# Design and Implementation of a Continuous Microwave Heating System for Ballast Water Treatment

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Design and Implementation of a Continuous Microwave Heating System for Ballast Water Treatment

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ABSTRACT

A continuous microwave system to treat ballast water inoculated with different invasive species was designed and installed at the Louisiana State University Agricultural Center. The effectiveness of the system to deliver the required heating loads to inactivate the organisms present was studied. The targeted organisms were microalgae (*Nannochloropsis oculata*), zooplankton at two different growth stages (newly hatched brine shrimp-*Artemia* nauplii and adult *Artemia*), and oyster larvae (*Crassostrea virginica*). The system was tested at two different flow rates (1 and 2 lpm) and power levels (2.5 and 4.5 kW). Temperature profiles indicate that depending on the species present and growth stage, the maximum temperature increase will vary from 11.8°C to 64.9°C. The continuous microwave heating system delivered uniform and near-instantaneous heating at the outlet, proving its effectiveness. The power absorbed and power efficiency varied for the species present. More than 80% power utilization efficiency was obtained at all flow rate and microwave power combinations for microalgae, *Artemia* nauplii and adults. Test results indicated that microwave treatment can be an effective tool for ballast water treatment and current high treatment costs notwithstanding, this technique can be added as supplemental technology to the palette of existing treatment methods.

KEYWORDS Continuous microwave, ballast water, de-ballasting, pollution control, invasive species, zooplankton, oysters, microalgae

BRIEFS. This research involves the development of an energy efficient continuous microwave system for treating ballast water in order to prevent introduction of invasive species in the environment during de-ballasting.
Introduction

Ballast water plays a critical role in maintaining the stability and maneuverability of ships during transit (1). Water is loaded on a ship in one port while unloading cargo and then discharged at another port when the cargo is reloaded. The loading and unloading of sea water poses substantial risk of introducing non-indigenous marine species native to one region into another region (2, 3). The newly introduced marine species could become invasive and upset the ecological balance of that region. The International Maritime Organization (IMO) estimates that each year about 10 billion tons of ballast water are transported and exchanged around the world during maritime shipping (4). To prevent the introduction of potentially invasive species, different treatment methods have been proposed: ballast water exchange (5, 6), chemical methods (1, 7, 8), heat treatment (9), use of ultra violet (UV) radiation (10), and filtration (11, 12). Selection and design of a suitable method depends on various factors like cost, safety, effectiveness, ease of operation and enforcement (13). Novel techniques such as ultrasonic, magnetic methods and use of electrical pulses (13) have also been investigated for their treatment efficacy.

Each of the methods mentioned above has its own advantages and disadvantages. For example, chemical treatments (using ozone, pesticides, gluteraldehyde, etc.) are considered to be effective but they also cause corrosion of the tanks, introduce toxic chemicals and generate undesirable byproducts. Heat treatments are considered a good option as there is no formation of by-products, but cold weather conditions reduce its effectiveness, it often requires additional piping and installation of large boilers, and in most cases it is difficult to achieve uniform heating rates. Attempts have been made to utilize the waste heat from the ships engines to heat the ballast water (9), but this heat might not be enough to substantially inactivate all the organisms present. Ultraviolet radiation treatment is effective only for extensively filtered water, increasing costs. The use of microwaves might be a suitable alternate to the available ballast water treatment methods. Microwaves have high heating rates (due to its short heating and exposure span) when compared to conventional heating, is effective even in non-clear water, is less
expensive to operate and requires fewer accessories to install. Conventional heating methods usually require installation of steam generators which adds to the cost of installation.

The oscillating electric field components in the microwaves excite the polar molecules in the liquid which vibrate/oscillate generating inter-molecular and intra-molecular friction. This polar rotation, coupled with movement of charged ions result in instantaneous heating throughout the product (14). The extent of heating produced depends on the dielectric properties of the medium (15, 16). Microwaves have been used extensively in the past to successively inactivate enzymes and bacterial cells present in foods (17, 18, 19, 20, 21, 22).

