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ORIGINAL PAPER

Volume Measurement of Large Volumetric Vessel Using Tap Water

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Abstract: Being a National Metrology Institute (NMI) of India, CSIR-National Physical Laboratory, India (NPLI), provides calibration services to the industries to improve the quality of products. In the last couple of years, NPLI has provided number of calibration services of volumetric vessels up to 2000 L (unique facility in India) to the petroleum industries, flow meter manufacturing industries, etc. In general, for the calibration of volumetric instruments, distilled water is used as the medium but in the case of large volumetric vessels (say 2000 L), the use of distilled water is not practical. Hence, tap water is used and every time the density of tap water is measured against distilled water to improve the accuracy of the measurement. In this process, we have achieved measurement uncertainty less than 50 mL in 2000 L. But due to influencing factors of environmental conditions of laboratory, change of density of supplied tap water, conversion factors of tap water and distilled water in desire temperature, we have restricted our calibration and measurement capability (CMC) up to 100 mL in 2000 L. In this paper, we have discussed the detailed procedure of volume measurement of 2000-L volumetric vessel and its associated uncertainty calculations using gravimetric method.

Keywords: Gravimetric method; Volume; Density; Tap water; Uncertainty

1. Introduction

Metrology is very important for activities related to science and society. It is a basic requirement for the economic and social development of any country. It is concerned with providing accurate measurements which impact our economy, health, safety, general well-being, etc. Measurements include all the parameters such as mass, volume, density, viscosity, length, dimension, temperature, optical radiation, force, hardness, pressure, vacuum, acoustics, vibration, fluid flow, voltage, current, power and energy. [1–2]

Volume is one of the very important parameters in petroleum industries, flow meter manufacturing industries, milk industries, pathological laboratories, etc. Hence, determination of the volume of volumetric instruments with sufficient accuracy is very important. There are two methods to measure volume: gravimetric method and volumetric method.

Gravimetric method In this method, capacity of volumetric instrument is determined by weighing the quantity of distilled water which the instrument contains or delivers at the temperature of the liquid and applying a correction to convert the weight of water to volume at the reference temperature. For precision determination of capacity, this method is used, since it is traceable to primary standard of mass through an unbroken chain [3, 4].

Volumetric method In this method, the capacity of volumetric instrument is compared with that of the standard volumetric instrument of same capacity. This method is applicable where high degree of accuracy is not required.

In NPLI, volumetric instruments/vessels up to 2000 L are calibrated using gravimetric method, since it is primary method and NPLI provides calibration services to the industries at the highest level in India.

In case of large volumetric vessels (say 2000 L), tap water is used as the medium, since the use of distilled water is not practical. However, every time, the density of tap water is measured against distilled water to improve the accuracy of measurement.

2. Weighing Balance Used

For gravimetric method, suitable weighing balance should be used. Hence, electronic weighing balance with the

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following specifications (this is a unique facility in India) was used for measurement (Fig. 1).

Model No.:	KE2000
Maximum capacity:	2500 kg
Readability:	1 g
Repeatability (up to 2000 kg):	10 g
Preload:	500 kg

3. Measurement Procedure

The whole procedure is divided into four major processes to perform the measurement of 2000 L volumetric vessel.

3.1. Measurement of Volumetric Vessel [5, 6]

a. Empty vessel is placed at the center of the balance and the balance reading is noted down, i.e., I_E.

Note: Balance may be tared instead of noting down I_E.

b. If weight of the vessel is more than 500 kg, the balance is adjusted using "Preload." For example, the weight of the empty tank is 725 kg and preload is 500 kg, so the remaining weight of 225 kg is I_E.

Note: In any case, weight of empty tank should not be more than 1000 kg. "Preload" is a special feature in this balance.

c. Vessel is filled with tap water up to the mark on the comparator. For initial calibration, flow of tap water is stopped when display unit of the balance indicates close to 2000 kg, i.e., I_L.

d. Temperature of tap water is measured using glass thermometer, i.e., t °C. Determination of density of tap water is shown separately in 3.2.

