

The Impact of Ultrasound-Assisted Freezing on Energy Consumption and Freezing Time of White Shrimp and Striped Catfish

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Abstract: This study investigates the effects of freezing with ultrasound intervention on the freezing time and energy consumption for two economically significant Vietnamese aquatic products: white shrimp and striped catfish fillets. The study begins by highlighting the importance of these products in Vietnam's export market and the need for energy-efficient freezing methods that maintain product quality. Ultrasound waves were used to enhance the freezing process with experiments conducted at various power levels and intermittent ultrasound application intervals. Results indicated that using ultrasound at a power level of 100W significantly reduced freezing time by 19% for striped catfish and by up to 18% at a power level of 125W for white shrimp when the ultrasound was applied intermittently at a 0.4 duty cycle (30 seconds on, 20 seconds off). The study also observed that optimal ultrasound application could reduce energy consumption by 17% for striped catfish and 8% for white shrimp. The findings suggest that ultrasound-assisted freezing can be an effective method to enhance freezing efficiency and reduce energy consumption, making it a viable option for industrial applications in aquatic products processing.

Keywords: Energy Saving; Freezing; Striped Catfish Fillets; Ultrasound; White Shrimp

1. Introduction

Energy conservation is a key factor in achieving sustainability and reducing the environmental impact of human activities. As global energy demand continues to rise, improving efficiency across all sectors becomes essential to minimize waste and lower costs. From industrial processes to household energy use, adopting advanced technologies and smart energy management can significantly enhance efficiency. In particular, thermal technology plays a vital role, as heating, cooling and thermal processes account for a large share of global energy consumption. Therefore, scientists have conducted and continue to carry out researches to achieve these objectives. F. Yulia *et al.* conducted a study on incorporating coconut oil as a phase change material (PCM) into building wall structures. Their findings demonstrated that this method could contribute to energy savings of approximately 9.8%¹. M. Nuriyadi *et al.* studied the integration of heat pipes into the air conditioning system of electric bus. The results revealed that cooling capacity increases about 15%². L. A. Rasheed

et al. experimentally investigated the wire mesh-based solar air heater. The results showed that thermal efficiency improved by 10.9%³. In order to utilize exhaust airflow from air conditioning systems to generate electricity, R. A. Jessam conducted experiments. The results indicated that a 3 HP air conditioning system can generate 14.28 W of AC power and 14.72 W of DC power⁴. Ashwni *et al.* investigated the use of various zeotropic refrigerant mixtures R245fa/butane, butane/R152a and R245fa/R152a in an Organic Rankine Cycle (ORC) refrigeration system combined with a basic refrigeration system. R245fa/butane mixture achieves the highest coefficient of performance⁵. So as to enhance the efficiency of floating PV panels, Y. S. Indartono *et al.* investigated a passive thermosiphon cooling system. The results showed that improves electric efficiency about 19% compared to without thermosiphon⁶. However, researches on energy savings in the freezing process of aquatic food with the application of ultrasound remains limited. Therefore, this article focuses on the experimental study of ultrasound-assisted freezing for white shrimp and striped catfish.

White shrimp is one of Vietnam's most valuable aquatic exports. According to Vietnam Association of Seafood Exporters and Producers, Vietnam exported up to 4 billion USD in 2024. Alongside, the export situation and demand for striped catfish consumption in Vietnam are also increasing. Striped catfish is not only a rich source of protein but also contains many unsaturated fatty acids, vitamins and minerals beneficial to health.

Reducing freezing time, saving energy and ensuring product quality have become top priorities. Currently, the common method used to preserve export shrimp is quick freezing and storage in cold storage at a temperature not greater than -18°C . However, the phase change of water is accompanied by a volumetric expansion of about 9% due to crystal formation and breaks down the tissue and cell structure of the products⁷⁾, leading to discoloration and a decrease in the nutritional value of the food. It can be said that the size of ice crystals significantly affects the quality of frozen products. If the size of ice crystals is large and unevenly distributed, there is a high risk of breaking the cell structure. This occurs when the freezing rate is not fast enough. Conversely, smaller and more homogeneous ice crystal formation results in better cellular structure preservation. This even distribution usually occurs at high freezing rates.

