HARMFUL AQUATIC ORGANISMS IN BALLAST WATER

Information on a new technology of ballast water management systems for economical and practical compliance with the Ballast Water Management Convention and its guidelines

Submitted by China

SUMMARY

Executive summary: This document provides, in the annex, a new technology "Inactivation of heterosigma akashiwo in Ballast Water by Conical Orifice Plate-generated Hydrodynamic Cavitation" of ballast water management systems. In comparison with traditional used single- and multi-hole orifice plates, the use of conical-hole orifice plate yielded the highest inactivation percentage of 51.12%, with only 6.84% energy consumption (based on 50% inactivation percentage). Moreover, it allowed the use of a low-pressure pump

Strategic direction: 13
High-level action: 13.0.3
Output: 13.0.3.1
Action to be taken: Paragraph 6
Related documents: None

Background

1 Regulation A-2 of the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004, requires that discharge of ballast water shall only be conducted through ballast water management in accordance with the provisions of the Annex to the Convention.

2 Regulation D-3 of the Ballast Water Management Convention provides that ballast water management systems used to comply with this Convention must be approved by the Administration, taking into account guidelines developed by the Organization.
3 The purpose of the *Guidelines for approval of ballast water management systems* (G8) is to ensure uniform and proper application of the standards contained in the Convention.

4 Currently, filtration, electrolysis and ultraviolet irradiation are the most commonly used techniques in most ballast water management systems (BWMS). However, these techniques possess some disadvantages such as high energy consumption, potential risk to the receiving water body, etc. In comparison with the traditionally used single- and multi-hole orifice plates, the conical-hole orifice plate yielded the highest inactivation percentage, 51.12%, and consumed only 6.84% energy (based on a 50% inactivation percentage). Moreover, it allowed the use of a low-pressure pump.

5 On the basis of the above, Shanghai Maritime University, China, conducted a series of experiments to gain a new environmentally friendly technology of BWMS with economic benefit and safety, as set out in the annex.

**Action requested of the Committee**

6 The Committee is invited to note the information contained in this document.

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ANNEX

NON-CONFIDENTIAL INFORMATION ON BALLAST WATER TREATMENT TECHNOLOGY BY CONICAL ORIFICE PLATE-GENERATED HYDRODYNAMIC CAVITATION

Table of contents

1. Introduction
2. Materials and Methods
   2.1 *Heterosigma akashiwo* and Culture Medium
   2.2 Hydrodynamic Cavitation Setup
   2.3 Determination of Viable Microalgae Concentration
   2.4 Calculation of the Energy Consumed Per Cubic Meter of Sea water
   2.5 Calculation of the Amount of Microalgae Inactivated Per Joule
3. Results and Discussion
   3.1 *Heterosigma akashiwo* Inactivation Using a Single-hole Orifice Plate
   3.2 *Heterosigma akashiwo* Inactivation by Multi-hole Orifice Plates
   3.3 *Heterosigma akashiwo* Inactivation by a Conical-hole Orifice Plate
   3.4 Repeating Inactivation of *Heterosigma akashiwo* by Orifice Plate
   3.5 Energy Consumption of *Heterosigma akashiwo* Inactivation by Orifice Plate-generated Hydrodynamic Cavitation
4. Conclusions
5. References
6. Appendix A-Calculation of the Energy Consumed Per Cubic Meter of Sea water
7. Appendix B-Calculation of the Amount of Microalgae Killed Per Joule
8. Tables
9. Figures
1 Introduction

According to the information updated in May 2014 by the International Maritime Organization (IMO), currently there are a total of 42 ballast water management systems which have received type approvals from their respective administrations (IMO, 2014). Among them, filtration, electrolysis, and ultraviolet irradiation are the most commonly used techniques (Tsolaki & Diamadopoulos, 2010; Werschkuna et al., 2014). However, all of these techniques possess some disadvantages and none of them completely meets all of the requirements for safety, practicality, economic benefit, effectiveness, and environmental friendliness, as proposed by the IMO (Nengye & Frank 2012).