Thermal and non-thermal effects of microwaves on the bacterial cells are believed to be the cause of inactivation/sterilization. Traditionally, it was assumed that killing of biological entities by microwaves are solely due to the heat generated by intermolecular friction (23, 24). More recent studies involving the use of scanning electron microscopy (SEM) and transmission electron microscopy (TEM), have led researchers to hypothesize that the existence of a non-thermal mechanism increasing the lethal effect of microwaves (25, 26, 27, 28). Another recent study (29) did not find any conclusive evidence supporting the non-thermal effects of microwave treatments on numerous chemical, physical and biochemical reactions including protein denaturation, Maillard reaction, mutagenesis of bacteria, polymer solubility and saturation solubility of sodium chloride. With high potential of microwave energy as an efficient processing tool being proven, there is keen interest in understanding the underlying mechanism of microwave radiation on the physical, chemical and biochemical structure of organisms. This study is part of a larger research effort undertaken to understand the effectiveness of microwave treatment in preventing introduction of invasive species during the de-ballasting process. A continuous microwave heating system was designed to process the ballast water, and the system effectiveness was ascertained by its ability to deliver the process conditions to inactivate various organisms.

**Materials and Methods**
Preparation of the Synthetic Ballast Media and Test Cultures

Sterilized deionized water was mixed with autoclaved synthetic sea salt (Crystal Sea MarineMix, Marine Enterprises International, Baltimore, MD, USA) to form salt solutions at two concentrations; one at 30 parts per thousand (3%) and the other at 20 parts per thousand (2%). The 2% water (representing a more brackish water) was used for inoculation and tests with microalgae as Nannochloropsis oculata grows best at this salinity. The 3% water was used for all other organisms and represents the more saline water found in the ocean. The water salinity was checked using a refractometer (Aquatic Eco-Systems, Apopka, FL). A total of four test organisms were prepared for this study: microalgae (N. oculata), zooplankton at two different growth stages (newly hatched brine shrimp-Artemia nauplii and adult Artemia), and oyster larvae (Crassosstrea virginica). The following procedures were adopted to prepare the test cultures of the various organisms that were studied.

**N. oculata (microalgae) culture**

N. oculata is one of the important feed materials used for feeding larvae and some commercial fish varieties. They have a high content of chlorophyll a (30). About 20 L of pre-cultured N. oculata having a concentration of at least $10^6$ organisms/ mL in one carboy (3 gallon) was used for the experiments. The microalgae were cultured by following standard protocol available. On the day of experimentation, about one carboy of algae (concentration $> 1 \times 10^6$/mL) was mixed thoroughly with 30 L of 2% concentration synthetic ballast water.

**Artemia nauplii**

Approx. 2-3 gm of Artemia cysts was added to 3% synthetic sea water ensuring the pH of the water was approx. 8.5-9.0, at a temperature of 26-28°C. The solution was aerated using an air pump to keep the cysts in suspension. After 24-48 hours, these cysts hatched to produce Artemia nauplii. The organisms’ concentration at the start of the experiment approximated 1000/liter of solution.

**Artemia adults**

The adult Artemia was cultured in a similar manner as the Artemia nauplii with the exception that
these organisms were fed for an additional period of time to allow for further growth, and the concentration was reduced to 85-100/liter. During the growth process of the *Artemia* from the nauplii stage to adulthood, the concentration decreases significantly as the growing organisms compete for limited resources. Hence, a lower concentration of *Artemia* adults was observed at the beginning of this portion of the study.

*Crassostrea virginica* (oyster larvae)

Six-day old oyster larvae were purchased in two batches from Coast Sea Foods Company (Quilcene, WA). The larvae from the two batches were then suspended in water immediately upon arrival to form a target concentration of 9-10 larvae/mL. The oyster larvae were prepared using ballast water at 3% concentration.