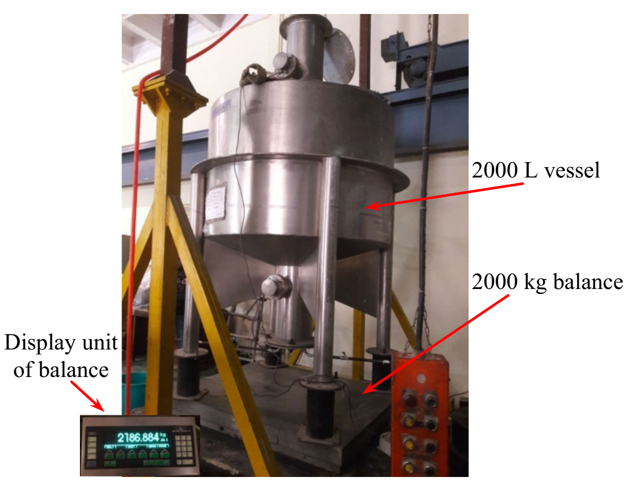

Fig. 1 Experimental setup of calibration of 2000 L volumetric vessel

Note: Since upper section of the vessel is very narrow and it is covered with sheet to protect from dust and foreign particles during measurements, there is very limited scope for water to contact with air. Hence, evaporation loss is assumed as negligible.

e. Density of air, ρ_a, is calculated from temperature (t), relative humidity (rh) and pressure (p) monitored during measurements using approximation formula given below [7, 8]. However, environmental conditions are not controlled because of large area of the laboratory.

$$\rho_a = \frac{0.34848 \cdot p - 0.009 \cdot \mathrm{rh} \cdot e^{(0.061 \cdot t)}}{(273.15 + t)} \tag{1}$$

f. The volume is calculated from the weight of water at the reference temperature of 27 °C (in India), using the following equation: [9]:

$$V_{27} = (I_L - I_E) \cdot \frac{1}{(\rho_w - \rho_a)} \cdot \left(1 - \frac{\rho_a}{\rho_b}\right) \cdot [1 - \gamma \cdot (t - 27)] \tag{2}$$

where I_L is the balance reading of vessel with water, in kg (weight of water, if balance is tared with empty vessel), I_E balance reading of empty vessel, in kg (zero, if the balance is tared with empty vessel); ρ_a density of air, in kg/m^3; ρ_b actual density of the weight which was used at the time of calibration of the balance, in kg/m^3; ρ_w density of tap water at t °C, in kg/m^3; γ coefficient of cubical thermal expansion of the material, of which the volumetric instrument vessel is made, in /°C and t temperature of tap water, in °C.

Observation data of a 2000 L volumetric vessel are given in Table 1.

3.2. Determination of Density of Tap Water Using Distilled Water

a. A 50 mL capacity measure with striking glass is chosen. Weigh the empty capacity measure, i.e., W_1 (balance reading).

b. Capacity measure is completely filled with distilled water and then covered completely using striking glass by sliding it (as shown in Fig. 2), so the excess water should be removed and there should not be any air bubble.

Note : However, in ISO 3696, Grade 3 water is recommended for volume measurements, but here, this is not taken into consideration, since tap water is used as the medium for large volumetric vessel.

c. Weigh the capacity measure with distilled water, i.e., W_2

Table 1 Volume measurement of 2000 L volumetric vessel

Sl. No.	Balance reading (kg)		Weight of tap water [$W = I_L - I_E$] (kg)	Temp. of tap water (t_i) (°C)
	Empty vessel (I_E)	Vessel + Tap water (I_L)		
1	204.189	2186.765	1982.576	28.5
2	204.195	2186.902	1982.707	28.5
3	204.172	2186.925	1982.753	28.5
4	204.191	2186.887	1982.696	28.6
5	204.185	2186.943	1982.758	28.6
6	204.183	2186.941	1982.758	28.6
7	204.192	2186.918	1982.726	28.6
8	204.189	2186.884	1982.697	28.6
9	204.199	2186.957	1982.758	28.6
10	204.191	2186.985	1982.794	28.6
Mean value			1982.7221	28.57

