Uncertainty Analysis of Primary Standard for Hydrocarbon Flow at NMIJ

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Abstract The uncertainty of the primary standard for hydrocarbon flow measurements at NMIJ has been evaluated experimentally and analytically in detail. The primary standard is based on the static and gravimetric method with a flying start and finish at flow rates in the range between 3 and 300 m^3/h. It consists of two separated test rigs with kerosene and light oil as working liquids. The expanded uncertainty is estimated to be better than 0.03 % for volumetric flow rates and 0.02 % for mass flow rates (coverage factor k = 2). The dominant sources of combined uncertainty of the flow rate are the mass of the oil accumulated in the weighing tank and the density of the oil flowing through the flowmeter being tested. A Coriolis flowmeter, a turbine meter and an ultrasonic flowmeter have been calibrated in both test rigs in order to verify the performance of the facility. The results indicate that the expanded uncertainty estimated analytically is adequate.

Keywords: Hydrocarbon flow measurement; Uncertainty; Primary standard

1. Introduction

The primary standard for hydrocarbon flow at NMIJ[1] has been designed to calibrate hydrocarbon flowmeters at flow rates in the range between 3 to 300 m^3/h with expanded uncertainty better than 0.04 % for volumetric flow rates and 0.03 % for mass flow rates (coverage factor: k = 2). This calibration facility has special features that enable highly accurate calibration.

In the present paper, first, an outline of the new hydrocarbon flow calibration facility is described. Second, the uncertainty of the calibration for the flowmeter is analytically estimated in accordance with the ISO Guide[2]. Finally, a Coriolis flowmeter, a positive displacement flowmeter, a turbine meter and an ultrasonic flowmeter are calibrated in both test rigs in order to verify the performance of the facility.

2. Primary standard for hydrocarbon flow measurement in Japan

2.1. Outline of the calibration facility

A schematic and the specifications of the primary standard for hydrocarbon flow are shown in Fig. 1 and Table 1, respectively. Light oil and kerosene are used as the working liquids; each oil has a separate test line. Although the flow rate range of the facility capacity is from 3 to 300 m^3/h, the normal calibration flow rate range is limited from 15 to 300 m^3/h. This primary standard is based on static and gravimetric methods with a flying start and finish, i.e., the total mass of fluid passing through the flowmeter via the diverter in a given time is measured.

It consists of a 10 t weighing scale, a 1 t weighing scale, a density meter and the diverter system which has double diverting wings. This diverter system was developed by NMIJ[3] and was applied to minimize the uncertainty in the collection time of the hydrocarbon into the weighing tanks. The test line diameters for the flowmeters are 50, 100 and 150 mm. Two 43 m^3 storage tanks are used for the two lines. The temperature stability of working fluids has a significant effect on the uncertainty of density, and hence, a sophisticated heat exchanger is installed in the test lines. Almost all the test lines and tanks are sufficiently covered by thermal insulator. A weighing system with dead weights is one of the advantages that enable high-performance calibration.

Three servo PD flowmeters [4] are installed in each of the test rigs as working standards. In the servo PD flowmeter, the spiral rotors are driven by a servomotor so that the differential pressure between the inlet and outlet of the flowmeter remains zero or at a certain value that results in reduced differential pressure across the rotors. Thus, a wide range of flow rate can be measured at high accuracy. These flowmeters of 50, 100, and 150 mm diameter are used in the flow rate ranges from 3 to 30, 7.5 to 75, and 30 to 300 m^3/h, respectively. The long stability of the servo PD flowmeter has been investigated by simultaneous calibration with a test meter.

The detailed information, including the calibration procedure, has been described in the previous paper[1].

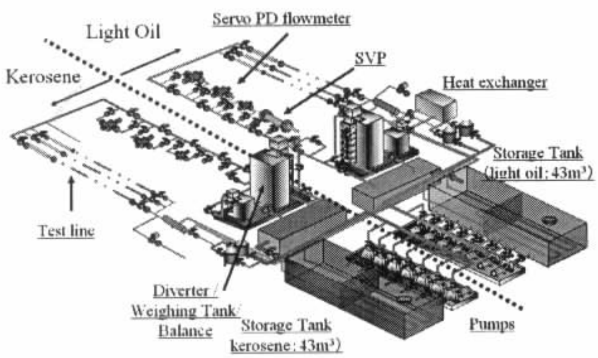

Fig. 1 Schematic of the hydrocarbon flow calibration facility.

