Measurement of Overflow Density in Spiral Classifiers Using a Vibrating Fork Densitometer with Accuracy Evaluation

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***Abstract* — This work concerns the application of a vibrating fork densitometer to the measurement of overflow density in spiral classifiers. A spiral classifier is a mineral processing equipment which receives an ore slurry input and performs a gravity separation process between the solids particles of ore and the water. The classifier has two outputs: the "underflow", formed by sedimented coarse solids; and the "overflow", in the form of an ore slurry with fine suspended solids particles. For proper performance of a spiral classifier, the density of its overflow needs to be controlled by a feeding of dilution water at the input of the classifier. Even in present days, this control is still performed manually from manual samples of the overflow density, due to the lack of a standard instrumentation solution for this application. In this context, this work describes the application of a vibrating fork densitometer for overflow density measurement in spiral classifiers. The instrument performance was evaluated in two steps: a bench testing and a field testing. In both cases, its measurement accuracy was statistically investigated. The results obtained indicated the feasibility of the instrument for the intended application.**

***Index Terms* — densitometer, density meter, slurry density, spiral classifier, vibrating fork, tuning fork.**

I. INTRODUCTION

DENSITY is an important property of liquids and a major process variable in many industries. The density of a liquid is mainly affected by its *temperature* and *composition*, and in less degree by its pressure. The degree in which the density is affected by these variables depends of the liquid [1].

Instruments intended to measure density are referred as *density meters*, *density gauges* or simply *densitometers*. Those instruments use specific measuring principles, such as: attenuation of ionizing radiation [2], resonance of mechanical vibrations [3;4], hydrostatic differential pressure [5], microwave transmission [6], and tomography [7]. Each measurement principle has specific advantages and drawbacks involving: sensing capabilities, physical installation aspects, operating conditions, and maintenance and calibration aspects, that must be taken into account for the intended application.

Depending on their measurement principle, some types of densitometers cannot be fully calibrated in factory, and their true accuracy can only be determined by *field calibration and proving*. Examples are nuclear and ultrasonic densitometers, whose output is related to the actual fluid being measured and the installation environment. If a densitometer has been calibrated only on a single fluid, its accuracy is likely to be based on a single density value, and such accuracy may not be the same for liquids with densities that differs from the calibration fluid. The same holds for a fluid with significant density variations, like ore slurries in mineral processing, if the densitometer is calibrated only on a single density value. Field proving of a densitometer is usually hard-working and time-consuming, or even unpractical in some cases. If the application depends on the ability to field-prove a densitometer, many issues such as reference liquids and sampling procedures must be addressed. The application must be carefully evaluated for potential installation problems and calibration limitations at the point in which the measurement needs to be made [1].

As alternative to the most commonly used, radioactive-based, densitometers for mineral slurries, the present work investigated a non-radioactive density meter based on the *vibrating fork* technology. This article is structured as follows: Section II summarizes the use of radioactive densitometers in the mineral processing industry. Section III presents a class of non-radioactive densitometers which can be used as an alternative to radioactive instruments. In Section IV, the challenges regarding density measurement of mineral slurries are discussed. Section V explains the application of interest for use of the vibrating fork densitometer. Sections VI and VII

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present, respectively, the bench and the field testings of the densitometer, with the corresponding accuracy evaluations. Finally, Section VIII summarizes the conclusions about the work.

II. THE USE OF DENSITOMETERS IN THE MINERAL PROCESSING INDUSTRY

Mineral processing plants deal with ores in two major forms: *bulk ore* and *ore slurry* [8]. An ore slurry is a mixture of ore solids particles and water. Most slurry processings such as hydrocycloning, filtering, thickening, and froth flotation, need information about the slurry density.

Nuclear or *radioactive* densitometers, shown in Fig. 1, have been the most used type of density meter in mineral processing, where they are applied to measure the density of ore slurries flowing in pipelines.

Some advantages of nuclear densitometers are: non-intrusive/non-contact measurement; easy external mounting on pipelines, with no need to stop the process operation; and robustness for harsh industrial environments. However, they have also drawbacks:

Fig. 1. Typical installation of a radioactive densitometer [2], as usually used in mineral processing.

