Journal of Food Engineering 353 (2023) 111537

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

A new approach for monitoring the alcoholic fermentation process based on acoustic emission analysis: A preliminary assessment

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ARTICLE INFO

Keywords:
Acoustic emission
Alcoholic fermentation
CO_2 bubbles
Monitoring
Control

ABSTRACT

A preliminary study focused on the feasibility of using a new acoustic emission approach to be applied as predictive monitoring tool of temperature variation during the alcoholic fermentation process is evaluated. The acoustic signal produced by the CO_2 bubbling from a model fermenting liquid inoculated with *saccharomyces cerevisiae* was directly acquired by immersing a hydrophone into a 8 L lab scale experimental reactor. Fermenting liquid temperature was measured with a type-J thermocouple. Acoustic and temperature measurements were automatically and simultaneously performed each 30 min for a total fermentation period of about 4 days. Signals were digitalized and processed in dedicated software programmed on MATLAB® and LabVIEW®. Frequency distribution analysis and maximum peak of the dominant frequency in function of the time were used as acoustic parameters to correlate with the temperature change behavior during fermentation in the reactor. The acoustic emission method proved to be a promising and sensitive tool to characterize and describe the alcoholic fermentation process.

1. Introduction

Alcoholic fermentation is the anaerobic transformation of sugars (hexoses), mainly glucose and fructose, into ethanol and carbon dioxide. This process, which is generally (but not exclusively) carried out by yeast can be summarized by the overall reaction (see equation (1)).

$$C_6H_{12}O_6\ \ (aq) \rightarrow 2\ CH_3CH_2OH\ (l) + 2{\cdot}CO_2\uparrow\ (g) + 98,324\ kJ \qquad (1)$$

During the alcoholic fermentation the CO_2 is released once the fermenting liquid is saturated. On the other hand, the formed ethanol still dissolved although a small fraction evaporates during fermentation.

The CO_2 escapes from the fermenting liquid in form of bubbles of different sizes thus producing a characteristic acoustic emission and the heat is accumulated in de fermenting liquid. However, alcoholic fermentation is a quite complex process where biochemical, chemical and physicochemical processes take place at the same time (Zamora, 2009).

In beverages fermentation processes in general (wine, spirits and beer), apart of ethanol, different other formed compounds by yeast metabolism have been identified such as higher alcohols, esters, glycerol among others. (Torija et al., 2003; Zamora, 2009).

One of the most important aspects that can affect the fermentation process is temperature. Temperatures below 18 °C decreases the yeast growing rate during fermentation and over 35 °C the yeast culture dies. Also, sudden temperature changes can seriously affect the yeast. Therefore, thermic control in bio-reactors during alcoholic fermentations is crucial. (GAO et al., 2018; Torija et al., 2003; Zamora, 2009) (Celorrio et al., 2015; Lian et al., 2002).

However, although the temperature control in the fermentation reactor is one of the main control systems in chemical production process, its thermic control has some difficulties to take into account such as large hysteresis, time variation and non-linearity (GAO et al., 2018). The

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https://doi.org/10.1016/j.jfoodeng.2023.111537
Received 7 December 2022; Received in revised form 17 March 2023; Accepted 3 April 2023

complexity on controlling biological processes is mostly due to the presence of living organism and their metabolism is sensitive to process conditions, such as temperature, pH and substrate concentrations (Lisci et al., 2021). To overcome these automatic control issues in order to optimizing the temperature control process several control techniques and sensors has been applied (Bowler et al., 2021; Çelik et al., 2018; GAO et al., 2018; Kumar et al., 2019; Lisci et al., 2021; Varner et al., 2010).

Complex linear and nonlinear control techniques applying inverse neural networks have been proposed thus evidencing that the control problem for this system is not trivial (Lisci et al., 2021). Soft sensor is an alternative through which available on-line measurements are used in conjunction with a process model and an estimation algorithm to determine unmeasured variables. On the other hand, predictive control methods are preferred and demonstrated to ensure an efficient control process and minimize energy, costs and time consumption (GAO et al., 2018; Lisci et al., 2021).

Acoustic emission (AE) has been widely applied to characterize in a non-invasive/destructive way physico-chemical events such as material failure, pump cavitation, cavity effects in propellers and have proven to be accurate and sensitive techniques (Čudina and Prezelj, 2009; Leighton and Walton, 1987; Macias et al., 2015; Trávniiček et al., 2012; Vazquez et al., 2008). Other AE applications recently reported have been focused on the high porous material characterization and acid-base titration. The characteristic sound of gas effervescence in liquids has been used to efficiently assess textural characteristics of materials and reaction kinetics (Crespo Sariol et al., 2017; Peacok et al., 2020a, 2020b; Sariol et al., 2016).

