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RESEARCH ARTICLE

Temperature control in an ultrasonic bath: a statistical experimental approach

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Abstract

This work aims to use ultrasound as a heating and stirring device, and its primary aim is to study the control of the operating temperature of an ultrasonic bath for various laboratory experiments in which temperature control is crucial. The combined effects of operating time (30-90 min), ultrasonic power (55-550 W) and frequency (35-130 kHz) on temperature control were systematically analyzed using a 23 full factorial design. The experimental data were used to develop a highly correct predictive model (R^2 = 0.999936) for effective temperature control across the studied parameter space. The simplified model is also included as a practical tool for controlling temperature during ultrasonic treatments. Moreover, the best conditions for stabilizing the temperature were found to be 30 minutes, 55 watts, and 130 kHz, which provided a stable and reproducible ultrasonic bath temperature. Such improvements provide a significant advantage over conventional temperature-control methods and open the door to potential applications in areas where correct temperature control is critical, such as sample preparation, analytical chemistry, quality control, and biotechnology. This work presents the first statistically optimized approach to ultrasonic bath temperature control.

Keywords: Statistical control, temperature variation, ultrasonic bath, experimental design, stability, optimization

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1. Introduction

Ultrasound, discovered by the English physiologist Francis Galton in the 19th century [1], is now widely used in various fields.

Ultrasound refers to mechanical waves with frequencies generally above 20 kHz that are beyond the threshold of human hearing. They propagate in a fluid or solid medium by vibratory transmission, which is characterized by a rapid alternation of compression and rarefaction phases. These vibrations are generated by a piezoelectric transducer that converts electrical currents into mechanical vibrations.

The use of ultrasound in liquid media produces significant physicochemical effects due to acoustic cavitation, which underlies many applications in chemistry and process engineering, especially in the food, pharmaceutical, and cosmetic sectors. They find themselves in many applications such as extraction [2–11], emulsification [2–6,10], drying, filtration and separation [2–6] and cleaning [2–6,12,13]. They are also used to promote alcoholic fermentation and control crystallization [14,15], for microbial inactivation and product stabilization [10,16-19], as well as for the development of sustainable energy technologies [20]. Moreover, ultrasounds can change biopolymers and enhance the efficiency of bioprocesses [16,17].

This versatility highlights a wider range of industrial applications for ultrasonic systems. Recent developments have shown that for industrial-scale ultrasound applications, such as extraction of natural products, it is important to have precise control of operation parameters, especially the temperature [21].

Moreover, ultrasound can be combined with other technologies like microwave, supercritical fluids, pressurized liquids,

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extrusion technology, osmotic dehydration and enzymatic extraction, which enhances the quality of the finished product and yields, reduces processing time and environmental impacts [22,23].

In an ultrasonic bath, cavitation microbubbles form in the bath liquid due to the propagation of ultrasonic waves. During the rarefaction phases these bubbles are formed and will increase in size until they suddenly burst open during the compression phases (Figure 1) [2,24].

This cavitation phenomenon handles mechanical, thermal, and chemical effects, thereby promoting the fragmentation of solid structures, enhancing mass transfer, or even easing the desorption of contaminants.

This phenomenon results in the generation of extreme temperatures and pressures [25,26]. However, the effectiveness of these effects strongly depends on the operating parameters: temperature, amplitude, frequency, power, and duration of sonication [8,12,22,27-31]. A notable increase in the temperature of the ultrasonic bath has been seen to depend on frequency and power levels. A substantial difference between the first and final temperatures was seen after a certain operating time [25,26], which directly affects the reproducibility of the results and the quality of the products obtained. This is why several studies have shown the need for careful temperature regulation to avoid thermal degradation of the extracted compounds and/or undesirable changes in the treated matrices [13,32-34]. As an example, Zhang et al. [35] showed that the control of the treatment temperature during ultrasonic processing can enhance the quality of the product and reduce the undesirable compounds. In the same way, Adamou et al. [36] pointed out that thermal control is an important aspect of ultrasonic reactors, which has direct impact on cavitation efficiency. The results are converging toward one conclusion: Fine temperature control is key to sensitive ultrasonic applications.

This study aims to control the operating temperature of an ultrasonic bath to provide stable and reproducible conditions for various laboratory applications. To achieve this aim, we modeled and optimized the operating parameters of the bath, namely duration, power, and frequency, and then checked the thermal stability of the bath over an extended period while applying the previously established best conditions.

