The proposed improvements of the hydrometer calibration system using Cuckow's method at NMISA

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Abstract. Hydrometers are instruments that are used for measuring the density or specific gravity of liquids. NMISA uses Cuckow's method which is based on hydrostatic weighing to calibrate hydrometers. This involves weighing the dry hydrometer in air and then in liquid. The liquid level is aligned with the horizontal scale mark of the hydrometer point to be calibrated and the reference density is determined at that point to get the correction for the scale. The horizontal scale mark setting, vertical alignment and reference liquid density are some of the key factors that need to be set and measured accurately to ensure the quality of results. The horizontal scale mark (point to be calibrated) is set with the assistance of a computer software and a magnifying camera. This setting also depends on how well the vertical alignment is set as the hydrometer is suspended from underneath the balance. Distilled water (reference liquid) temperature is measured at three different depths and used to determine the liquid density at the time of measurement. This work discusses the setup of the hydrometer system at NMISA and also highlights the required improvements that need to be implemented to address all the uncertainty contributions associated with the system. We also report some results found for hydrometers calibrated at the minimum and maximum points of their respective scales using the current system. Three hydrometers with scale ranges of 0.600 – 0.700 g/ml, 0.700 – 0.800 g/ml and 0.800 – 0.900 g/ml were calibrated at a temperature of 20 °C. The uncertainty of measurement was found to be better than ±0.001 g/ml.

1. Introduction

The liquid's sugar contents, alcohol concentration or density are some of the important characteristics which need to be known for the liquid's specific use. For many applications, a simple measurement of dipping the hydrometer in the liquid and reading off the graduation mark is good enough. A hydrometer is a graduated glass hollow tube that is weighted at the bottom end to make it float upright inside a liquid. It is used to measure the specific gravity, concentration, percentage of salts or density of liquids between 0.5 g/ml and 20 g/ml [1]. Hydrometers are classified into constant-volume or constant-mass hydrometers. A constant-volume hydrometer is made to float in liquids of different densities by adding mass pieces such that the same scale mark is in line with the liquid level in each liquid which means the volume under each liquid remains constant. On the other hand, a constant-mass hydrometer on which this work focuses, floats at various levels for a variety of liquids with a range of densities and its mass is kept constant [2]. Over time, various liquids may result in slight drifts in the scale reading of the hydrometer due to mechanical stress, abrasion and ageing process of glass [2]. These slight changes need to be quantified to ensure the quality of measurement by a

hydrometer. This is done through regular calibration of hydrometers traceable to a relevant national standard.

Hydrometers have previously been calibrated in a range of reference liquids with different densities which is a bit expensive since a range of suitable liquids had to be made available and also time-consuming since the measurements had to be carried out in each of these liquids. A much cheaper method was introduced by Cuckow. In Cuckow's method, a single reference liquid is used for the calibration of the whole range of the hydrometer scale [3, 4]. This method is based on hydrostatic weighing where the hydrometer is first weighed in air and then in the reference liquid with a known density. The process involves immersing the hydrometer in the reference liquid and setting the scale mark to be calibrated to be aligned with the level of the reference liquid and then determining what would be the density of the reference liquid at that point. In the same way, other points can be calibrated by simply shifting the same liquid level vertically to align with the scale mark of the hydrometer without any additional mass pieces on the hydrometer. The correction to the calibrated hydrometer scale is then determined by subtracting the scale mark of the hydrometer from the measured reference liquid density at that point.

Cuckow's method for determining the reference liquid density is based on three scenarios which generate three equilibrium force equations [3]. In the first scenario, the hydrometer floats freely in a reference liquid. In the second scenario, the hydrometer is weighed in air. Thirdly, the hydrometer is weighed partially immersed to the same scale mark as in the first scenario [2]. After combining the equilibrium force equations that resulted from the three scenarios and some simplifications, the reference liquid density ρ_x is then given by

$$\rho_x = (\rho_L - \rho_a)\frac{\left[M_a\left(1-\frac{\rho_{a2}}{\rho_s}\right)+\pi D\gamma_x g^{-1}\right]}{\left[M_a\left(1-\frac{\rho_{a2}}{\rho_s}\right)-M_L\left(1-\frac{\rho_{a3}}{\rho_s}\right)+\pi D\gamma_L g^{-1}\right]}\left[1+\beta(T_3-T_0)\right]+\rho_{a2} \qquad (1)$$

where M_a, M_L : mass of the hydrometer in air and in reference liquid respectively,

ρ_L : liquid density at a measurement temperature T_3,

ρ_a : air density when the hydrometer scale is read,

ρ_s : density of the reference weights,

γ_x : surface tension of the liquid in for which the hydrometer is to be used,

g : local gravitational acceleration,

D : diameter of the hydrometer stem at the graduation mark to be calibrated,

ρ_{a2}, ρ_{a3} : air density while weighing in air and in liquid respectively,

γ_L : surface tension of the reference liquid,

β : volumetric thermal expansion coefficient [3].