Acoustic emission methods and ultrasonic techniques have been proposed to characterize and control the alcoholic fermentation process in wine and beer production (Bowler et al., 2021; Çelik et al., 2018; Varner et al., 2010). Piezoelectric sensors attached to the fermentation reactor surface were used to monitoring fermentation. The sensors' purpose was to acquire the sound of carbon dioxide bubbles emerging inside of the reactor and further processing the signal of the mechanic wave replicated in the reactor wall. However, no satisfactory results were obtained. As the sensor is attached to the reactor surface, acquires an indirect measurement of the fermenting sound which is affected by other external factors such as vessel shape, surface area, material structure and homogeneity level (Varner et al., 2010).Results of (Varner et al., 2010) were also confirmed by our research group when installing a piezoelectric sensor on the reactor wall did not satisfactorily and clearly detect the CO_2 bubbling process.

Several papers can be found concerning to the application of acoustic emission method to monitoring fermentation processes. However, those studies can be classified according to its approaches in two main groups: (1) Use of external piezoelectric sensors attached to the reactor's wall to monitoring the vibro-acoustic signal in the reactor, as in the case of the preliminary study published by Varner et al. (2010) which was also referred in this paper. In short, in this published report, 3 piezoelectric sensors were placed on the outside of the fermentation tank assembly and acoustic signals were measured continuously for the entire fermentation period. (2) The use of ultrasonic waves to detect changes in the density and viscosity of the fermenting liquid which in turn was correlated with the variation of saccharose/ethanol content during fermentation as in the case of N. Lamberti et al. (2009)and Bowler et al. (2021) where an ultrasonic technique was applied to the monitoring of alcoholic wine and beer fermentation. In this case, an external device was attached to the fermentation reactor consisting of a test tube, containing the analyzing fluid, between two matched ultrasonic piezoelectric transducers, one used as transmitter and the other as receiver. The transmitter generates an ultrasonic wave in the liquid sample which is acquired by the receiver; the attenuation and the delay of the received signal in respect to the transmitted one was used to characterize the testing fluid. It was correlated the propagation velocity of the ultrasonic wave with the saccharose concentration thus putting in evidence the possibility of monitoring the process using ultrasonic methods.

In the vibro-acoustic approach of (Varner et al. (2010)), they acquire the vibration of the vessel which in turn is an indirect and attenuated signal coming from the CO_2 bubbling. As explained previously, this approach is highly dependent from the reactors characteristics (reactor geometry, metal characteristics, wall thickness, volume of liquid in the reactor and pressure) thus a proper calibration for each specific condition is needed in this system since the acoustic interferences and impedances are a major problems to generalize this acoustic method in fermentation process. On the other hand, ultrasonic approach is just related with the use of higher frequencies (>20 kHz) in a transducer –receiver arrangement.

Comparing both cases with the presented study it is possible to notice the approaches differences. Instead of piezoelectric sensors, the study is conducted by applying a hydrophone and the acoustic signal is processed below the ultrasonic range and based on another physical context. So far, no references were found about using direct acoustic measurement of the CO_2 bubbling process by immersing a hydrophone directly into the fermenting liquid. The main advantage of the proposed acoustic method is the direct signal acquisition thus reducing the interferences effect compared with reported indirect methods and with a simpler concept compared with the ultrasonic measurements. This advantage, it places the proposed acoustic method in a more suitable position to be generalized as it is less dependent of the reactor's characteristics. Therefore, this study presents as novelty the use for first time a hydrophone as sensor in the measuring chain for directly monitoring the fermentation process focused not only in possible application in order to assess the physico-chemical variation in the liquid properties during fermentation but also the possibility to use the method as predictive temperature control tool.

In this study, acoustic emission is applied as predictive temperature monitoring tool for the alcoholic fermentation process. The acoustic signal produced by the CO_2 bubbling from a model fermenting liquid was directly acquired by immersing a hydrophone into the liquid. This work is a primary approach to evaluate the use of AE for the characterization, monitoring and predictive control optimization of temperature in alcoholic fermentation process with potential applications at industrial scale.

2. Materials and methods

2.1. Fermentation process preparation

Eight liters of a solution of brown sugar cane and distilled water were prepared at 14 °Bx. The pH of the solution was fixed at 3.8 by applying citric acid. Two liters of the solution were separated from the prepared solution and 3 g of dry yeast (*Saccharomyces Cerevisiae*) were inoculated. Ammonium phosphate was used as nitrogen substrate. An air flow of about 50 L/min (1 atm/25 °C) was vigorously injected to the 2 L of the inoculated sugar solution. The air was uniformly distributed in a bubble curtain from the bottom by applying a specific designed air diffusor system with bubble size average of 0.8 mm. The aerobic stage of the inoculated solution was kept for 6 h in order to guarantee a convenient microbial biomass growing till reach the 6 g/L in yeast concentration. After the aerobic stage, the 2 L enriched in yeast cells (biomass) was inoculated (mixed) to the other 6 L of brown sugar solution to complete the operational capacity (8 L) of an experimental reactor of 20 cm in diameter and 40 cm in height made of acrylic in order to perform regular visual inspections during the fermentation process.

2. 2- Acoustic emission analysis and set up

In order to acquire the acoustic signal produced by the CO_2 bubbles during the fermentation process, a Teledyne RESON ® TC-4033 hydrophone (Fig. 1a) was applied, with frequency range: 1 Hz −144 kHz and Sensitivity: 1 V/μPa. The hydrophone was introduced into the

Fig. 1. (a) Hydrophone TC4033. (b) Photography of the fermenting liquid and sensors location through the inspection window of the 8 L experimental reactor. 1-Hydrophone, 2-Type-J thermocouple sensor, 3-Fermenting liquid (after 24 h).

fermenting liquid in about 7 cm depth as depicted in Fig. 1b.

