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A new image processing system for hydrometer calibration developed at CENAM

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Abstract

The present work illustrates the improvements made to the hydrometer calibration sys-tem of CENAM, the NMI of Mexico, making use of an image processing technique to align the scale mark of the hydrometer to the surface of the liquid where it is immersed, reducing the variability in the apparent mass determination during the hydrostatic weighing in the calibration process, decreasing the relative uncertainty of calibration (k=2) from $1x10^{-4}$ to $5x10^{-5}$ or better.

Keywords: Hydrometer, image processing, Cuckow's Method.

1. Introduction

The hydrometer is an instrument widely used in Industry for measurements of density of liquids. Depending on the application, the hydrometer could change its name, i.e., alcoholmeter to measure the percent of alcohol in breweries; Brix hydrometer, to measure the percent of sugar in sugar cane solutions; lactometers, to determine the fat content from the density of milk. At the end, no matter the units in which the hydrometer is graduated, it measures the density of the liquid [1]. This instrument generally is manufacture in glass, having two main parts: the body, sometimes with a bulb and a stem. The body has a cylindrical shape with a load in the bottom; the steam is a thin hollow tube attached to the upper portion of the body. A paper with a graduated scale is fixed inside the steam. The hydrometer floats vertically in the liquid where it is immersed by means of the Archimedes' principle; the density of the liquid is the reading of the scale mark at the surface level of the liquid.

The Cuckow's method is used for the calibration of hydrometers [2]. Consists in obtaining the mass of the hydrometer both in air and when it is submerged to a desired point of its scale mark, in a liquid of known density (hydrostatic weighing).

The image processing technique in hydrometer calibration has been employed in other NMIs like Istituto Nazionale Di Ricerca Metrologica – INRIM (Italy) [3] and Korea Re-search Institute of Standards and Science – KRISS (Korea) [4].

2. Hydrometer Calibration System

The system that has been developed in CENAM for hydrometers calibration, includes a thermostatic bath with an external temperature controller, a glass vessel to contain the reference liquid, a platinum resistance thermometer to measure the temperature of the liquid, an hygro-thermometer and a barometer to obtain the density of air, a set of mass standards and a weighing instrument (balance) capable to perform hydrostatic weightings.

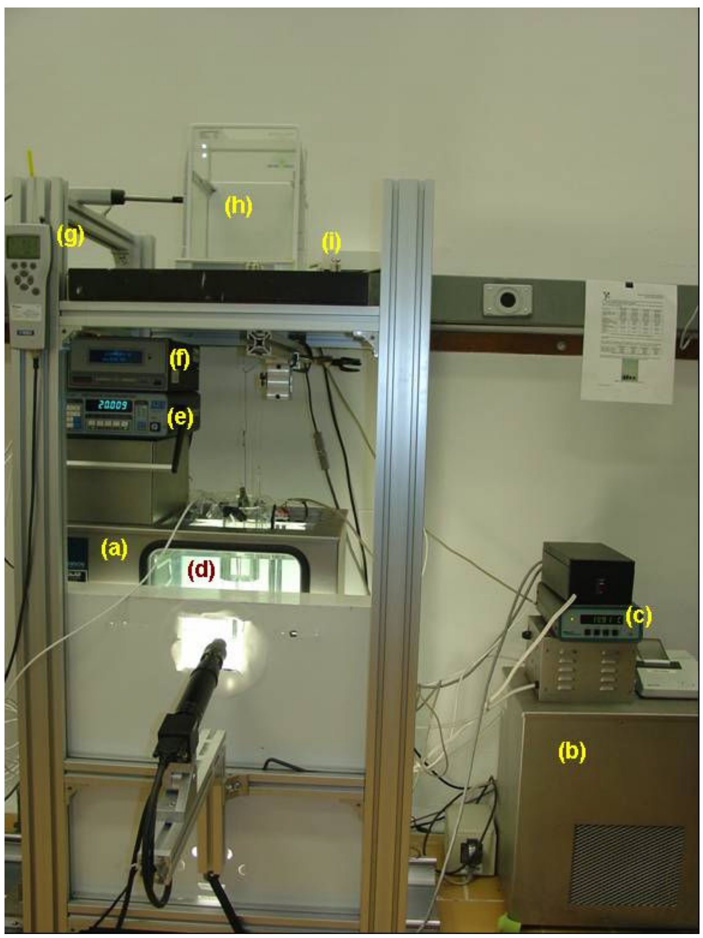

Figure 1.Hydrometer Calibration System of CENAM: (a) thermostatic bath, (b) external cooler, (c) external temperature controller, (d) glass vessel containing the reference liquid, (e) thermometer for temperature of liquid, (f) barometer, (g) thermo-hygrometer, (h) weighing instrument (balance), (i) mass standards.