1) *Need for permanent safety care*
Nuclear densitometers for mineral processing applications use radioactive sources, normally with Cesium-137 or other gamma ray radioisotopes, which are potentially hazardous elements. Despite the radioactive sources are sealed and shielded, the handling of nuclear densitometers needs permanent safety care to prevent occupational injuries. Due to OHS (Occupational Health and Safety) concerns, some mining companies are working to reduce/eliminate the use of nuclear densitometers, by trying alternative non-radioactive density instruments.

2) *Need for field calibration*
Unlike other kinds of instruments, calibrating a nuclear densitometer in a workbench is unpractical, because of the difficulties to reproduce process and installation conditions in a workbench. This brings the need of *field calibration and proving*, through which the instrument is calibrated directly in the process line where it is installed. In mineral processing plants, a major restriction for field calibration is the difficult to vary the process density along its full operating range to allow a representative calibration. Because of this restriction, the field calibration is often underperformed in a narrow density range, normally around the nominal process density (nominal operating point), leading to a non representative calibration along the full operating density range. As a consequence, the measures provided by the instrument may be inaccurate when the process gets out the narrow density range used in the field calibration.

Although nuclear densitometers are a suitable measurement technology for several applications, some industries like chemical, petrochemical, and pharmaceutical have succeeded in the use of alternative *non-nuclear density meters* [9]. Those instruments are not yet common in the mineral processing industry, due to a lack of assured knowledge on how to properly apply them to the measurement of ore slurries.

III. VIBRATING ELEMENT DENSITOMETERS

A class of alternative non-nuclear density meters are the *vibrating element densitometers*, which measure the frequency of vibration of a mechanical element in contact with the process liquid. There are two types of vibrating element densitometers: the coriolis density meter and the vibrating fork density meter, shown in Fig. 2.

Fig. 2. Vibrating element density meters: (a) Coriolis [4]. (b) Vibrating fork [3].

Coriolis densitometers [4] measure the frequency of resonant vibration of a tube through which the process liquid flows. This resonant frequency depends on the mass of liquid inside the tube, which is directly related to the density of the liquid, since the volume of the tube is fixed. The instrument usually include an integrated temperature sensor to allow temperature compensation of the measured density.

Vibrating fork or *tuning fork densitometers* [3] measure the vibrating frequency of a resonant fork inserted in the process liquid. The resonant frequency is directly related to the density of the liquid in which the fork is inserted. Those instruments can also be characterized for viscosity measurement.

Vibrating element densitometers are the most accurate instruments for density measurement of liquids, provided that *the liquid characteristics and the process conditions are compatible with the measuring principle of the densitometer*. They are widely used in the hydrocarbon, chemical, and petrochemical industries.

The need for contact with the liquid being measured may impose restrictions to the use of vibrating element

densitometers, mostly if the liquid is corrosive, abrasive, or flows at high velocities. Abrasive effects are the most limiting aspect for the use of those densitometers in mineral processing.

IV. THE CHALLENGE OF MEASURING ORE SLURRIES

An ore slurry is a mixture of water and suspended solids particles of ore. Because the solids particles tend to sediment by gravity, the slurry is inherently a non-homogeneous mixture whose solids concentration may vary between different points within it. As discussed in Section 2, nuclear densitometers have been the most used type of density meter in mineral processing, but there are motivations to move towards the use of non-nuclear densitometers.

Two main factors affect the measurement of ore slurries by contact: *abrasion* and *solids segregation*. Abrasion is a wear effect caused by the relative movement of the slurry regarding a fixed object in contact with it, including its container. Solids segregation, by its turn, is a preferential separation of solids particles between themselves or between the water in the slurry, and causes the slurry to be non-homogeneous so that its properties (e.g.: solids concentration, density) vary from one point to another within it.

Abrasion is perhaps the main restriction for contact/intrusive measurement of slurry properties, as it gradually destroys the sensing element in contact with the slurry. Avoiding abrasion effects is the major reason for the use of nuclear densitometers since they have absolutely no parts in contact with the slurry. Microwave- and tomography-based densitometers usually have tubular body coated with some lining material (e.g.: polyurethane, natural rubber, ceramics) that *will not last forever* when subjected continuously to abrasive slurry flows. Moreover, vibrating element densitometers may have their sensing elements quickly damaged by abrasion, as they need to stay in direct contact with the slurry being measured.