The reactor was covered with thermal isolation foam in order to reduce the heat loss to the environment. The thermal isolation allows to intentionally increasing the temperature of the fermenting liquid in the reactor according to the fermentation kinetics. As the idea is addressed to compare the acoustic and thermo-physical changes experimented by the liquid in the reactor during the alcoholic fermentation, the thermal isolation provides a better contrast to the temperature changes process which in turn will be compared with the acoustics variations measured.

As previously presented in Fig. 1 (b), for monitoring the temperature changes in the liquid during the fermentation process, a Type –J thermocouple was used. The thermocouple was placed keeping a close distance (about 2 cm) from the hydrophone sensor to take acoustic and temperature measurements almost at the same point. Both, the hydrophone and the thermocouple were placed in the central region of the reactor (Figs. 1 and 2) in order to avoid possible interferences on the sound and temperature measurements due to influence of geometry and other effects such as bubbles colliding with the wall of the reactor or lower temperature gradients formed nearby from the reactor wall.

Fig. 2 depicts the simplified scheme of the experimental set up. The alcoholic fermentation acoustic emission is captured by the hydrophone and amplified using a G.R.A.S.® Power Module. The signals from the hydrophone and the thermocouple are digitalized using a NI USB 6211 (0–100 kHz) data acquisition card to be recorded by the computer using dedicated software programmed on LabView®. The acoustic data was processed using MATLAB® software. In order to discard any external interference associated with the frequency of interest, spectrogram and components of frequency within the range of 0.2–100 kHz were recorded in the reactor filled with water. No external interferences (noise) were found in the original signal in the selected frequency range. A high-pass (HP) filter was applied for the signal filtering in the range of interest (0.2–10 kHz).

The uncertainty/accuracy estimated for the experimental setup considers the acoustical chain and data acquisition card contributions. NI USB-6211 acquisition card is designed for fast settling times at high scanning rates, ensuring 16-bit accuracy (Absolute Accuracy at full scale = 2.69 μV). The G.R.A.S. Power Module Type 12AQ has a gain error of ±0.1 dB. To minimize the error, the measurement chain was calibrated by applying a G.R.A.S® 42AP intelligent pistonphone.

Different descriptors of the fermentation acoustic signal acquired by the hydrophone were evaluated in function of the time, such as amplitude, frequency distribution and the root-mean-square power of the signal (RMS). Additionally, the fermenting liquid temperature and the room temperature were simultaneously recorded in the time domain.

The RMS of the signal was calculated applying the Parseval's theorem (with the contribution of Plancherel and Rayleigh) which takes into account the energy conservation law and being recommended for non-periodic signals analysis (Oppenheim et al., 2001; Peacok et al., 2020a) which is often described for discrete time signals with equation (2).

$$\sum_{n=1}^{N} x^2[n] = \frac{1}{N}\sum_{m=1}^{N} |X[m]|^2 \tag{2}$$

Where $X[m]$ is the discrete time Fast Fourier Transform (FFT) of $x[n]$ and N is the sample size.

Acoustic and temperature measurements were automatically performed in real time each 30 min in time laps (windows) of 30s. The whole process of measuring took a total period of 100 h (about four days of fermentation and 200 data points per fermentation experiments were obtained). After four days, the fermentation finished and the temperature and the acoustic parameters exhibited an asymptotical behavior in the time domain thus falling to the initial values recorded at "time zero". Fermentation experiments were replicated eleven times for further math processing and ensuring the reproducibility of the acquired data.

3. Results and discussion

Fig. 3 depicts the time–frequency spectrogram of the alcoholic fermentation acoustic signal. The sound produced by gas bubbles into liquids is a complex process which parameters basically depend on the gas nature, the physical properties of the liquid as wave propagation media and the bubble size. In general, the propagation of sound waves in a bubbly liquid involves the dynamics of the individual bubbles and their interactions. Each bubble acts as a resonator in which the gas acts as the spring and the moving mass is the liquid adjacent to the bubbles. Therefore, they produce an increment in pressure pulsation and a turbulent sound in a wide frequency range (Leighton and Walton, 1987; Trávniiček et al., 2012; Vazquez et al., 2008).