Continuous Microwave System Design and Set-up

The experiments were conducted using a 5 kW, 915 MHz continuous flow microwave unit provided by Industrial Microwave Systems, LLC (Morrisville, NC). This unit is comprised of a power generation unit, waveguide to transport the microwaves, circulator, power coupler, tuning coupler, elliptical focusing cavity which holds the applicator tube through which the process fluid flows and water load to absorb the microwaves reflected from the focusing cavity. The entire processing system consisted of the feed-tank, microwave processing unit, insulated holding tubes, and positive displacement pumps to circulate the fluid through the entire system (Figure 1A). The initial tuning of the system was performed using synthetic seawater at both 20 and 30 ppt salinities. Tuning stubs height (tuning parameters) in the tuning coupler were adjusted at the start of the study using a network analyzer (HP8753C, Hewlett Packard, Palo Alto, CA) to maximize the power absorbed in the focusing cavity. The tuning parameters were the same at both salinities for maximum power absorption when no organisms were present (stub 1 = 93 mm, stub 2 = 42 mm, stub 3 = 44 mm; stub 3 being closest to generator). Though the dielectric properties after inoculation differed between different organisms (*31*), the tuning stubs heights were not subsequently changed to prevent introduction of an additional variable in the study that cannot be easily
accounted for. Tuning needs to be performed not only for technological reasons to maximize efficiency, but also for economic reasons (reducing operating costs) and to protect the generator from reflected microwaves. For more details on the tuning procedure see references (32, 33).

In Figure 1A the inlet and outlet temperatures of the product entering and leaving the microwave unit are denoted by $T_{\text{in}}$ and $T_{\text{out}}$, respectively. Sampling locations on the holding tube ($h_1$, $h_2$, $h_3$ and $h_4$ in Figure 1A) were placed equidistant (1.5 m) from each other. The number of sampling sites was increased to six for adult *Artemia* and to seven (denoted by A, B, and C) for oyster larvae studies, in an attempt to quantify these less heat-resistant organisms’ survival after shorter residence times. For the current experiment protocol two flow rates were selected: 1 and 2 liters per minute (lpm). The residence times at each sampling location for the selected flow rates of the ballast water are given in Table S1.

The experiments were aimed at determining the heating loads the system could produce for the pre-selected flow rates and two power levels (2.5 and 4.5 kW). The temperature responses recorded for each experiment was plotted to observe the heating profiles produced and the temperature uniformity at the exit. Due to the different organisms investigated, and related logistical difficulties in obtaining similar population density in the medium, the organisms were not compared to each other, but rather individual behavior under microwave and conventional heating were compared for the same organism. The main objective of the study was to understand the heating characteristics of the microwave system for the different organisms present in the test ballast water. The characteristics investigated included temperature values and distribution, as well as power absorbed, at the preselected flow rates and power level. All experiments were performed in triplicate.

The process fluid was pumped through the system using a progressive cavity pump (model #1P610, Dayton Electric Manufacturing Co., Lake Forest, IL) controlled by a variable-speed DC electric motor (model #4Z528B, Dayton Electric Manufacturing Co., Lake Forest, IL). The applicator tube was a PTFE (polytetrafluoroethylene) tube of 100 cm height and 3.81 cm diameter, housed inside the elliptical focusing cavity chamber of the microwave unit (Figure 1B), and affixed in place using aluminum
fittings at both ends. The focusing cavity ensures that the maximum amount of microwave radiation generated gets concentrated onto the fluid to be processed, thus increasing the process efficiency of the unit.

![Diagram of continuous microwave heating system](image)

**FIGURE 1.** A) Schematics of the continuous microwave heating system; B) AutoCAD rendering of microwave system (generator, circulator and water load are not shown).

The holding tubes (304SS, 1.5” nominal diameter) were well insulated in order to maintain isothermal conditions throughout the tube and minimize heat loss. The sampling ports were made using 3/8” (0.95 cm) diameter stainless steel T-junctions connected to 3/8” (0.95 cm) diameter stainless steel ball valves at each sampling location.

