSS was expanded by increasing the conduit diameter and the pump size. In addition, a flow diverter was installed to calibrate the flow rate as well as the liquid volume measured by the fuel-oil flow meters. The flow diverter timing error was an important uncertainty factor in determining the uncertainty of the LFSS. When the location of the dove-tail switch of the flow diverter was adjusted at 400 L/h, the diversion timing error was -0.0019 s with its standard uncertainty of 0.0055 s. However, when the flow rate was decreased, the flow diversion timing error, the reproducibility of flow rate, and the temperature dependence of flow metering were increased. The uncertainty factors regarding these effects dominated more than 95 % of the total uncertainty of the LFSS. In the uncertainty distribution in the flow rate of (50 – 1,000) L/h, the uncertainty was decreased from 1.0 % at 50 L/h to 0.07 % at 800 L/h, as Q is increased. The uncertainty distribution was affected by the adjustment of the flow diverter at a certain flow rate, and also by the design of the flow nozzle in the flow diverter.

5. ACKNOWLEDGEMENT

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