Ultrasonic waves increase freezing speed chiefly by initiating nucleation, promoting heat and mass exchange processes⁸⁾. However, the effectiveness of ultrasonic in assisting freezing depends on the ultrasonic intensity, exposure time and properties of the frozen materials. Each type of materials will require a suitable ultrasonic regime during freezing. Therefore, selecting an appropriate ultrasonic regime is necessary to optimize the freezing time of the respective materials.

Freezing with ultrasonic intervention has been researched both globally and in Vietnam. Regarding the impact of ultrasonic on the preservation of nutritional quality and color during freezing, R. R. Franco *et al.* investigated the impact of 40 kHz/50 W ultrasonic treatment on banana quality attributes during freezing. The findings revealed that ultrasonic effectively enhanced antioxidant properties and retained phenolic components, thus maintaining color and nutrients better. Additionally, studies revealed that ultrasonic-augmented freezing demonstrated enhanced antibacterial properties relative to traditional approaches⁹⁾. R. Chow *et al.* studied how 20 kHz ultrasound influences both initial and subsequent ice formation stages in sucrose-based systems. The application of ultrasound was observed to elevate ice nucleation temperatures in sucrose solutions during primary nucleation events. Ice crystals on the surface could be fragmented into smaller pieces by ultrasound waves¹⁰⁾. In addition, X. Zhang *et al.* studied the phase change of water with ultrasonic freezing. It promoted ice nucleation in supercooled water, enhancing phase transition control. However, selecting the

appropriate ultrasonic intensity was crucial for process efficiency¹¹⁾. J. Tu *et al.* investigated the ultrasound-assisted freezing process of lotus root at 30 kHz and powers of 90, 150 and 210 W. The study revealed that ultrasound assistance at 150 W achieved faster freezing, improved quality of lotus root¹²⁾. Regarding the direction and frequency of ultrasound emission and their effect on freezing efficiency. Y. Tian *et al.* conducted studies on potatoes. The results showed that combining frequencies of 20 kHz and 28 kHz simultaneously with perpendicular emission achieved the best efficiency¹³⁾. B. Xu *et al.* investigated the effect of ultrasonic at 20 kHz with various intensities and initial ultrasonic temperatures on nucleation temperatures during the freezing of radish in a CaCl_2 -ultrasonic bath system. It helped control nucleation temperatures¹⁴⁾. Y. Xin *et al.* investigated ultrasound assistance at 20 kHz and 30 kHz with different power levels, using a 60s on/60s off cycle during the freezing of broccoli. The findings showed that ultrasound significantly shortened freezing time, especially at 150 W (30 kHz) and 175 W (20 kHz). The authors emphasized that determining appropriate ultrasound frequency, power, initial temperature and duration was crucial for material quality and freezing time¹⁵⁾. Regarding ultrasonic-assisted freezing of salmon fillets, S. Kono *et al.* confirmed that freezing rate, ice crystal formation, size and distribution were critical for the quality of frozen materials. They found that reducing crystal size and increasing uniformity were necessary¹⁶⁾. S. Qiu *et al.* studied the impact of ultrasonic freezing at 25 kHz. Results showed that ultrasonic at 250 W promoted protein oxidation, while 200 W was more effective in water retention and protein stability compared to other power levels¹⁷⁾. Y. He *et al.* conducted experiments on ultrasonic freezing of tuna fillets at a frequency of 20 kHz. They found that freezing with ultrasonic reduced water separation, improved elasticity and better preserved the protein composition of the material¹⁸⁾. X. Ma *et al.* investigated freezing of Large Yellow Croaker fish at power of 175 W and different frequencies ultrasonic. They showed that compared to other freezing methods, combining different ultrasonic frequencies improved water-holding capacity, ensured more uniform water distribution in cells and effectively reduced ice crystal size¹⁹⁾. M. H. Ngo *et al.* conducted experiments on the ultrasonic freezing of Bo Chinh ginseng under continuous and intermittent modes at 20 kHz. At 100 W power and an intermittent emission ratio of 60 seconds on and 90 seconds off achieved the best outcomes²⁰⁾. J. Li *et al.* found that ultrasound at 400 W reduced cooking loss in beef from 49.04% to 39.74%, while hardness values dropped by approximately 50%²¹⁾. S. Hu *et al.* reported a 11% reduction in freezing time for dough cylinders treated with ultrasound during immersion freezing at 288 W and 360 W. Enhanced heat transfer efficiency contributed to the accelerated freezing

