UFSM

CIÊNCIA e NATURA

ISSN 2179-460X
OPEN ACCESS

Ci. e Nat., Santa Maria, v. 46, spe.3, e86991, 2024 • https://doi.org/10.5902/217946086991
Submitted: 07/03/2024 • Approved: 17/05/2024 • Published: 08/11/2024

II Feira de Ciências, Tecnologia e Inovação da UFSM-CS

Digital monitoring of alcoholic beverage fermentation

Monitoramento digital da fermentação de bebidas alcoólicas

Charles Rech[I], Simone Ferigolo Venturini[I], André Francisco Caldeira[I], Mathias Verdum de Almeida[I], Arthur Sandri Lunkes [I], Maximiliano Silveira de Souza [I]

[I] Universidade Federal de Santa Maria, Cachoeira do Sul, RS, Brazil

ABSTRACT

In this paper, a solution for real-time measurement of the density of alcoholic fermentation is proposed. Two pressure sensors are placed in two vertical locations inside the fermentation tank of a brewery to calculate the density, considering basic hydrostatic concepts. The obtained signals are converted by a 14-bit A/D device equipped with Bluetooth technology. Pressure data are collected by these sensors, which operate in the 0 – 10 kPa range. This approach results in a resolution of 1/163884, measuring a range of 0 to 5 V, an accuracy of 0.61 Pa, and a total density uncertainty of 0.15 %. The results are compared to two commercial instruments, a conventional hydrometer and a portable refractometer. The best concordance is obtained with a conventional hydrometer, with a maximum deviation of 0.37 %.

Keywords: Craft beer; Alcoholic fermentation; Wort density

RESUMO

Neste artigo é proposta uma solução para medição em tempo real da densidade da fermentação alcoólica. Dois sensores de pressão são instalados em dois locais verticais dentro do tanque de fermentação para calcular a densidade considerando os conceitos hidrostáticos básicos. Os sinais obtidos são convertidos por um dispositivo A/D de 14 bits equipado com tecnologia *Bluetooth*. Os dados de pressão são coletados por esses sensores, que operam na faixa de 0 a 10 kPa. Esta abordagem resulta em uma resolução de 1/16384, medindo uma faixa de 0 a 5 V, uma resolução de 0,61 Pa e uma incerteza de total de 0,15%. Os resultados são comparados com dois instrumentos comerciais, um hidrômetro convencional e um refratômetro portátil. A melhor concordância é obtida com um hidrômetro convencional, com desvio máximo de 0,37%.

Palavras-chave: Cerveja artesanal; Fermentação alcoólica; Densidade do mosto

1 INTRODUCTION

The craft beer scenario in Brazil is growing constantly. Comparing the years of 2021 and 2022, an increase of 11,6% in the number of breweries was registered by the Brazilian Ministry of Agriculture (Brasil, 2023). The amount of jobs generated by the craft beer sector reflects the increase in the number of breweries. In 2023, 41.346 direct jobs were created in breweries (Caged, 2023).

One of the main challenges of micro craft breweries is to guarantee production quality and repeatability in a process that involves many steps. The precise execution of the process is important to guarantee the final product quality. Measuring the outcomes of each step and comparing them with a baseline becomes an important task, especially during the fermentation phase, which is based on the usage of yeasts to consume sugar and generate sub-products, such as ethanol and carbon dioxide (CO2), among others (Kunze, 2014; Palmer, 2010). These products of the fermentation generally add flavor, aroma, and other characteristics to the beer (Kunze, 2014). To control how these sub-products are generated, parameters as temperature, density, pH, and the amount of CO2 must be controlled on a real-time basis (White & Zainasheff, 2010).

Lachenmeier et al. (2010) point out the disadvantages of using infrared spectroscopy in combination with multivariate regression in craft and industrial breweries scenario. This method consumes and requires time for Fourier Transform Infrared Sensors and applies the calibration with the matrix-dependent technique. The authors used a device consisting of the multiple-beam infrared sensor in combination with a flow-through cell for alcohol analysis and, compared to densimetric methods, the infrared sensors are simpler to handle, but the hydrometer-type alcoholmeters are still widely applied in industry. Furthermore, the densiometric measurement methods have to be preceded by a distillation step to avoid the sugars and other solutes induce erroneous measurements.