Therefore, *the main challenge in measuring ore slurry properties is to rightly match the measurement technology to the process characteristics*. Measurement technology concerns the measurement principle and installation requirements, whereas process characteristics relates to slurry properties and operating conditions. Each slurry measurement application must be carefully addressed in this sense.

Slurries formed with very fine solids particles and low to medium solids concentration, have normally reduced abrasion effects that may allow measurements by contact. A particular case of interest in mineral processing is the slurry produced by spiral classifiers, discussed in the next section.

V. DENSITY OF OVERFLOW IN SPIRAL CLASSIFIERS

A spiral classifier, shown in Fig. 3, is a mineral processing equipment intended to perform a gravity solids-liquid separation of ore slurries, based on the density differences between the solids (ore particles) and the liquid (water).

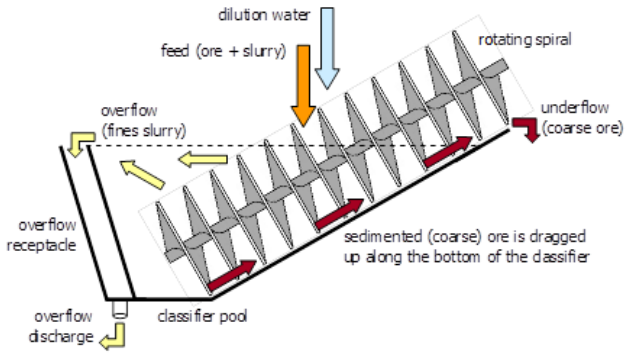

Fig. 3. Operating principle of a spiral classifier.

The classifier receives ore slurry as a *feeding input*, and dilution water as a *control input*. The coarse solids in the slurry sediment to the bottom of the classifier and are dragged up by a rotating spiral to produce an output referred as *underflow*, which is sent to a further processing stage. The part of the slurry containing *fine particles of solids* that did not sediment, flows freely through the borders of the classifier and is referred as *overflow* [8]. The overflow density is mostly defined by the concentration of fine solids in the input slurry and should be controlled by the dilution water. The proper operation of a spiral classifier requires a regulation of its overflow density around a specific operating point.

When the input slurry becomes more concentrated, the amount of sedimented solids at the bottom of the classifier will increase – and may lock the rotating spiral, stopping the classifier. The overflow density will also increase from its current operating point, so that its measurement by an instrument can be used in a *control loop* to increase the dilution water flowrate in order to compensate the increased concentration of the input slurry. In the opposite way, when the input slurry becomes less concentrated, the overflow density will decrease from its current operating point, for the current dilution water flowrate. In this case, the control loop

Fig. 4. Overflow of a real spiral classifier.

should reduce the dilution flowrate to avoid wasting of water. In both cases, the manipulation of the dilution water flowrate a the control loop will act to adjust the overflow density at a

specified operating point (density set-point) that meets the needs of the next processing stage to where the overflow slurry goes. This will reduce the input variability of the next processing stage and improve process quality.

The Carajás Iron Ore Plant has seven spiral classifiers in its Secondary Screening facility, one of which is shown in Fig. 4. The overflow density of those classifiers is measured from samples collected by a field operator at a one-hour interval. Manipulations of the dilution water flowrate are made manually from the control room upon request from the field operator. This doesn't allow a proper regulation of the density at the desired operating point.

What sort of density instrument could be successfully applied to the overflow in a spiral classifier? Unlike in pipelines, the installation of a nuclear densitometer in a spiral classifier is not suitable from an occupational safety perspective, due to risks of people exposure to ionizing radiation.

In the search for a non-nuclear density meter, some characteristics of the overflow slurry were considered:

1) *Small particle sizes*
Overflow slurries are formed by fine ore particles, typically with sizes smaller than 1.0 mm. Slurries with such small particle sizes are easier homogenized and have low abrasion effects.

2) *High degree of homogenization*
The rotating movement of the spiral generates a strong homogenization of the slurry inside the classifier, leading to a good uniformity of the overflow density. It was expected that such homogenization would be good enough to make point measurements of the overflow density be representative for the entire overflow.

