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OPTIMIZING THE DENSITY OF ULTRAFINE BUBBLES FLUID BY TIME AND PRODUCTION VOLUME IN A CLOSED-LOOP SYSTEM

OPTIMASI DENSITAS FLUIDA ULTRAFINE BUBBLES BERDASARKAN VARIASI WAKTU DAN VOLUME PRODUKSI DALAM SISTEM UNTAI TERTUTUP

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ABSTRAK

Ultrafine bubbles (UFBs) memiliki peran penting sebagai katalis dalam pengolahan air, farmasi, biomedical engineering, dan proses industri yang salah satunya melibatkan aspek mekanisme perpindahan kalor. Beberapa periset Indonesia telah mengkaji potensi fluida ultrafine bubbles sebagai media perpindahan kalor dalam model sistem pendinginan pasif. Melalui model pendinginan pasif, perubahan densitas fluida ultrafine bubbles menjadi faktor utama penggerak aliran. Ultrafine bubbles mengalami perbesaran ukuran diameter saat dipanaskan, sehingga untuk menjamin ketersediaan ultrafine bubbles dalam aliran, perlu dikaji model produksi yang optimal. Yaitu hasil produksi fluida ultrafine bubbles yang didapatkan adalah nilai densitas terkecil terhadap fluida dasar (referensi). Penelitian ini kemudian mengeksplorasi optimasi densitas ultrafine bubbles dalam sistem produksi closed-loop, dengan fokus pada dampak variasi waktu produksi dalam volume tertentu. Tujuannya yaitu untuk mendapatkan densitas optimal fluida ultrafine bubbles dengan variasi waktu produksi selama 30, 60, 90, 120, 150, dan 180 menit dengan volume tangki 20, 40, 50, dan 60 liter. Model produksi ultrafine bubbles dalam closed-loop menggunakan kavitasi hidrodinamik menghasilkan aliran fluida berkelanjutan. Jeda waktu produksi pertama dan selanjutnya dilakukan selama 15 menit. Kondisi tersebut memungkinkan pencuplikan sampel karena sudah tidak ada pergerakan gelembung yang membesar. Berdasarkan pengamatan dan analisis statistik menggunakan Response Surface Method (RSM), diperoleh hubungan nonlinier antara waktu produksi dan densitas fluida ultrafine bubbles. Densitas optimal dicapai pada waktu produksi 60 menit untuk volume 40 liter. Selain itu, model closed-loop ini juga dapat meningkatkan temperatur fluida ultrafine bubbles hingga 54,3^{0}C untuk volume 20 liter. Akumulasi panas terjadi akibat aliran yang digerakkan oleh pompa secara terus menerus tanpa menggunakan sistem pendingin tambahan.

Kata kunci: *Produksi closed-loop; Optimasi; Densitas fluida ultrafine bubbles; Efek akumulasi panas; Kavitasi hidrodinamik.*

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ABSTRACT

Ultrafine bubbles (UFBs) play a crucial role as catalysts in water treatment, pharmaceuticals, biomedical engineering, and industrial processes, particularly those involving heat transfer mechanisms. Several researchers in Indonesia have explored ultrafine bubble fluids' potential as a heat transfer medium in passive cooling system models. In this context, changes in the density of ultrafine bubble fluids serve as the primary driver for flow. Since ultrafine bubbles increase in diameter when heated, examining an optimal production model is essential to ensure their availability in the flow. This study aims to optimize the production of ultrafine bubble fluids with the lowest possible density compared to the base fluid (reference). The research investigates the effect of production time and volume variations on ultrafine bubble density in a closed-loop system. Production times of 30, 60, 90, 120, 150, and 180 minutes are tested across tank volumes of 20, 40, 50, and 60 liters. The closed-loop production model utilizes hydrodynamic cavitation to maintain continuous fluid flow, with sample collection occurring at 15-minute intervals after the initial production time to allow for stable bubble size. Observations and statistical analysis using the Response Surface Method (RSM) reveal a nonlinear relationship between production time and ultrafine bubble fluid density. The optimal density is achieved with a production time of 60 minutes for a 40-liter volume. Additionally, this closed-loop model increases the temperature of the ultrafine bubble fluid to 54.3 °C in a 20-liter volume. Heat accumulation occurs due to the continuous pump-driven flow without additional cooling systems.