The mathematical model employed in hydrometer calibration (Cuckow's Method) is:

$$\rho_x = \left(\rho_L\left[1+\alpha\left(t_L - t_0\right)\right] - \rho_{a1}\left[1+\alpha\left(t_a - t_0\right)\right]\right)\cdot\left[\frac{m_a + \frac{\pi D \gamma_x}{g}}{m_a - m_L + \frac{\pi D \gamma_L}{g}}\right] + \rho_{a1}\left[1+\alpha\left(t_a - t_0\right)\right] - \varepsilon_d \qquad (1)$$

with:

$$m_a = m_{p1}\left(1 - \frac{\rho_{a1}}{\rho_{p1}}\right) + \Delta m_1 - \varepsilon_{d(bal)} \qquad (2)$$

$$m_L = m_{p2}\left(1 - \frac{\rho_{a2}}{\rho_{p2}}\right) + \Delta m_2 + C_g - \varepsilon_{d(bal)} \qquad (3)$$

$$C_g = \frac{m_{p2}}{g}\frac{\partial g}{\partial h}\Delta h \qquad (4)$$

where:

ρ_x *density of the hydrometer at selected scale mark x.*
ρ_L *density of reference liquid.*
ρ_{a1} *density of air during mass determination of hydrometer in air (m_a).*
m_a *mass of the hydrometer in air.*
m_L *apparent mass of hydrometer immersed in the liquid up to scale mark x.*
g *acceleration due to local gravity.*
π *Pi value = 3,14159265.*
D *diameter of the hydrometer steam at the selected scale mark x.*
γ_x *surface tension coefficient of the liquid where hydrometer is used.*
γ_L *surface tension coefficient of reference liquid.*
α *thermal expansion coefficient of hydrometer (usually glass).*
t_L *temperature of reference liquid.*
t_0 *nominal temperature value of hydrometer's scale.*
ε_d *error due to hydrometer's resolution.*
m_{p1} *mass standard used during mass determination of hydrometer in air.*
m_{p2} *mass standard used during apparent mass determination of hydrometer immersed in liquid.*
ρ_{p1} *density of mass standard used during mass determination of hydrometer in air.*

ρ_{p2} *density of mass standard used during apparent mass determination of hydrometer immersed in liquid.*

ρ_{a2} *density of air during apparent mass determination of hydrometer in liquid (m_L).*

Δm_1 *mass difference during weightings in air.*

Δm_2 *mass difference during weightings in liquid.*

C_g *gravity correction due to difference in centre of mass.*

$\varepsilon_{d(bal)}$ *error due to resolution of the balance.*

$\partial g/\partial h$ *vertical gravity gradient.*

To obtain the mass both in air and in liquid of the hydrometer, the simple substitution method is used; the mass m_a for weightings in air, and apparent mass m_L, when the hydrometer is immersed in the liquid, are compared against mass standards using the balance as a comparator.

The alignment of the desired point of scale mark at the horizontal level of the reference liquid is a difficult task, because the meniscus formed around the hydrometer steam due to the surface tension of the liquid hides the scale mark. The operator performs manually this alignment using a magnifier lens and reading the scale mark below the surface of the liquid, introducing human errors caused by the operator's skill, sight and experience. The contribution to the uncertainty due to repeatability in the apparent mass determination in the liquid Δm_2 is highly significant.

3. The vision system

In order to reduce this human error, a vision system was adapted to the actual hydrostatic weighing system consisting in a high resolution (1300 H x 1030 V pixels) monochromatic CCD camera PULNIX TM-1320-15CL, a lens array, an 8-bits frame grabber NI-PCI-1428 camera link and a light source. Also, a glass sinker controlled by a stepper motor was installed to adjust the level of the reference liquid. The level of the liquid will rise (or fall) when the sinker is immersed (or emerged) in the liquid. The motorized-sinker is used for the finest adjustment of the scale mark to the surface of the liquid.