Power levels were measured using power diodes connected to the directional coupler for the algae and *Artemia* nauplii experiments. The nominal power (set on the microwave control unit) generally differed than the power levels measured with the diodes, probably due to the errors introduced during conversion from the millivolt signal (generated by the diode) into microwave power value, involving multiple diode coefficients and complex power-log calculations (not shown here). The net absorbed power was determined by subtracting reflected power from forward power. Due to potential large uncertainties in
power measurements using diodes, a secondary method was used to determine the net power absorbed based on energy balance and temperature difference between the inlet and outlet of the microwave heating cavity (34):

\[ Q = m C_p \Delta T \]  

(1)

Where: \( Q \) = absorbed power, Watts

\( m \) = mass flow rate, kg/s

\( C_p \) = specific heat capacity of salt water, J/kg-K; assumed 3850 J/kg-K

\( \Delta T \) = change in temperature, K

**Design of Temperature Measurement System**

To measure the temperature distribution during heating within the applicator tube during microwave treatment, a custom measurement system was designed and built in-house. The details of the measurement system are discussed thoroughly by Gerbo et al. (35). The inlet and outlet temperatures were measured using 10 T-type thermocouples (#OSK2K1540/PP3-60-T-116U-1-SMPW-M, Omega Engineering, Inc., CT); one at the inlet and nine at the outlet. The outlet thermocouples were arranged in groups of three at equal radial distances (5 mm) from each other (Figure S1), similar to the configuration described by Coronel et al. (36). A data logger (model #TC-08, PICO Technologies, Cambridgeshire, UK) connected to a PC-compatible computer with Windows XP (Microsoft Corp., Redmond, WA) operating system was used to record all thermocouples responses.

**Results and Discussion**

**Observed Temperature Distributions for Each Species during Microwave Treatment**

Due to different dielectric properties of the ballast water on account of the various organisms present it was expected that the temperature profiles observed during various treatment regimes will differ for each organism. Boldor et al. (31) have shown that there is a significant decrease in dielectric loss of the medium containing the different organisms with increase in microwave frequency and decrease in temperature. Hence, investigation on the temperature profiles observed for each organism will help in
designing an efficient microwave treatment protocol for ballast water.

**Temperature profiles for N. oculata inoculated ballast water**

Temperature histories at the outlet, inlet and holding tube for ballast water inoculated with microalgae are shown in Figures 2 and S2. The temperature curves were plotted using SigmaPlot (Version 9.01, Systat Software, Inc., San Jose, CA). From figures it can be noticed that the outlet temperatures reach equilibrium at a rapid rate. The holding tubes 3 and 4 (h₃ and h₄, respectively), have a much slower response time. The forward (incident) power and the reflected power are denoted by P_F and P_R respectively. The initial cooling trend noticed in the temperatures in Figure S2B is due to the experimental design in which the 4.5 kW experiment was followed by the 2.5 kW test. Table 1 presents the difference in temperature between the ballast water (with algae) at the inlet and outlet (average of nine thermocouples). It can be seen that the system’s design produced uniform temperatures at the outlet (as indicated by the low standard deviations), eliminating the need for additional mixing mechanisms. A combination of low flow rate and high power (1 lpm/4.5 kW) maximized the temperature increase to approx. 60°C. This was expected as low flow rates increase the residence times inside the applicator tube, and thus resulting in more power being absorbed.

**FIGURE 2.** Sample temperature and power profiles during continuous microwave treatment of algae in ballast water at various flow-rate and power combinations; (A) 2 lpm/ 2.5 kW (B) 1 lpm/
Table 1. Temperature increase observed during microwave treatment of the ballast water containing the various organisms.