According to the spectrogram presented in Fig. 3, during the alcoholic fermentation, the CO_2 bubbling process is chaotic and bubbles of

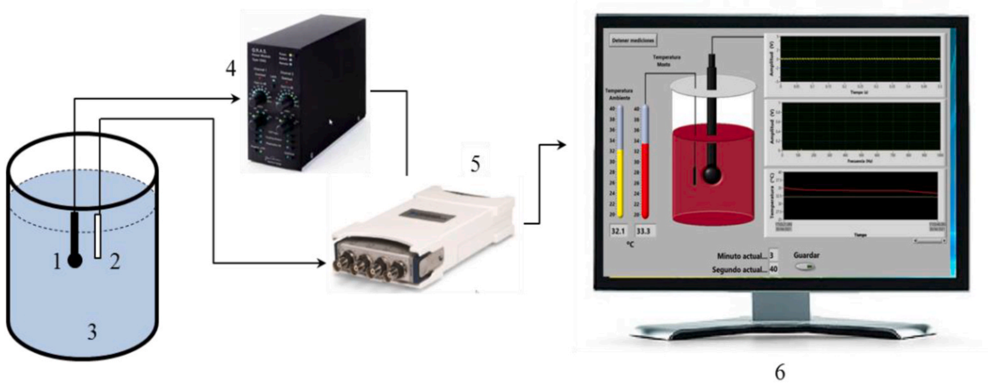

Fig. 2. Simplified scheme of the experimental set up. 1- Teledyne RESON ® TC-4033 hydrophone, 2-Type-J thermocouple, 3-Reactor with the fermenting liquid, 4-G.R.A.S.® Power Module type 12AQ, 5- NI USB 6211(0–100 kHz) data acquisition card, 6-Computer.

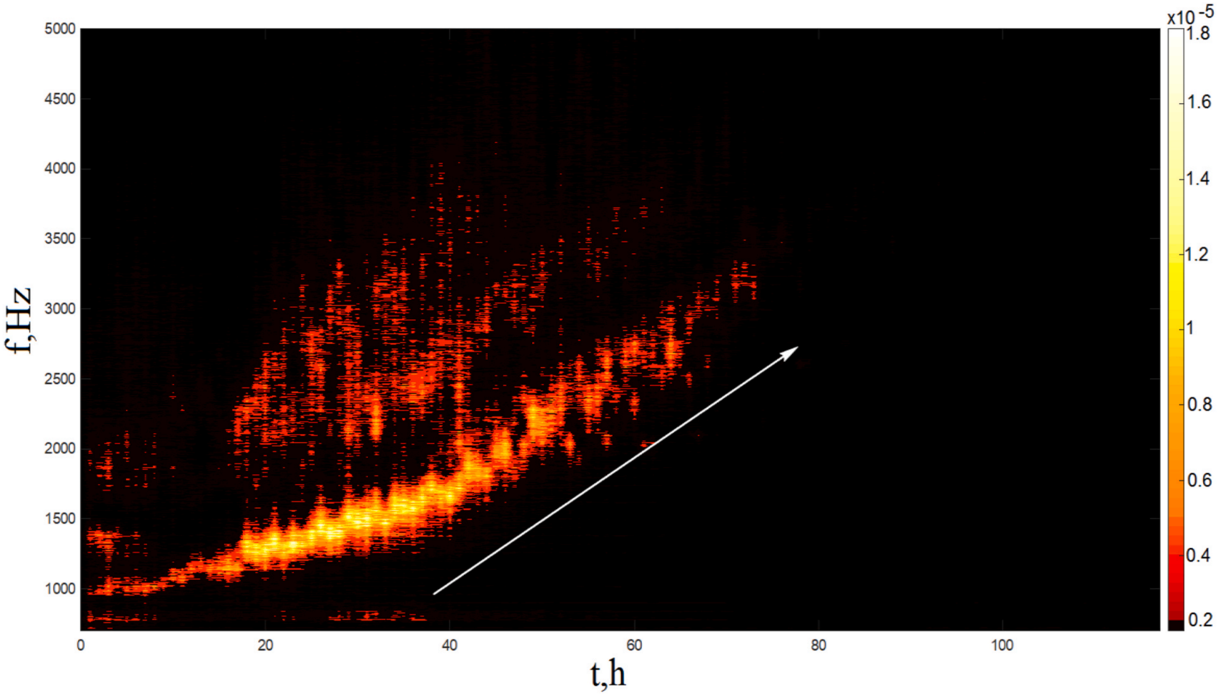

Fig. 3. Time (t) -frequency (*f*) spectrogram of the alcoholic fermentation acoustic signal. The arrow indicates a tendency of increasing of dominant high frequencies with the fermentation time.

different size appears at the same time defined by a specific frequency based on the Minnaert theory (1933) (Minnaert, 1933). Additionally, differences in the bubbles sizes and its volumetric concentration in the liquid as a function of the time can be noticed from the spectrogram in Fig. 3. The acoustic signal produced by the CO_2 bubbles during fermentation is obtained as the result of the contribution of different sounds at different frequencies which oscillates in the range of 1–4.5 kHz.

However, as indicated with the tendency line (arrow) drawn on the spectrogram in Fig. 3, it is noticeable a clear trend of increasing the dominant high frequencies with the fermentation time.

The CO_2 bubbles production process is ruled by the metabolic dynamics of the microorganism for the conversion of sugars into ethanol. Based on the Minnaert theory, the change of frequency distribution with the fermentation time observed in Fig. 3 occurs in first place (higher influence) due to the reduction of the dominant CO_2 bubbles size produced and in a second place (with a lower influence), due to the reduction of the density of the fermenting liquid by the ethanol formation and sugar consumption as substrate. Both, influences of the bubble size and density reductions in the fermenting liquid are bio-chemically and physically correlated as inherent part of the whole fermentation mechanism.

