A study on the geometry of sinkers used for calibration of hydrometers with the ring method

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Abstract: The geometry of three types of sinkers used during the calibration of hydrometers by the ring method in a density standard liquid was studied. An experiment was designed with two factors: the geometry and the metrologist, with three levels for the geometry of sinkers and two levels for the metrologist factor. Even when the variable under study was the geometry, it was useful to observe the variation due to the metrologist when same method, system, hydrometer, and the temperature was used (reproducibility of the metrologist). Two response variables were monitored: the measurement bias and the time to carry out the calibration at one point. The calibration point selected was the closest point to the sinker in the measurement scale. The results show that the best geometry regarding measurement bias also results in the worst geometry regarding the productivity of the calibration laboratory, that is, the geometry which gives the lower time for calibration is also the geometry with the bigger measurement bias, and vice versa. These results allow the calibration laboratories to choose the best trade-off design of the sinkers to use for calibration of hydrometers in a density standard liquid.

1. Introduction
A hydrometer is among the simplest, inexpensive, but accurate and hence reliable instruments for measuring the density of liquids [1, 2, 3]. The most popular methods used for calibration of hydrometers are the direct comparison method, the ring method, and hydrostatic weighing [2, 3]. The ring method got its name because a metallic ring with known mass and volume is inserted onto the stem of the hydrometer to sink it onto the liquid of reference. The use of this plummet allows eliminating the need to use some volatile liquids as references [3, 4].

Even when the ring method has been studied only from the National Metrology Institutes (NMI) approach, i.e., the establishment of the method or the use of the sinker as a reference standard mass [2, 3, 4], there is also important the productivity approach, from the industrial metrology and the calibration laboratories. In this work, three stainless steel sinkers with different geometry were tested following a calibration procedure in an accredited laboratory. Of course, all the sinkers have a hole drilled vertically. The first type of sinker is the classical ring, the second one has the geometry of a truncated cone, and the third one has the shape like a bell, with a concavity at the bottom to improve its fit to the top of the hydrometer bulb.

A complete factorial experiment [5] was design and the results analyzed to compare which of the three geometries proposed for the sinkers was the optimal regards two outputs: the instrumental bias and the time to calibrate the hydrometer at one point of calibration. The results show that the geometry of the sinker has an influence on both outputs and, at least with the three types of geometries included here, there is an important contribution due to the dimension of the hole through which the sinker is inserted on the hydrometer stem, provided an experimented metrologist was done the calibrations.

2. Materials and Methods

2.1. Sinkers design
The pictures, shapes, and dimensions of the sinkers are shown in figure 1, figure 2, and table 1.
Figure 1. The three geometries of sinkers studied: (i) ring, (ii) cone, and (iii) bell.

Figure 2. Dimensional characteristics of the sinkers: (i) ring, (ii) cone, and (iii) bell.

Table 1. Dimensions of the sinkers: (i) ring, (ii) cone, and (iii) bell.

| Sinker geometry | a   | b   | c   | d   | e   |
|-----------------|-----|-----|-----|-----|-----|
| Ring / mm       | 7.98| 7.92| 29.99| -- | -- |
| Cone / mm       | 12.09| 9.94| 26.97| -- | -- |
| Bell / mm       | 7.15| 7.41| 11.16| 19.81| 25.22|

2.2. Design of experiments

A Design of Experiments (DOE) helps the researcher to investigate the effects of some inputs (called the factors) onto one output (called the response) at the same time [5]. A complete factorial DOE with two factors and two replicates was designed using Minitab® [6]. One of the factors was the geometry of the sinker, and it has three levels, one per sinker type. The second factor was the metrologist, and it has two levels, one per metrologist that carried-out the calibration procedure. Also, two outputs were monitored: the instrument bias and the time to complete the calibration procedure. Table 2 shows the DOE summary.

Table 2. The design of the experiment.

| Standard order | Run order | Levels of factors | Standard order | Run order | Levels of factors |
|----------------|-----------|-------------------|----------------|-----------|-------------------|
|                | (randomized) | metrologist | sinker | metrologist | sinker |
| 8              | 1         | M<sup>a</sup>   | Ring | 6         | 7       | H     | Bell |
| 2              | 2         | M                 | Ring | 1         | 8       | M     | Cone |
| 5              | 3         | H<sup>b</sup>    | Ring | 7         | 9       | M     | Cone |
| 4              | 4         | H                | Cone | 9         | 10      | M     | Bell |
| 11             | 5         | H                 | Ring | 12        | 11      | H     | Bell |
| 3              | 6         | M                | Bell | 10        | 12      | H     | Cone |

<sup>a</sup> M is a woman with five years of experience in the calibration of hydrometers.