The measuring equipment used to calibrate the hydrometer is the main contributor to the achieved measurement uncertainty and the quality of the measurement result [2]. In this work, we discuss the hydrometer calibration system setup at NMISA and some of the proposed improvements on the current system.

2. Experimental details

2.1. The hydrometer calibration system

The hydrometer calibration system used at NMISA is shown in Figure 1. This system consists of an electronic balance with a resolution of 0.01 mg. The thermostatic liquid bath (outer) contains tap water

that is used to maintain the temperature of distilled water (reference liquid) in the inner vessel at around the reference temperature of 20 °C. The inner liquid vessel contains three temperature sensors positioned at different depths (in case of any temperature gradient inside the reference liquid) to measure the temperature of distilled water at the time of weighing the hydrometer in liquid. A desktop computer has the software that is used for finer adjustments of the scale mark to the liquid level and for the collection of measurement data from the sensors (air temperature, relative humidity, pressure and water temperature) as well as from the balance. The image from the CCD camera is magnified and viewed on a computer monitor.

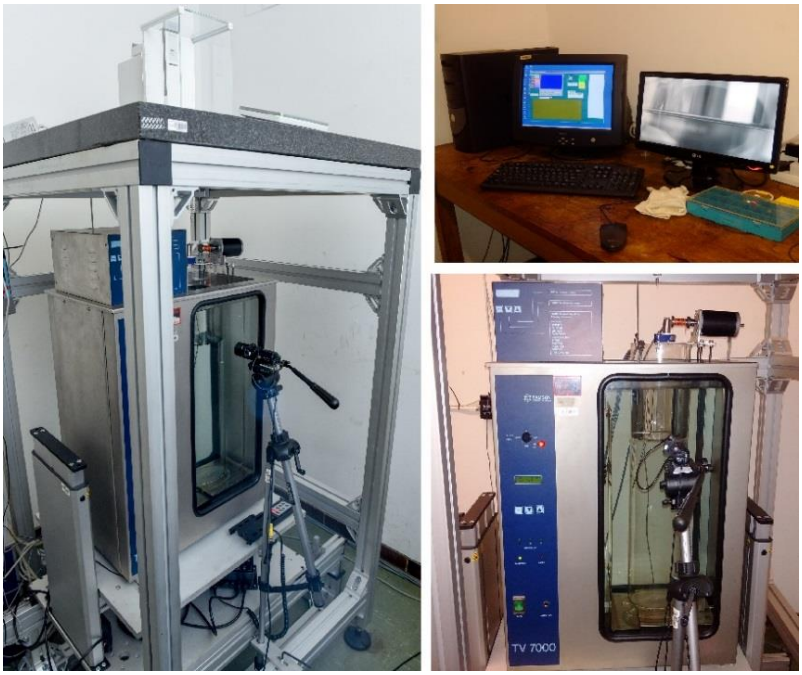

Figure 1: The hydrometer system at NMISA.

Figure 2 is a schematic representation of the hydrometer system which shows the connections of each component to another. The figure also shows a thermostat which regulates the water temperature in the thermostatic bath.

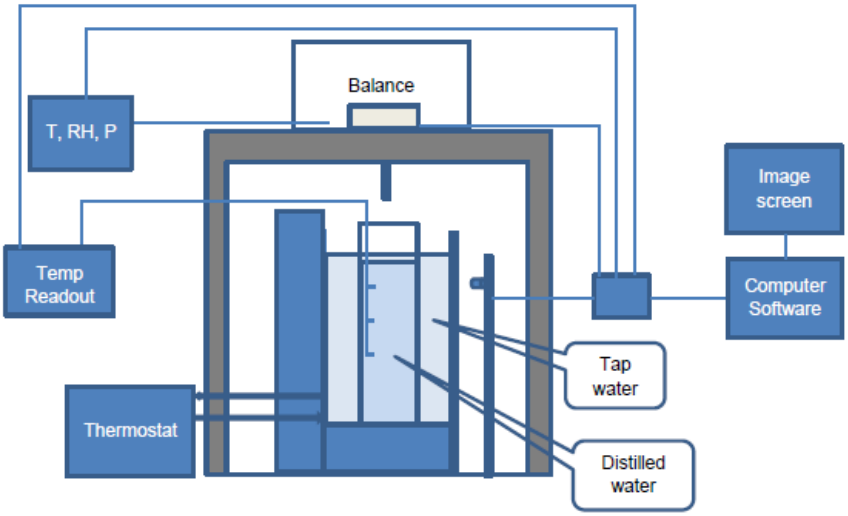

Figure 2: A schematic representation of the hydrometer system.