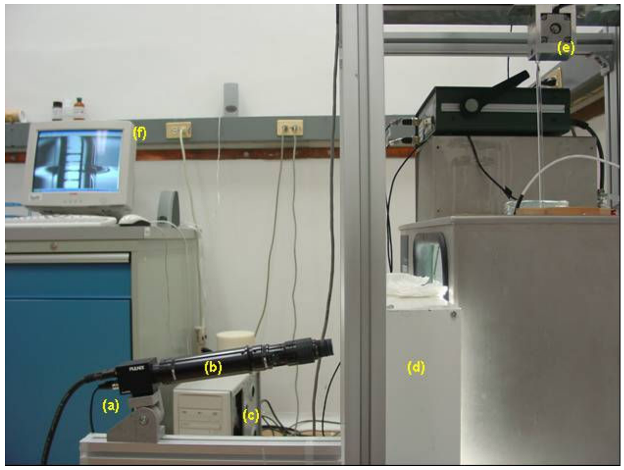

Figure 2.Vision system adapted to the hydrometers calibration system: (a) camera, (b) lens array, (c) frame grabber installed in the PC, (d) light source, (e) motorized-sinker, (f) image displayed in the monitor of the scale marks of the hydrometer immersed in liquid.

Using the vision system, it is possible acquire images of the scale mark of the hydrometer at the level of the liquid; the frame grabber converts the images into digital data for future image processing. The camera is located at an angle θ below the horizontal level of the liquid so the target mark *L* can be seen. The mark of the scale below the target mark *A* is reflected on the surface of the liquid, so there is a virtual image of mark *A*, *A'*. The alignment of *L* at the surface level is accomplished when the distance in pixels between *A* and *L* and that between *L* and *A'* is the same at the image plane. However, due to the position of the camera, corrections of these two distances should be made [3].

In order to obtain the relation *K* between the distances from *A* to *L* (d_1) and form *L* to *A'* (d_2) a pin-hole camera model approach has been employed as shown in Figure 2. The relation between d_1 and d_2 is as follows:

$$\frac{d_2}{d_1} = K \qquad (5)$$

K is obtained by means of the following equation:

$$K = \frac{1}{\dfrac{(\sin\beta)\cdot\sqrt{{x_1}^2 + {y_1}^2}}{x_1\cdot\sin\alpha} - 1} \qquad (6)$$

with:

$$\beta = 180^\circ - \alpha - \theta \qquad (7)$$

$$\alpha = \arctan\left(\frac{y_2}{x_T}\right) \qquad (8)$$

$$\theta = \arctan\left(\frac{y_1}{x_1}\right) \tag{9}$$

$$x_1 = \frac{x_T}{\frac{y_2}{y_1} + 1} \tag{10}$$

The known values that can be measure are: the horizontal distance from the hydrometer steam to the camera (x_T), the vertical distance (y_1) between two consecutive marks of the hydrometer (usually the mark to be aligned and the mark below immersed in the liquid) and the vertical distance from the liquid surface to the camera (y_2).

4. Image processing

The image processing algorithm developed to perform the alignment of the hydrometer's calibration scale mark at the surface level of the reference liquid is shown in Figure 3.