3) *Low density range*
According to manual measurement records from the Carajás Plant, the overflow density ranges typically from 1.01 to 1.45 g/cm^3. It was expected that this density range would not lead to significant abrasion effects.

4) *Low flow velocity*
For a given spiral classifier, the velocity of the overflow slurry at the borders of the classifier depends on its operating throughput. This velocity is typically lower than 1.0 m/s at the borders of the classifier. It was expected that low velocities would not lead to significant abrasion effects.

The above characteristics suggested that the overflow slurry would produce very low abrasion effects on a sensor that would be immersed into it to perform a measurement by contact. Hence, a vibrating fork densitometer was chosen for the application. An additional advantage of using a vibrating fork is that it could be easily mounted over the surface level of the overflow slurry, with a properly designed mechanical support.

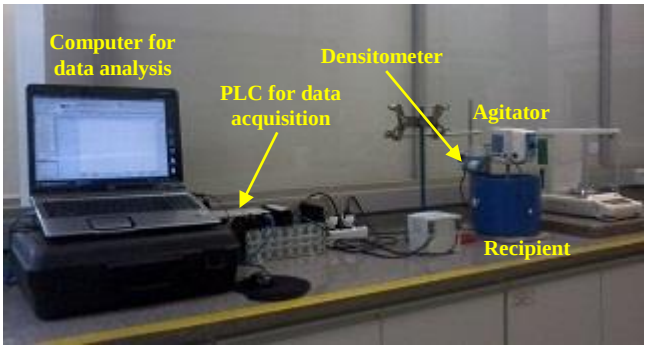

Fig. 5. Workbench for testing the vibrating fork densitometer.

To investigate the technical viability of a vibrating fork densitometer for the application, a testing deal was established with a manufacturer of the instrument. The testing deal comprised two steps: a *bench testing*, by which the instrument would be tested under controlled conditions in a laboratory; and a *field testing*, by which the instrument would be installed in a spiral classifier for field performance evaluation.

The validation requirements for the instrument in the application were its *measurement accuracy* and its *robustness to abrasion effects*. The desired accuracies for the bench testing and the field testing were, respectively, ±0.5% and

TABLE I - DENSITY VALUES AND CORRESPONDING DEVIATIONS OBTAINED FROM THE BENCH TEST

Sample	Sample Density (g/cm^3)	Measured Density (g/cm^3)	Measurement Error (g/cm^3)	Measurement Error (%)
1	0,997747	0,998541	0,000794	0,080 %
2	1,015693	1,014464	-0,001229	-0,121 %
3	1,028062	1,026106	-0,001956	-0,190 %
4	1,044758	1,036825	-0,007933	-0,759 %
5	1,050832	1,048222	-0,002610	-0,248 %
6	1,061328	1,054829	-0,006499	-0,612 %
7	1,090931	1,081058	-0,009873	-0,905 %
8	1,116707	1,107633	-0,009074	-0,813 %
9	1,102343	1,122080	0,019737	1,790 %
10	1,152681	1,143724	-0,008957	-0,777 %
11	1,178705	1,170285	-0,008420	-0,714 %
12	1,185590	1,192173	0,006583	0,555 %
13	1,224917	1,198467	-0,026450	-2,159 %
14	1,231150	1,240572	0,009422	0,765 %
15	1,276576	1,262909	-0,013667	-1,071 %
16	1,303631	1,318132	0,014501	1,112 %
17	1,298987	1,295120	-0,003867	-0,298 %
18	1,334929	1,331696	-0,003233	-0,242 %
19	1,363432	1,365545	0,002114	0,155 %
20	1,402273	1,420635	0,018362	1,309 %
21	1,452780	1,455035	0,002255	0,155 %
22	1,470905	1,480419	0,009514	0,647 %
23	1,504593	1,508305	0,003712	0,247 %
24	1,540685	1,545078	0,004393	0,285 %

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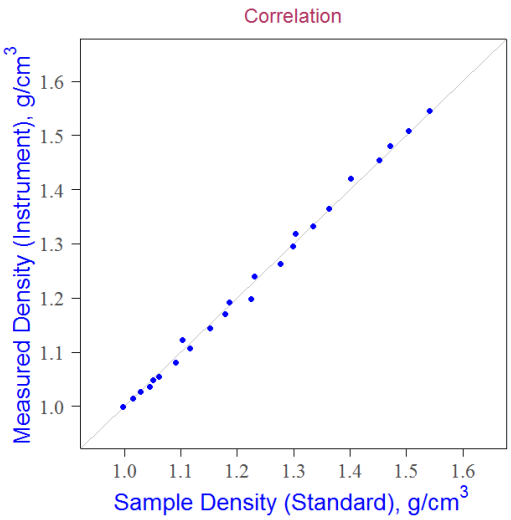

Fig. 6. Sample and measured density values, from the bench testing.