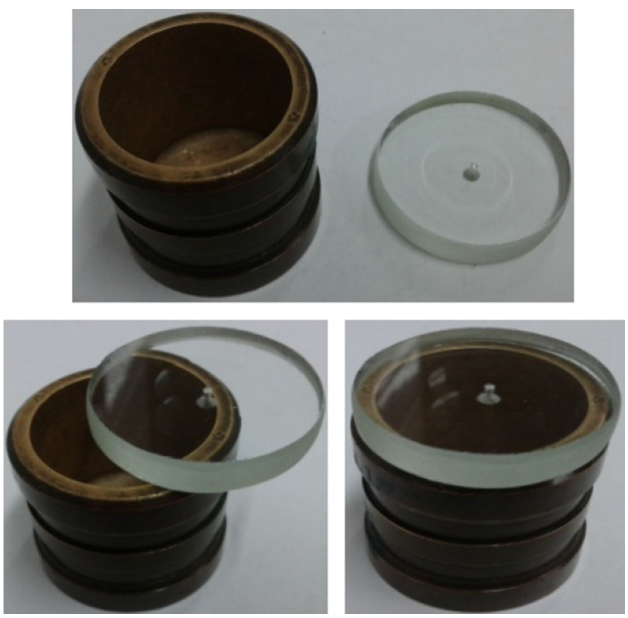

Fig. 2 Capacity measure with striking glass

d. Calculated weight of distilled water, i.e., $W_{dw} = (W_2 - W_1)$ which is apparent mass of water.

e. Temperature (t), relative humidity (rh) and pressure (p) are monitored during measurements, and density of air is calculated using Eq. 1.

f. Corrected weight of distilled water (W_{dw_c}) is calculated by applying air buoyancy correction as follows:

$$W_{dw_c} = W_{dw} \cdot \left(1 - \frac{\rho_a}{\rho_s}\right) \tag{3}$$

where ρ_s is the density of the standard weight used during balance calibration

g. Temperature of distilled water (t_1 °C) is measured using glass thermometer, and density of distilled water at t_1 °C is calculated using Tanaka formula, given below:

$$\rho_{w_{t_1}} = 999.974950 \cdot \left[1 - \frac{(t_1 - 3.983035)^2 \cdot (t_1 + 301.797)}{522528.9 \cdot (t_1 + 69.34881)}\right] \tag{4}$$

h. Volume of distilled water (capacity measure) is calculated at t_1 °C by using following equation :

$$V_{t_1} = \frac{W_{dw_c}}{\rho_{w_{t_1}}} \tag{5}$$

i. Steps a to f are repeated with tap water, and corrected weight of tap water is calculated (W_{tw_c}).

j. Temperature of tap water is also measured using glass thermometer, i.e., t_2 °C.

k. Volume of capacity measure is converted from t_1 °C to t_2 °C using the following equation:

$$V_{t_2} = V_{t_1} \cdot [1 + \beta \cdot (t_2 - t_1)] \tag{6}$$

where V_{t_2}: volume of capacity measure at t_2 °C; V_{t_1}: volume of capacity measure at t_1 °C; β coefficient of cubical thermal expansion of the material, of which the capacity measure is made, in /°C

l. Density of tap water at t_2 °C,

$$\rho_{tw_{t_2}} = \frac{W_{tw_c}}{V_{t_2}} \tag{7}$$

A complete example of measurement of density of tap water using distilled water is given in Table 2.

Table 2 Observations of distilled water

Sl. No.	Weight of empty vessel $[R_1]$ (g)	Weight of vessel + distilled water $[R_2]$ (g)	Weight of distilled water $[W_1 = R_2 - R_1]$ (g)	Temp. of distilled water $[t_1]$ (°C)
1	0.0000	17.7695	17.7695	23.9
2	0.0000	17.7703	17.7703	23.9
3	0.0000	17.7716	17.7716	23.9
4	0.0000	17.7692	17.7692	24.0
5	0.0000	17.7716	17.7716	24.0
6	0.0000	17.7696	17.7696	24.0
7	0.0000	17.7709	17.7709	24.0
8	0.0000	17.7715	17.7715	24.0
9	0.0000	17.7699	17.7699	24.1
10	0.0000	17.7728	17.7728	24.1
Mean value			17.77069	23.99