<table>
<thead>
<tr>
<th>Organism</th>
<th>Operating Parameters</th>
<th>Temperature, °C</th>
<th>β (curve fitting)</th>
<th>R² (adjusted)</th>
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<tr>
<td></td>
<td>Flow rate (lpm)</td>
<td>Power (kW)</td>
<td>Inlet, ( T_{in} )</td>
<td>*Outlet, ( T_{out} )</td>
</tr>
<tr>
<td>N. oculata</td>
<td>2.0 2.5</td>
<td>27.91 ± 0.13</td>
<td>41.88 ± 0.02</td>
<td>13.97 ± 0.20</td>
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<td></td>
<td>2.0 4.5</td>
<td>27.87 ± 0.08</td>
<td>52.77 ± 0.01</td>
<td>22.89 ± 0.15</td>
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<td></td>
<td>1.0 2.5</td>
<td>27.45 ± 0.20</td>
<td>57.52 ± 0.03</td>
<td>30.06 ± 0.33</td>
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<td>1.0 4.5</td>
<td>27.41 ± 0.11</td>
<td>86.77 ± 0.02</td>
<td>59.35 ± 0.67</td>
</tr>
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<td>A. nauplii</td>
<td>2.0 2.5</td>
<td>22.02 ± 0.21</td>
<td>34.00 ± 0.22</td>
<td>11.84 ± 0.28</td>
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<tr>
<td></td>
<td>2.0 4.5</td>
<td>22.05 ± 0.09</td>
<td>47.57 ± 0.22</td>
<td>25.52 ± 0.22</td>
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<td></td>
<td>1.0 2.5</td>
<td>26.25 ± 0.28</td>
<td>46.00 ± 0.49</td>
<td>19.75 ± 0.58</td>
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<td></td>
<td>1.0 4.5</td>
<td>26.17 ± 0.16</td>
<td>59.85 ± 0.29</td>
<td>33.68 ± 0.35</td>
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<td>Artemia adults</td>
<td>2.0 2.5</td>
<td>24.58 ± 0.03</td>
<td>43.59 ± 0.20</td>
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<tr>
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<td>61.04 ± 0.24</td>
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<td>C. virginica</td>
<td>2.0 2.5</td>
<td>26.50 ± 0.11</td>
<td>39.37 ± 0.30</td>
<td>12.87 ± 0.31</td>
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<tr>
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<td>23.36 ± 0.09</td>
<td>88.26 ± 0.83</td>
<td>64.91 ± 0.77</td>
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*The grand mean and standard deviation of the means of all nine outlet thermocouple readings.

**Obtained by subtracting the inlet temperature values from the means of all nine thermocouple readings for each observation, and then calculating the mean temperature difference and standard deviation.
Temperature profiles for Artemia nauplii and Artemia adults inoculated ballast water

Typical temperature profiles obtained during the processing of 3% salinity ballast water containing *A. nauplii* are shown in Figures 3 and S3. As noticed for the ballast water containing microalgae, near instantaneous heating was produced at the outlet. Total heating produced was lower than that observed for microalgae (average inlet and outlet temperatures are given in Table 1). The maximum temperature increase (>33°C) was again greatest at a power and flow rate combination of 4.5 kW and 1 lpm. The differences compared to microalgae in terms of power absorbed and temperatures are due to the difference in their dielectric properties (31). The tuning of the system was initially performed to maximize the efficiency of absorption for pure salt water. As the dielectric loss of salt water is depressed in the presence of *A. nauplii* (31), it was expected to have reduced absorption and lower heating efficiency.