Considering this context, in this paper, a novel method is proposed to measure the wort density in a real-time and continuous fashion. A device is designed to collect data during the whole beer fermentation process. Wort density is controlled because it impacts in different ways on the quality of the final product. The wort density is used to measure the Alcohol by Volume (ABV) of the beer and to identify the different phases of fermentation. For example, precise identification of the end of the fermentation is important to avoid the beer to have long-term contact with inactivated yeast and also to reduce the fermentation time, what is of high importance for a commercial brewery. The measurements are gathered utilizing Bluetooth technology and transmitted to a cloud-based wireless solution. The data stored in the cloud is accessible through a web interface, which can be tailored to inform breweries about the progression of fermentation. Consequently, the objective of this endeavor is to aid, leveraging the principles of Industry 4.0 and lean methodology, in enhancing productivity while mitigating expenses associated with storage, energy consumption, and manufacturing time.

2 MATERIALS AND METHODS

2.1 Density calculation

During the fermentation process, the sugars contained in the wort are converted into CO_2 and alcohol by the action of yeasts. For this purpose, yeast fungus of the Saccharomyces cerevisiae species is used (Kunze, 2014). The density of wort is largely dependent on the sugar content. In this process, the specific gravity decreases as the extract in the pitching wort ferments because ethanol is appreciably less dense than water.

ABV is a standard measure of the ethanol contained in one volume of alcoholic beverage. This value is expressed as a percentage of volume. The percentage of alcohol can be calculated from the difference between the wort original gravity and the current specific one. By monitoring the density decrease over time, one can obtain information about the progress of the fermentation and determines when the process is complete. To calculate ABV, most brewing sites use equation 1 (Brewer’s Friend, 2011).

$$ABV = (OG - FG)131.25 \tag{1}$$

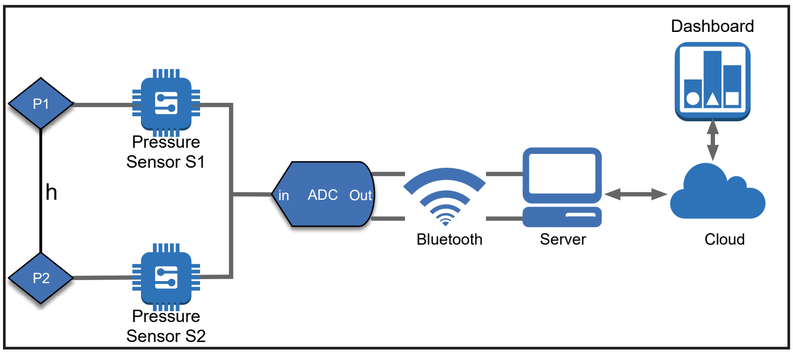
In this case, OG represents the Original Gravity (specific gravity measured before fermentation) and FG is the Final Gravity (specific gravity measured at the completion of fermentation).

2.2 Experimental methodology

The device designed to measure the wort density was composed of two pressure sensors installed in two different positions inside the fermentation tank, distant by a height h, in the vertical direction. A Bluetooth compliant A/D converter was used to communicate with a wireless network to send the acquired data to a computer that pre-processed and sent the resulting information to a cloud-based solution to be stored for further analysis. The information stored in the cloud consisted of sensor signals converted to pressure values according to the calibration equation. These data were processed via software and converted to values of specific density and alcohol content, considering the basic principles of hydrostatics of fluid mechanics. The resulting information could be accessed through a web interface, accessed by the breweries to monitor the fermentation process and to support decision making.

The design of the proposed measurement device was illustrated in Fig. 1, where P1 and P2 were the pressure measurement points and h represented the vertical distance between them.

Figure 1 – Schematic of the measurement device



Source: Authors (2024)

The device main sensors and instruments are described in Tab. 1, followed by their specific measuring range and uncertainty. The symbolism is the same used in Fig. 1.