Table 1 Specifications of the primary standard

Flow rate	3 – 300 m^3/h
Uncertainty	0.03 % for volumetric flow 0.02 % for mass flow
Working liquid	Kerosene; 790 kg/m^3, 1.7 × 10^{-6} m^2/s at 20 °C Light oil; 830 kg/m^3, 6.8 × 10^{-6} m^2/s at 20 °C
Primary standard	10 t, 1 t Weighing scales, Diverter, Density meter
Calibration method	Static and gravimetric methods with flying start and stop
Working standard	Small volume prover Servo PD meter
Pipe diameter	50, 100, 150 mm
Temperature	15 – 35 °C.
Pressure	0.1 – 0.7 MPa

2.2. Calculation of the calibration factor of the flowmeter (K-factor)

The calculation of the K-factor obtained at the hydrocarbon flow calibration facility is based on the same concept as that of the large water facility at NMIJ, where static and gravimetric methods with flying start and finish are applied [5]. Furthermore, the K-factor for the volumetric flowmeter, K_f, is described by

$$K_f = \frac{\rho_{LFM}}{M_L} \cdot \frac{t_D}{t_P} I_P, \quad (1)$$

where ρ_{LFM} represents the density through the flowmeter. t_D, I_P and t_P denote the diversion time, the number of pulses generated by the flowmeter and the duration for which the flowmeter pulse is counted, respectively. The mass of the oil in the weighing tank, M_L, is obtained as

$$M_L = \frac{k_{mL} \cdot m_L}{\left(1 - \rho_{Gm}/\rho_{LW}\right)}, \quad (2)$$

where m_L, ρ_{Gm} and ρ_{LW} represent the reading on the weighing scale, the density of the air around the weighing tank and the density of the oil in the weighing tank. k_{mL} denotes the calibration factor of the weighing scale corresponding to m_L. The calibration factor k_{mL} is calibrated by the dead weight.

The K-factor for the mass flowmeter, K_{fm}, is obtained as

$$K_{fm} = \frac{\left(1 - \rho_{Gm}/\rho_{LW}\right)}{k_{mL} \cdot m_L} \frac{t_D}{t_P} I_P. \quad (3)$$

More detailed information on the calculation has been presented in the previous paper [1].

2.3. Uncertainty analysis

The relative combined standard uncertainty of the K-factor for volumetric flow, $u_c(K_f)$, is expressed by

$$\left\{\frac{u_c(K_f)}{K_f}\right\}^2 = \left\{\frac{u(I_P)}{I_P}\right\}^2 + \left\{\frac{u(t_P)}{t_P}\right\}^2 + \left\{\frac{u(\Delta M_{LDV})}{M_L}\right\}^2 + \left\{\frac{u(\Delta(\rho_{LFM} q_{FM}))}{\rho_{LFM} q_{FM}}\right\}^2 + \left\{\frac{u(M_L)}{M_L}\right\}^2 + \left\{\frac{u(\rho_{LFM})}{\rho_{LFM}}\right\}^2 + \left\{\frac{u(t_D)}{t_D}\right\}^2, \quad (4)$$

where $u(i)$ denotes the standard uncertainty of uncertainty source i. The terms on the right in Eq.(4) indicate the number of pulses generated by the flowmeter, the duration for which the flowmeter pulse is counted, the effect of the dead volume, the effect of the correlation between mass flowrate and density through the flowmeter, the mass of oil in the weighing tank, the time-averaged oil density through the flowmeter under calibration, and diversion time, respectively.