Fig. 3 is the starting point to define the signal processing methodology to follow up for the fermentation acoustics in terms of frequency range selection for the signal descriptors extraction and analysis in time domain to correlate it with the temperature changes during the fermentation process. In a closer view on the color scale in Fig. 3, the signal amplitude increases significantly to reach a maximum value within the fermentation time of 20–40 h with a progressive growing in the dominant frequency range of 1.3–1.8 kHz thus indicating a reduction in the dominant bubble size distribution in this stage. After 40 h of fermentation, although with a lower amplitude, the dominant frequency range still increasing to reach values around 4 kHz with the smallest CO_2 bubbles formed and dominating the system.

Based on the analysis of Fig. 3, a band–pass (BP) digital filter in the range of 0.7–5 kHz was applied to process the signal in order to capture just the fermentation sound within the frequency range of interest only related with the bubbling process in fact. After processing the signal within de BP filter at selected frequency range; the dominant frequency of the acquired signal each 30 min (with 30 s measuring window) was extracted based on the main peak value obtained from its frequency distribution analysis.

Fig. 4 displays the change in the maximum peak of the frequency distribution in function of the fermentation time. In this case, it is evident the change of the dominant frequency expressed as maximum peak in frequency distribution thus confirming the trend of smaller CO_2 bubbles formation in function of the time observed in the spectrogram of Fig. 3. Acoustically speaking and according to Fig. 4, at least two fermentation stages can be acoustically identified for this specific case.

The first 50 h of fermentation can be acoustically described by a low-disperse linear growing of the dominant frequency in the range of 1–2

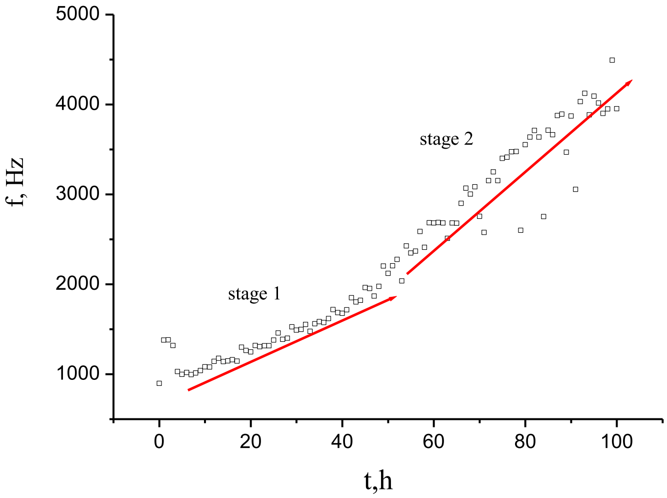

Fig. 4. Change in the maximum peak of the frequency (*f*) distribution (dominant frequency) of the alcoholic fermentation acoustic signal in function of the time (t).

kHz with a rate of change in about 20 Hz/h. The second stage for this case (Fig. 4) can be demarked from 50 to 100 h and 2–5 kHz (final period) where the dominant frequency growing rate is higher than the first period thus reaching about 34 Hz/h but with higher dispersion compared with the first period. However, as observed in Fig. 3, the amplitude of the signal in the stage 1 was higher than the stage two. Comparing both stages in terms of acoustics, the second fermentation stage is dominated for smaller gas bubbles. However, the number of formed bubbles of the first stage is higher thus indicating a more intense/vigorous fermentation stage.

Descriptive curves of the change of the fermenting liquid maximum peak amplitude (MP (in V)) of the acoustic signal at the dominant frequency and temperature (T (in °C)) in function of fermentation time (t) for eleven replicated experiments are depicted in Fig. 5(A) and (B) correspondently.

Comparing graphics (A) and (B), differences in terms of curves "morphology" are noticeable. Although the general shape and trajectory in function of the time are similar, the temperature curves describe a blunter envelope than the acoustic curves which present a more defined and higher peak.

Differences between curves can be explained based on the significant differences in the nature of each variable measured. The hydrophone acquire directly the sudden pressure waves from a chaotic bubbling system in liquid phase thus measuring in a very sensitive way the surrounding pressure changes. The acoustic signal measured is an expression of the combined result of the continuous thermos-physic and chemical changes in fermenting liquid and the bio-chemical reaction kinetics of the metabolic process of the microorganism to consume the subtracts and convert sugar into ethanol.

The bio-chemical reactions taking place affect other thermophysical and chemical properties of the fermenting liquid such as temperature, density, viscosity and pH due to the increasing of ethanol concentration and reduction of the sugar concentration in stoichiometric correlation. On the other hand, the temperature is a global and attenuated expression of the thermodynamic state of the fermenting liquid.

Therefore, temperature changes are inertial and represent an overall view of the dynamics between the heat generated during the fermentation and the heat loss through the reactor wall and gas released to the surroundings.

Therefore, the increment of the fermenting liquid temperature must be preceded by a proportional increment of the bio-chemical reaction rate of sugar conversion into ethanol which in turn produces a stoichiometric increment in the volume of CO_2 produced. Then the concentration of carbonic gas increases thus producing an increment in the bubbling sound amplitude. Based on that, prior to a temperature arising, an increment of the bubbling sound might be expected and then the acoustic method could be used to predict the thermodynamic change in the fermenting liquid to efficiently control the temperature in an optimal way.