Keywords: *Closed-loop production; Optimization; Ultrafine bubbles fluid density; Heat accumulation effect; Hydrodynamic cavitation.*

INTRODUCTION

Bubble behavior and dynamics in multiphase flows are critical in numerous industrial applications, including water treatment, food processing, and bioreactor operations. In biomedical engineering, ultrafine bubbles are effective as drug delivery systems and can significantly enhance therapeutic outcomes (Tran *et al.*, 2024). This highlights fluid density as a critical parameter in monitoring the quality of ultrafine bubble production. Specifically, optimizing bulk ultrafine bubble density based on production time variations can significantly influence system efficiency and performance. In heat transfer processes, bubbles act as thermal resistance when dispersed in water. During bubble generation from surfaces under nucleate boiling conditions, thermal energy is rapidly dissipated into the environment due to the higher buoyancy forces (Ghazivini *et al.*, 2022). Existing research has provided valuable insights into the fundamental principles governing bubble flow. For example, Particle Tracking Velocimetry (PTV) studies have measured bubble-bubble interactions, uncovering the complex dynamics in multiphase environments (Ashihara *et al.*, 2003). These findings emphasize the importance of understanding the balance between buoyancy-driven accumulation and turbulence-induced diffusion of bubbles near solid boundaries, which can lead to bubble clouds and intermittent motion.

Similarly, research on the effects of void fraction, bubble size, and liquid velocity on coalescence rates has yielded a mechanistic model for predicting how these parameters influence bubble dynamics (Kamp *et al.*, 2001). These studies lay the foundation for optimizing ultrafine bubble production and distribution, which are crucial for enhancing mass transfer, promoting chemical reactions, and improving overall process efficiency. Controlling the production time of ultrafine bubbles can directly affect their density and distribution, ultimately influencing system performance (Kamp *et al.*, 2001; Ashihara *et al.*, 2003; Kitagawa & Murai, 2013).

Ultrafine bubbles (UFBs), defined as bubbles with diameters less than one µm, exhibit unique physical and chemical properties (Yasuda, 2024). The ability to manipulate UFB density has significant implications for industrial applications. UFBs dispersed in water offer a considerable advantage by increasing the heat dissipation rate of a system. This phenomenon has been studied using UFBs as a working fluid for passive cooling systems. The small size of UFBs provides a higher surface area-to-volume ratio, improving heat transfer efficiency by facilitating rapid thermal energy removal. These properties make UFBs particularly suitable for applications in cooling technologies. In Indonesia, research on passive cooling systems focuses on optimizing heat exchanger models and working fluid characteristics (Sitorus & Abda, 2022; Juarsa *et al.*, 2024). Researchers are investigating various system parameters, including fluid dynamics (Roswandi *et al.*, 2024), heat exchanger designs (Antariksawan *et al.*, 2019; Haryanto *et al.*, 2024), and UFB production methods (Li & Zhang, 2022; Terasaka *et al.*, 2022), to enhance overall cooling efficiency. Ongoing research in this area aims to deliver more energy-efficient and effective solutions for thermal management.

Closed-loop production systems, which recycle inputs and outputs, offer a sustainable approach to bubble generation. In similar studies, the closed-loop ultrafine bubble production model using sonication resulted in a nonlinear density profile for production times of 1, 3, 5, 7, 10, and 15 minutes. The sonication method led to a temperature increase due to the absence of a dedicated cooling system acting as a heat exchanger (Budiman *et al.*, 2024). Unlike other production methods, this study employed hydrodynamic cavitation with a pump as the flow generator in a closed-loop production model. This model demonstrated that there was no change in fluid volume.