In this study, three main innovations for temperature control in ultrasonic baths are introduced. First, statistical modelling of the operating parameters (power, frequency, duration) to predict temperature accurately. Innovative combination of experimental design and real-time thermal stability monitoring for long testing times (up to 4 hours). Applications in temperature sensitive processes (such as extraction, processing) within industrial applications with a requirement for a precision of ± 1 °C.

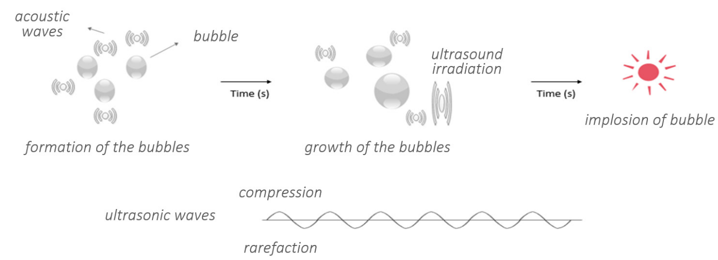


Figure 1. Ultrasonic cavitation dynamics in a liquid medium

2. Material and method

The study was performed using an Elma Transsonic TI-H 5 ultrasonic bath model, running at frequencies of 35 kHz and 130 kHz and powers ranging from 55 to 550 watts. This bath is fitted with a control system that enables very precise regulation of frequency and power, which is important for perfecting operating conditions.

2.1. Temperature monitoring

A digital thermometer with a measurement range of [-50 to 200] ± 0.1 °C was used to check the temperature in the ultrasonic bath, in real-time. It is sufficiently correct to measure temperature changes as small as desired in all experiments to ensure thermal control.

2.2. Physical principles of ultrasound

The thermal efficiency of ultrasound is based on three basic mechanisms:

Acoustic Cavitation: Rayleigh Plesset equation [25, 26] describes it:

$$R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{1}{\rho}\left(p_g - p_0 - P(t) - \frac{2\sigma}{R} - \frac{4\mu}{R}\frac{dR}{dt}\right) \quad (1)$$

where R = bubble radius, P(t) = acoustic pressure, σ = surface tension.

Thermal Effects: Bubble implosion causes localized temperatures > 5000 K and pressures > 1000 atm [26], with heat transfer being modeled by:

$$Q = \alpha \cdot P \cdot t \cdot e^{-\beta f}$$

Q = thermal energy, P = power, f = frequency, α,β = medium-specific constants.

Parameter Influence:

Power: Linearly correlated with the cavitation amplitude ($r^2 > 0.95$) [2],

Frequency: Inversely proportional to bubble size [37].

2.3. Optimization of parameters

It is important to optimize parameters that affect the temperature of the ultrasonic bath. Variables studied include the frequency, power, and operating time of the ultrasonic bath. The respective ranges of these variables are presented in Table 1.

Table 1. Experimental factors and intervals studied

Factors	Units	Coded variables	Low level (-1)	High level (+1)
Ultrasonic operating time	Minute	X_1	30	90
Ultrasonic power	Watt	X_2	55	550
Ultrasonic frequency	kHz	X_3	35	130

The power extremes (55-550 W) were selected to span the full operational range.

- Initial Conditions: The first bath temperature for all experiments was set at ambient temperature (20.1 ± 0.8 °C). The volume of water in the ultrasonic bath was always kept at 3/4 of the bath capacity to ensure uniformity.
- Full Factorial Design: Table 2 shows all possible combinations ($2^3 = 8$) of the high (+1) and low (-1) levels of the three variables studied, being a full factorial design. This factorial design is important for understanding the potential interactions among the variables and their effects on the response.

Each factorial point was replicated three times, with a 24-hour interval between replicates.

- Experimental Constants: In all experiments, two factors were kept constant: the first bath temperature, which equaled the ambient temperature, and the volume of water filled in the ultrasonic bath, which was 3/4 of the bath's volume.
- Theoretical Modeling: The equation of the theoretical model is built as: $\hat{Y} = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_{12}X_1X_2 + a_{13}X_1X_3 + a_{23}X_2X_3$

where: - $\hat{Y}$ is the response function,

- X_i are independent coded variables,
- a_0, a_i, and a_{ij} are the model coefficients.

2.4. Statistical analysis

Statistical analyses of the experimental data were performed using JMP software, version 3.2. This software was used to fit the model, estimate the coefficients, evaluate the statistical significance of the factors studied, and perfect them. An analysis of variance (ANOVA) was performed to assess statistical differences, with a significance level set at $\alpha = 0.05$. Regression coefficients and confidence intervals were also calculated to confirm the predictive model.

