

Primary standard for liquid hydrocarbon at low flow rates using light oil, kerosene and industrial gasoline

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Abstract

Motivated by the need to establish a measurement traceability in engine fuel consumption for the industry (automobile, shipping and aviation) as well as in the household fuel metering and bio-fuel production (bio-fuel blending), NMIJ developed a primary standard for low liquid hydrocarbon flow rates that works on three common types of liquid fuels, namely light oil (diesel), kerosene and industrial gasoline (flash point over 40°C). To achieve a high calibration accuracy below 0.1 % which is needed by the industry, this primary standard adopted the gravimetric method performing static weighing with flying-start-and-finish as the calibration method. To cater to a wide flow range from 0.02 L/h to 100 L/h, the calibration facility operates on two gravimetric systems, one using a compactly designed conical rotating double-wing diverter for 1 L/h to 100 L/h and another using a pair of high-speed switching valves as a diverter for 0.02 L/h to 1 L/h. Features of each gravimetric system and its performance are highlighted in the paper. For validation of the calibration capability of the primary standard, uncertainty analysis as well as intra-comparisons with other facilities at NMIJ are also reported.

1. Introduction

Flow metering for liquid hydrocarbon at low flow rates is mainly applied to industrial practices such as measurement of engine fuel consumption in the automobile, shipping and aviation industry as well as metering of household fuel consumption and blending of bio-fuel with petrol. In particular, the race for achieving better fuel efficiency among the automakers is becoming highly competitive, urging the need for stricter monitoring of the accuracy and credibility of flow metering at engine test bench. This initiated the work to develop a calibration facility as a primary standard at National Metrology Institute of Japan (NMIJ) with the aim of establishing measurement traceability for low flow range encountered in the industrial practices mentioned above.

Flow range at engine test bench may span from few hundreds of L/h to as low as 0.02 L/h and flow metering instruments used at engine test bench such as radial piston positive displacement (PD) flowmeters have a high turndown ratio of over 1000:1 with the best accuracy claimed at about 0.1 %. This posed a huge challenge for us in

developing a calibration facility versatile enough to cater to the wide flow range with an uncertainty aimed at below 0.1 %. Primary standards at NMIJ had been providing calibration coverage from 0.1 m³/h to 300 m³/h. Hence a new facility was intended to expand the bottom limit (0.1 m³/h = 100 L/h) of the calibration coverage to the lowest flow rate of 0.02 L/h performed at engine test bench. We faced different challenges and problems in different flow ranges as we expanded the flow range downwards. Two different gravimetric diverting systems performing static weighing with flying-start-and-finish were newly designed: one is a compact conical rotating double-wing diverter [1] for the upper flow range (1 L/h~100 L/h) and another is a set of two instantaneous switching valves [2] for the lower flow range (0.02 L/h~1 L/h).

This paper presents the main features of the calibration facility incorporating the two gravimetric systems mentioned above in the succeeding section, followed by the uncertainty analysis and verification of the calibration capability of the facility through internal comparison.

2. Calibration facility

A 3D illustration of the facility is shown in Figure 1. The facility comprises three main sections, namely (a) flow generation section, (b) test section and (c) weighing section. The flow generation section consists of a storage tank, a magnetic gear pump, a heat exchanger and a header tank. The working fluid, either light oil, kerosene or industrial gasoline, is delivered into the flow loop by the magnetic gear pump whose revolution speed is variable. Temperature of the working fluid can be maintained at any value in the range of 15 °C ~35 °C. In the flow generation section, the flow circulates from the pump to the header tank and back to the storage tank. From the header tank, a portion of the working fluid is released into the test line. The header tank takes the role of stabilizing any pulsating flow as well as adjusting the fluid pressure.

The test section where DUTs (device under test) are mounted was built inside a thermostatic chamber for better stabilization of liquid temperature in the test line. Thermometer sensors and pressure transmitters are being set up upstream and downstream of each DUT.

The weighing section comprises two gravimetric systems, one using a 2 kg weighing scale (for 1 L/h~100 L/h) and the other using a 100 g weighing scale (for 0.02 L/h~1 L/h). Both gravimetric systems perform static weighing with flying-start-and-finish as the calibration method. Features of each gravimetric system are described in the following sections.