This study explores how time and production volume variations can optimize UFB fluid density. Production time variations are based on the UFB generator's minimum capacity of 30 minutes. A 15-minute delay is used for sampling, with an additional 5 minutes for the UFB fluid to stabilize, ensuring no bubble movement. Volume variations range from 20 to 60 liters, considering that the maximum capacity of the thermofluids testing facility is 60 liters. Optimization uses response surface methodology (RSM) for statistical analysis, which optimizes independent variables based on initial data and improves outcomes (Susaimanickam et al., 2023). The study's independent variables are production time and fluid volume, while the response variables are density and temperature.

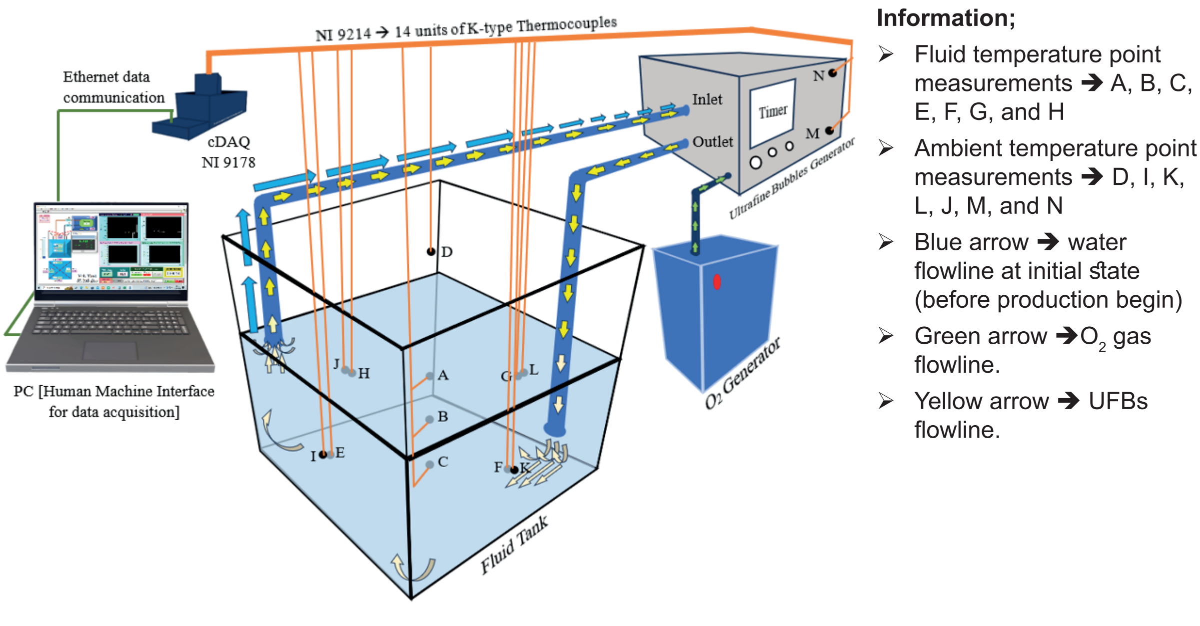


Figure 1.
Illustration of the temperature measurement points.
Source: Research document (2024)

The RSM approach involves experimental design analysis, ANOVA model validation, and post-analysis using contour plots to optimize system performance (Montgomery, 2013). The selected experimental design employs full factorial terms and is then evaluated against the experimental data.

Method

This study utilizes a closed-loop production model in which a pump circulates the fluid in the tank, allowing it to flow through the loop for a specified duration continuously. Demineralized water, with an electrical conductivity of <5 μS/cm, is used as the base fluid (reference) and is contained in the tank in a volume of N liters, where N represents the experimental matrix volume. Oxygen gas is injected at a controlled rate of 0.8 LPM into the loop, produced using an oxygen generator. Temperature data is collected using a National Instruments data acquisition system integrated with LabVIEW. The location of the temperature observation points is shown in Figure 1. A total of 14 K-type thermocouples were installed on the inner and outer surfaces of the tank, achieving a maximum standard deviation of 0.3. This configuration accurately monitors the temperature dynamics during and after ultrafine bubble production. As shown in Figure 1, the arrows indicate the direction of fluid flow. The pump is housed within the ultrafine bubbles generator, with the inlet connected to the oxygen (O_2) gas injection line. The combined flow of water and O_2 gas enters the production chamber and is expelled through the outlet. To minimize contamination and maintain sample quality, a valve at the bottom of the tank is used for sampling. The collected fluid samples were subjected to mass measurements, and their density was determined using the following equation:

$$\rho = \frac{m_{nett}}{V_f} \quad \text{...(1)}$$

Where at the equation 1, density ρ (mg/ml) is defined as the ratio of the fluid mass m_{nett} (mg) to the fluid volume V_f (ml). Note that 1 mg/ml = 1 kg/m^3. The m_{nett} is determined by the mass difference of the fluid-filled sample bottle compared to its void state.