Table 3 Measurement of density of tap water using distilled water

Sl. No.	Description	Value (unit)
1	Density of air	0.001 139 g/cm^3
2	Weight of distilled water (average of ten readings)	17.770 69 g
3	Corrected weight of distilled water	17.768 17 g
4	Temperature of distilled water (average of ten readings)	23.99 °C
5	Density of distilled water at 23.99 °C	0.997 300 g/cm^3
6	Volume of distilled water (capacity measure) at 23.99 °C	17.816 27 cm^3
7	Weight of tap water (average of ten readings)	17.779 97 g
8	Corrected weight of tap water	17.777 45 g
9	Temperature of tap water (average of ten readings)	23.62 °C
10	Volume of capacity measure (tap water) at 23.62 °C	17.815 91 cm^3
11	Density of tap water at 23.62 °C	0.997 841 g/cm^3
12	Density of distilled water at 23.62 °C	0.997 391 g/cm^3
13	Density of distilled water at 28.57 °C	0.996 071 g/cm^3
14	Density of tap water at 28.57 °C = $\frac{\text{Density of tap water at } 23.62\,^{\circ}\text{C}}{\text{Density of distilled water at } 23.62\,^{\circ}\text{C}} \times$ Density of distilled water at 28.57 °C	0.996 520 g/cm^3

Coefficient of cubical thermal expansion of brass (capacity measure) is taken as 54×10^{-6}/°C

3.3. Conversion of Density of Tap Water in Desired Temperature (t °C)

Density of distilled water is calculated at t °C and t_2 °C using the formula given in Eq. 4. Then, density of tap water is calculated at desired temperature (t °C) using the following equation:

$$\rho_{\mathrm{tw}_t} = \frac{\rho_{\mathrm{tw}_{t_2}}}{\rho_{\mathrm{dw}_{t_2}}} \cdot \rho_{\mathrm{dw}_t} \tag{8}$$

where ρ_{tw_t} is the density of tap water at t °C; $\rho_{\mathrm{tw}_{t_2}}$ density of tap water at t_2 °C; $\rho_{\mathrm{dw}_{t_2}}$ density of distilled water at t_2 °C; and ρ_{dw_t} density of distilled water at t °C.

3.4. Determination of volume of 2000 L volumetric vessel

W, weight of tap water ($I_L - I_E$) = 1982.722 1 kg; t, temperature of tap water = 28.57 °C; ρ_w, density of tap water at 28.57 °C = 996.520 kg/m^3 (taken from Table 3); ρ_a, density of air (mean values: t = 31.40 °C, rh = 34.05%, p = 990.17 mbar) = 1.126 kg/m^3; ρ_b, density of the weight used during calibration of balance = 8042 kg/m^3; γ, coefficient of cubical thermal expansion of stainless steel (volumetric vessel) = 33×10^{-6}/°C; volume of volumetric vessel at 27 °C (using Eq. 1): 1991.515 L (Tables 4, 5).

Table 4 Uncertainty budget (density of tap water)

Source of uncertainty		Estimates	Limits	Probability distribution		Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	DOF
X_i		x_i		Type	Divisor	$u(x_i)$	c_i	$u_i(y)$	
Balance	Repeatability (distilled water)	0.00117 g	0.00117 g	A, Normal	$\sqrt{10}$	0.000 37 g	1 mL/g	0.00037 mL	9
	Repeatability (tap water)	0.00102 g	0.00102 g	A, Normal	$\sqrt{10}$	0.000 32 g	1 mL/g	0.00032 mL	9
	Uncertainty	0.00022 g	0.00022 g	B, Normal	2	0.000 11 g	1 mL/g	0.00011 mL	∞
Water temp.	Distilled water	0.20 °C	0.20 °C	B, Rectangular	$\sqrt{3}$	0.115 47 °C	2×10^{-4} mL/°C	0.00002 mL	∞
	Tap water	0.10 °C	0.10 °C	B, Rectangular	$\sqrt{3}$	0.057 7 °C	2×10^{-4} mL/°C	0.00001 mL	∞
Air	Temperature	0.20 °C	0.20 °C	B, Normal	2	0.10 °C	4.5×10^{-4} mL/°C	0.00005 mL	∞
	Pressure	0.40 mbar	0.40 mbar	B, Normal	2	0.20 mbar	1.2×10^{-4} mL/mbar	0.00002 mL	∞
	Relative humidity	1.40%	1.40%	B, Normal	2	0.70%	1×10^{-5} mL/%	0.00001 mL	∞
Device (capacity measure)	Cubical expansion coefficient	1×10^{-5}/°C	1×10^{-5}/°C	B, Rectangular	$\sqrt{3}$	5.8×10^{-6}/°C	− 200 mL °C	− 0.00120 mL	∞
Combined standard uncertainty, u_C								0.00130 mL	
Effective degree of freedom, ν_{eff}								$880 \approx \infty$	
Coverage factor, k								2.00	
Expanded uncertainty, U, associated with the density of tap water								0.00260 mL = 0.000003 L	