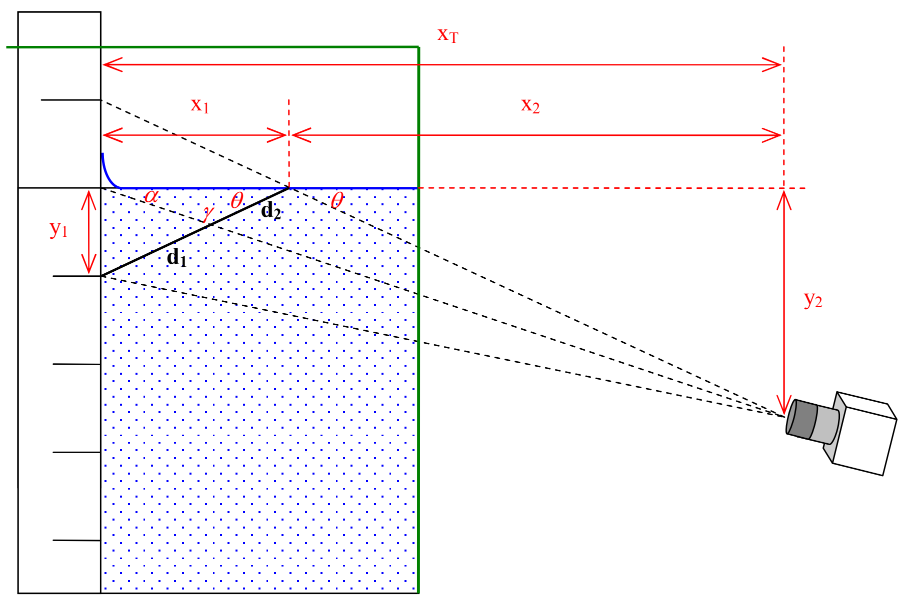

Figure 3. Scheme to obtain the relation between d_1 and d_2 (K value) based on pin-hole camera model approach.

Once the image $I_1(x,y)$ is obtained, a pre-processing procedure is performed by normalizing the gray levels from integer values of 0 – 255 to double floating point values of 0 – 1 and inverting the normalized image (negative image) using the following equation:

$$I_2(x,y) = 1 - I_1(x,y) \tag{11}$$

From $I_2(x,y)$ the region of interest (ROI) is selected which includes the calibration mark, the mark below the reference mark and its reflection on the surface of the liquid. Afterwards, a procedure to detect the three marks is applied to a column vector of the ROI, which includes a noise reduction subroutine, where information of pixel position against gray level is relevant. A plot of the data obtained after this procedure shows that each scale mark can be approach to a second order equation by ordinary least square fitting. The pixel position at maximum gray level for each mark is obtained: p_1 for the pixel position of the mark below the calibration mark, p_2 for the pixel position of the calibration mark, and p_3 for the virtual image (the reflection) of the mark below the reference mark. Then, the distance of d_1 and d_2 are calculated using the values of p_1, p_2 and p_3 as follows:

$$d_1 = |p_1 - p_2| \tag{12}$$

$$d_2 = |p_3 - p_2| \tag{13}$$

With d_1 and d_2 the K relation is calculated. If the calculated K value is not equal to the K value expected, the motorized sinker is used to adjust the liquid level so the value of d_2 changes till the K value is obtained, because d_1 remains the same. Figure 4 and 5 shows the procedure step by step of the image processing algorithm.

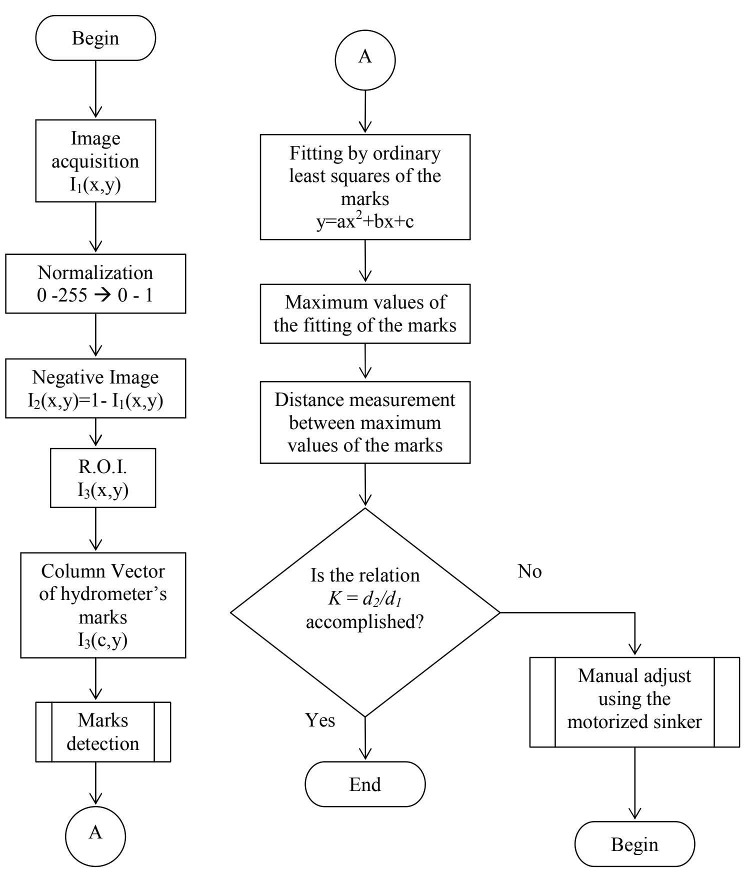

Figure 4.Image processing algorithm.

