

Measurement of hydrocarbon liquid flow rate using volumetric and gravimetric methods: comparison between KRISS and PTB hydrocarbon standard systems

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Abstract

In this study, the hydrocarbon liquid flow rate was measured using both volumetric and gravimetric methods. Both methods are representative reference techniques for measuring the hydrocarbon flow rate. The volumetric method uses a calibrated volume tank, while the gravimetric method is based on a calibrated balance. Using these two methods, which have different traceability systems, a Coriolis flowmeter was calibrated under comparable flow conditions. The deviation and uncertainty of the flow measurement results obtained from the volumetric and gravimetric methods were analyzed.

The study included the calibration of a 1000 L reference volumetric tank at the PTB hydrocarbon facility by using two different approaches: a filling method and a gravimetric method. For the filling method, a 100 L reference volume pipette was installed above the volume tank. A balance system under the 1000 L tank was used to calibrate the tank based on the gravimetric method. The uncertainties of the filling and gravimetric methods were 325.18 ml and 171.39 ml ($k=2$), respectively, and the maximum difference between these methods was 78.06 ml. Thus, the calibration values of both methods were found to agree with each other within the estimated uncertainties.

For the final comparison, a Coriolis flowmeter was calibrated using the 1000 L volume tank at the PTB flow facility. The diameter of the pipeline was 80 mm and the flow rate ranged from 13.68 t/h to 54.81 t/h. A balance reference was used at the hydrocarbon flow systems of KRISS. Since the fluid properties (density and viscosity) used at the two institutes are different, the flow measurements were compared based on the Reynolds number to compensate for these fluid properties. The calibration values of the Coriolis flowmeter at KRISS and PTB were 0.21–0.23% ($U=0.08\%$, $k=2$) and 0.18–0.24% ($U=0.05\%$, $k=2$), respectively, for an Re number range between 35,000 and 145,000. The results from the gravimetric method in KRISS matched very well with the results from the volumetric at PTB, within the estimated uncertainties. Thus, we confirmed that the hydrocarbon flow standard systems of KRISS and PTB have traceability when using the volumetric and gravimetric methods in the given range of Re number. The procedure and results of the volume tank calibration at the PTB hydrocarbon facility will be given during the presentation. In addition, the results of the flow comparison between PTB and KRISS will be presented to demonstrate the traceability of both hydrocarbon laboratories.

1. Introduction

Both volumetric and gravimetric methods are representative standard methods for measuring the flow rate. The volumetric method uses calibrated volume tanks, while the gravimetric method uses a calibrated balance. The volumetric method can measure the volume flow rate without the need to convert the mass flow rate into the volume flow rate;

however, the measurement accuracy is highly dependent on the changes in temperature.

In general, when calibrating a volume tank, the gravimetric method has a lower uncertainty than the volumetric method [1]. Both volumetric and gravimetric methods show consistent results within the uncertainty range during flow rate measurement [2]. However, previous studies have compared the volumetric and gravimetric methods separately using different facilities.

In this study, we performed the calibration of a volume tank by using both volumetric and gravimetric methods simultaneously in the same facility. Also, the hydrocarbon flow system was compared using the volumetric method of PTB and gravimetric method of KRISS.

2. Experiment

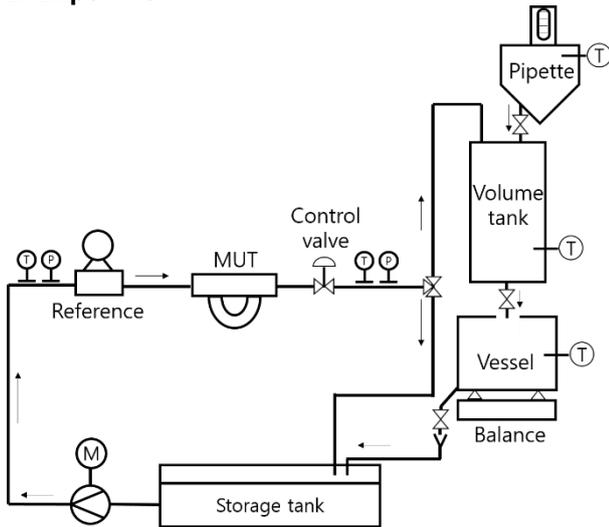


Figure 1: Schematic of measurement setup using volumetric and gravimetric methods.