process²²). B. Liu *et al.* found that freezing with ultrasonic at 150 W significantly improved freezing quality by creating small, uniform ice crystals. This approach effectively maintained protein conformation integrity, suppressed oxidative degradation and conserved scallop muscle's textural and microstructural properties throughout the 90-day frozen storage period²³). A. Kamińska-Dwórznička *et al.* found that ultrasonic at 21.5 kHz (chopped mode) reduced freezing time and resulted in the smallest crystal sizes (9 μm) compared to 25 μm in conventional methods. This produced a smoother texture and improved structural integrity²⁴). A. Ciużyńska *et al.* explored the impact of ultrasonic, blanching and freezing on red beet quality. Ultrasonic treatment reduced water activity and shrinkage during freezing, improving structural integrity and porosity. Combined freezing and ultrasonic produced better results than other pretreatment methods²⁵). I. Szymanska *et al.* investigated ultrasound pretreatment on freeze-dried chicken breast. Ultrasound enhanced the water removal during freeze-drying, reducing moisture content by approximately 30% compared to untreated samples²⁶). K. Nakagawa *et al.* demonstrated that lower nucleation temperatures, characterized by higher degrees of supercooling, resulted in the formation of numerous small ice crystals. Conversely, higher nucleation temperatures, associated with lower degrees of supercooling, led to the development of larger, more directionally oriented ice crystals, exhibiting a dendritic growth pattern²⁷). K. Fan *et al.* studied Kiwifruit underwent osmotic dehydration at 30°C for 30 minutes using ultrasonic at 20 kHz (0-300 W). The process enhanced water loss and increased solid gain in the kiwifruit compared to conventional osmotic dehydration²⁸). K. You *et al.* combined ultrasound and magnetic fields in pretreatment for freeze-thawed blueberries. Compared to other freezing treatments, those treated with ultrasound pretreatment followed by static magnetic field freezing exhibited significantly lower drip loss and reduced cell membrane permeability after the freeze-thaw cycle²⁹). Z. Zilei *et al.* demonstrated that specific ultrasound frequency combinations significantly enhance water freezing rates and mitigate subcooling. Optimal results occurred at 28+33 kHz and 60 W, yielding a 5.28 K reduction in subcooling and a 60-second decrease in solidification time compared to non-ultrasound conditions³⁰). O. Zheng *et al.* studied the effects of various freezing methods on the golden pompano (*Trachinotus ovatus*) muscle. They showed that the magnetic field-assisted immersion freezing and ultrasonic-assisted immersion freezing methods significantly outperformed the other freezing techniques in reducing freezing time, achieving reductions of 84.35% and 85.81%, respectively compared to air freezing³¹). A comprehensive analysis was conducted on frozen wheat dough to evaluate its texture, viscosity, rheological properties and structural quality. The study