Hydrodynamic cavitation is generally defined as the phenomenon of nucleation, growth and collapse of cavitation bubbles due to the quick drop and recovery of hydrostatic pressure (Sawant et al., 2008). The collapse of cavitation bubbles generates very localized, violent fluid turbulence in the form of high velocity liquid jet, shock wave or other form, which can be used to inactivate microorganisms in wastewater, to degrade organic pollutants, to extract biofuel, to synthesize nanocalcite etc. (Save et al., 1994; Arrojo & Benito, 2008; Gogate, 2007; Pal et al., 2010; Sonawane et al., 2010). Apparently, hydrodynamic cavitation technology is environmentally friendly and the hydrodynamic cavitation setup is, for the most part, quite simple to operate and maintain (Gogate, 2007; Wu & Shen, 2012). These advantages exhibit the potential benefits of introducing hydrodynamic cavitation to treat ballast water.

In this work, we have designed a conical-hole orifice plate to generate hydrodynamic cavitation for inactivation of microalgae with size <50 um in ballast water. A typical red tide microalga, Heterosigma akashiwo, was chosen as the test microorganism. The inactivation percentage and energy efficiency under different treatment conditions were determined and analyzed. Moreover, energy consumption between our experimental orifice plate inactivation set-up and typical commercial ballast water management system was compared. The purpose of this work is to determine the efficacy of treating ballast water by orifice plate generated hydrodynamic cavitation.

2 Materials and Methods

2.1 Heterosigma akashiwo and Culture Medium

Heterosigma akashiwo was purchased from Ocean University of China. Transparent rectangular glass tank and f/2 medium were used to culture Heterosigma akashiwo. The culture condition includes: light/dark ratio 14h/10h, temperature 20℃, light intensity 4000 lux, aeration rate 3 L/min. 1L culture medium containing Heterosigma akashiwo in logarithmic growth stage was diluted by 19 L artificial sea water to simulate ballast water. 1 kg commercial sea salt was dissolved into 30 L distilled water to form artificial sea water.

2.2 Hydrodynamic Cavitation Setup

The inactivation of Heterosigma akashiwo was conducted using a hydrodynamic cavitation setup (Fig. 1) (Gogate, 2011; Patil & Gogate, 2012). An orifice plate was placed in the pipe system to induce hydrodynamic cavitation. The specifications and parameters of the circular orifice plates used here are presented in Table 1, Table 2, and Fig. 2. First, a start-up high-pressure centrifugal pump using frequency conversion control (Y2-80M1-2, Southern Pumps Corporation, China) was used to drive simulated ballast water flow through the pipe system. Subsequently, hydrodynamic cavitation occurred continuously when simulated ballast water passed through the orifice plate. Two pressure transducers (PX409-150GUSB, Omega Engineering, Ohio) were placed before and after the orifice plate to determine the water pressure and temperature. An electromagnetic flow meter (XKD99Z, Shanghai Star Instrument Co., Ltd.,
China) was installed in the pipe system and was used to determine the flow rate. For each experiment, blank control samples are taken from the location of pressure transducer 1. Inactivation percentages of blank control have been subtracted from the inactivation percentages presented in the text and figures.

2.3 Determination of Viable Microalgae Concentration

A flow cytometer (Cyflow Cube 6, Partec GmbH, Münster, Germany) was used to accurately determine the low viable Heterosigma akashiwo concentration in simulated ballast water. Guava® ViaCount® reagent (Guava Technologies Inc., Millipore, USA) was used to stain and distinguish between viable and non-viable cells, nucleus-containing debris, and other impurities based on the differential permeability of DNA-binding dyes in the ViaCount® reagent. The staining procedure was as follows: a 10 mL water sample containing microorganisms in a 40 mL centrifuge tube was continuously agitated to maintain homogeneity of the tube contents. Subsequently, 400 uL homogeneous sample and 400 uL Viacount® reagent were added into a sample tube and were well agitated. After 30 min staining in the dark and storage at a temperature below 10°C, the stained sample was distilled by 200 uL 0.2 um filtered sea water, and then numerated using flow cytometry.