The experimental procedure begins with instrument calibration, followed by testing the data acquisition system and preparing demineralized water, as illustrated in the flow diagram in Figure 2. This systematic approach ensures the reliability and accuracy of the data collected during ultrafine bubble production, enhancing our understanding of the system's dynamics. The analytical balance AND GF-300 were calibrated at three mass measurement points: 50, 100, and 200 grams, with a tolerance standard of M1 OIML class. The sample bottles were weighed three times without fluid to serve as a reference mass. Repetitions were conducted to provide more precise data for the measured variables. Subsequently, the data acquisition system for temperature recording was tested by observing the temperature measurement response through the HMI. Temperature measurements were recorded using a National Instruments NI 9214 data acquisition temperature module.

The module is integrated with the LabVIEW program as the central panel of the HMI. Data communication between the PC and the module was established using the ethernet protocol through the module connected to the NI 9178 cDAQ. Measurement points were placed in a particular position to observe changes in fluid temperature and the environment due to the production of ultrafine bubbles. Samples were collected according to the experimental matrix presented in Table 1. A successful sampling is determined by the impurity of samples by visual checking; if there are any contaminants, such as dust, the sample is discarded and collected again from the production tank. The production tank is designed to be open, making it vulnerable to contaminants. To avoid contaminant sampling, the sample sampling position was in the center of the production tank. Sampling was performed under a steady state, which was reached at 3 minutes after producing ultrafine bubbles.

Optimization was performed by analyzing the relationship between the independent and response variables using Response Surface Methodology (RSM). RSM is a mathematical and statistical approach used to design experiments and optimize a response influenced by multiple independent variables. Minitab was used to analyze the measurement data statistically. The general correlation of the relationship between the independent variables to predict the response variable (S) using RSM is expressed as:

$$S = \alpha_0 + \sum_{i=1}^{k} \alpha_i X_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \alpha_{ij} X_i X_j + \sum_{i=1}^{k} \alpha_{ii} X_{ii}^2 \qquad \text{..........(2)}$$

At the equation 2, where α_0 is a constant, k is the number of factors, and the coefficients α_i, α_{ii}, *and* α_{ij} represent the linear, quadratic, and interaction terms (Montazer *et al.*, 2017; Veza *et al.*, 2023). ANOVA analysis assessed the relationship between production time, volume, density, and temperature using F-value and P-value tests (Chen *et al.*, 2022). If the F-value exceeds the critical F-value, the null hypothesis is rejected, indicating statistically significant differences among the test data groups. Conversely, if the P-value exceeds 0.05, there is insufficient evidence to reject the null hypothesis, suggesting that the differences between the tested groups are statistically insignificant and likely due to random variation rather than a genuine effect of the independent variables (Dhemla *et al.*, 2022). Figure 2 outlines the experimental stages for the 20-liter volume matrix. The experiment was then conducted using new demineralized water for the 40-liter volume matrix. The experiments for the 50-liter and 60-liter volume matrices were performed with a one-day interval between them, adhering to the initial conditions for each matrix

Table 1.
UFBs Fluid Density Profile

Volume (liter)	Production Time (min)	Average Density (mg/ml)
20	0 (reference)	987.090
	30	982.131
	60	982.852
	90	984.617
	120	974.950
	150	977.100
	180	986.194
40	0 (reference)	983.841
	30	981.240
	60	967.591
	90	987.339
	120	980.967
	150	980.339
	180	974.251
50	0 (reference)	987.239
	30	982.071
	60	987.016
	90	972.557
	120	979.083
	150	980.050
	180	986.178
60	0 (reference)	988.070
	30	982.066
	60	984.361
	90	972.421
	120	981.583
	150	976.889
	180	990.533

Source: Measurement and Analysis Data (2024)

The initial condition was set with a 1°C bulk temperature difference. A 15-minute break was implemented to allow the bubbles to stabilize and reach a steady-state condition. This break minimizes the possibility of bubble instability or fluctuations, promoting more consistent results. Once the sample reached the reference temperature, the samples were weighed to ensure consistent measurements.