utilized multi-frequency ultrasound treatments with varying durations, Z. Amed *et al.* demonstrated that the 20/40/60 kHz ultrasound treatment for 30 minutes is effective mode³²). H. Yu, J. Xie examined the differential impacts of single-frequency versus dual-frequency ultrasonic freezing systems, focusing on how orthogonal ultrasonic treatment impacted the quality of sea bass. The application of orthogonal ultrasonic waves significantly enhanced the efficiency of ultrasonic utilization³³). L. M. Carrillo-Lopez *et al.* investigated the impact of high-intensity ultrasound (HIU) treatment on rabbit meat quality. They revealed that rabbit meat subjected to HIU treatment prior to freezing exhibited a more pronounced and vibrant orange-yellow hue. In contrast, samples treated with HIU after the freezing process displayed a paler red coloration³⁴). In order to assess the ultrasonic waves effectiveness on ice freezing, H. Daghooghi-Mobarakeh *et al.* applied intermittent exposures of ultrasonic waves. The use of ultrasonic at 3.52 W and 8.25W reduced freezing energy consumption by 12.4% and 10.8% relative to non-assisted freezing methods³⁵). Q. Jiang *et al.* combined CO₂ pressurization with ultrasonic immersion freezing for enhancing honeydew melon quality. With 0.5 MPa CO₂-pressurized exhibited a 60.8% reduction compared to the conventionally immersion freezing³⁶). S. Gai *et al.* studied the freezing of micro-droplets into ice particles using power ultrasound. Although an ice fraction exceeding 90% was attained, the resulting ice particles exhibited poor roundness³⁷).

2. Ultrasound-assisted freezing process

Table 1 presents the experimental and measurement equipment used in the freezing process of striped catfish and white shrimp and Table 2 presents the technical specifications of the freezing equipment used in the experiments.

Figure 1 illustrates the schematic diagram of the freezing machine, both the conceptual design and installation freezing machine are shown in Figure 2.

The experiments are conducted independently for each type of material. The experimental procedure is as follows: the freezing machine is first started and run until the air temperature in the freezing chamber reaches -35°C. During this time, shrimp are peeled and striped catfish fillets are cut, then cooled to 10°C. When the air temperature in the chamber reaches -35°C, a temperature probe is attached to the middle of the shrimp and fish fillets, then the shrimp and striped catfish are placed on the freezing tray in the cabinet. Shrimp and striped catfish are placed on the tray in a single layer and not stacked (each batch of experimental materials weighs 1 kg) as shown in Figure 3. The shrimp and fish fillets with temperature probes in all experiments are placed in the same position (above the ultrasound emitter). The product temperature is recorded

Table 1: Experimental and Measurement Equipment

Equipment	Description
Compressor stage 1: SECOP SC18CL	- Refrigerant: R404A - Operating voltage: 220 VAC - Power input: 5/8 HP
Compressor stage 2: TECUMSEH CAJ2446Z	- Refrigerant: R404A - Operating voltage: 220 VAC - Power input: 1 HP
Air-cooled condenser: Kewely FNF-1.2/5.4	- Heat exchange area: 5.4 m ² - Air flow rate: 1250 m ³ /h - Operating voltage: 220VAC
Air-cooling evaporator: SUPCOOL DE- 0.45/2.5	- Heat exchange area: 2.5 m ² - Air flow rate: 400 m ³ /h - Operating voltage: 220 VAC
Super SS weight scale: TPS15	- Pan size: 19×23 cm - Accuracy: Class 3
Thermometer: Fox 1004	- TEMP. RANGE: -40°C ÷ +90°C - Accuracy: ± 0.1 °C
Ultrasound power meter: PZEM-022	- Power Range: 0~22000 W - Accuracy: ± 1%
Alternating relay timer: Omron DH48S-S	- Power supply: 220 VAC - Range of adjustable time: 0s - 99 hrs - Delay control accuracy: ≤ 0.3% ± 0.05s
Single-phase 220V electricity meter: Emic CV140	- Rated voltage: 220/240 VAC - Accuracy: Class 2
Ultrasound Generator: CDEXIM0620	- Frequency: 20 kHz - Power adjustment: 0 – 2600 W