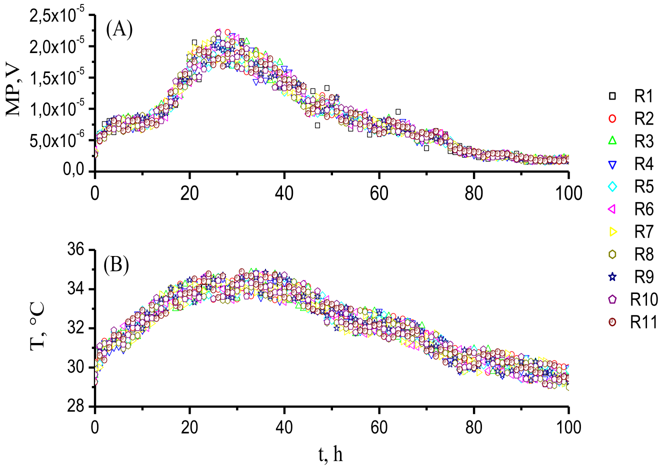

Fig. 5. Change of the fermenting liquid maximum peak amplitude (MP in V) of the acoustic signal at the dominant frequency (A) and temperature (B) in function of fermentation time. Ri: Replicated fermentation experiment (Run "i").

Fig. 6 displays the averaged acoustic (A) and temperature (B) curves obtained from Fig. 5(A) and (B) correspondently. Curves were also smoothed by applying fast Fourier transform (FFT) method in order to reduce the "noise" in the comparative analysis of the acoustic and thermodynamic behavior.

As previously discussed, the trajectory in function of the time described for both curves are similar. Therefore, Figs. 5 and 6 suggest the possibility to apply the CO_2 bubbling acoustic signal of the fermentation process in terms of maximum peak amplitude at dominant frequency as parameter to correlate with the temperature changes of the fermenting liquid.

According to the described specific experimental conditions, the average maximum temperature reached in the 8 L reactor was around 34 °C (Fig. 5 (B)) in the period of the maximum fermentation intensity (20–40 h) thus exhibiting a temperature increment from the average initial value (31 °C) in around 11%. In contrast, for the acoustic parameter evaluated (MP) at the same period, the average maximum amplitude reached around 7.5 times the initial value recorded at the beginning of the fermentation process (Fig. 6 (A)). This confirms that the changes found in the acoustic parameters are in a higher scale if compared with the temperature changes during the alcoholic fermentation. The high sensibility constitutes an advantage of applying the acoustic emission methods to characterize and monitoring in real time the alcoholic fermentation process. During the alcoholic fermentation process, temperature is a variable that describes the total thermophysical changes in the fluid. However, as it is a global variable with a significant inertial response in terms of automatic control. From the temperature profile in a fermentation reactor is not possible to obtain rapid and specific information about the biochemical activity in real time to take operational decisions on the process. In that sense, the acoustic measurements (if properly processed and interpreted) can continuously provide potential information about the microbiological activity and metabolic kinetics of the saccharose conversion into ethanol and CO_2 with significant sensibility. Then, the idea is not to substitute but complement both thermic and acoustic measurements in order to improve the accuracy in the fermentation monitoring and control.

Fig. 7 depicts the smoothed acoustic and temperature main curve peaks in the temporal window from 10 to 50 h plotted on a XYY graph.

Based on Fig. 7, for the studied experimental conditions, the main

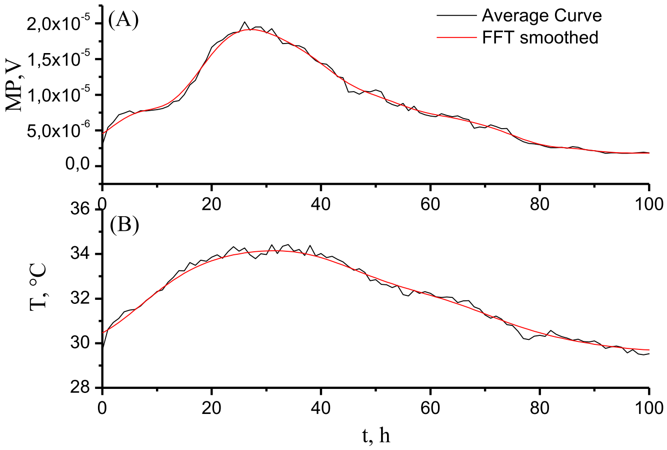

Fig. 6. Averaged and smoothed Curves of the acoustic peak amplitude (MP in V) (A) and temperature (B) in function of fermentation time. FFT: Fast Fourier transform.