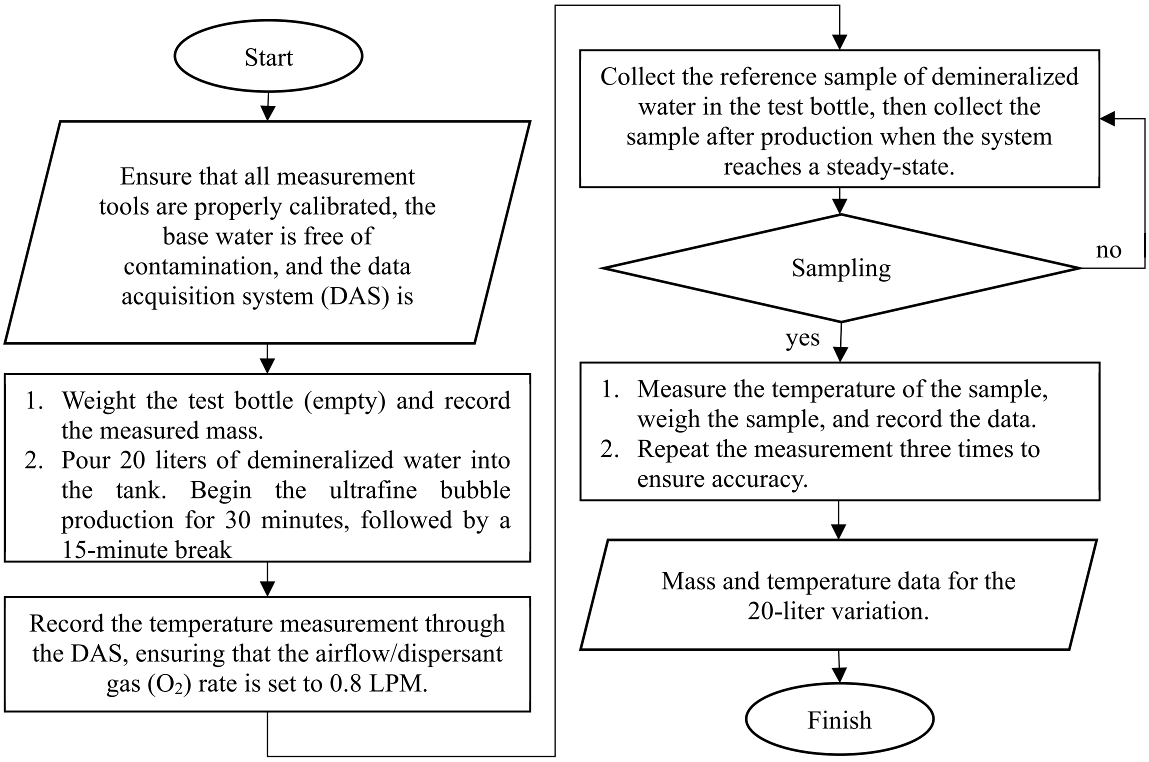


Figure 2.
Flow diagram of the experimental procedure for the 20-liter volume matrix.
Source: Research document (2024)

RESULT AND DISCUSSION

Temperature Analysis

Temperature is the critical point of ultrafine bubble quality production. If temperature changes are significant for internal pressure (Tran *et al.*, 2024), the experiment was taken with all temperature measurement points. The measurement data collected over 15,000 seconds reveals that the closed-loop production process significantly increases the bulk temperature of the UFBs fluid. Figure 3 illustrates the average UFB fluid temperature distribution at the central point of the tank (measurement points A, B, and C), where *t* (s) denotes the elapsed production time.