The relative combined standard uncertainty of the K-factor for mass flow, $u_c(K_{fm})$, is expressed by

$$\left\{\frac{u_c(K_{fm})}{K_{fm}}\right\}^2 = \left\{\frac{u(I_P)}{I_P}\right\}^2 + \left\{\frac{u(t_P)}{t_P}\right\}^2 + \left\{\frac{u(\Delta M_{LDV})}{M_L}\right\}^2 + \left\{\frac{u(M_L)}{M_L}\right\}^2 + \left\{\frac{u(t_D)}{t_D}\right\}^2 \quad (5)$$

The uncertainty sources for volumetric flow are listed in Table 2. The combined relative standard uncertainty for volumetric flow is estimated to be 0.0083 to 0.011 % by detailed analysis using the 10 t weighing system at the kerosene test rig. The dominant sources of the combined uncertainty of flow rate are the mass of the oil accumulated in the weighing tank and the density of the oil flowing through the flowmeter being tested. Although the overall uncertainty depends on the flow rate and the test rigs, the combined relative standard uncertainty for volumetric flow at this calibration facility is simplified to be 0.015 %. The relative combined standard uncertainty of the K-factor is estimated in combination with the uncertainty of the experimental standard deviation of the mean due to the random effect, which normally is negligible. Accordingly, the relative expanded uncertainty of the K-factor for volumetric flow is estimated to be 0.03 % (coverage factor $k = 2$).

On the other hand, the combined relative standard uncertainty for mass flow is estimated to be 0.004 to 0.008 % using the 10 t weighing system at the kerosene test rig. Although this uncertainty also depends on the test rig used, the combined relative standard uncertainty for mass flow in this calibration facility is simplified as 0.01 %. Thus, the relative expanded uncertainty for mass flow is estimated to be 0.02 % ($k = 2$).

3. Experiment for calibration uncertainty

3.1. Comparison of K-factor with the different weighing system at the same test rig

The servo PD meter and a test meter were simultaneously calibrated at 30 m^3/h in order to investigate the agreement between K-factors obtained using 10 t and 1 t weighing systems at the same test rig. K-factors obtained using the servo PD meter and the PD meter at the light oil test rig are shown in Fig. 2 as Youden plots. This result indicates that the difference between the K-factors when using the 10 t weighing system and the 1t weighing system is negligible in comparison with the expanded uncertainty, 0.03 %.

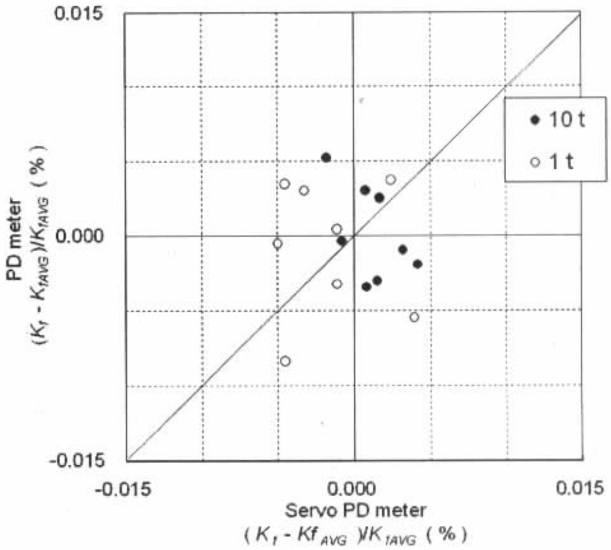

Fig. 2 K-factors obtained using the 10 t weighing system and the 1 t weighing system at the light oil test rig. Flow rate was 30 m^3/h. The result was a single diversion.

Fig. 3 shows results as Youden plots, obtained using the servo PD meter and the turbine meter at the kerosene test rig. The averaged K-factor obtained with the servo PD meter and the turbine meter using the 10 t weighing system are 0.012 % and 0.007 % higher than those obtained using the 1 t weighing system, respectively. Furthermore, positive correlation with both K-factors indicates that this difference is caused by the calibration facility.

On the other hand, the average K-factor obtained using the 10 t weighing system under the vapor-rich condition without the exhaust system, which prevents vapor from flowing from the diverter to the weighing room, is 0.005 % lower than that of the normal calibration. This difference is observed to decreases as the flow rate increases, indicating that working liquid is lost at a constant rate during measurement, in the form of the vapor and mist. On the contrary, the difference for the 1 t weighing system is less than 0.002 %, indicating that the effect of liquid loss is negligible. Furthermore, this effect is not observed for the light oil test rig.

Although the difference between the K-factor of the turbine meter at the 10 t weighing system without exhaust and that at the 1 t weighing system is less than 0.003%, the value obtained using the servo PD meter is 0.010%. One of the reasons is considered to be the interaction between the flowmeter and the test rig, however, this requires further investigation.