**FIGURE 3.** Sample temperature and power profiles during continuous microwave treatment of *A. nauplii* in ballast water at various flow-rate and power combinations; (A) 2 lpm/ 2.5 kW (B) 1 lpm/ 4.5 kW.
Temperature profiles obtained while processing the ballast water (3% salinity) containing the adult *Artemia* are represented by Figure S4 and Table 1. It can be noticed that for the same processing conditions, the temperature increase for *Artemia* adults (Table 1) was always higher (nearly double at 1 lpm and both power levels) than in the case of *Artemia* nauplii. With all the other conditions being identical, it can be postulated that for the same organism at different growth stages, different heating profiles will be obtained. The young *Artemia* immediately after hatching is rich in proteins, carbohydrates, lipids and fatty acids (37). The percentage of these nutrients reduces as the *Artemia* grows and reaches adulthood in about 8 days after hatching. The presence of these nutrients in large quantities at the earlier stages of growth would have had an influence on the dielectric properties of the mixture. This is supported by other studies on the dielectric properties of water with varying concentrations of carbohydrates, proteins, fats, etc. indicating the influence of the dielectric properties on the microwave power converted into heat by these materials (16, 38). Hence, it is critical to understand the properties of the medium to design an effective microwave treatment method. The maximum temperature increase produced for adult *Artemia* was about 61°C, at a power-flow rate combination of 4.5 kW and 1 lpm (Table 1). At power and flow rate combinations of 4.5 kW and 2 lpm, and 2.5 kW and 1 lpm, the temperature increases observed were nearly similar to each other. *Artemia* are considered to be resilient to treatments like ozone (39), and survive at temperatures between 15-55°C (37). The performance of the continuous microwave system indicates that temperatures above 55°C could be achieved by carefully controlling the flow rate and power input, thus creating environments hazardous/detrimental to *Artemia* survival.

The sample temperature profiles encountered (for *Artemia* nauplii and *Artemia* adults) in the holding tubes measured at fixed distances in the process flow line (see Table S1 for more information) are shown in Figure S5. Analyzing the temperature profiles by curve fitting, it can be deduced that the heating patterns within the holding tubes follow a first order heating curve obeying the equation (40):

\[
y = y_o + A \left(1 - e^{-\beta t}\right) \tag{2}
\]
Where $y = \text{outlet temperature}$

$y_o = \text{initial sample temperature}$

$A = \text{temperature difference between the initial and target temperature, } \Delta T$

$\beta = \text{time constant dependent on the rate of temperature increase}$

$t = \text{time}$

The various calculated values of $\beta$ obtained by curve fitting while analyzing the output temperatures during microwave processing of ballast water containing *Artemia* at two different growth stages is shown in Table 1. For *Artemia* nauplii, the value of $\beta$ was found to be nearly the same for both the flow rates. However, the values of $\beta$ were greater at a flow rate of 2 lpm than for 1 lpm in the case of *Artemia* adults. The same trend in the values of $\beta$ was noticed for the other two organisms as well. The ballast water containing these three organisms namely *Artemia* adults, microalgae and oyster larvae exhibited the greatest temperature increase. In almost all cases the value of $\beta$ was dependent on the flow rate and independent of the power input. The results are encouraging and further optimization trials will yield better control on the microwave heating process using these modeling parameters. During the experiments it was noticed a high level of microwave reflection for the ballast water mixture containing *Artemia* nauplii. In this case, the stubs situated on the tuning coupler should be adjusted to match the impedance of the focusing cavity to the dielectric properties of the organisms-water mixture (32, 33) – not performed here as to not change the experimental design.

**Temperature profiles for oyster larvae inoculated ballast water**

Figure S6 shows the typical temperature profiles obtained at the different flow rate-power combinations during the treatment of ballast water containing oyster larvae. From Table 1, it is evident that at lower flow rates there is a higher heating effect produced due to the increased residence times inside the applicator tube/microwave process chamber. As observed in the other species, the highest temperature increase (65°C) for oyster larvae in ballast water was noticed at the highest power and lowest flow rate combination (4.5 kW and 1 lpm). For the same power level, the temperature increase produced at the lower flow rate was nearly three times the temperature increase produced at the higher
flow rate. In contrast, the temperature increase produced for the ballast water containing the other organisms were much lower at the different flow rates. For instance, the temperature increase noticed at the lower flow rate was approximately twice the temperature increase at a higher flow rate for the same power input for *Artemia* adults (refer Table 1). This increase was also much lower for *Artemia* nauplii, indicating the importance of understanding the dielectric and thermal properties of the process medium prior to designing a microwave process system.