Each peak in the curve is caused by the intermittent production mechanism at 15-minute intervals. The results indicate that larger fluid volumes exhibit a slower temperature rise than smaller volumes. The black line, representing 20 liters of water, demonstrates the most rapid temperature increase, indicating that smaller fluid volumes heat up more quickly and reach peak temperature faster. In contrast, the purple line, representing 60 liters of UFB fluid, and the dark green line, representing 50 liters, show a more gradual temperature rise.

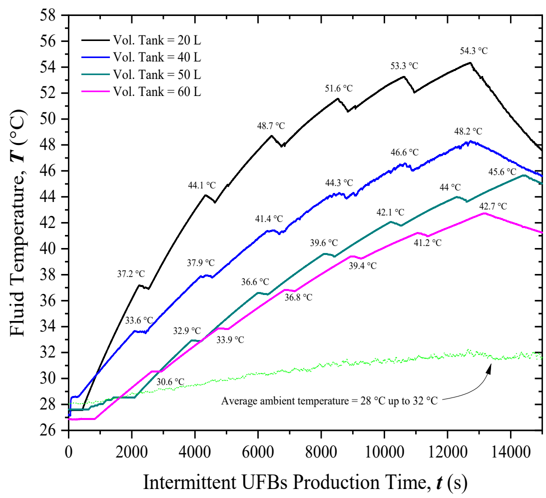


Figure 3.
Temperature profile during UFBs production.
Source: Observation and Analysis Data (2024)

The blue line, representing 40 liters of water, follows a trajectory between these extremes, with a temperature rise faster than that of 50 and 60 liters but slower than 20 liters. This inverse relationship between fluid volume and temperature increase suggests that larger volumes heat more slowly during UFB production. Additionally, the green line indicates a notable rise in ambient temperature, showing an increase of 4.67 °C during UFB production. Notably, this production model is similar to the sonication method, which increases temperature during production (Budiman *et al.*, 2024).

Density Analysis

According to Table 1, by mass measurement for each production sample, the density data was analyzed based on its deviation from the reference value. Figure 4 illustrates the extent of changes in UFB fluid density as a function of production time across various tank volumes. This visualization clarifies the correlation between production duration and density variations, emphasizing the impact of tank volume on fluid properties. The blue region labeled "Reference" indicates the baseline density measurement, serving as a standard against which all other values are compared.

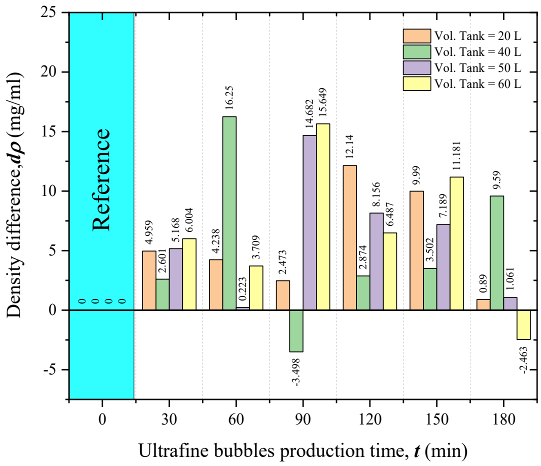


Figure 4.
Density differences across various production times.
Source: Analysis Data (2024)

During the 30-minute production period, density differences were relatively consistent across volumes from 20 to 60 liters. However, after 60 minutes of production, more varied density results were observed, with the highest value recorded at 40 liters (16.25 mg/ml) and the lowest at 50 liters (0.233 mg/ml). Similarly, the 90-minute production period showed variability, with negative density values of -3.498 mg/ml at 40 liters and two of the highest values at 50 and 60 liters. This indicates a nonlinear relationship between production time and UFBs fluid density, with the maximum observed density difference reaching 16.25 mg/ml, reflecting a reduction in overall density.

According to the temperature records, temperature increases often occur during the production run. Similar to previous production methods using sonication (Budiman *et al.*, 2024), temperature changes can affect nonlinear trends. However, in this study, in addition to temperature changes, the dynamics of the circulating fluid significantly impacted the coalescence of bubbles. The significant change in bubble diameter also causes a change in fluid density (Li *et al.*, 2021).