±1.5%. The resistance to abrasion would be assessed visually.

VI. BENCH TESTING OF THE VIBRATING FORK DENSITOMETER

The bench testing was performed at the Metallurgical Laboratory of VALE's Fábrica Iron Ore Plant, in the city of Ouro Preto, Minas Gerais state, Brazil.

A set of n = 24 sample densities were synthetized by mixing a fixed volume of pure water with a calculated mass of dried solids from overflow slurry. The slurry samples were synthetized in a recipient with a fixed volume of water by adding successive increments of solids mass. A mechanical agitator was inserted into the recipient to agitate the slurry and avoid the sedimentation of the solids. The vibrating fork densitometer was attached inside the recipient to measure the density of the slurry. Fig. 5 shows the workbench during the testing.

For each synthetized slurry sample with known density, the corresponding measured density provided by the instrument was recorded, and the error was calculated. Those results are shown in Table I. Fig. 6 shows the relationship between the sample densities and measured densities.

The measures obtained in the bench testing had the following statistics:

- Correlation coefficient: 0.998
- Mean of the relative errors: –0.075%
- Standard deviation of the relative errors: 0.863%

The high correlation between the density measures provided by the instrument and the sample density values indicates the great ability of the instrument to follow variations in the slurry density. The small values of the mean and standard deviation of the measurement errors suggest that the instrument was accurate. Its accuracy was investigated statistically, as described in the following.

A. Instrument Accuracy in the Bench Testing

The instrument accuracy for the bench testing was investigated in a statistical sense through a hypothesis test using the measurement data obtained.

The very small average measurement error of –0.075 % suggests that, in a statistical sense, the true measurement error could be ideally 0.0 %. We can *suppose* that if new bench testings would have been run indefinitely under the same conditions of the testing already performed, *the true average measurement error will be equal to 0.0 %*, for all the set of bench testings. This supposition was regarded as the Null Hypothesis. The Alternative Hypothesis was that *the true average measurement error differs from 0.0 %*. Therefore:

- Null Hypothesis: H_0: $\mu_E = 0$
- Alternative Hypothesis: H_A: $\mu_E \neq 0$

Since any sample data (the measurement errors in this case) has some degree of likelihood to occur, a hypothesis test considers a confidence level, which means the degree of confidence by which the Null Hypothesis is accepted as true. The confidence level was chosen as β = 95% = 0.95. The corresponding significance level is: $\alpha = 1–\beta = 5\% = 0.05$.

The statistics to be used for hypothesis testing of average values is [10;11]:

$$\lambda = \frac{\overline{E} - \mu_E}{s_E / \sqrt{n}} \tag{1}$$

where $\overline{E}$ is the *sample mean* of the measurement errors; μ_E is the hypothetical value considered for the *true mean* of the measurement errors (μ_E = 0); s_E is the *sample standard deviation* of the measurement errors; and n is the sample size (the number of measurement errors).

The value of the test statistics λ for the measurement data is:

$$\lambda = \frac{\overline{E} - \mu_E}{s_E / \sqrt{n}} = \frac{-0.07536667 - 0}{0.8633606 / \sqrt{24}} = -0.42765 \tag{2}$$

Since n = 24 < 30 (small sample size), the statistics λ was assumed to follow a t-Student probability distribution with $v = n–1$ degrees of freedom [10;11]. The two-sided score of the t-Student distribution with 23 degrees of freedom, at 0.05 significance level, is:

$$t_{(\alpha/2;v)} = t_{(0.025;23)} = 2.0687 \tag{3}$$

Since the value of the test statistics λ is within $\pm t_{(\alpha/2;v)}$ (the acceptance region for H_0), we *cannot reject the Null Hypothesis that the true average measurement error is equal to 0.0%, with 95% confidence*. The measurement data does not provide evidence that the average measurement error differs significantly from 0.0% in order to reject the Null Hypothesis.