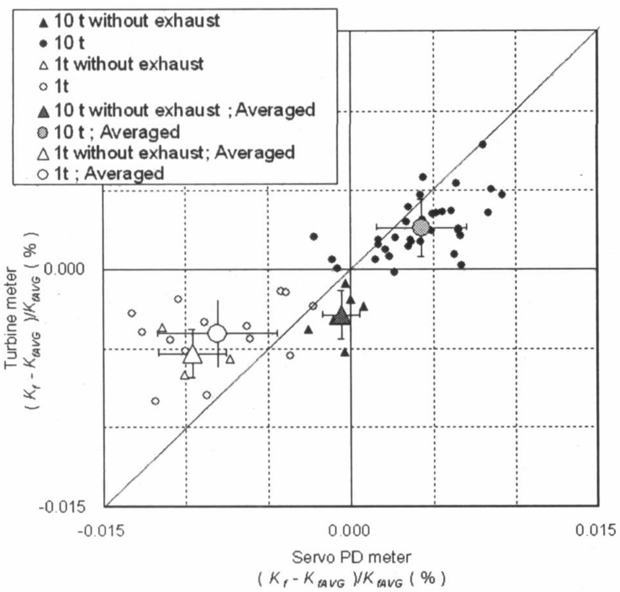

Fig. 3 Results for the 10 t and 1 t weighing systems at the kerosene test rig. The result was a single diversion.

3.2. Comparison of K-factors for the different test rigs

A Coriolis flowmeter was calibrated to verify the agreement between the two test rigs using kerosene and light oil. The liquid temperature was 20 °C. The corrected K-factors K_{fm0C} using the Coriolis meter are shown in Fig. 4. K_{fm0C} is corrected K-factor using Eq.(6) due to the pressure effect, F_{FM} (=0.09 %/MPa), and the effect of zero stability.

$$K_{fm0C} = K_{fm}\left(1 + F_{FM}\cdot p_{FM}\right)\left(1 - \frac{Q_{m0}}{Q_{FM}}\right) \quad (6)$$

p_{FM}, Q_{m0} and Q_{FM} represent the estimated pressure at the test meter, the flow rate reading for a zero flow, and the actual flow rate, respectively. The agreement between the corrected K-factors of the both test rigs was within ±0.02 %, which indicates that the expanded uncertainty of mass flow estimated analytically is adequate.

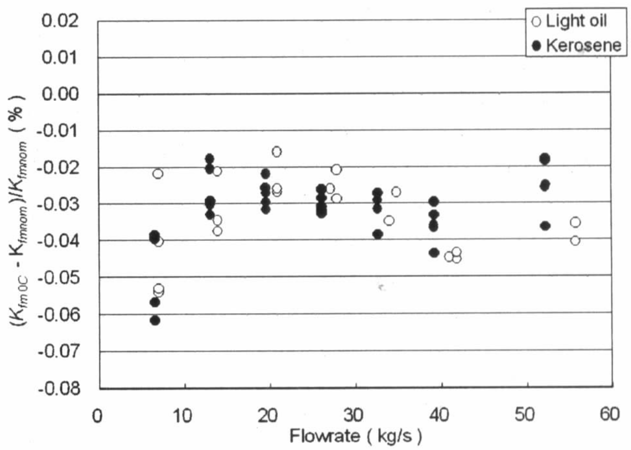

Fig. 4 Corrected K-factor of Coriolis meter. The result was a single diversion.

The turbine meter, whose K-factor is dependent on the Re number, was calibrated at both test rigs to verify the calibration performance at the volumetric flow rate. The results are shown in Fig. 5. The temperature of the working liquid was 20 and 30 °C to enable the change of viscosity. Therefore, the corrected K-factor K_{f20} based on 20 °C was calculated using the thermal expansion coefficient of 0.0041 %/°C of the flowmeter. The corrected K-factor was fitted by Eq.(7) against Re number. The difference between the calibrated K_{f20} and the fitted values K_{f20fit} are shown in Fig. 6.

$$K_{f20,fit} = 33.077 + \frac{1.5459\times10^{4}}{\mathrm{Re}} - \frac{1.0238\times10^{2}}{\mathrm{Re}^{0.5}} - 3.6322\times10^{-8}\,\mathrm{Re} \quad (7)$$

It is shown in Fig. 6 that the K-factors for both test rigs in the Re number range from 60,000 to 80,000 agree within the expanded uncertainty for volumetric flow, 0.03 %.