Optimization Analysis

Based on Table 1, the relationships among the variables were analyzed using ANOVA, resulting in the F-value and P-value shown in Table 2. The results demonstrate that the relationship between density and production time has a higher F-value than the volume variable, although the P-value is more significant than 0.05. This suggests that the observed variations are likely due to random factors. Meanwhile, analyzing the interaction plot in Figure 5 reveals a unique relationship between time and volume in influencing the response variable, density.

The interaction plot helps identify whether the effect of one factor on density depends on the level of another factor (Katemukda, 2023). The figure shows a complex interaction between time, volume, and density in UFB production. The density is influenced non-linearly by both volume and time, and this behavior is likely critical for optimizing UFB production parameters. In the plot on the upper right (volume and time), the horizontal axis represents volume values (20, 40, 50, 60), and the vertical axis shows average density values. Three lines represent different time values (0, 90, and 180). The blue line (time = 0) shows slight fluctuations in density as volume increases but no significant change. The green line (time = 180) follows a similar pattern. However, the red line (time = 90) shows a lower density, with the lowest value at 40 liters.

Table 2.
ANOVA results for density, production time, and volume

Variable	Source	Degree of Freedom	Adjusted Sum of Square	Adjusted Mean Squares	F-Value	P-Value
Density vs Production Time	Time	6	214.9	35.82	1.23	0.330
	Error	21	610.3	29.06		
	Total	27	825.2			
Density vs Volume	Volume	3	40.75	13.58	0.42	0.743
	Error	24	784.46	32.69		
	Total	27	825.21			

Source: Analysis Data (2024)

This suggests that there is only a slight interaction between volume and time in their effect on density.

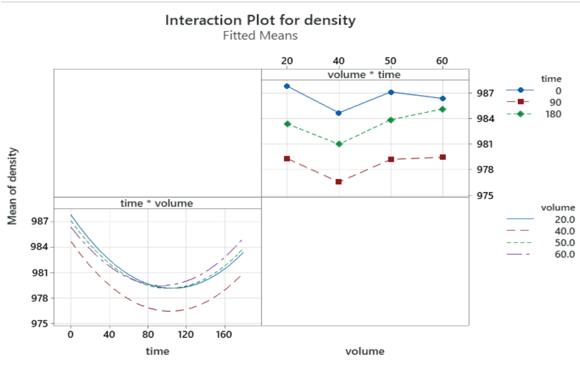
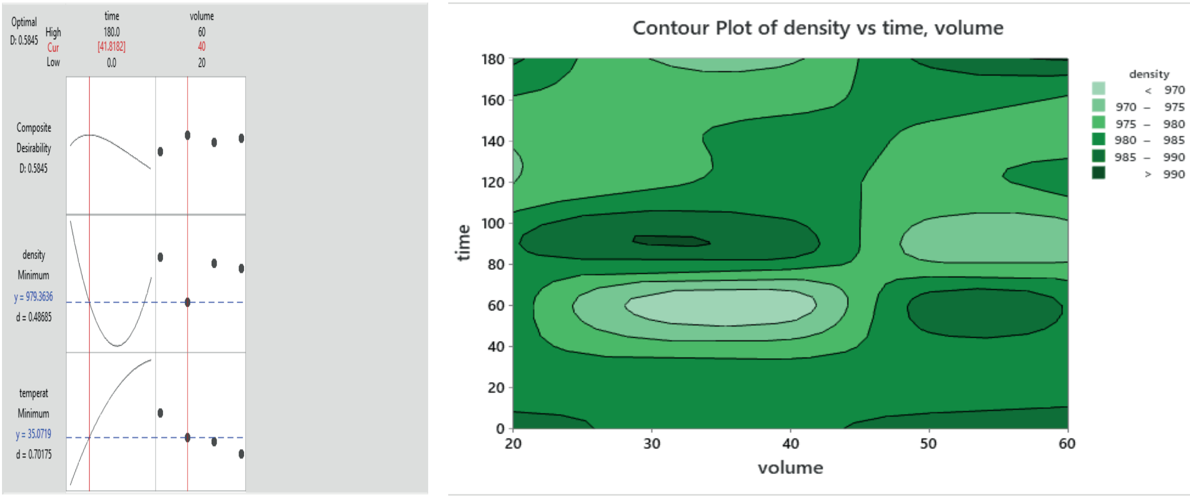