There is no evidence to reject the Null Hypothesis. The sample average error of –0.075% observed in the data was more likely due to random chance.

The confidence interval for the average measurement error is given by:

$$I_E = \overline{E} \pm t_{(\alpha/2;\nu)} \times s_E / \sqrt{n} \quad (4)$$

$$I_E = -0.07536667 \pm 2.068658 \times 0.8633606 / \sqrt{24}$$

$$I_E = -0.07536667 \pm 0.3645653 \quad (5)$$

Fig. 7. Installation of the vibrating fork densitometer in a spiral classifier for field testing.

$$I_E = [-0.44; 0.29]\% \quad (6)$$

The confidence interval includes the hypothetical value $\mu_E = 0$, also meaning that the Null Hypothesis cannot be rejected, at the given significance level. Additionally, the confidence interval is entirely within the desired accuracy interval of ±0.5%, meaning that the instrument was fully compliant with the desired accuracy.

From the above statistical inferences, *the instrument was approved in the bench testing* and qualified for the field testing.

VII. FIELD TESTING OF THE VIBRATING FORK DENSITOMETER

The field testing of the vibrating fork densitometer was performed in the Carajás Iron Ore Plant. The instrument was installed on the spiral classifier CS-131-07, in the Secondary Screening facility, as shown in Fig. 7.

A specific mechanical support with adjustments for horizontal and vertical positions was designed to hold the instrument slightly over the slurry level of the classifier. The instrument was wired to the I/O module of the Plant Control System, so that its analog 4-20 mA density signal could be acquired. The wiring was implemented with a shielded cable, in order to protect the density signal against field electromagnetic interferences.

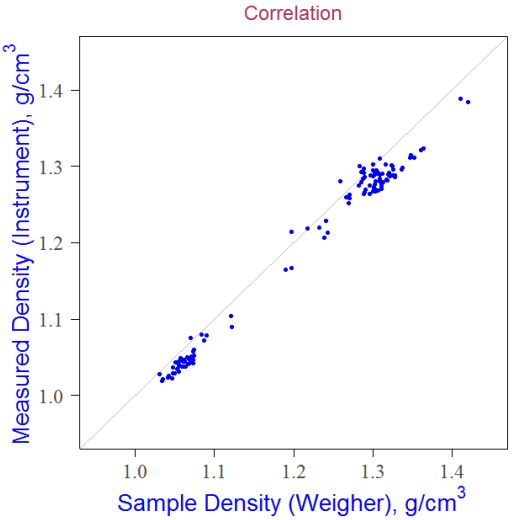

Fig. 8. Sample and measured density values, from the field test.

The validation of the instrument was done by comparing the densities of overflow samples taken manually from the classifier with the corresponding density measures provided by the instrument. A set of 228 overflow samples were collected from 17th March to 8th April, 2015. Several of those samples were outliers. After removing the outliers, a set of 117 valid density samples was obtained. The desired accuracy was ±1.5%. For a process range of 1.00 to 1.45 g/cm^3, this accuracy means a maximum error of ±0.0218 g/cm^3.

Fig. 8 shows the relationship between the sample densities and their corresponding measured densities provided by the instrument. The measures appear in two clusters because the process line was running in only two operating points: at full throughput (higher overflow densities, around 1,30 g/cm^3) or at no feeding (low overflow densities, around 1,05 g/cm^3).

The measures obtained in the bench testing had the following statistics:

- Correlation coefficient: 0.994
- Mean of the relative errors: –1.620%
- Standard deviation of the relative errors: 1.042%

The correlation between the density measures provided by the instrument and the sample density values also resulted high as for the bench testing. The mean relative error was –1.620%, meaning a very small off-set deviation in the instrument measures. This deviation was probably caused by the flow of the overflow slurry, as well as by the sampling process, which could have introduced sampling errors in the observed deviation.