The results for an ultrasonic flowmeter will be shown in the presentation.

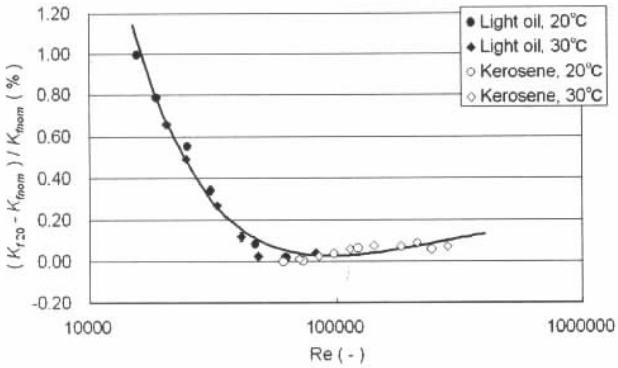

Fig. 5 Corrected K-factor of turbine meter. The solid line indicates Eq.(7). Each maker presents an average of more than five repeated measurements.

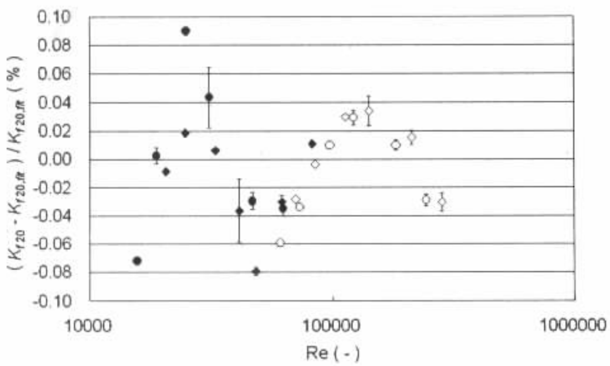

Fig. 6 Difference of K-factor from the fitting curve. The symbols are the same as in Fig. 5.

4. Conclusion

The uncertainty of the primary standard for hydrocarbon flow measurements at NMIJ has been evaluated in detail analytically. Several kinds of flowmeters have been calibrated in both test rigs in order to verify the performance of the facility. The results indicate that the expanded uncertainty estimated analytically is adequate.

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Table 2 Uncertainty of calibration for volumetric flow using the 10 t weighing system at kerosene test rig.

Uncertainty Sources				Relative standard uncertainty × 10^{-5}		
Number of pulses						~ 0
Duration of pulse counting						1.6
	Resolution				0.1	
	Correction				1.3	
	Reproducibility				1.0	
Dead volume						< 1
Fluctuation of flow rate and density						< 1
Mass of liquid						2.4 ~7.4
	Calibration factor				2.1	
		Density of dead weight		0.1		
		Density of air		0.1		
		Repeatability		0.6		
		Resolution of calibration		0.1		
		Effect of center off		0.6		
		Linearity		0.5		
		Temperature		1.3		
		Standard dead weight		0.9		
		Reproducibility		0.8		
	Resolution				0.1	
	Buoyancy correction				0.8	
		Density of air		0.8		
		Density of liquid		0.2		
	Vapor and mist				0.7 ~ 7.0	
Density of liquid						6.2 ~ 7.3
	Density meter				1.9	
	Thermal coefficient				0.2	
	Temperature measurement				5.4	
		Density meter		2.6		
		Liquid temperature		2.8		
			Fluctuation	1.9		
			Correction	2.0		
			Resolution	0.0		
			Effect of the measurement point	0.9		
	Compressibility				0.3 ~ 1.5	
	Pressure measurement				1.0 ~ 3.9	
		Fluctuation		0.4		
		Correction		0.9		
		Resolution		0.0		
		Effect of the measurement point		0.0~3.9		
	Reproducibility of working liquid				2.2	
Duration of installation						1.6~2.1
	Timer				1.6	
	Correction time (Diverter timing error)				0.2 ~ 1.6	
	Combined relative standard uncertainty				8.3 ~ 11	