Table 2: Technical Specifications of Freezing Equipment

Description	Unit	Value
Freezing capacity	kg/batch	1
Dimensions of the freezing machine	mm	1630 x 800 x 700
Dimensions of material trays	mm	580 x 240 x 2
Dimensions of the emitter plate	mm	260 x 130 x 30
Freezing chamber temperature	°C	-35 to -40
Air freezing velocity in chamber	m/s	3.5
Operating voltage	V	220 ± 5%
Operating frequency	Hz	50

every 5 minutes until the product core temperature reaches -18°C, at which point the experiment ends. In the continuous ultrasound exposure mode, ultrasound is activated as soon as the shrimp and striped catfish fillets are placed into the cabinet and remains on throughout the entire duration of the experiment and ultrasound is turned on and off alternately during the core temperature of materials from 0 to -5oC in the intermittent mode. Adjusting ultrasound power: The power is stopped on the power supply unit, then adjusted to the desired power level. The desired power level is measured and displayed digitally on the PZEM-022 power meter.

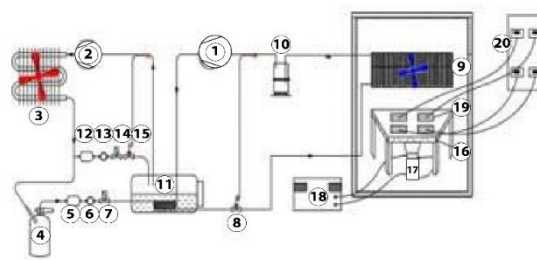


Fig. 1: Schematic diagram of system
1- Compressor stage 1; 2- Compressor stage 2; 3- Air-cooled condenser; 4- High pressure receiver; 5- Filter 1; 6- Refrigerant sight glass 1; 7- Solenoid valve 1; 8- Thermal expansion valve 1; 9- Air-cooling evaporator; 10- Suction accumulator; 11- Intermediate cooler; 12- Filter 2; 13- Refrigerant sight glass 2; 14- Solenoid valve 2; 15- Thermal expansion valve 2; 16- Material tray; 17- Ultrasound emitter; 18- Ultrasound generator; 19- Frozen materials; 20- Thermometers

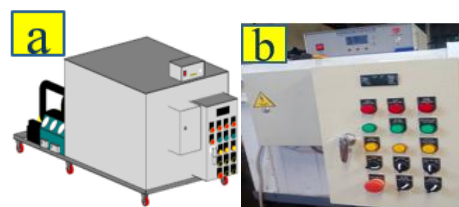


Fig. 2: The freezing machine: a) Conceptual design machine and b) Installation machine

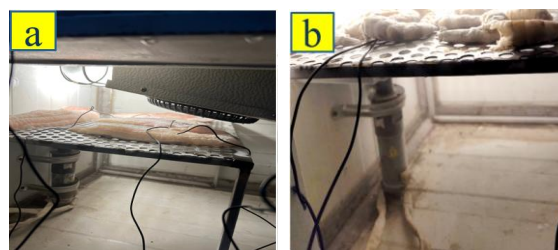


Fig. 3: Materials are placed on tray in the cabinet: a) Striped Catfish fillets and b) White Shrimp

Creating intermittent ultrasound ratios (start-stop time): The alternating relay is connected to the input port on the ultrasound power supply, the start-stop time value is set on the alternating relay, and then power is supplied to the relay.

Measuring energy consumption for each batch: The system's energy consumption is measured using a CV140 single-phase electricity meter.

3. Results and Discussion

3.1. Impact of Ultrasound on Freezing Time

Figure 4 shows the freezing time of striped catfish fillets at various ultrasound power levels and continuous ultrasound exposure at power levels of 75, 100, 125, 150, and 175 W at a frequency of 20 kHz. The results show that when continuous ultrasound exposure is applied at 100 W, the