2.5. Monitoring thermal stability

To study the stability of the ultrasonic bath temperature over time under the defined best conditions, we checked the bath temperature every 10 minutes for four hours using a calibrated digital thermometer (± 0.1 °C). The continuous monitoring enabled us to confirm the temperature stability under best conditions and to detect temperature changes.

Table 2. Experimental full factorial design using real and coded values

	Factors					
	Operating time		Power		Frequency	
Experiences	x_1 (min)	X_1	x_2 (Watt)	X_2	x_3 (kHz)	X_3
1	30	-1	55	-1	35	-1
2	30	-1	55	-1	130	1
3	30	-1	550	1	35	-1
4	30	-1	550	1	130	1
5	90	1	55	-1	35	-1
6	90	1	55	-1	130	1
7	90	1	550	1	35	-1
8	90	1	550	1	130	1

3. Result and discussion

3.1. Experimental results

All experiments in the experimental matrix were conducted in random order, and the results are presented in Table 3.

Table 3. Obtained results (experimental and predicted responses)

	Factors			Responses	
Experiences	Operating time	Power	Frequency	Texp. (°C)	Tpre. (°C)
1	-1	-1	-1	21.8	21.66
2	-1	-1	1	20.8	20.94
3	-1	1	-1	40.8	40.94
4	-1	1	1	40.7	40.56
5	1	-1	-1	24.8	24.94
6	1	-1	1	22.9	22.76
7	1	1	-1	65.3	65.16
8	1	1	1	63.2	63.34

Texp.: experimental response, **Tpre.:** calculated response

3.2. Variance analysis (ANOVA)

The analysis of variance (ANOVA) for the response variable "Temperature" is summarized in Table 4. Results prove that the model explains 99.99 % of the experimental variance (R^2 = 0.9999, Table 4), confirming its strong agreement with observed values [38,39]. The experimentally calculated Fisher-Snedecor value for temperature (F_{exp} = 2594.080) is higher than the critical Fisher-Snedecor $F_{critical}$ value ($F_{0.05}(6, 1)$ = 234) [38,39]. In addition, the model proves excellent fit, with near-unity values for both determination coefficients (R^2 = 0.999936 and $R^2_{Adjusted}$ = 0.99955) [39].

Table 4. ANOVA analysis

Source	Degree of freedom	Sum of squares	Mean square	$F_{exp.}$	Prob. > F
Model	6	2354.1275	392.355		
Error	1	0.1512			
Corrected total	7			2594.080	0.0150*
R square	0.999936	2354.2787	0.151		
R adjusted squared	0.99955				

$F_{exp.}$: Experimental Fisher-Snedecor, *: Significant at 95 % ($F_{0.05}(6, 1)$ = 234) [38,39].

3.3. Coefficients estimation and statistical study of factors effects

Table 5 displays the model coefficient values, effect magnitudes, and statistical significance. At the 95% confidence level, the analysis reveals that only time, power, and their interaction term have a significant influence on the response variable. Additionally, all significant coefficients show positive directional effects, as presented in Table 5.

Table 5. Coefficients of the estimated model

Term	Estimate	Ratio t	Prob. > |t|
Constant	37.5375	273	0.0023*
Time	6.5125	47.36	0.0134*
Power	14.9625	108.82	0.0059*
Frequency	-0.6375	-4.64	0.1352
Time x power	5.2375	38.09	0.0167*
Time x Frequency	-0.3625	-2.64	0.2308
Power x Frequency	0.0875	0.64	0.6392

*: Significant at a level of 5 % [38,39].

The length of the bars in Figure 2 visually is the relative *influence* of each factor in the statistical model. Analysis of the bar heights and coefficient signs in this graph shows that the most influential factors are power, time, and their interaction. The other terms, although they have positive or negative signs, are not significant and do not substantially affect the response. These results highlight the importance of focusing on power and time during optimization, while also considering their interaction to perfect their effect on the response. Non-significant factors can be considered less important or negligible in the analysis.