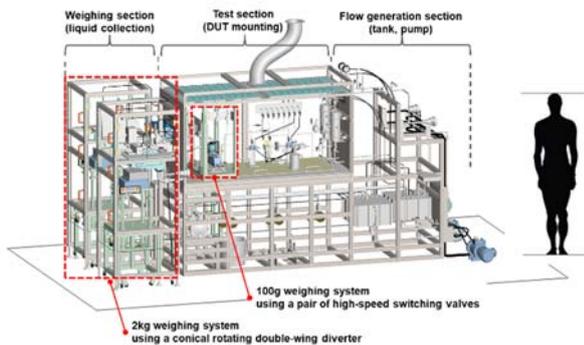


Figure 1: Calibration facility for low liquid hydrocarbon flow rates

2.1 Gravimetric system using a conical rotating double-wing diverter

As illustrated in Figure 2, this 2 kg weighing system comprises a conical rotating double-wing diverter (CRDWD), a rectangular weighing tank sitting on a weighing scale and a liquid discharge mechanism using a suction nozzle. The diverter takes the shape

of a conical structure with a small window (opening) on the cone surface and two wings protruding from both sides of the window. These two wings move in the same direction at constant speed across the liquid jet to perform symmetric diversion, a common characteristic with double-wing diverter. The diverter rotates in the same direction around the center axis of the cone which runs parallel to the liquid jet flowing vertically downward. The window leads the liquid jet into the weighing tank while the rest of the cone surface acts as the bypass sloping 'roof', letting the liquid to flow down its surface with little splashing and head towards the exit of the diverter box. The gravimetric system is being discussed in more details in [1].

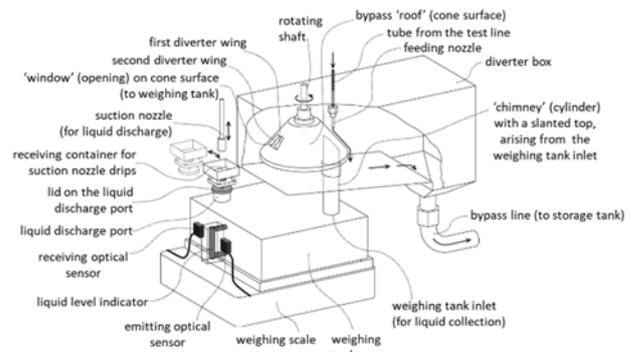


Figure 2: Gravimetric system using a conical rotating double-wing diverter

2.2 Gravimetric system using a pair of high-speed switching valves

As shown in Figure 3, this 100 g weighing system comprises the three main components of: i) a pair of switching valves as a flow diverter, ii) a weighing vessel enclosed in a chamber and iii) a liquid discharging mechanism with a bypass-cum-discharge bin. The pair of switching valves (of diaphragm type) is mounted on a flow module platform (a metal block inside which symmetrical flow channels are machined). Liquid from the DUT enters the module platform and passes through either one of the valves before exiting the module platform. We constructed two symmetrical (in terms of path configuration) flow paths with one departing from the module platform to the weighing vessel and the other to the bypass line. As a result, the flow rates going through either one of the flow paths will always be identical to maintain a constant flow rate passing through the DUT in conformity with the flying-start-and-stop (FSS) method. A detailed description of the gravimetric system is being made in [2].

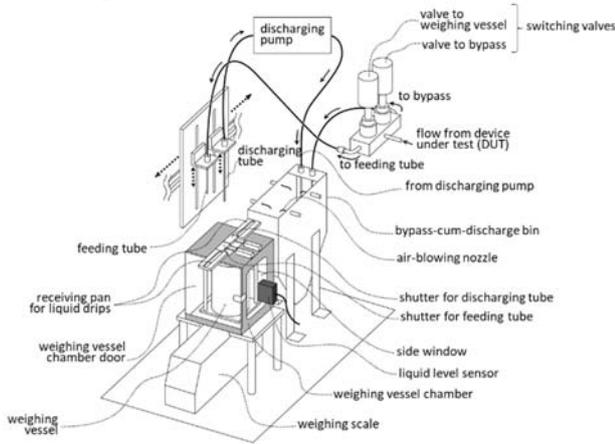


Figure 3: Gravimetric system using a pair of high-speed switching valves

3. Uncertainty analysis

Analysis of measurement uncertainty is based upon the following model equations; Equation (1) for mass flow rate and Equation (2) for volumetric flow rate.