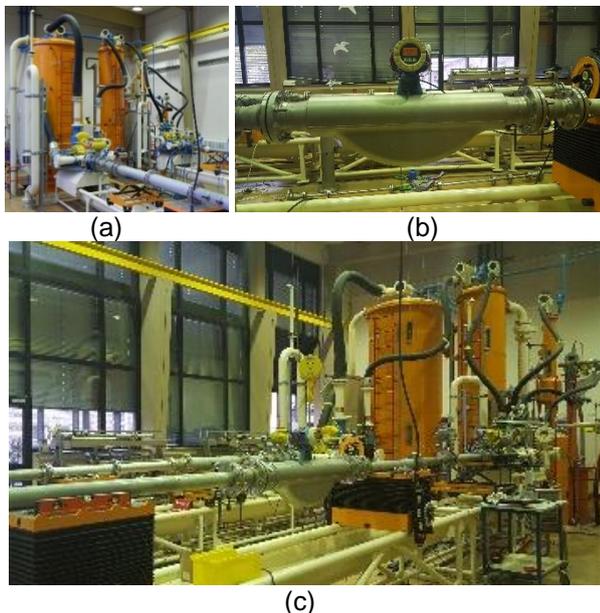


Figure 2 (a) hydrocarbon flow calibration rig, (b) Coriolis flowmeter DN 100, and (c) hydrocarbon flow calibration rig with flowmeter installed in PTB

Figure 1 shows the schematic of the hydrocarbon flow rate measurement setup using volumetric and gravimetric methods.

A 1000 L volume tank was used for flowrate measurement and a 100 L reference volume tank and the calibrated balance were used simultaneously to calibrate the volume tank. A Coriolis flowmeter (Endress + Hauser, 83F1H) with a diameter of 100 mm was used to compare the PTB and KRISS hydrocarbon flow facilities. Figure 2(c) shows the installation of the flowmeter on the 80 mm pipeline of the PTB hydrocarbon flow facility.

3. Calibration of the volume tank at the hydrocarbon facility at PTB

The Department of Liquid Flow at PTB operates a test facility for the calibration of flow meters in the range between 0.6 m³/h and 120 m³/h. The test fluid is white spirit. The test facility has four separate volume tanks with capacities of 5000 L, 1000 L, 200 L, and 100 L. For the final filling stage of the tanks, the liquid level can be detected by manual meniscus reading. Additionally, in the 1000 L tank, the liquid level is measured gradually by using a magnetostriction displacement sensor. For traceable gravimetric calibrations of flow meters, a balance system with a maximum weight of 500 kg is also installed.

In this section, we evaluate the proven uncertainty of the facility (0.05 %, $k = 2$) by performing a recalibration of the 1000 L volumetric standard tank. Through a comparison between gravimetric and volumetric methods, the best practical procedure is determined and discussed.

The calibration procedures for the gravimetric method and volumetric method are based on the EURAMET guidelines “cg-19” [1] and “cg-21” [2], respectively. For the volumetric calibration, the filling method was applied using a 100 L traceable pipette and a 5 L pipette. For the gravimetric method, a specially installed high-resolution balance system (max. weight: 100 kg, resolution: 1 g) was used.

3.1 Calibration of the volume tank using volumetric method

We calibrated the 1000 L volume tank with five individual measurements by using a 100 L reference pipette for liquid levels lower than 2200 mm. For the upper part of the volume tank, a higher resolution was required. For that purpose, a 5 L pipette was used for liquid levels between 2000 mm and 2650 mm. In principle, the calibration procedure was based on the calibration guidelines of a standard capacity measure using a volumetric method [3]. For the calibration of one 1000 L tank, all single 100 L and 5 L pipette fillings were summed up.