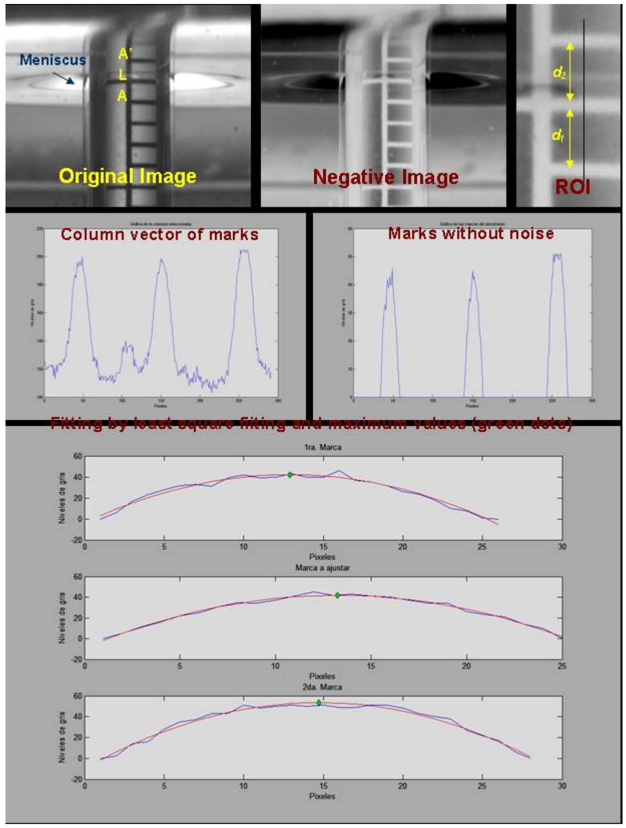

Figure 5. Step by step procedure of the image processing algorithm.

5. Results

Two calibrations of the same hydrometer at the same scale mark were performed, one employing the traditional method -using a magnifier lens- and the other with the image processing technique for the adjustment of the scale mark. The calibration point was 640 kg/m^3, scale division of 0,02 kg/m^3, distance between marks is 1,3 mm. The expected K value was obtained using equations (6) to (10) with the following data: x_T = 315 mm, y_1 = 1,3 mm and y_2 = 13 mm; so that K = 0,91. The camera had an inclination angle θ = 10º over the horizontal plane.

With the traditional method, the standard deviation of Δm_2 was 4,56 mg, meanwhile with the image processing technique was 0,31 mg. Tables 1 and 2 illustrate the uncertainty budget for both calibration processes.

Uncertainty Budget							
R1	ci		Inc. Estándar		Contrib.	varianza	%
					$kg\ m^{-3}$	$kg^2\ m^{-3}$	
δρx/δρliq =	0.882593104		1.06E-02		0.0094	8.811E-05	9.40
δρx/δρa1 =	0.117406873						
δρx/δma =	1372.028373						
δρx/δmliq =	10304.16138						
δρx/δtliq =	0.008721924		0.01		0.0001	7.607E-09	0.00
δρx/δta =	1.78599E-05		0.2		0.0000	1.276E-11	0.00
δρx/δγliq =	-16.54840542		1.00E-03		-0.0165	2.738E-04	29.21
δρx/δd =	-1		0.014433757		-0.0144	2.083E-04	22.22
δma/δmp1 =	0.999878253		2.36E-08		0.0000	1.048E-09	0.00
δma/δρa1 =	-9.52867E-06		0.000777754		0.0001	8.338E-09	0.00
δma/δρp1 =	1.16E-09		78.71		0.0001	1.570E-08	0.00
δma/δΔm1 =	1		9.88826E-08		0.0001	1.841E-08	0.00
δma/δd =	-1		2.88675E-08		0.0000	1.569E-09	0.00
δmliq/δmp2 =	0.999879396		4.50E-08		0.0005	2.150E-07	0.02
δmliq/δρa2 =	-3.7757E-06		0.000777754		0.0000	9.156E-10	0.00
δmliq/δρp2 =	4.55365E-10		79.46		0.0004	1.390E-07	0.01
δmliq/δΔm2 =	1		1.85825E-06		0.0191	3.666E-04	39.11
δmliq/δd =	-1		2.88675E-08		-0.0003	8.848E-08	0.01
δmliq/δCg =	1						
δCg/δΔh =	-9.46544E-09		0.01		0.0000	9.513E-13	0.00
Punto	**610**	kg/m^3					
Unc. (k=2)	**0.061**	kg/m3		Urel (k=2)	**1.00E-04**		