Figure 5.
Interaction plot for density.
Source: Analysis Data (2024)

The lower-left plot shows time values on the horizontal axis (0 to 200) and average density values on the vertical axis, with four lines representing different volume levels (20, 40, 50, and 60). The general trend shows an initial decrease in density as time progresses, followed by an increase after reaching a minimum point. The interaction between time and volume is minimal, with minor variations, particularly for the 40-liter volume, which exhibits a sharper decline and rise compared to other volumes.

The interaction details were analyzed using RSM analysis, and the contour plot in Figure 6 aims to optimize for the lowest density based on variations in time and tank volume. The analysis focused on optimizing two response variables, density, and temperature, about time and volume. The desirability value of 0.5845 suggests moderate optimization, though it is not ideal. According to Figure 6a, the optimal time for production ranges from 0 to 180 minutes, with the current value at 41.8182 minutes (highlighted in red). The optimal volume lies between 20 and 60 liters, with the current value at 40 (highlighted in red). The predicted minimum density for the density response variable is 979.3636 mg/ml, with a desirability score of 0.48685. This indicates that the optimization is adequate but not optimal for minimizing density. The graph in Figure 6a shows a parabolic curve, where the density reaches its minimum at approximately 41.8182 minutes and 40 liters of volume. Another response variable, the predicted minimum temperature, is 35.0719°C, with a desirability score of 0.70175, which is a better outcome than for density.



(a) (b)

Figure 6.
(a) Response optimization; and (b) Contour plot of density vs. time and volume.
Source: Analysis Data (2024)

The curve in Figure 6a also indicates that temperature initially decreases with increasing time, eventually stabilizing around this minimum value. Figure 6b presents the contour plot showing the relationship between time (vertical axis) and volume (horizontal axis) concerning fluid density. As time increases, particularly between 60 and 120 minutes, density decreases. Additionally, density varies with volume, indicating that an increase in volume affects density. The lighter contours identify optimal conditions for achieving low-density fluid, while distinct regions indicate minimized density. The contour shapes reveal the interaction between time and volume, where flat areas represent stable density regions, and steeper gradients suggest that minor adjustments in either parameter can significantly impact density.

CONCLUSION

This study examined the closed-loop production model of ultrafine bubbles (UFBs), utilizing a pump to generate the flow of UFBs fluid. The mass measurement data produced a detailed density profile, while temperature recordings highlighted a unique relationship influenced by volume. Production time and volume variations contributed to response dynamics, which could be random or nonlinear. Through optimization using Response Surface Methodology (RSM), optimal values were identified for the most minor response variable. Considering the temperature rise caused by circulation, the optimal conditions are predicted to occur at a production time of approximately 41.8 minutes and a volume of 40 liters. Under these conditions, the temperature is expected to reach around 35.1°C. The optimization results are a form of statistical approach that can be applied using the same production model.

For futher research, maintaining the bulk fluid temperature throughout production is critical in producing low-density ultrafine bubbles (UFBs). Due to the closed-loop production model, the observed temperature increase contributes to the nonlinear density profile. So, it should focus on developing precise temperature control mechanisms that maintain UFB production at biologically relevant temperatures (e.g., 35-37°C). Temperature fluctuations during production could affect bubble stability and performance in sensitive biomedical applications like drug delivery and tissue engineering. Maintaining optimal temperatures is crucial to avoid thermal degradation of drugs or cells in tissue scaffolds.

Additionally, extending the production duration to a daily scale using hydrodynamic cavitation methods offers a promising avenue for further investigation. This approach could significantly enrich the dataset, deepening our understanding of the complex dynamics involved in UFB formation and behavior. Therefore, future research should focus on temperature control and extended production times to optimize UFBs production and maximize their potential applications.

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