The mathematical expression of the calibrated volume $V_{T,vol}$ is given by equation (1). The final

approach of the calibration was to obtain a continuous function for the relation between the liquid level and tank volume. For that purpose, separate linear models for each linear level range were fit to the five individual calibration curves. The difference between the calibrated and modelled values gives the uncertainty of V_{Approx} .

$$V_{T,vol} = V_0[1 - \gamma_{RS}(T_{ORS} - T_{RS}) + \beta(T_{VT} - T_{RS}) + \gamma_{VT}(T_0 - T_{VT})] + \delta V_{men} + \delta V_{rep} + \delta V_{approx} + \delta V_{add} \quad (1)$$

Here,

- V_0 Volume of reference standard in L
- T_{ORS} Water temperature of reference standard in the volume certificate in °C
- T_{RS} Water temperature of reference standard in °C
- T_0 Reference temperature of volume tank in °C
- T_{VT} Water temperature of the volume tank in °C
- γ_{RS} Coefficient of cubical thermal expansion of reference standard material in °C⁻¹
- γ_{VT} Coefficient of cubical thermal expansion of volume tank material in °C⁻¹
- β Coefficient of cubical thermal expansion for water in °C⁻¹
- δV_{men} Meniscus reading in L
- δV_{rep} Measurement repeatability in L
- δV_{approx} Approx. function in L
- δV_{add} Additional factors in L

Table 2 presents the main results of the uncertainty budget for the volume tank using the volumetric method. The measurement uncertainty was estimated to be 0.325 L ($k = 2$). The main input parameters for the budget are the approximation function (52.8%), the calibration of reference pipette (31.0%) and the additional parameters (15.8%) such as evaporation, water loss, and air bubbles. The volume of the reference standard was estimated to be 1025.085 L for calibration and modelled with 1024.919 L. The deviation of 0.166 L between both values was less than the estimated measurement uncertainty of the volumetric method that was used.

Table 2: Results of uncertainty calculation for volume tank calculation using volumetric method

Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty $u_i(V_0) = c_i u(x_i)$
$u(V_0)$	Volume of the RS	9.06E-02 (L)
$u(T_{RS})$	Water temperature of RS	5.86E-03 (L)
$u(T_{VT})$	Water temperature of volume tank	1.19E-03 (L)

$u(\gamma_{RS})$	Coefficient of cubical thermal expansion of the RS	2.23E-04 (L)
$u(\delta VT)$	Coefficient of cubical thermal expansion of volume tank	3.12E-04 (L)
$u(\delta V_{men})$	Meniscus reading of the RS	7.22E-04 (L)
$u(\delta V_{rep})$	Measurement repeatability	8.99E-03 (L)
$u(\delta V_{approx})$	Approximation function	1.18E-01 (L)
$u(\delta V_{add})$	Additional factors	6.47E-02 (L)
$U_{T,vol}$	$U(V_{T,vol})$ 3.25E-01 L ($k = 2$)	

3.2 Calibration of the volume tank using gravimetric method

In addition to the previously described volumetric method, we calibrated the same 1000 L tank by using a high-resolution reference balance (max weight = 100 kg). The calibration procedure is described in the determination guidelines of uncertainty in gravimetric volume calibration [4]. Further, for the calibration of one 1000 L tank, the 100 kg balance tank was filled 10 times in a row to obtain a summed up value of the total 1000 L tank volume. The mathematical expression for the calibrated volume $V_{T,Mass}$ is given in equation (2). Based on a previous approach, a function for the relation between the liquid level and tank volume was derived. The difference between the calibrated and modelled values also gives an uncertainty of V_{Approx} .

$$V_{T,Mass} = m \frac{1}{\rho_W - \rho_A} \left(1 - \frac{\rho_A}{\rho_B}\right) [1 - \gamma_{VT}(T_{VT} - T_0)] + \delta V_{rep} + \delta V_{approx} + \delta V_{add} \quad (2)$$