$$K_{FM} = \frac{I_p}{(M_L + \Delta M_{LDV})} \frac{t_D}{t_p} \quad (1)$$

$$K_{FV} = \frac{I_p}{1000} \frac{t_D}{t_p} \frac{\rho_{FM}}{(M_L + \Delta M_{LDV})} \quad (2)$$

- K_{FM} : K-factor for mass flow rate (pulse/kg)
- K_{FV} : K-factor for volumetric flow rate (pulse/L)
- I_p : number of pulses totalized by the pulse counter over the duration of liquid collection (pulse)
- M_L : mass of liquid collected in the weighing vessel (kg)
- ρ_{FM} : liquid density in the flow meter (kg/m^3)
- ΔM_{LDV} : variation of liquid mass in the dead volume (volume between flow meter and the end of nozzle heading into the weighing vessel) over the duration of liquid collection (kg)
- t_D : liquid collection time for one run of calibration (s)
- t_p : time interval measured from the first rising edge of the pulse output of flowmeter detected right after the diverter trigger signal is 'on' to the first rising edge of the pulse output detected right after the diverter trigger signal is 'off' (s)

Thus, the relative combined standard uncertainty of K-factor for mass flow rate and volumetric flow rate are expressed as follows.

$$\left\{ \frac{u_c(K_{FM})}{K_{FM}} \right\}^2 = \left\{ \frac{u(I_p)}{I_p} \right\}^2 + \left\{ \frac{u(t_p)}{t_p} \right\}^2 + \left\{ \frac{u(t_D)}{t_D} \right\}^2 + \left\{ \frac{u(M_L)}{M_L} \right\}^2 + \left\{ \frac{u(\Delta M_{LDV})}{M_L} \right\}^2 \quad (3)$$

$$\left\{ \frac{u_c(K_{FV})}{K_{FV}} \right\}^2 = \left\{ \frac{u(I_p)}{I_p} \right\}^2 + \left\{ \frac{u(t_p)}{t_p} \right\}^2 + \left\{ \frac{u(t_D)}{t_D} \right\}^2 + \left\{ \frac{u(M_L)}{M_L} \right\}^2 + \left\{ \frac{u(\Delta M_{LDV})}{M_L} \right\}^2 + \left\{ \frac{u(\rho_{FM})}{\rho_{FM}} \right\}^2 \quad (4)$$

The terms on the right side of Equation (3) and Equation (4) represent uncertainties due to pulse count, measurement of time interval of pulse output, measurement of liquid collection time, measurement of liquid mass, variation of liquid mass in dead volume and estimate of liquid density in flow meter (Equation (4) only) respectively.

Uncertainty budget for the calibration flow range of 1 L/h ~ 100 L/h (2 kg weighing system) and 0.02 L/h ~ 1 L/h (100 g weighing system) are listed in Table 1 and Table 2 respectively. The values presented in Table 1 and Table 2 are all relative uncertainties for light oil, kerosene and industrial gasoline, respectively. The relative combined standard uncertainties given in Table 1 and Table 2 are meant for volumetric flow rate.

Table 1: Uncertainty budget for 1 L/h ~ 100 L/h using 2 kg weighing system

Uncertainty sources	Light oil	Kerosene	Industrial gasoline
Pulse count	8.2×10^{-5}	8.2×10^{-5}	8.2×10^{-5}
Time interval of pulse output	1.4×10^{-5}	1.4×10^{-5}	1.4×10^{-5}
Liquid collection time	8.1×10^{-5}	8.1×10^{-5}	8.1×10^{-5}
Measurement of liquid mass	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}
Dead volume effect	6.1×10^{-6}	6.4×10^{-6}	6.6×10^{-6}
Estimation of liquid density	2.6×10^{-4}	3.0×10^{-4}	3.2×10^{-4}
Relative combined standard uncertainty	2.8×10^{-4}	3.2×10^{-4}	3.4×10^{-4}

Table 2: Uncertainty budget for 0.02 L/h ~ 1 L/h using 100 g weighing system

Uncertainty sources	Light oil	Kerosene	Industrial gasoline
Pulse count	8.2×10^{-5}	8.2×10^{-5}	8.2×10^{-5}
Time interval of pulse output	1.4×10^{-5}	1.4×10^{-5}	1.4×10^{-5}
Liquid collection time	8.1×10^{-5}	8.1×10^{-5}	8.1×10^{-5}
Measurement of liquid mass	1.8×10^{-4}	1.8×10^{-4}	1.8×10^{-4}
Dead volume effect	1.2×10^{-4}	1.3×10^{-4}	1.3×10^{-4}
Estimation of liquid density	2.6×10^{-4}	3.0×10^{-4}	3.2×10^{-4}
Relative combined standard uncertainty	3.5×10^{-4}	3.8×10^{-4}	4.0×10^{-4}