**Sample Inactivation Results**

Sample inactivation results (41) for the various organisms are presented in Table S2 and Figures 4, S7 and S8. Complete inactivation was obtained for the *Artemia* nauplii at a temperature of 47°C and for *Artemia* adults at even lower temperatures (43°C) during microwave treatment (Figure 4). Slightly higher temperatures of 53°C and 51°C respectively were required for complete inactivation of the *N. oculata* and *C. virginica* using the continuous microwave system (Table S2 and Figure S8). With the above mentioned results, it can be concluded that an optimum process temperature of 55°C with a holding time of 200 seconds should be targeted for inactivating the tested organisms. The treatment system presented in this study can achieve this temperature using different power/flow rate combinations. Current and future studies focus on the detailed survival kinetics of different models of species present in ballast water, and optimizing the system for maximum power utilization and energy efficiency by recovering part of the process heat through heat exchangers.
FIGURE 4. Sample survival curves after treatment at 4.5 kW, 2 lpm (47°C) for *Artemia* nauplii (left) and at 2.5 kW, 2 lpm (43°C) for adult *Artemia* (right).

**Power Absorbed**

The power absorbed by the medium was calculated using equation 1 and substituting the ΔT values obtained for different power-flow rate combinations. One assumption made was that the specific heat of salt water was 3850 J/KgK; the same value for sea water (42). The calculated power values absorbed by the medium containing the different organisms and the input power as read on the microwave control panel are shown in Table S3. As the dial was an analog instrument small variations from the assumed values were possible. The absorbed power for the microalgae and *Artemia* nauplii experiments were calculated from the measured reflected power and input power readings. During the course of the experiments with *Artemia* adults and oyster larvae, the power diodes for measuring the reflected power malfunctioned, and hence, the absorbed power for these experiments was calculated only from the energy balance. From Table S3 it can be seen that the efficiency of microwave power utilization was above 80% for the ballast water containing *N. oculata, Artemia* nauplii, *Artemia* adults and *C. virginica* at flow rate of 1 lpm. For *C. virginica*, at higher flow rates, the efficiency decreased to 65-70%. More detailed studies on the thermal and dielectric properties of the medium will be helpful in understanding...
the heating phenomena observed. Based on preliminary economic analysis using the laboratory system, the implementation of this system by itself would be prohibitively expensive costing about $2.55/m³ for a system without heat exchanger and about $1.09/m³ for a system having a heat exchanger (calculations were based on a unit treating water at 2313 kW/m³ per min totaling about 38.6 kWh/m³ energy consumption and are presented in page S12). The environmental advantages of this technology cannot be overlooked and, presumably, the economy of scales would reduce the costs to competitive levels. Another implementation option would be to use the technology in conjunction with another treatment method (hurdle technology). Overall, the continuous microwave system could be used to deliver uniform heating loads and shows promise of being an effective tool for ballast water treatment.

Acknowledgements

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Supporting Information Available

Figure S1 shows the arrangement of the thermocouple at the outlet of the microwave applicator tube. The temperature profiles during microwave treatment of ballast water containing the various organisms at different flow rate and input power combinations are shown in Figures S2 through S6. Table S1 shows the residence times at the different flow rates and sampling locations on the microwave process line. Table S2, and Figures S7 and S8 show sample inactivation results obtained for the different
organisms during the continuous microwave treatment. Table S3 shows the calculated power utilization
efficiency during the microwave treatment of the ballast water containing the different organisms.
Sample calculations on the energy requirement and operating costs for the proposed system are
presented in page S12.

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TABLE OF CONTENTS BRIEF:

Presentation of a novel treatment technology of ballast water from ocean-going ships using electromagnetic energy to prevent introduction of invasive species in native coastal waters