Here,

- m Weighing result in kg
- ρ_W Liquid density in kg/m³, at calibration temperature
- ρ_A Air density in kg/m³
- ρ_B Density of mass pieces during balance calibration = 7900 kg/m³
- γ_{VT} Coefficient of cubical thermal expansion of volume tank material in °C⁻¹
- T_0 Reference temperature of volume tank in °C
- T_{VT} Water temperature of the volume tank in °C
- δV_{rep} Measurement repeatability in L
- δV_{approx} Approx. function in L
- δV_{add} Additional factors in L

Table 3 shows the uncertainty budget for volume tank calculation using the gravimetric method. The measurement uncertainty was 0.171 L ($k = 2$). The main input parameters for the budget are the approximation function (34.4%), the repeatability of the calibrations (19.8%) and the additional

parameters (45.7%) such as evaporation, water loss, and air bubbles. The volume of the reference standard was 1004.193 L, and the modelled volume at the same liquid level was also 1004.193 L. Thus, we confirmed that the volumes calculated using both volumetric and gravimetric methods were well matched with the reference standard under measurement uncertainty.

Table 3: Results of uncertainty budget for volume tank calculation using gravimetric method

Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty $u_i(V_0) = c_i u(x_i)$
$u(m)$	Balance reading	3.44E-06 (L)
$u(T_{VT})$	Water temperature of volume tank	2.43E-07 (L)
ρ_W	Density fluid	3.02E-06 (L)
ρ_A	Density Air	2.53E-08 (L)
ρ_B	Density mass pieces	1.12E-07 (L)
$u(\delta VT)$	Coefficient of cubical thermal expansion of volume tank	1.34E-07 (L)
$u(\delta V_{rep})$	Measurement repeatability	3.82E-02 (L)
$u(\delta V_{approx})$	Approximation function	5.02E-02 (L)
$u(\delta V_{add})$	Additional factors	5.80E-02 (L)
$U_{T,Mass}$	$U(V_{T,Mass}) 1.71E-01 L (k = 2)$	

3.3 Comparison of volumetric and gravimetric methods

The aim of the study was to estimate a liquid-level dependent function for the volume of a 1000 L tank by comparing two different calibration methods. The results summarized in Table 4 show that the uncertainty of the gravimetric method is nearly half of that of the filling method.

For using the investigated functions, only the linear level ranges of the 1000 L tank were relevant (Figure 2). On comparing these three ranges (Table 4 and Figure 3), the best agreement between the volume and the gravimetric model was found for the upper linear level. Here, the observed variation between both models was 78.06 mL, which is fully covered by the uncertainty of both methods.

Table 4: Summarized results of uncertainty budget for volume tank calculation using gravimetric and filling method

	$u (k = 1)$		$u (k = 2)$	
	ml	%	ml	%
Filling method	162.59	0.016	325.18	0.031
Gravimetric method	85.69	0.008	171.39	0.016

Table 4: Summarized results of uncertainty budget for volume tank calculation using gravimetric and filling method

Linear range of liquid level in mm	Differences between both models		
	Min in mL	Max in mL	Mean in mL
160 ... 950	8.66	237.79	109.46
2000 ... 2200	242.92	497.70	370.31
2450 ... 2650	5.68	78.06	29.88

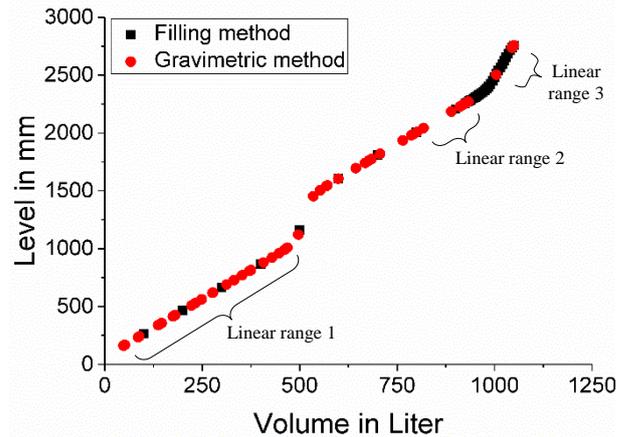


Figure 2 Calibrated volume at reference temperature using filling and gravimetric methods. The linear level ranges are marked.