Comparing Table 1 and Table 2, estimation of liquid density is the largest uncertainty source in both flow ranges. However, in the flow range of 0.02 L/h ~ 1 L/h, measurement of liquid mass and dead volume effect show the same order of magnitude as estimation of liquid density in terms of uncertainty contribution. Here, how these two uncertainty sources gain importance is discussed.

One has to take note that the uncertainties shown in Table 1 and Table 2 are relative values. In 100 g weighing system, the reason for dead volume effect to become relatively larger is that the value is evaluated in relative to the smallest amount of liquid collection which is 10 g. 10 g of liquid collection is performed at 0.02 L/h and it takes about 40 minutes for one collection. To cut down the dead volume effect, the dead volume between the flow meter and the end of nozzle is made as small as possible and temperature variation of liquid in the dead volume is controlled and stabilized by placing the measurement setup in a thermostatic chamber. At 0.02 L/h, liquid temperature variation in dead volume was evaluated as $\pm 0.025^\circ\text{C}$ in one hour duration.

On the other hand, contributing factors that cause the larger uncertainty of liquid mass measurement in the 100 g weighing system are liquid evaporation and leakage possibility. Industrial gasoline is the most evaporative among the three types of liquid. For safety reason and to reduce the evaporation error, the highest liquid temperature set for industrial gasoline is 20°C whereas light oil and kerosene are being operated up to 35°C . At 20°C , the evaporation rate of industrial gasoline was evaluated as 0.0015 g for a duration of 1 hour which equals to that of kerosene at 35°C . In relative to 10 g of liquid collection, this produces 1.5×10^{-4} in terms of uncertainty.

The second largest contributing factor to uncertainty of liquid mass measurement in the 100 g weighing system is undetectable leakage. Leakage amount can be so small that it cannot be detected by pressure variation. Yet this tiny amount is not negligible in relative to 10 g of liquid collection. In practice, leakage check is performed by monitoring the pressure and temperature variation for the longest time of liquid collection (40 minutes). During this period, variation of pressure and temperature has to be maintained within ± 10 kPa and $\pm 0.01^\circ\text{C}$ respectively. In other words, leakage that is not detectable within ± 10 kPa and $\pm 0.01^\circ\text{C}$ is treated as an uncertainty factor in liquid mass measurement and is estimated as 1.0×10^{-4} in relative to 10 g of liquid collection.

Uncertainty sources shown in Table 1 and Table 2 are all due to the calibration facility. Combined with the uncertainties due to flowmeter (DUT), the ultimate uncertainty of calibration is obtained in Table 3.

Table 3: Ultimate uncertainty of calibration

Flow range, Q (Weighing system)	Volumetric flowrate (%)	Mass flowrate (%)
1 L/h \leq Q \leq 100 L/h (2 kg weighing system)	LO: 0.029 <i>(0.058)</i>	LO, KE, IGA: 0.010 <i>(0.020)</i>
	KE: 0.032 <i>(0.064)</i>	
	IGA: 0.034 <i>(0.068)</i>	
0.02 L/h \leq Q < 1 L/h (100 g weighing system)	LO: 0.036 <i>(0.072)</i>	LO, KE, IGA: 0.025 <i>(0.050)</i>
	KE: 0.039 <i>(0.078)</i>	
	IGA: 0.040 <i>(0.080)</i>	

Note: Calibration and measurement capability in italic; coverage factor, $k=2$; LO: light oil, KE: kerosene, IGA: industrial gasoline.

4. Validation of calibration and measurement capability (CMC) through intra-comparisons

To justify the calibration capability of the facility (hereafter, small oil flow facility), we performed intra-comparisons with other primary standard facilities (small water flow facility; medium oil flow facility) in NMIJ which are linked to international comparisons. Intra-comparisons using light oil and kerosene have been reported in previous papers [3, 4]. In this paper, we present the intra-comparison conducted between the small oil flow facility and the medium oil flow facility [5] using industrial gasoline.