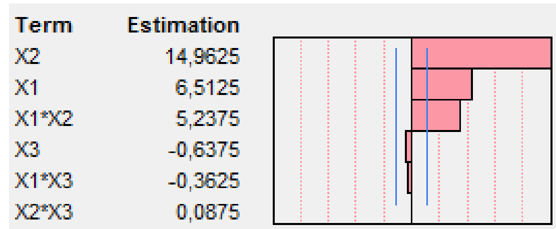


Figure 2. Estimation of model-term coefficients with a visual representation of their relative importance

From the Pareto chart (Figure 3), the most influential factor on the response variable is power (coefficient = 14.9625). This result is a reminder of the significance of power in our model; the effects of time and the interaction time x power are considerable, but not as strong as the effect of power.

The results agree with the first hypothesis, namely that the observed variation is mainly due to power. The Pareto chart clearly confirms this dominance and shows that the other terms, such as frequency and the power x frequency and time x frequency interactions, have comparatively small effects due to their smaller coefficient values.

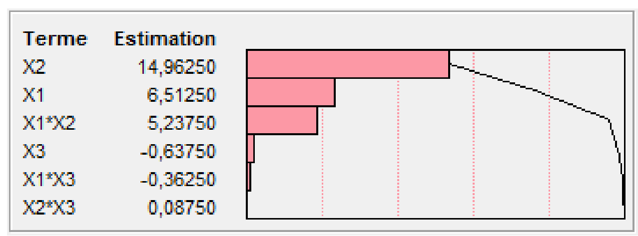


Figure 3. Pareto chart of coefficient estimates for the model terms

The Pareto chart shows the relative importance of the terms in the statistical model based on their coefficient estimates. The bars are the individual effect of each term, while the black curve shows the cumulative effect.

3.4. Modelization

Estimating the coefficients of the mathematical model yields the following equation:

$$\hat{Y} = 37.5375 + 6.5125X_1 + 14.9625X_2 - 0.6375X_3 + 5.2375X_1X_2 - 0.3625X_1X_3 + 0.0875X_2X_3$$

However, the presence of non-significant coefficients in the mathematical model can impair its quality. Therefore, to address this, we need to simplify it [40-44]. At a significance level of 95%, the equation of the mathematical model is formulated as follows:

$$\hat{Y} = 37.5375 + 6.5125X_1 + 14.9625X_2 + 5.2375X_1X_2$$

Within the experimental range, the simplified model (Eq. 3) is rigorously valid:

- Parameter ranges: 55-550 W / 35-130 kHz / 30-90 min,
- Operating conditions: aqueous bath, 3/4 fill level, initial temperature of 20.1 ± 0.8 °C.

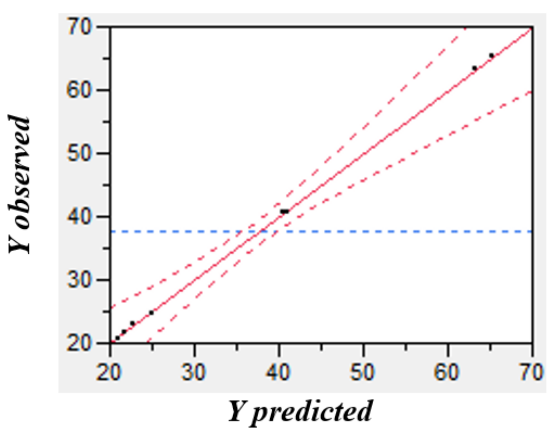
This validation is confirmed by:

- Statistical criteria (R^2 ~1, $p < 0.05$),
- Model-experiment agreement (deviation ≤ 0.1 °C),
- Test reproducibility (triplicate runs).

These findings are consistent with the recent results of Cauduro et al. [21] who found that the thermal variation during ultrasonic extraction is one of the main challenges for large-scale reproducibility.

3.5. Validation of the model

The experimental and predicted results are presented in Table 3. The results of the statistical analysis show no significant difference between the experimental and predicted values, thereby confirming the specified model. In addition, the experimental and predicted values are correlated, as shown in Figure 4. The coefficient of determination (R^2) is 1, and the p-value for the regression is <0.05. This means that 100 % of the variability in temperature can be explained by the established model [39].



R^2 = 1, P = 0.015, Residual standard deviation = 0.3889

Figure 4. Correlation between saw and predicted values

3.6. Model generalizability

The developed model is based on power and time, which are fundamental parameters for most ultrasonic bath systems, showing that the model may apply to other bath systems. However, different changes might be needed based on the technical specifications of each system.