4. Comparison of hydrocarbon facilities between KRIS and PTB

The hydrocarbon flow rate was measured and compared with the results of the volumetric method from PTB and the gravimetric method from KRIS. The density and viscosity of the hydrocarbon used by PTB and KRIS are summarized in Table 5. Since PTB and KRIS use fluids with different densities and viscosities, the difference in fluid properties is compensated by using the Re number. The mass and volume flow rates of PTB and KRIS according to the Re number used are shown in Table 6.

Figure 3 shows the measured deviations from PTB and KRIS according to the Re number. The deviations measured in PTB and KRIS show good agreement within the uncertainty range ($U_{PTB} = 0.05$, $U_{KRIS} = 0.08$). The En values were found to be less than 1 in the measured Re numbers of PTB and KRIS (Table 6).

Table 5: Fluid properties of water and hydrocarbon

20 °C, 1 atm	Density (kg/m ³)	Viscosity (cP)
Water	1000	0.001
Hydrocarbon in PTB	784.816	0.00135
Hydrocarbon in KRIS	805.37	0.00295

Table 6: Uncertainty budget for volume tank calculation using volumetric method

Re. number	KRISS flowrate		PTB flowrate		En number
	t/h	m ³ /h	t/h	m ³ /h	
3.59E+04	30	37.25	13.69	17.45	0.32
7.18E+04	60	74.50	27.39	34.90	0.37
1.08E+05	90	111.75	41.08	52.35	0.37
1.44E+05	120	149.00	54.78	69.80	0.27

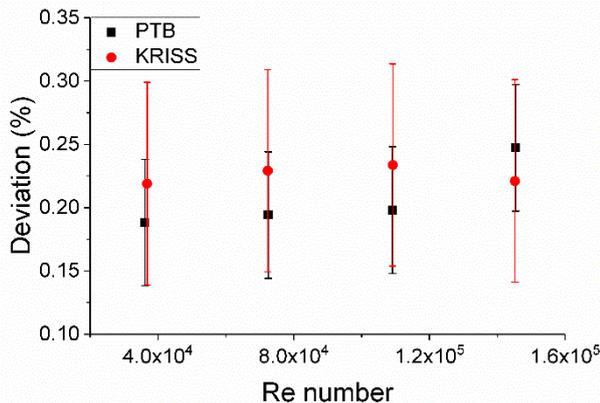


Figure 3: Comparison of hydrocarbon facilities between KRISS and PTB

7. Conclusion

In this study, we used the volumetric and gravimetric methods simultaneously to measure the hydrocarbon flow rate. A 1000 L volume tank was calibrated by both a filling method using a standard volume tank and a gravimetric method using a calibrated balance. The maximum difference between the filling method and the gravimetric method was 78.06 ml. In addition, we compared the hydrocarbon flow facilities of PTB with the volume tank and that of KRISS using the gravimetric method. The Re number was used to compensate for the density and viscosity differences in the working fluid. The calibration values of the Coriolis flowmeter in KRISS and PTB were 0.21–0.23% ($U=0.08\%$, $k=2$) and 0.18–0.24% ($U=0.05\%$, $k=2$), respectively, for an Re number range between 35,000 and 145,000. The results from the gravimetric method at KRISS matched very well with the results from the volumetric method at PTB, within the estimated uncertainties. Thus, we confirmed that the hydrocarbon flow standard systems of KRISS and PTB have traceability when using the volumetric and gravimetric methods in the given range of Re number.

References

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