Table 1 – Device list of sensors and instruments, according to Figure 1

Description	Model
Pressure sensor (S1/S2)	JF 302 - 0 to 10 kPa
WIFI A/D Module	ESP 32

Source: Authors (2024)

2.3 Pressure calculation

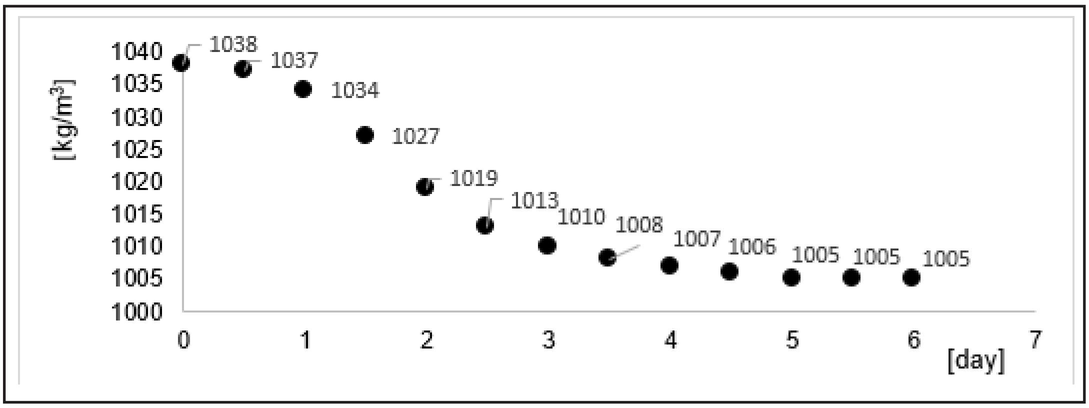
Equation (2) shows the definition of the principle of Pascal (Çengel and Cimbala, 2015), which establishes that pressure exerted anywhere in a confined incompressible liquid is equally transmitted throughout the fluid, so the pressure does not depend on the amount of liquid or the shape of the container. According to the hydrostatic law, the increase of pressure between two elevations equals the local specific weight of the fluid multiplied by the distance between these points.

$$\Delta P = \rho g h \tag{2}$$

where is the hydrostatic pressure (Pa), is the fluid density (kg/m³), is acceleration due to gravity (m/s²) and is vertical distance between the two pressure sensors (m).

The pressure sensors installed inside the fermentation tank were effective to measure the pressure of the wort during the experiments. These values are converted to fluid density using Eq. (2). The expected results in time are shown in Fig. 2 (Kunze, 2014).

Figure 2 – Example of variation of specific gravity during fermentation



Source: adapted Kunze 2014

As can be observed in the graph, the values of wort density decreased as expected and became approximately constant after 4 days of observation. It is important to emphasize that these results are valid for the considered experimental scenario. This fermentation time and the behavior of the density may vary depending on the type of fermentation and on other parameters related to the style of the beer which is being produced.

3 UNCERTAINTY

The pressure measurement to determine the wort density is quasi-static, since the pressure values are collected from predetermined periods of time. The density determination presented in Eq. (2) depends on local gravitational acceleration (), the vertical distance between the two pressure sensors (), and the pressure difference () measured between the two sensors. Each measured value has some uncertainty and to estimate the overall uncertainty, it assumes that each uncertainty is small enough according to first-order Taylor expansion. Under this approximation, the overall uncertainty is a linear function of the independent variables and this approach was established by S. J. Kline and F. A. McClintock (Beckwith et al., 1993).