A. *Instrument Accuracy in the Field Testing*

A hypothesis test was also performed with the field testing measures. The value of the test statistics λ considering the measurement data is:

$$\lambda = \frac{\overline{E} - \mu_E}{s_E / \sqrt{n}} = \frac{-1.620053528 - 0}{1.042240216 / \sqrt{24}} = -16.81336 \quad (7)$$

The number of measurements was n = 117 > 30 (large sample size) so that the statistics λ can be assumed to folow a normal probability distribution [10;11]. Nevertheless, for the sake of coherence with the hypothesis test done for the bench testing, the statistics λ was still assumed to folow a t-Student probability distribution with $v = n–1$ degrees of freedom. This assumption is valid because the t-Student distribution tends to a normal distribution for large sample sizes [10;11]. The two-sided score of the t-Student distribution with 116 degrees of freedom, at 0.05 significance level, is:

$$t_{(\alpha/2;v)} = t_{(0.025;116)} = 1.9806 \quad (8)$$

Since the value of the test statistics λ is out of $\pm t_{(\alpha/2;v)}$ (the acceptance region for H_0), we *reject the Null Hypothesis that the true average measurement error is equal to 0.0%, with 95% confidence*. The measurement data provides evidence that the average measurement error *differs significantly* from 0.0% so that the Null Hypothesis should be rejected. The sample average error of –1.620% observed in the data *was not* likely due to random chance.

According to equation (4), the confidence interval for the average measurement error is:

$$I_E = -1.620053528 \pm 1.980626 \times 1.042240216 / \sqrt{117}$$

$$I_E = -1.620053528 \pm 0.1908435 \quad (9)$$

$$I_E = [-1.81; -1.43]\% \quad (10)$$

The confidence interval does not include the hypothetical value μ_E = 0, also meaning that the Null Hypothesis should be rejected, at the given significance level.

In the early stages of the project, it was supposed that accuracies of ±0.5% and ±1.5% could be reached, respectively, in the bench testing and the field testing. There was no prior knowledge to make a hard decision about those desired accuracies, and therefore, they can be regarded as reasonable references. Those accuracies could have been chosen as ±2.0% or ±2.5% as well, provided that they are not excessive, like 5% or greater.

Although the field testing did not meet exactly the desired accuracy of ±1.5%, the achieved accuracy (confidence interval) resulted very close to the desired accuracy. The small difference between the confidence interval and the desired accuracy *does not mean that the instrument is inaccurate*, specially because it achieved a very good accuracy in the bench testing. Moreover, the Process Division of the Carajás Iron Ore Plant stated that the maximum tolerable error for overflow density measurement is ±2.0%. This means maximum error of 0,03 g/cm^3 at the higher operating density of 1,45 g/cm^3. Notice that such tolerance of ±2.0% is greater than the desired accuracy of ±1.5% originally chosen.

Additionally, regarding to Fig. 8 and Fig. 6, the high correlations between the instrument measures and the sample measure indicates that the instrument is able to follow density variations within the full operating density range of the spiral classifier. This also justifies the feasibility of the instrument for the application. Finally, a small off-set error between the measures from the instrument and the samples can be easily compensated in the Plant Control System by programming a correction factor.

From the above discussions, *the instrument was approved in the field test*.

VIII. CONCLUSION

Density meters have important applications in process monitoring and control, in the mineral processing industry. Density measurement technologies can be divided in two major groups: nuclear and non-nuclear. The decision about the best technology for an specific application is the major issue for its success. This is truly verified in the mineral processing industry, where the main challenge on measuring ore slurry properties is to rightly match the measurement technology to the process characteristics. The key to a successful density meter application is a thorough understanding of the process variables and fluid properties which affect the density of the fluid, and the purpose of the density measurement.

As instrumentation technology capabilities are improved, new measurement principles are developed, and acquisition costs are reduced, more applications become feasible, allowing better process monitoring and control, and leading to improved business profitability.

The problem of how to directly measure the overflow density in a spiral classifier remained unsolved for several years, mainly due to a lack of technologies for this application. The application of a vibrating fork densitometer to this problem was an entirely new application. The success of the application, as concluded from the results of this project, defines a new paradigm for process monitoring and control of spiral classifiers. Further developments are in progress to design and implement a control strategy for overflow density in spiral classifiers.

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used to generate the process measurements for validation of the densitometer in the field testing.

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