Figure 4 shows the intra-comparison results between the small oil flow facility (2 kg weighing system) and the medium oil flow facility using industrial gasoline as the working liquid and a piston

type volumetric flow meter as the transfer standard. Difference of K-factors (shown in percentage in relative to the nominal K-factor) obtained from the two facilities is shown in the ordinate axis in Figure 4. The error bar indicates the expanded uncertainty of each facility. Overall the difference is within $\pm 0.03\%$ which is within the expanded uncertainty of the facilities for volumetric flow rate calibration, hence providing supporting evidence for the calibration capability of the 2 kg weighing system of small oil flow facility.

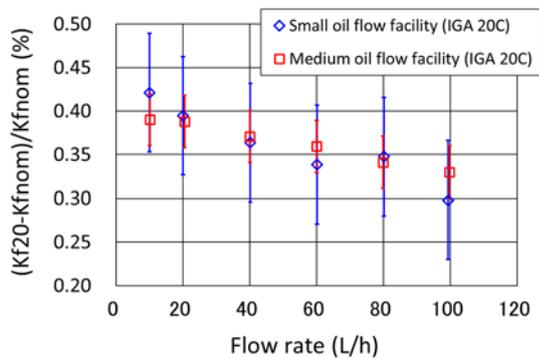


Figure 4: Intra-comparison between small oil flow facility and medium oil flow facility using industrial gasoline.

To justify the calibration capability of the 100 g weighing system of small oil flow facility, a comparison was conducted between the two weighing systems of 100 g and 2 kg over an overlapping flow range of 0.6 L/h \sim 6 L/h using a volumetric flow meter as a transfer standard. As shown in Figure 5, the two weighing systems agree well within the expanded uncertainties of the facilities ($E_n < 1$). Hence the calibration capability of the 100 g weighing system is justified. As such, the comparison results in Figures 4 and 5 provide supporting evidence that validates the overall calibration capability of the small oil flow facility.

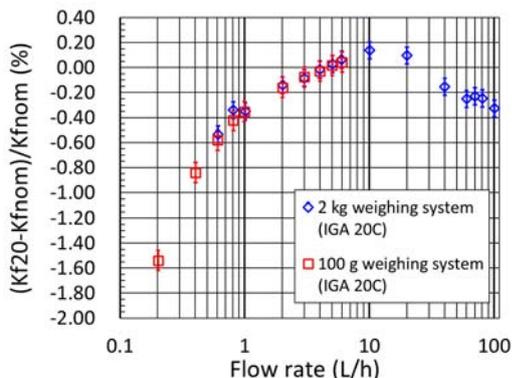


Figure 5: Comparison between 100 g weighing system and 2 kg weighing system within the small oil flow facility.

5. Summary and conclusions

To provide measurement traceability in engine fuel consumption for the industry (automobile, shipping and aviation) as well as in the household fuel metering and bio-fuel production (bio-fuel blending), NMIJ developed a primary standard for low liquid hydrocarbon flow rates that works on three common types of liquid fuels, namely light oil (diesel), kerosene and industrial gasoline.

The primary standard comprises two gravimetric systems, one using a 2 kg weighing scale with a conical rotating double-wing diverter in the flow range of 1 L/h \sim 100 L/h, and the other using a 100 g weighing scale with a pair of high-speed switching valves as diverter in the flow range of 0.02 L/h \sim 1 L/h. Calibration method of static weighing with flying-start-and-finish is performed in both gravimetric systems.

From the uncertainty analysis, the expanded uncertainty for calibration of the upper range of volumetric flow rates from 1 L/h \sim 100 L/h by using the 2 kg weighing system is estimated at 0.058 %, 0.064 % and 0.068 % for light oil, kerosene and industrial gasoline respectively whereas the expanded uncertainty for the corresponding mass flow rates is estimated at 0.020 % for all working liquids. On the other hand, the expanded uncertainty for calibration of the lower range of volumetric flow rates from 0.02 L/h \sim 1 L/h by using the 100 g weighing system is estimated at 0.072 %, 0.078 % and 0.080 % for light oil, kerosene and industrial gasoline respectively whereas the expanded uncertainty for the corresponding mass flow rates is estimated at 0.050 % for all working liquids.

Intra-comparisons with other primary standards in NMIJ that are linked to the international comparisons (CCM.FF.K1, CCM.FF.K2) show a good agreement between the facilities, hence justifying the CMC claimed by the primary standard (small oil flow facility) being discussed in this paper.

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