3.7. Optimization of operating conditions

Figure 5 plots the prediction profiles along the central axis and reveals the impact of experimental parameters on the response T. There is a very high positive correlation of response T with both power and time, which shows that the bath temperature increases proportionally with power and time. In contrast, frequency has a negligible impact within the experimental range studied. The heating of the medium is due to the acoustic wave. The latter must be sufficiently powerful to ensure cavitation formation in the medium during the sonication duration [15].

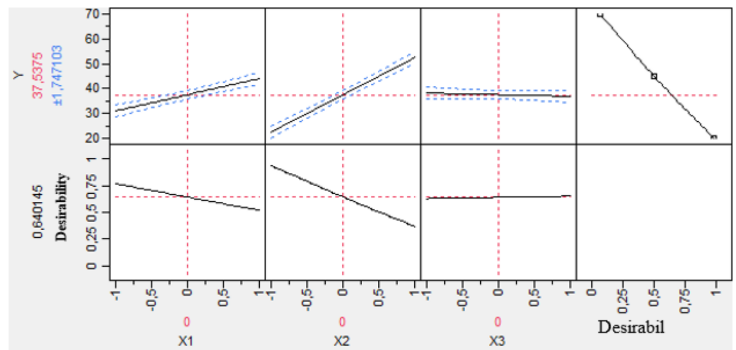


Figure 5. Profile of predicted factor values on temperature along the central axis

Figure 6 shows how each factor influences response T and how these effects translate into overall desirability at the point of interest. The goal is to adjust the studied variables to minimize response T while maximizing desirability. In this context, power appears to be the most influential factor controlling temperature, followed by time. Frequency seems to have a negligible effect. The interaction between time and power may be relevant, but the other interactions appear to have little influence. These results suggest that special attention should be paid to power when perfecting the temperature.

Therefore, the search for the best operating conditions of the ultrasonic bath to minimize temperature variability, guided by the established mathematical model (Figure 6), has led to the following results:

- X_1 = -1 in coded value, corresponding to a time of 30 minutes,
- X_2 = -1 in coded value, corresponding to a power of 55 watts,
- X_3 = +1 in coded value, corresponding to a frequency of 130 kHz.

These conditions have been identified as best for stabilizing the temperature of the ultrasonic bath within the experimental domain studied.

Our study reveals no significant frequency effects in the range from 35 kHz to 130 kHz, but earlier work [37,45] shows that outside this range frequency is a critical parameter controlling the main ultrasonic phenomena.

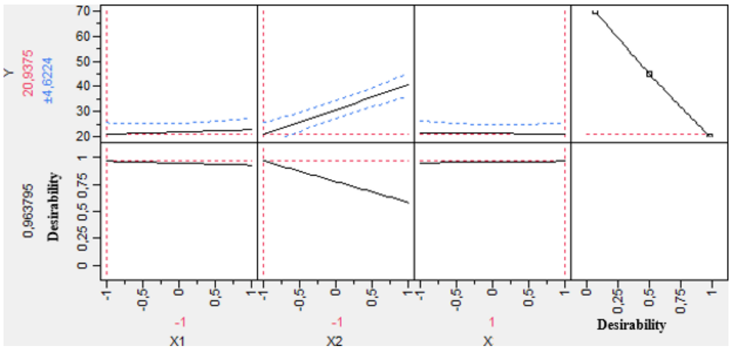


Figure 6. Profile of predicted factor values on temperature along the point of interest

3.8. Experimental validation

Experimental validation of the best conditions is needed to confirm the concordance between empirical data and model predictions. Experimental verification at the best point, performed with 3 repetitions, was imperative. The average result from the three experiments will be compared with the predicted value. The purpose of repeatability in this case is to minimize the experimental error inherent in the process. The average temperature of the ultrasonic bath at the end of the three repetitions at this point is 20.8 °C ± 0.1 °C, knowing that the first ultrasonic processing temperature was 20.1 °C ± 0.8 °C, compared to 20.94 °C ± 0.1 °C under best conditions. This result shows only a small difference between the calculated and experimental values. These findings show that the temperature change under best ultrasonic processing parameters is negligible. Thus, the model is representative of the response under study.

3.9. Control chart of temperature

Under the designed best conditions, the operating temperature of the bath over time is shown in the control chart in Figure 7. The chart shows temperatures measured at various time points and includes lines showing the upper and lower control limits (UCL and LCL) and the meaning. The measured temperatures stay well below the upper limit (UCL) and well above the lower limit (LCL). This suggests that the operation of the bath under the predefined best conditions is stable and that the temperatures are kept within acceptable control limits throughout the study period. This study has proved successful temperature control in the ultrasonic bath.