2.2. Weighing in the reference liquid

The clean and dry hydrometer is first weighed in air against the reference mass pieces. After completing a set of weighing measurements in air, the hydrometer is then weighed in the reference liquid by suspending it from the balance using a wire connected to two O-rings. This may somewhat make the hydrometer to be tilted slightly which also impacts on the graduation marks causing the scale to be at an angle to the horizontal position. Hydrometers with scale range of less than 1 g/ml require additional ring weights on the neck/stem so that they can be immersed to the desired scale mark for calibration since the density of water is close to 1 g/ml. This may further affect the vertical alignment of the hydrometer when the ring has a much bigger inner diameter than the hydrometer stem. Therefore, the suspension of the hydrometer from the balance should be performed carefully and the inner diameter of the additional ring weight should be such that the hydrometer stem just fits inside the ring to ensure proper vertical alignment of the hydrometer.

When weighing the hydrometer in the reference liquid, the scale mark to be calibrated is set to align with the level of the reference liquid by moving the fluid bath up until the liquid level just close enough to the calibration point. Then, some finer adjustments are required to get the meniscus correctly on the scale mark. This is performed with the assistance of the CCD camera and the computer software. The image from the camera is magnified by the software for a better view of the horizontal alignment of the scale mark and the liquid level. The software is also used to driving a step motor for finer vertical adjustments. When the alignment is completed, the apparent mass of the hydrometer is recorded when the balance reading is stable. Air temperature, pressure, humidity and liquid temperature are recorded for determining the air and liquid densities. The liquid density is mainly dependent on the liquid temperature and so this temperature needs be measured accurately as it has a direct impact on the resulting reference density at the scale mark of the hydrometer [4].

One of the biggest challenges of this system is the alignment of the hydrometer scale mark to the reference liquid level. Some institute(s) address this challenge by using a laser sheet (a horizontal laser beam which is in a form of a horizontal sheet) which is aligned to the hydrometer scale to be calibrated. By bringing the reference liquid towards the scale, the measured laser power increases once the laser sheet passes through the liquid instead of air due to more light being refracted towards the power meter on the opposite end [5]. The alignment of the liquid level and the hydrometer scale is determined to be somewhere within this measured laser power transition. Other institutes have developed software which automatically process the image of the scale and liquid level interface then adjusts the hydrometer to the correct liquid level [2]. NMISA plans to improve the software to automate the alignment of the scale to be calibrated and reference liquid level and to also use this software to check and confirm the vertical alignment of the hydrometer.

2.3. Surface tension

The reference liquid density determination is also affected by the surface tension γ which results in the liquid pulling the hydrometer downwards at its stem. γ, as per Equation (1), must be known at a measurement T_3 and reference T_0 temperatures. For this purpose, γ was measured using a tensiometer system in the temperature range 18.0 °C $\leq T \leq$ 22.0 °C in which the hydrometer calibrations are performed. In this temperature region, the mean surface tension of the reference liquid was found to be 71.11 mN/m ± 1.00 mN/m. Investigations of a more suitable reference liquid are also underway as distilled water (high density and high surface tension) is not ideally the best for this work. The meniscus of distilled water is also not reproducible in shape which results in a different surface tension force. Alkane liquids like nonane, tridecane, etc. are used by other institutes because of their better surface tension [2, 5].

3. Results

Three hydrometers with ranges of 0.600 – 0.700 g/ml, 0.700 – 0.800 g/ml and 0.800 – 0.900 g/ml were calibrated using Cuckow's method. The measurement results at a reference temperature of 20 °C are shown in Table 1. This table shows the calibrated hydrometer points against the measured reference

density at that point. The calculated measurement uncertainties were found to be better than ± 0.001 g/ml across the calibrated points.

Table 1: The hydrometer calibration results with their measurement uncertainties.

Number	Hydrometer Reading at 20 °C (g/ml)	Reference Density at 20 °C (g/ml)	Uncertainty of Measurement (g/ml)
1	0.600	0.599	± 0.001
	0.700	0.701	± 0.001
2	0.700	0.701	± 0.001
	0.800	0.799	± 0.001
3	0.800	0.801	± 0.001
	0.900	0.900	± 0.001

4. Conclusions

We have identified the improvements that are required on the current hydrometer system. The vertical and horizontal alignment of the hydrometer scale with the reference liquid level play a vital role in the quality of the measurement result and therefore will be incorporated accordingly in the analysis of results. The uncertainties may be improved by studying and quantifying each significant contributor in the uncertainty budget.

References

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