Table 5 Uncertainty budget (volumetric vessel)

Source of uncertainty X_i		Estimates x_i	Limits	Probability distribution Type	Divisor	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$	DOF
Balance	Repeatability	0.061 kg	0.061 kg	A, normal	$\sqrt{10}$	0.019 1 kg	1 L/kg	0.0191 L	9
	Uncertainty	0.005 kg	0.005 kg	B, normal	2	0.002 5 kg	1 L/kg	0.0025 L	∞
Water (tap)	Temperature	0.10 °C	0.10 °C	B, rectangular	$\sqrt{3}$	0.057 7 °C	2×10^{-2} L/°C	0.0012 L	∞
	Density	0.000003 L	0.000003 L	B, normal	2	0.000 0 L	1	0.0000 L	∞
Air	Temperature	0.20 °C	0.20 °C	B, normal	2	0.10 °C	4.5×10^{-4} L/°C	0.0000 L	∞
	Pressure	0.40 mbar	0.40 mbar	B, normal	2	0.20 mbar	1.2×10^{-4} L/mbar	0.0000 L	∞
	Relative humidity	1.40%	1.40%	B, normal	2	0.70%	1×10^{-5} L/%	0.0000 L	∞
Device (vessel)	Cubical expansion coefficient	1×10^{-5}/°C	1×10^{-5}/°C	B, rectangular	$\sqrt{3}$	5.8×10^{-6}/°C	− 200 L °C	− 0.0012 L	∞
Combined standard uncertainty, u_C								0.0193 L	
Effective degree of freedom, v_{eff}								9.38	
Coverage factor, k								2.28	
Expanded uncertainty, U, associated with the volume V_{27} measured with the gravimetric method								0.044 L	

Table 6 Observations of tap water

Sl. No.	Weight of empty vessel [R_3] (g)	Weight of vessel + tap water [R_4] (g)	Weight of tap water [$W_2 = R_4 - R_3$] (g)	Temp. of tap water [t_2] (°C)
1	0.0000	17.7800	17.7800	23.6
2	0.0000	17.7796	17.7796	23.6
3	0.0000	17.7780	17.7780	23.6
4	0.0000	17.7805	17.7805	23.7
5	0.0000	17.7798	17.7798	23.6
6	0.0000	17.7815	17.7815	23.6
7	0.0000	17.7800	17.7800	23.7
8	0.0000	17.7788	17.7788	23.6
9	0.0000	17.7805	17.7805	23.6
10	0.0000	17.7810	17.7810	23.6
Meanvalue			17.77997	23.62

Balance was tared with empty vessel for both the cases

3.5. Calculations of Uncertainty [10, 11]

Uncertainty is an integral part of any measurements. Hence, it is essential to calculate considering all the influencing factors. All the uncertainty components like weighing process, temperature and density of water, balance(s), thermometer(s), barometer, hygrometer used and cubical thermal expansion of material of volumetric vessel are taken into account, but it is found that all are negligible compared to weighing process. An uncertainty budget is given in Table 6.

4. Conclusion

In this paper, we have described detailed calibration procedure of large volumetric vessel using tap water. In this procedure, we have achieved expanded uncertainty less than 50 mL in 2000 L at $k = 2$ against the approved CMC of 100 mL.

Now, we are working on the effect of tap water at different locations in volume measurements using the same volumetric vessel.

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