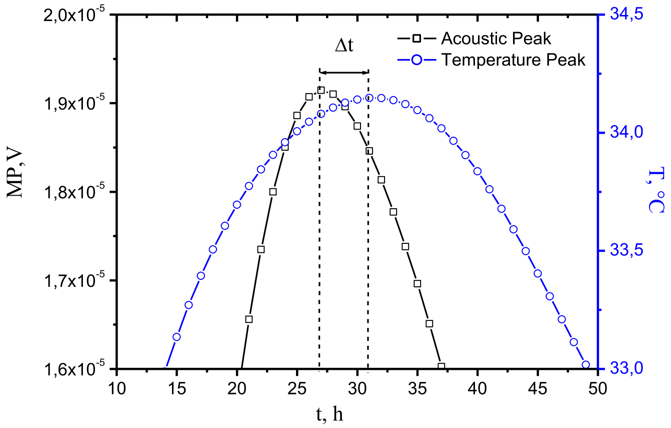

Fig. 7. Acoustic/thermodynamic delay in the curves of temperature and signal maximum peak amplitude.

peak in the temperature curve is delayed in about $\Delta t \approx 4$ h compared with the peak found in the acoustic curve.

A peak in terms of acoustics represents an increment in the fermentation activity where a higher amount of CO_2 in form of bubbles is released, thus the rate of metabolic conversion of sugar into ethanol and heat production also increases.

The heat produced by the biochemical reaction is then adsorbed by the liquid thus augmenting the temperature in the reactor. Therefore, a high acoustic peak will be traduced into a peak in the temperature curve later on.

The correlation between peak amplitude of both, acoustic and temperature will depend on the equilibria established between the rate of the heat produced linked with the fermentation intensity, the heat capacity of the liquid, and the rate of heat loss dissipated to the environment. However, the heat dissipated depends on the heat transference coefficients stablished and the heat transfer surface of the reactor.

Under that approach, the larger the reactor the lower its surface to volume ratio and the fermentation heat will be easily accumulated and the temperature increases faster in comparison with smaller reactors (see supplementary materials). Based on that, for large fermentation reactors (let's say more than 10000 L) it is expectable to obtain a shorter acoustic/thermodynamic delay compared with the presented experimental conditions.

The found acoustic/thermodynamic delay during fermentation process can be potentially applied for optimizing the predictive temperature control in alcoholic fermentation reactors at industrial scale. In Fig. 8, a general scheme of the predictive temperature control during alcoholic the fermentation process based on acoustic emission method is depicted. The proposed methodology and the dynamics of the process allows the

