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Water density formulations and their effect on gravimetric water meter calibration and measurement uncertainties

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ABSTRACT

In the gravimetric calibration method of water meters, the volume of water that has passed through the equipment under test (EUT) is generally collected into a tank and the quantity (mass) determined by weighing. The mass of water collected is then converted into a volume. This conversion of mass into volume requires knowledge of the water density, which can be estimated, measured directly or determined by other means. The error of measurement of the EUT is determined by comparing the volume recorded by the EUT and the volume collected in the tank. The density of water is, therefore, one of the major causes of measurement uncertainty in laboratory calibration of water meters using the gravimetric method. Water meter calibration facilities commonly use density formulations proposed by the International Standards Organisation (ISO) and the Organisation for International Legal Metrology (OIML). In Australia, additional guidance in water density determination is provided by the National Measurement Institute (NMI). In this study, testing was undertaken using ten positive displacement water meters arranged in series in the test rig to evaluate some of the common water density formulations used in Australia. The effect of these different formulations on the water meter error measurement was determined, as well as the effect on the measurement uncertainties. The results shows that the use of these different density formulations evaluated do not significantly affect the water meter error of measurement or the uncertainty of measurement. There was no apparent correlation between the water meter error and the meter position in the test rig. It was also determined that if the water density was adjusted only for temperature effects, a maximum of 0.05 and 0.15% drift in meter error and measurement uncertainty respectively, can be expected.

1. Introduction

In many urban and peri-urban areas all over the world, water supplied to residents for domestic, industrial and irrigation purposes is metered as a means determining the charges to be levied. Therefore, water metering has equity, fairness and legal implications as inaccurate metering may lead to some users being randomly advantaged or disadvantaged [1]. A water meter that under-reads (has a negative error), implies that cumulatively it will record less volume of water than actually supplied, and hence a direct loss to the supplier. On the other hand, a water meter with a positive error means a financial loss to the client.

Mechanical meters, and particularly the positive-displacement type, are widely used for metering water for domestic purposes. This type of meters consists of a tiny compartment (oscillating piston or nutating disc) of known volume of water which moves with the flow of water. Each rotation of the meter displaces a known volume of water and hence the name positive displacement. The movement of the disc or piston is transferred to a sealed register which records flow either by mechanical or magnetic coupling. During testing, these meters are typically arranged in series in the test rig without the requirement of upstream or downstream straight pipe sections.

In Australia for instance, it is a legal requirement that the measurement accuracy of water metres be verified either *in situ* or under laboratory conditions. The testing is required to be undertaken in accordance to OIML R 49-2 [2] by testing facilities accredited to the National Association of Testing Australia (NATA). The Australian national standard version of this international standard is NMI R 49-2 [3]. Testing may also be done as per AS 3565.4 [4] which has additional guidance on timely sampling and assessment of in-service compliance of populations of water metres.

The two principal laboratory techniques used for the calibration of water meters are the volumetric and gravimetric methods. The volumetric method uses a calibrated reference volume while

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the gravimetric method measures the mass of water that has passed through the equipment under test (EUT – in this case a water meter). Typically, the mass of water, collected in the tank, is converted to an equivalent volume and then compared with the volume of water recorded by the EUT. This conversion of mass into volume requires knowledge of the water density, which can be estimated, measured or determined by other means.

For many practical cases, the standard density of pure water at 4 °C of approximately 1000 kg/m^3 may be applicable. However, for accurate measurement purposes (for instance in meter testing facilities), it is often necessary to accurately determine the density of water for a range of influential conditions. Water temperature, compressibility, and salinity are the main factors known to affect the density of water. There are a number of different formulations proposed by the International Standards Organisation (ISO) and the Organisation for International Legal Metrology (OIML) for use in the determination of water density for use in calibration facilities.

Inevitably every measurement procedure, including the gravimetric method, has elements of uncertainties or potential sources of error. In metrological facilities, measurement uncertainties are quantified in order to understand the quality of measurement and to allow objective comparison with results from different laboratories. The density of water is one of the major causes of measurement uncertainty in laboratory calibration of water meters using the gravimetric method [5]. Other potential sources of uncertainty are those that are directly associated with the procedure and equipment used, for example, calibration error, resolution and drift. The Australia's NMI recommends that the uncertainty analysis be undertaken in accordance with the Guide to Expression of Uncertainty in Measurement [6]. The procedure is also explained in [7] and [8].