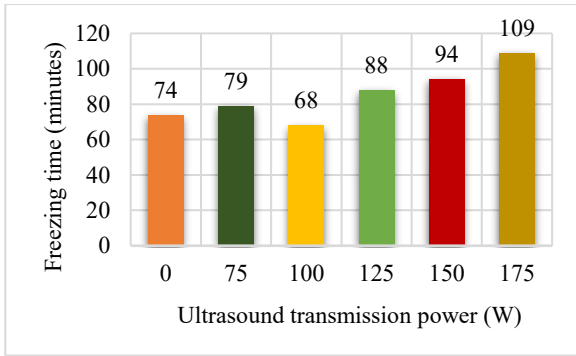


Fig. 4: Freezing time of striped catfish fillets at various ultrasound power levels

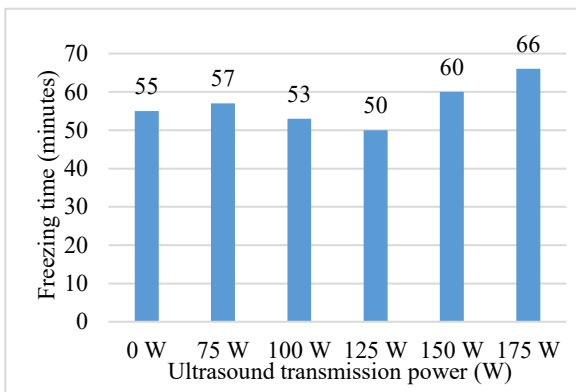


Fig. 5: Freezing time of white shrimp at various ultrasound power levels

freezing time is shortened by about 8% compared to without ultrasound assistance, specifically 68 minutes versus 74 minutes. This indicates that continuous ultrasound exposure causes a thermal effect; therefore, at power levels of 75, 125, 150, and 175 W, the freezing time increases compared to without ultrasound assistance.

Similarly, Figure 5 presents the freezing time of white shrimp at ultrasound power levels of 75, 100, 125, 150, and 175 W at a frequency of 20 kHz. The results show that at power levels of 100 W and 125 W, the freezing time is shortened compared to without ultrasound assistance, specifically 53 minutes and 50 minutes compared to 55 minutes without ultrasound. This confirms that for shrimp, ultrasound power levels of 100 W and 125 W are effective in reducing freezing time. Meanwhile, the freezing time using ultrasound power levels of 75 W (57 minutes), 150 W (60 minutes), and 175 W (66 minutes) is higher compared to without ultrasound. This value tends to increase as ultrasound power increases.

3.2. Impact of Intermittent Ultrasound Exposure on Freezing Time

Continuous ultrasound exposure has been found in earlier studies to influence freezing time. Prolonged ultrasound exposure causes a thermal effect, increasing freezing time³⁸. From experimental results on the impact of ultrasound on freezing time, it is observed that ultrasound

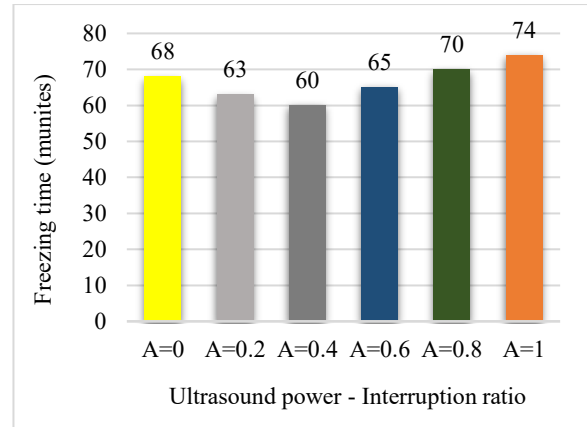


Fig. 6: Impact of intermittent ultrasound exposure on freezing time of striped catfish fillets

only positively affects the phase change during the process. Therefore, the experiments on freezing striped catfish fillets was conducted at 100 W power (ultrasound exposure temperature 0 to -5°C) with intermittent ratios of 0, 0.2, 0.4, 0.6 and 0.8. The intermittent ultrasound ratio is calculated using the formula:

$$A = \frac{T_{off}}{T_{off} + T_{on}} \quad (1)$$

In which:

T_{off} : freezing time without ultrasound exposure

T_{on} : freezing time with ultrasound exposure

Therefore:

- Continuous ultrasound exposure (A = 0)
- 7.5s off - 30s on (A = 0.2)
- 20s off - 30s on (A = 0.4)
- 45s off - 30s on (A = 0.6)
- 120s off - 30s on (A = 0.8)
- Without ultrasound exposure (A = 1)

Research results show that intermittent ultrasound exposure positively affects freezing time. Figure 6 shows that at intermittent ratios of 0.2, 0.4 and 0.6, the freezing time is lower than without ultrasound assistance and with continuous ultrasound exposure. Among the various freezing modes, the shortest freezing time is observed at a 0.4 ratio, representing an 18.9% reduction compared to the non-ultrasound-assisted condition. This can be explained by the fact that for the 0.4 intermittent ratio at 100 W power, corresponding to 30s on and 20s off, this is a reasonable intermittent ratio for ultrasound to create compression and expansion effects on the material, creating bubbles to enhance heat transfer. Then, voids will form inside the material combined with a reasonable intermittent time to favorably form and develop ice crystals. At a 0.2 intermittent ratio with 100 W power (30s on, 7.5s off), the off duration is too brief, leading to a thermal effect from

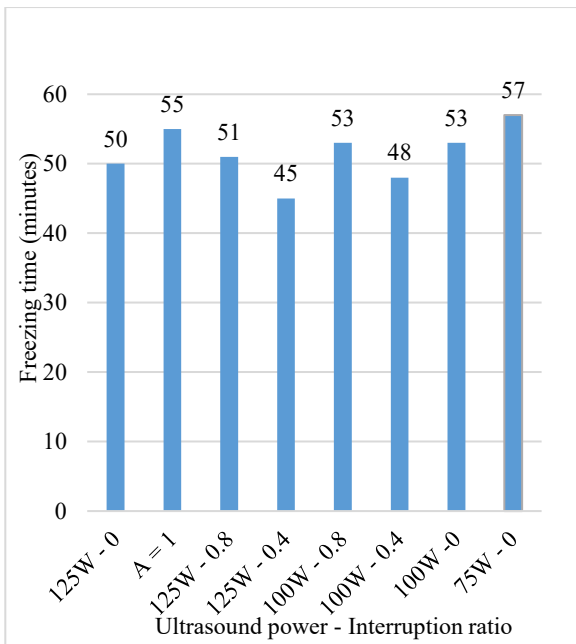


Fig. 7: Impact of intermittent ultrasound exposure on freezing time of shrimp

the ultrasound that melts the formed ice crystals. Conversely, at a 0.8 ratio, the off time is significantly longer than the on time, reducing the beneficial effects of ultrasound on the material. Therefore, selecting a suitable intermittent ratio is very important in shortening freezing time.

Similarly, the impact of intermittent ultrasound exposure on the freezing time of shrimp was also investigated. The test cases for shrimp include:

- Without ultrasound exposure. (A = 1)
- Ultrasound power 75 W. (A = 0 – Always on)
- Ultrasound power 100 W. (A = 0, A = 0.4, A = 0.8)
- Ultrasound power 125 W. (A = 0, A = 0.4, A = 0.8)

Figure 7 shows the freezing time of shrimp at various ultrasound power levels and intermittent exposure ratios. Figure 7 indicates that at a 0.4 intermittent ratio with 125 W ultrasound power, the freezing time is the shortest at only 45 minutes compared to 55 minutes without ultrasound, a reduction of 18.2% in freezing time. This marks a considerable reduction in the time required for freezing.

3.3. Impact of Ultrasound on Freezing Energy Consumption

Experimental results comparing to the energy consumption of freezing striped catfish fillets with ultrasound assistance at 100 W power and various intermittent ratios and without ultrasound assistance are presented. Figure 8 shows that with ultrasound assistance at 100 W power and a 0.4 intermittent ratio, the energy consumption is the lowest at 1.9 kWh/kg compared to 2.3 kWh/kg without ultrasound, a 17.4% reduction in energy consumption.