In accord to JCGM GUM (2008), the uncertainty parameter characterizes the dispersion of the measured values in the experimental evaluation. In this work, the measured density depends on three variables which attend the quasi-static state and a combined standard uncertainty are used. This uncertainty is equal to the positive square root of a sum of the variances from the quantities weighted according to the measurement evaluation with changes in these quantities. The Eq. (3) shows a generic function which is determined from other quantities.

$$\boldsymbol{Y} = \boldsymbol{f}(\boldsymbol{x}_1, \boldsymbol{x}_2, \cdots, \boldsymbol{x}_{\boldsymbol{N}}) \tag{3}$$

Assuming that each variable is independent, the standard uncertainty of y (the estimate of the measurand) is described from the combination of the standard uncertainties of the input estimates as shown in Eq. (4).

$$\boldsymbol{u}_{\boldsymbol{c}}^2(\boldsymbol{y}) = \sum_{\boldsymbol{i}=1}^{\boldsymbol{N}} \left(\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}_{\boldsymbol{i}}}\right)^2 \boldsymbol{u}^2(\boldsymbol{x}_{\boldsymbol{i}}) \tag{4}$$

where is the generic function from Eq. (2) and each quantities represent the standard uncertainty evaluated according to Type A (or Type B) evaluation. In this present paper, in the experimental evaluation was collected from predetermined periods of time and obtained from repeated observations; so Type A evaluation was applied. Expanding the Eq. (4) results in Eq. (5).

$$\boldsymbol{u}_{\boldsymbol{y}} = \sqrt{\left(\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}_1}\boldsymbol{u}_1\right)^2 + \left(\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}_2}\boldsymbol{u}_2\right)^2 + \cdots + \left(\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}_{\boldsymbol{n}}}\boldsymbol{u}_{\boldsymbol{n}}\right)^2} \tag{5}$$

where is the uncertainty in , is the calculated result, is the independently measured variables and is the uncertainty of each measured? The nonlinearity is not significant in the pressure calculation model, then the higher-order terms in the Taylor series expansion were not included in the expression of the standard combined uncertainty. The Eq. (5) is applied to Eq. (2) to obtain the Eq. (6).

$$\Delta\boldsymbol{\rho} = \sqrt{\left(\frac{\partial\boldsymbol{\rho}}{\partial\boldsymbol{P}}\Delta\boldsymbol{p}\right)^2 + \left(\frac{\partial\boldsymbol{\rho}}{\partial\boldsymbol{g}}\Delta\boldsymbol{g}\right)^2 + \left(\frac{\partial\boldsymbol{\rho}}{\partial\boldsymbol{h}}\Delta\boldsymbol{h}\right)^2} \quad (6)$$

Expanding the terms, it results in Eq. (7).

$$\Delta\boldsymbol{\rho} = \sqrt{\left(\frac{1}{\boldsymbol{gh}}\Delta\boldsymbol{p}\right)^2 + \left(-\frac{\boldsymbol{p}}{\boldsymbol{g}^2\boldsymbol{h}}\Delta\boldsymbol{g}\right)^2 + \left(-\frac{\boldsymbol{p}}{\boldsymbol{gh}^2}\Delta\boldsymbol{h}\right)^2} \quad (7)$$

The pressure measurement is conducted using a sensor which operates within the 0 – 10 kPa range in a 14 to bit A/D converter with the resolution of 1/16384 divisions and measuring a range of 0 to 5 V, resulting in an accuracy of the pressure measurement of 0.61 Pa. Considering h = 1 m ±1 mm, g = 9.81 m/s^2 ±0,01 m/s^2 and p = 10000 Pa ± 0,61 Pa, the total uncertainty of density, from the Eq. (7) is 0,15 % fs.

4 VALIDATION PROCEDURE AND RESULTS

The validation of the proposed equipment was based on density reference values according to Fig. 2, which shows the comparison between the reference values and those obtained on the digital hydrometer according to Tab. 2. In practical terms, eight samples were prepared using a mixture of alcohol and water in different proportions, following the specifications presented in Tab. 2.

The density values of each sample were determined by dividing the mass obtained using a digital scale, with a resolution of 0.1 g, by the volume obtained using a burette with a resolution of 0.1 ml. Five measurements were conducted, and the mean value was utilized. Subsequently, these samples were carefully inserted into the digital hydrometer, one at a time, and the density was measured. After each measurement using the reference values, the digital hydrometer was washed to receive a new sample. Table 2 shows the reference values obtained from the samples with the respective values measured in the digital hydrometer and the percentual relative variation between them. Both results were obtained from the arithmetic mean of five measures of each event.