Table 1. Uncertainty budget (traditional alignment method).

Uncertainty Budget							
R1	ci		Inc. Estándar		Contrib.	varianza	%
					$kg\ m^{-3}$	$kg^2\ m^{-3}$	
δρx/δρliq =	0.781641041		1.06E-02		0.0083	6.911E-05	35.65
δρx/δρa1 =	0.218360631						
δρx/δma =	1585.305531						
δρx/δmliq =	5667.762089						
δρx/δtliq =	0.005947889		0.01		0.0001	3.538E-09	0.00
δρx/δta =	1.67709E-05		0.2		0.0000	1.125E-11	0.00
δρx/δγliq =	-9.525340552		1.00E-03		-0.0095	9.073E-05	46.81
δρx/δd =	-1		0.005773503		-0.0058	3.333E-05	17.20
δma/δmp1 =	0.999880116		3.35E-08		0.0001	2.820E-09	0.00
δma/δρa1 =	-1.04271E-05		0.000775493		0.0002	2.867E-08	0.01
δma/δρp1 =	1.25E-09		79.31		0.0002	2.470E-08	0.01
δma/δΔm1 =	1		4.77261E-08		0.0001	5.724E-09	0.00
δma/δd =	-1		2.88675E-08		0.0000	2.094E-09	0.00
δmliq/δmp2 =	0.999881539		2.28E-08		0.0001	1.670E-08	0.01
δmliq/δρa2 =	-2.2634E-06		0.000780526		0.0000	1.003E-10	0.00
δmliq/δρp2 =	2.68124E-10		80.07		0.0001	1.480E-08	0.01
δmliq/δΔm2 =	1		1.27585E-07		0.0007	5.229E-07	0.27
δmliq/δd =	-1		2.88675E-08		-0.0002	2.677E-08	0.01
δmliq/δCg =	1						
δCg/δΔh =	-5.71773E-09		0.01		0.0000	1.050E-13	0.00
Punto	**610**	kg/m3					
Unc. (k=2)	**0.028**	kg/m3		Urel (k=2)	4.56E-05		

Table 2. Uncertainty budget (alignment method with the image processing technique).

6. Conclusions

The main goals of this work introducing the image processing technique in calibration of hydrometers by Cuckow's method is to reduce significantly the variability obtained in the apparent mass when the hydrometer is weighted in the liquid and eliminate the possible error of manual alignment introduced by the operator.

With this new technique it is possible to reduce more than 10 times the standard deviation of the difference in mass during the hydrostatic weighing of the hydrometer immersed in the liquid. The uncertainty budget demonstrates that main uncertainty source in the calibration of hydrometers with the traditional method is around 40% of the uncertainty of calibration. With this new method, the contribution due to alignment was reduce around 0,30 %. Also the relative uncertainty of calibration with a confidence level of 95% decreased from $1x10^{-4}$ to $4,56x10^{-4}$.

The density laboratory at CENAM could establish a new procedure to offer calibration services of reference standard hydrometers to their customers more accurate and with less uncertainty of measurement.

Future work for improvements to hydrometer calibration system at CENAM will be the complete automation of the calibration process using the image processing as a feedback to perform automatically the alignment of the scale mark at the surface level of the reference liquid.

7. Acknowledgments

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