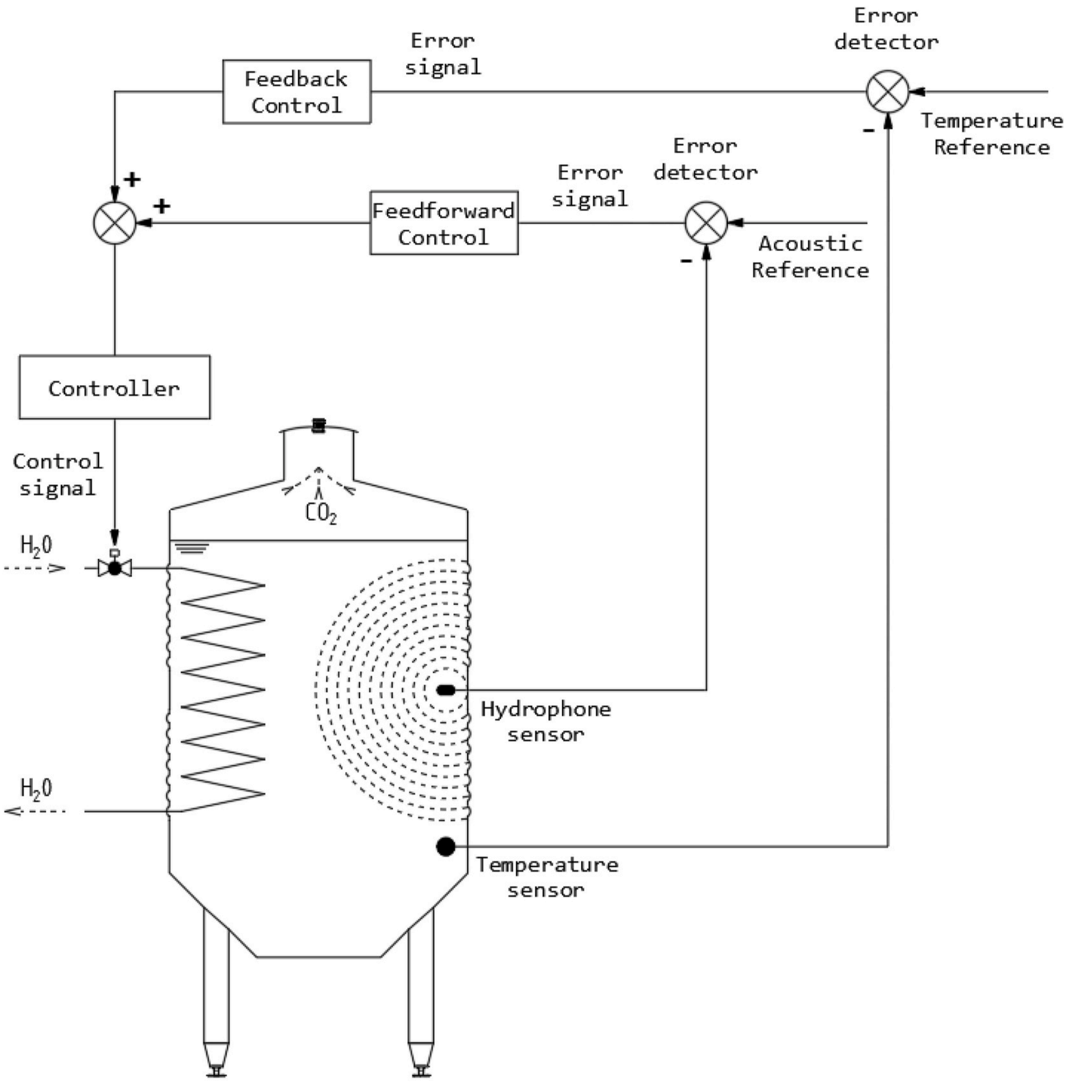

Fig. 8. General scheme of the predictive temperature control during alcoholic the fermentation process based on acoustic emission.

application of control methods that guarantee to maintain the controlled variable within the oenological limits compatible to stabilize the alcoholic fermentation. In this case, when the acoustic emission rate ($dACO_2/dt$), in other words, CO_2 production, exceeds a previously established limit ((ACO_2) set point), and taking into account a pre-established hysteresis value ($\Delta(ACO_2)$), the cooling control valve (Fig. 8) is opened to maintain the temperature at the desired value. In the other case, when the acoustic emission rate ($dACO_2/dt$), i.e. CO_2 production, is lower than a previously defined limit ((ACO_2) set point), taking into account a preset hysteresis value ($\Delta(ACO_2)$), the cooling control valve is closed, allowing the temperature to rise within compatible enological limits to reactivate the alcoholic fermentation. The value of $\Delta(ACO_2)$ selected in this algorithm is very important because this band will have a significant influence on the cooling system energy consumption of the plant.

However, further studies at larger (industrial) scale in wine fermentation process are under study in order to confirm the predictive accuracy and robustness of the proposed acoustic monitoring method. Different algorithms for signal processing need to be explored on the CO_2 bubbling sound during fermentation in order to obtain other signal descriptors which can be correlated with key parameters for fermentation assessment.

4. Conclusions

After analysing the obtained results, it can be stated that acoustic emission method showed to be a promising and sensitive tool to characterize and describe the alcoholic fermentation process specially focus on predicting temperature changes.

The increasing of the dominant frequency peaks in the acoustic signal in the range of (1–4 kHz) indicated a significant reduction of the CO_2 bubbles size distribution in function of the fermentation time. This is in correspondence with the diminishing of the liquid density due to the conversion of sugar into ethanol. Therefore, this suggests the possible application of the acoustic method to monitoring the changes in the physico-chemical properties in the fermenting liquid.

The acoustic method resulted to be a more sensitive method to detect subtle changes in the fermentation process compared with the temperature measurements. For the described experimental conditions in the 8 L reactor, as an average, each Celsius degree of temperature change in the fermenting liquid corresponds to a variation of $4.6\ E-6$ V in the acoustic emission signal amplitude of the maximum peak at the dominant frequency.

Temperature and acoustic curves described analogous envelope patterns in time domain. Replication of the acoustic peak in the temperature curve is expected to occur with a time delay which might be mainly dependent on the liquid characteristics, fermentation intensity and the reactor geometry. For the described experimental conditions, a delay of about 4 h in the maximum peak of the temperature curve compared to the acoustic curve was found for the most intense fermentation period (20–40 h).

For the 8 L fermentation reactor studied, the period of the maximum fermentation intensity was registered between (20–40 h). In this period, the temperature exhibited and increment in around 11% and the maximal peak the (acoustic parameter evaluated) increased 7.5 times its initial amplitude thus demonstrating that acoustic parameters variations are highly affected by overall changes during fermentation process compared with the temperature as monitoring variable.

The simplicity and advantages of the proposed acoustic emission analysis can be very interesting to be applied as predictive method to monitoring and optimize the temperature control in alcoholic fermentation reactors at industrial scale. The proposed methodology and the dynamics of the process suggests the application of control methods that guarantee to maintain the temperature within the oenological limits compatible to stabilize the alcoholic fermentation.

Nevertheless, further studies on the proposed acoustic method have to be addressed at larger scale and exploring other signal parameters to be correlated with other fermentation variables and fermenting liquid properties.

Author contributions

Conceptualization, S. Mamolar, H. Crespo-Sanol, and J.Blanco; data curation, S. Mamolar, H. Crespo-Sanol and A. Sanchez-Roca; formal analysis, A. Sanchez-Roca and J.C. Saenz-Diez; investigation, S. Mamolar, J.I. Latorre-Biel and H. Crespo-Sanol; methodology, J.Blanco and H. Crespo-Sanol; resources, A. Sanchez-Roca and J.C. Saenz-Diez; validation, J.Blanco and H. Crespo-Sanol; visualization, S. Mamolar, H. Crespo-Sanol and J.I. Latorre-Biel; writing—original draft, S. Mamolar; writing—review and editing, H. Crespo-Sanol, and J.Blanco.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jfoodeng.2023.111537.

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