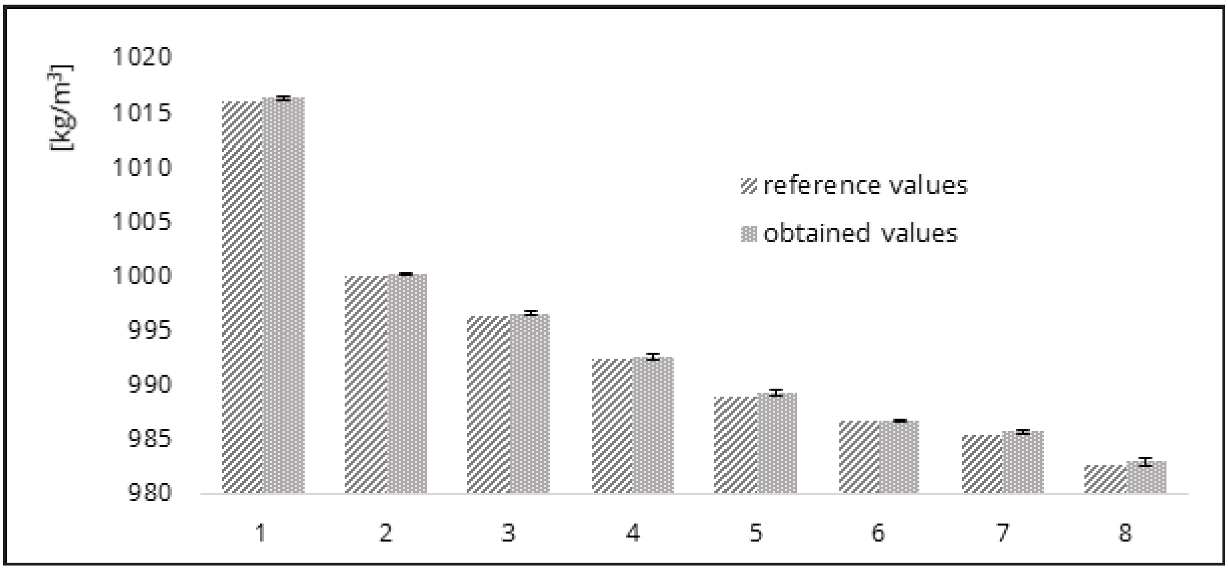
Table 2 – Comparison of reference values with values obtained in the digital hydrometer proposed

Samples	Reference values	Obtained values	% variation relative
1	1016.15	1016.36	-0.020
2	1000.06	1000.21	-0.014
3	996.35	996.52	-0.018
4	992.38	992.68	-0.029
5	988.96	989.23	-0.028
6	986.78	986.73	-0.005
7	985.46	985.50	-0.024
8	982.63	982.56	-0.034

Source: Authors (2024)

Figure 3 shows the reference values used in relation to the values obtained in the digital hydrometer according to Tab. 2.

Figure 3 – Reference values vs obtained values in the digital hydrometer proposed with percentual variation relative



Source: Authors (2024)

After validating the proposed equipment, it was used in a realistic scenario to measure the density during the fermentation of a lager beer of Doppelbock style. In this phase of the experiment, the results obtained using the proposed measurement device was compared to the results of two instruments commonly used to the same end: a conventional hydrometer and a refractometer.

The conventional hydrometer is an instrument that measures the relative density of fluids. It is composed of a closed hollow glass tube where the base contains granular lead trapped by a resin and a narrow stem with a graduated scale in grams per milliliters. The hydrometer makes use of Archimedes principle, i. e., a suspended solids in a fluid is buoyed by a force equal to the weight of the fluid displaced by the submerged part of the suspended solids. The liquid to test is poured into a graduated cylinder, and the hydrometer is gently lowered into the liquid until it floats freely. The point at which the surface of the liquid touches the stem of the hydrometer correlates to relative density. The hydrometers are calibrated for use at 20 °C (Kunze, 2014), therefore, in the case of fluid being at another temperature, correction of the measured value should be made.