Similarly, the impact of intermittent ultrasound exposure

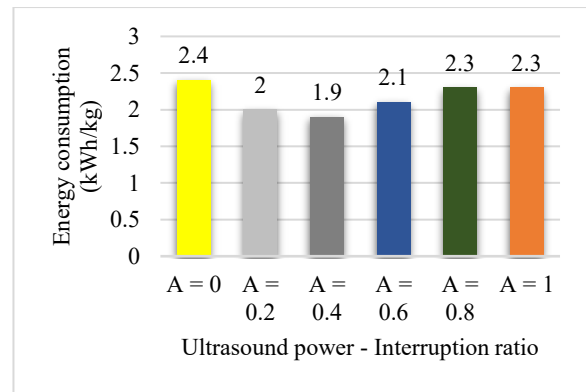


Fig. 8: Impact of ultrasound on energy consumption for striped catfish fillets freezing

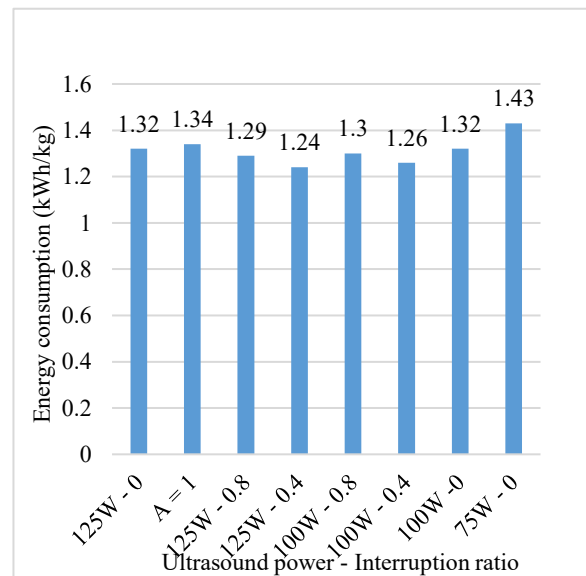


Fig. 9: Impact of ultrasound on energy consumption for shrimp freezing

on the energy consumption of shrimp freezing was also investigated. Figure 9 presents the energy consumption of shrimp freezing at ultrasound power levels of 75 W, 100 W, and 125 W with various intermittent ratios. At 125 W and a 0.4 intermittent ratio, the system achieves its most efficient energy use, with a reduction of around 7.5% compared to freezing without ultrasound.

As presented, the energy consumption of ultrasound generator is negligible compared with that of the freezing machine. Therefore, ultrasound-assisted freezing significantly shortens the freezing time, resulting in reduced energy consumption compared with freezing without ultrasound assistance.

4. Conclusion

This paper presents an experiment on the impact of using ultrasound at 20 kHz frequency to assist the freezing process of striped catfish fillets and shrimp on freezing time and energy consumption. The results show that ultrasound power significantly affects freezing time. For

striped catfish freezing, ultrasound power at 100 W will help reduce freezing time compared to without ultrasound. For shrimp freezing, the ultrasound power is 125 W. The difference in ultrasound power can be explained by the thickness and structure of the frozen product. Both cases of freezing striped catfish and shrimp show that the 0.4 intermittent ultrasound ratio will yield the shortest freezing time. Regarding energy consumption, the experimental results show that the lowest energy consumption corresponds to the case of freezing striped catfish and shrimp at ultrasound powers of 100 W and 125 W, respectively, both with a 0.4 intermittent ratio. The energy savings in these two cases are about 17% for striped catfish and 8% for shrimp. This indicates that selecting a suitable ultrasound power and intermittent ratio can shorten freezing time and reduce energy consumption during the freezing process. The encouraging results from this study could be applied on an industrial scale to reduce freezing time and save energy consumption.

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