<sup>b</sup> H is a man with eleven years of experience in the calibration of hydrometers.
3. Results

Table 3 shows the results obtained after the twelve calibrations were done. Two responses are included: the time needed for calibration of the hydrometer in one point (820 kg/m$^3$), and the instrument bias, to seek trends regarding the geometry of the sinker used during the calibration. Table 4 shows the results of the analysis of variance (ANOVA), including the p-value, for both responses [5].

| Standard order | Time for calibration / min | Instrument bias / kg·m$^{-3}$ |
|----------------|----------------------------|--------------------------------|
| 1              | 0,32                       | - 0.017                        |
| 2              | 1,21                       | - 0.072                        |
| 3              | 1,82                       | - 0.128                        |
| 4              | 1,79                       | - 0.028                        |
| 5              | 1,61                       | - 0.089                        |
| 6              | 2,65                       | - 0.066                        |

Table 4. Analysis of Variance.

| Source                  | DF$^a$ | Response: calibration time | Response: Instrument bias |
|-------------------------|--------|----------------------------|---------------------------|
|                         |        | Adj SS$^b$ | F-value | p-value     | Adj SS$^b$ | F-value | p-value     |
| Model                   | 5      | 4,496       | 2.94    | 0.111       | 0.008      | 2.64    | 0.135      |
| Linear                  | 3      | 3,394       | 3.70    | 0.081       | 0.006      | 3.81    | 0.077      |
| metrologist             | 1      | 0.407       | 1.33    | 0.292       | 0.000      | 0.86    | 0.390      |
| sinker                  | 2      | 2.986       | 4.89    | 0.055       | 0.006      | 5.28    | 0.048      |
| 2-way interactions      | 2      | 1,102       | 1.80    | 0.244       | 0.001      | 0.89    | 0.459      |
| metrologist*sinker      | 2      | 1,102       | 1.80    | 0.244       | 0.001      | 0.89    | 0.459      |
| Error                   | 6      | 1,833       | 5.04    | 0.006      | 0.003      | 6.47    | 0.001      |
| Total                   | 11     |             |         |             |            |         |             |

$^a$ Degrees of freedom

$^b$ Adjusted sum of squares

The figure 3 and the figure 4 show the factorial plots that include the mains effects plots. The main effects are the differences in the mean response between the two levels of the metrologist factor and the three levels of the sinker factor.
4. Discussion and Conclusion

The p-value results included in the table 4 points that, at a significance level of 0.05, only the sinker factor could be considered statistically significant, due that its p-value is lower than the significance level, particularly for the instrument bias. The other factor (metrologist) and the two-way interactions are statistically no-significant. This result could be explained due that the two metrologists involved in the experiment have enough experience in the calibration of hydrometers in a density standard liquid, so the change of metrologist or the interaction between metrologist and sinker do not affect either of the responses.

Once the p-values analysis has done, an analysis of the main effects plots must follow. Because the metrologist factor has no statistical significance, the focus will be on the sinker geometry. At the right-side of figure 3 could be seen that the lowest mean calibration time is for the cone geometry sinker, whereas the highest time was consumed with the bell sinker. The explanation is that the bell-shaped sinker tends to capture more bubbles, and its removal takes time during the calibration setup. On the other hand, cone sinker has the wider diameter in the central hole what provides two advantages during the setup: the easy liberation of the bubbles and more stability and adaptation to the irregular surface of the top of the hydrometer bulb.

Finally, in figure 4 at the right-hand side, could be seen that the lowest mean instrument bias is also for the cone geometry sinker, whereas the highest instrument bias corresponds to the bell sinker. The same reasons explained lines above also apply to this response.

This work concludes that different shapes of sinkers other than the classical ring could be tested, to get the best performance during the calibration of hydrometers in a density standard liquid. Even when the p-values of the sinker for the responses are barely thousandths around the significance level, important insights regarding the geometry of the sinker influence in laboratory productivity, and in the accuracy and reliability of the calibration result have been obtained.

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