The portable refractometer determines the specific value of a fluid based on the reading of the refraction index of the fluid, determining the sugar concentration of liquid solutions. The refractometer consists of a cover plate, a prism assembly, calibration screw, focus adjustment and eyepiece. The scale is graduated in Brix. The Brix scale corresponds to one gram of sugar (sucrose) in 100 grams of solution (water) according to Viginoski (2013). To measure relative density, place a few drops soft the liquid sample on the prism, then close the cover plate and make sure the sample spreads across the prism without air bubbles or dry spots. Wait for about 30 seconds to let the reading stabilize. Align the prism assembly with the light source, look into the eyepiece and you can get the reading. The refractometer is calibrated for use at 20 °C, therefore, in the case of fluid being at another temperature, correction of the measured value should be made. Furthermore, the refractometer presents a distortion in the reading wort fermented, i.e., in the presence of ethanol and carbon dioxide (CO2). Therefore, it is necessary to correct the values obtained. The instruments used for measurements are shown in Tab. 3.

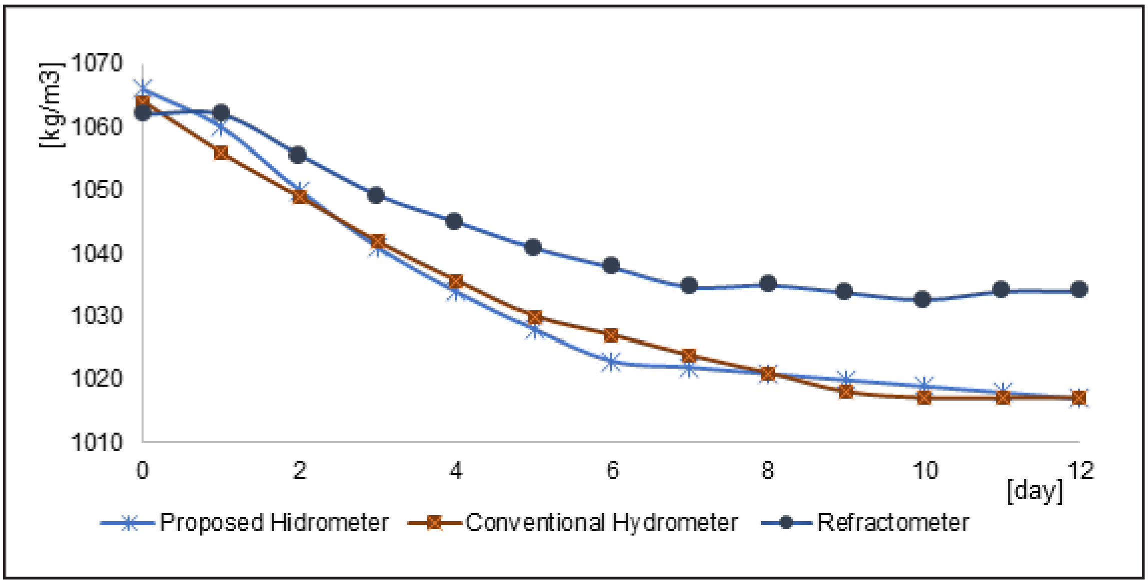
Table 3 – List of measuring instruments

Description	Model	Obtained range	Uncertainty
Hydrometer	Incoterm	1.000 - 1.100 g/ml	± 1 g/ml
Refractometer	ATC	0 - 32 % Brix	± 0.2 Brix
Thermometer	Salvi3	0 - 120°C	±0.5°C

Source: Authors (2024)

The wort was fermented in the range of 8 to 12 °C during 12 days. The measurements of temperature and density were performed daily and logged in a spreadsheet. Figure 4 shows the results of the three methods applied to measure the wort density. It is possible to observe that the tendency of the proposed digital hydrometer is close to that presented in the conventional hydrometer. However, the refractometer showed greater dispersion since it has a deficiency in measuring the wort density in the presence of alcohol and CO2, according to Kunze (2014).