An analysis undertaken by Batista and Paton [9] on a large number of density formulations showed that there are small differences in the results when comparing density formulae. This investigation did not however include the majority of the expressions commonly used in water meter testing facilities for density determination, especially in Australia. The main purpose of this study was to evaluate the different density expressions and recommendations commonly used in meter calibration facilities and to quantify their impact on the error of measurement and the uncertainty of measurement. This is particularly important because accredited testing facilities are required to demonstrate the theoretical basis of their meter error determinations and uncertainty analysis. As domestic meters are traditionally arranged in series during testing, an analysis was undertaken to determine if there was a correlation between the meter error and the position of the meter in the test rig.

2. Meter error measurement

Water metre error or error of indication is the deviation of the measurement indicated by the metre or equipment under test (EUT) from the actual or reference value and is expressed as a percentage (Eq. (1)). This equation is applicable both to the gravimetric method and volumetric method which uses a reference metre.

$$\textit{Error of indication}\ (\%) = \frac{V_i - V_a}{V_a} \times 100 \tag{1}$$

where, V_i is the volume recorded by the EUT and V_a is the actual (net) volume measured (as determined by the volumetric or gravimetric reference).

The gravimetric method is typically used for tests that require a lower degree of uncertainty [5]. The method generally involves collecting water that has passed through the EUT into a container and then weighing by means of a strain gauge. However, as the meter readings are displayed in terms of volume, the mass of water collected has to be converted into an equivalent volume to enable determination of the error of measurement of the EUT.

This conversion requires measurement or estimation of the water density using Eq. (2):

$$V_a = \frac{m}{\rho} \tag{2}$$

where, ρ is the density, kg/m^3; m is the mass (net measured), kg; and V_a is the volume (net measured), m^3.

Combining Eqs. (1) and (2), the resulting equation describing the error of indication of a water meter may be expressed as follows:

$$\textit{Error of indication}\ (\%) = \frac{V_i\rho - m}{m} \times 100 \tag{3}$$

3. Water density determination

For many applications, the standard density of pure water of approximately 1000 kg/m^3 (measured at 4° C) may be applicable. However, for accurate measurement purposes, it is often necessary to accurately determine the density of water for a range of influential conditions. While water density for high-accuracy water meter calibration may be determined by direct measurement, for instance using a densitometer [5], in many testing facilities water density is routinely determined using standard expressions. Water temperature, compressibility and salinity are the main factors known to affect the density of water.

A comprehensive listing and evaluation of equations commonly used for the determination of water density is provided by Batista and Paton [9]. Only expressions relevant to gravimetric systems used in meter testing facilities will be discussed in this paper. Furthermore, all but two (Eqs. (5) and (11)) evaluated in this paper were excluded in the analysis undertaken by Batista and Paton [9]. The expressions are categorised as those relating to (i) temperature, (ii) pressure, and (iii) salinity.

3.1. Water density as a function of water temperature

In meter testing facilities, temperature of water is monitored because of its effect on the density. The density of pure water is approximately 1000 kg/m^3 at 4 °C, and decreases in a nonlinear fashion to about 994 kg/m^3 at 35 °C [10]. The relationship is illustrated in Fig. 1.

There are three common expressions used by water metre testing facilities, including in Australia, to express the density of water as a function of temperature. The Thiesen–Scheel–Diesselhorst equation, (Eq. 4, [10]) has been used since the beginning of the twentieth century [9] to determine the density of water as a function of water temperature at standard atmospheric pressure (101,325 Pa).

$$\rho_w = 1000\left[1 - \frac{(T + 288.9414)}{508929.2(T + 68.12963)}(T - 3.9863)^2\right] \tag{4}$$

where ρ_w and T are density (kg/m^3) and temperature (°C) of pure water respectively.

The NMI R 49-2 [3] and OIML R 49-2 [2] standards recommend the use of the following International Association for the Properties of Water and Steam or IAPWS formulation [11] to calculate the density of water at standard atmospheric pressure (101,325 Pa):