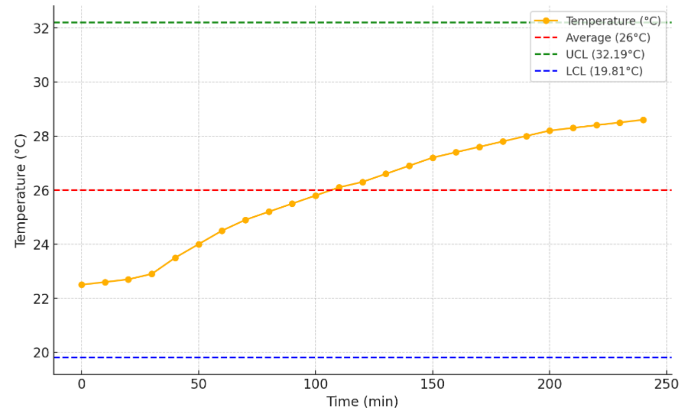


Figure 7. Operating temperature control chart of ultrasonic bath at best conditions as follows: Time = 30 min, power = 55 watts and frequency = 130 kHz, with: T_0 = 22.5 °C

This ongoing monitoring showed that:

- Target maintenance: Temperature remained within ± 0.5 °C of the target value.
- Inter-experiment consistency: Between triplicate runs, the maximum variation was 0.1 °C, meeting reproducibility standards for sensitive processes.
- Safety compliance: No excursions exceeded +5 °C above ambient temperature, preventing the risk of thermal degradation.

3.10. Relevance of the study

As was the case in the study by Perez et al. [46] who developed a thermal characterization method for ultrasonic baths, it is important to consider the relevance of the study; our study highlights the importance of buying the right thermal parameters. But this study is different from Perez et al., as it not only characterizes these parameters, but also optimizes them for temperature control. Optimization is important for applications in which temperature changes, even small ones, may affect results, such as large-scale industrial processes. Further studies on the effect of high-intensity ultrasound on the extract show that the temperature must be controlled precisely. The temperature changes in such systems can cause large deviations in quality such as texture, color and nutritional value [47]. Of particular interest is the control of temperature in ultrasonic baths, which helps minimize these effects while keeping the desired properties of sensitive products during processing.

In addition, studies have focused on the issues of implementation of power ultrasound technology in large-scale operations where the ability to control and check the heating process with accuracy is very important [48]. Our model is confirmed at laboratory scale and can be scaled up to industrial scale. Future research could involve scaling up the method and integrating it with real-time monitoring systems to enable its application for consistent temperature control in large-scale industrial processes with complex systems.

4. Conclusion and future perspectives

The use of the ultrasonic system with the application of statistical process control (SPC) greatly reduced temperature variability. Considering the influencing factors, we built a predictive mathematical model of the temperature response using experimental design method. Temperature variability under best operating conditions did not exceed 6 °C during the four-hour operating cycle. This study aims to address the need for thermal control in applications where temperature is critical to product quality and/or process efficiency, for example, in heat-sensitive applications. The model would enable the use of ultrasonic baths as effective tools for real-time control systems, so they can be integrated into industrial applications without compromising their reliability as processing devices.

The three problems to be solved for industrial application are adaptive dynamic control systems, compensation for thermal losses during large-volume operation, and optimization of power efficiency in transducers. These will guide future research. The model has good fit (correlation coefficient $R^2 \approx 1$) in controlled lab conditions (Elma Transsonic TI-H-5 bath), but it needs to be confirmed in a broader range. Research priorities include scale-up parameters (model validation under different tank configurations and transducers), fluid properties (investigation of non-aqueous media, such as solvents and fluids with different cavitation characteristics), and volume effects (systematic analysis of the power-to-volume ratio to achieve the model scaling laws).

Author contributions statement

Khadija Outalb: Investigator, formal analysis, writing – original draft; Hassan Chaair: Methodology, formal analysis, validation, writing – review & editing, supervision, Khalid Digua: Methodology, formal analysis, software; Soumia Belouafa: Conceptualization, method, formal analysis, validation, visualization, writing – review & editing, supervision.

Declaration of interests

The authors have no financial or personal conflicts of interest related to this work.

Data availability

All the data in the manuscript are available upon request.

Declaration of generative AI and AI-assisted technologies in the writing process

No generative AI or AI-assisted technologies were used in the writing process.

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