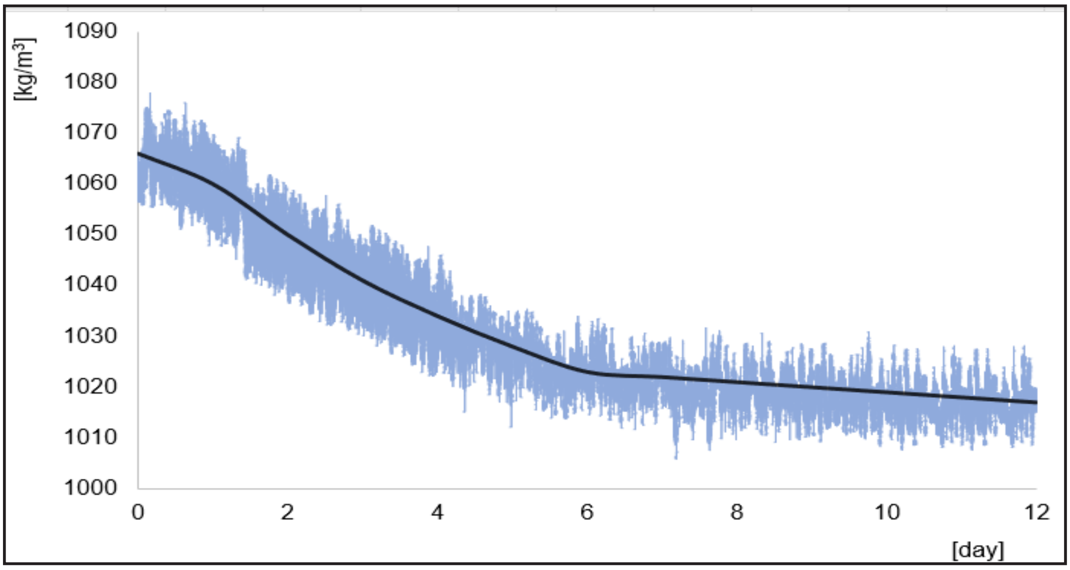
Figure 4 – Wort density measured results for the three applied



Source: Authors (2024)

Figure 5 presents the behavior of the wort density during the 12 days period. In this case, it was possible to identify a high dispersion in the measurements. This occurred due to the allowed temperature variation of up to 4 degrees Celsius in the fermentation tank and also by electrical noise caused by the power supply of the pressure sensors. However, the average tendency curve was consistent with the curve proposed by Kunze (2014) and has a concordance with the mean curve with the conventional hydrometer presented in Fig. 4.

Figure 5 – Results wort density measurements with digital hydrometer proposed



Source: Authors (2024)

5 CONCLUSIONS

In this paper, a novel device is proposed to measure wort density in a real-time and continuous fashion. The evaluation of the device was conducted by measuring the wort density during the whole process of fermentation of a Doppelbock lager. The density variation was monitored for 12 days, identifying a variation of 0.048 in the relative density, which results in 6.3 % of abv, which is consistent with the selected beer style.

The results obtained using the proposed digital hydrometer were compared with other devices commonly used by breweries to measure the wort density during the fermentation process. The proposed device performed well, obtaining results close to those measured with the conventional hydrometer, with a maximum deviation of 0.37 % at the beginning of the process. The results show that the implementation of the proposed solution by craft and commercial breweries is feasible since it permits continuous monitoring of fermentation, optimization of process time, and measured data history.

ACKNOWLEDGEMENTS

Projelmec Ventilação Industrial Ltda. for donating materials and carrying out the project.

REFERENCES

Beckwith, T.G., Marangoni, R. D., & Lienhard, J.H. (2011). *Mechanical Measurements*. 6. ed. Nova York: Pearson Education.

Brewer's Friend. (2011). *"Alcohol By Volume Calculator Updated".* Retrieved from: https://www.brewersfriend.com/2011/06/16/alcohol-by-volume-calculator-updated/.

Çengel, Y. A., & Cimbala, J. M. (2015). *Mecânica dos Fluidos:* Fundamentos e Aplicações. 3. ed. Porto Alegre: AMGH.

Caged. (2023). *Cadastro Geral de Empregados e Desempregados.* Retrieved from: https://www.gov.br/trabalho-e-emprego/pt-br/assuntos/estatisticas-trabalho/novo-caged/novo-caged-2023/dezembro.

Joint Committee for Guides in Metrology. (2008). *JCGM 100:2008: GUM: 1995 with minor corrections:* Evaluation of measurement data — Guide to the expression of uncertainty in measurement. Europe.

Kunze, W. (2014). *Technology of Malting and Brewing.* 5. ed. Berlim, Alemanha.

Lachenmeier, D. W., Godelmann, R., Steiner, M., Ansay, B., Weigel, J., & Krieg, G. (2010). Rapid and mobile determination of alcoholic strength in wine, beer and spirits using a flow-through infrared sensor. *Chemistry Central Journal*, 4(5), 10. DOI: https://doi.org/10.1186/1752-153X-4-5.

Brasil. (2023). *Ministério da Agricultura e Pecuária.* Anuário da Cerveja 2022. Ministério da Agricultura e Pecuária. Secretaria de Defesa Agropecuária. Brasília: MAPA/SDA.

Palmer, J.J. (2017). *How to Brew:* Everything you need to know to brew great beer every time. 4. ed. Brewers Publications.

Viginoski, C. L. F. (2013). Sistema utilizando vibração de um transdutor piezoelétrico para medir densidade de um líquido. *Dissertação (Mestrado em Engenharia Elétrica*) - Universidade Federal do Paraná, Curitiba, PR.

White, C., & Zainasheff, J. (2010). *Yeast:* the practical guide to beer fermentation. Colorado: Brewers Publications.

Authorship contributions

1- Charles Rech

PhD in Mechanical Engineering, Professor of the Mechanical Engineering Course, Universidade Federal de Santa Maria – Cachoeira do Sul.
https://orcid.org/0000-0001-8523-6300 • charles.rech@ufsm.br Contribution: Conceptualization, Methodology, Writing - original draft preparation, Formal analysis and investigation

2 – Simone Ferigolo Venturini

Master’s Degree in Mechanical Engineering, Professor of the Mechanical Engineering Course, Federal University of Santa Maria – Cachoeira do Sul.
https://orcid.org/0000-0002-9439-0008 • simone.venturini@ufsm.br Contribution: Conceptualization, Methodology, Writing – original draft preparation– review & editing

3 – André Francisco Caldeira

PhD in Electrical Engineering Professor of the Electrical Engineering Course, Federal University of Santa Maria – Cachoeira do Sul.
https://orcid.org/0000-0002-4939-2709 • andre.caldeira@ufsm.br Contribution: Review & editing

4 – Mathias Verdum de Almeida

Mechanical Engineering Academic, Universidade Federal de Santa Maria – Cachoeira do Sul
https://orcid.org/0009-0002-5371-9441 • mathias.verdum@acad.ufsm.br
Contribution: Review & editing

5 – Arthur Sandri Lunkes

Mechanical Engineering Academic, Universidade Federal de Santa Maria – Cachoeira do Sul
https://orcid.org/0009-0005-7750-8421 • arthur.lunkes@acad.ufsm.br
Contribution: Review & editing

6 – Maximiliano Silveira de Souza

Mechanical Engineering Academic, Universidade Federal de Santa Maria – Cachoeira do Sul.
https://orcid.org/0009-0000-5236-0196 • maximiliano.silveira@acad.ufsm.br
Contribution: Review & editing

How to quote this article

Rech, C., Venturini S. F., Caldeira, A. F., Almeida, M. V., Lunkes, A. S., & Souza, M. S. Digital monitoring of alcoholic beverage fermentation. *Ciência e Natura*, Santa Maria, v. 46, spe. 3, e86991, 2024. DOI: https://doi.org/10.5902/217946086991.