2.4 Calculation of the Energy Consumed Per Cubic Meter of Sea water

The energy consumed per cubic meter of sea water (specific energy consumption, $W_s$, J·m$^{-3}$) during hydrodynamic cavitation treatment was used to evaluate the energy consumption, and then compared with the energy consumption of the typical commercial ballast water treatment system. Appendix A describes the derivation process for calculating $W_s$ using the following expression:

$$W_s = 6.89 \times 10^3 (p_1 - p_2)$$

Where $p_1$ and $p_2$ are the pressure just before and after the orifice plate, respectively, PSI.

2.5 Calculation of the Amount of Microalgae Inactivated Per Joule

The amount of microalgae inactivated per joule (AMIJ, $A_s$, cells·J$^{-1}$) during hydrodynamic cavitation treatment was used to evaluate energy efficiency. Appendix B describes the derivation process of calculating AMIJ, and the result was calculated from the following formula:

$$A_s = \frac{1.45 \times 10^2 (n_1 - n_2)}{(p_1 - p_2)}$$

Where $n_1$ and $n_2$ are the concentrations of viable microalgae before and after treatment, respectively, expressed as cells·mL$^{-1}$.

3 Results and Discussion

3.1 Heterosigma akashiwo Inactivation Using a Single-hole Orifice Plate

For a single-hole orifice plate, the impact of hole-area percentage on the inactivation effect of hydrodynamic cavitation was investigated, and the results are presented in Fig.3. The inactivation percentage negatively associated with the hole-area percentage, and the maximal inactivation percentage of 49.24% was achieved using a No.3 orifice plate with 6% hole-area percentage. In contrast, AMIJ positively associated with hole-area percentage, and the maximal AMIJ of $1.53 \times 10^7$ cells·J$^{-1}$ was obtained using a No.7 orifice plate with 66% hole-area percentage.
In comparison, the highest inactivation percentage of 82% for zooplankton, using an orifice plate with 75% hole-area percentage, was achieved elsewhere (Sawant et al., 2008), which was much higher than that achieved here for *Heterosigma akashiwo*. The zooplankton cell sizes were >50um, in contrast with that of 18 to 34 um for *Heterosigma akashiwo* (Bowers et al., 2006). Thus, microorganisms with small sizes appear to be more resistant to hydrodynamic cavitation, while other unknown biological characteristics, such as morphology, physiology and behaviour, may also contribute to the difference in inactivation percentage.

The pressure difference before and after the orifice plate (Hereinafter referred to as the pressure difference) decreased with hole-area percentage (Fig. 3B), and higher pressure differences associated with higher inactivation percentages (See Fig. 3). Nevertheless, higher pressure differences also associated with lower energy efficiency and higher pressure requirement to the pump.

The viable *Heterosigma akashiwo* concentration before and after No.3 orifice plate-generated hydrodynamic cavitation inactivation was determined using flow cytometry, and a typical result is presented in Fig. 4. After inactivation, the concentration of viable *Heterosigma akashiwo* reduces 34,241 cells∙mL⁻¹, while the concentration of dead *Heterosigma akashiwo* and its nucleus-containing debris increases 7,116 cells∙mL⁻¹. Therefore, over 79.2% of the inactivated *Heterosigma akashiwo* were broken into tiny cell debris that could not be detected by flow cytometry. The results clearly indicate that *Heterosigma akashiwo* is inactivated by breaking it into cell debris, which is most likely due to the impingement from violent fluid turbulence.

3.2 *Heterosigma akashiwo* Inactivation by Multi-hole Orifice Plates

Multi-hole orifice plates were also introduced to generate hydrodynamic cavitation and to inactivate *Heterosigma akashiwo*. For multi-hole orifice plates with constant hole-number, the relationships between hole-area percentage and inactivation percentage, AMIJ, flow rate and pressure difference were similar to that of the single-hole orifice plates (results for plates with 4 holes shown in Fig. 5).

The impact of the hole-number of multi-hole orifice plate on inactivation effect was also researched, and the results are presented in Fig.5. For orifice plates with 6% and 25% hole-area percentages, the inactivation percentage and pressure difference both decreased with hole-number, while AMIJ and flow rate increased with hole-number. E.g.: For orifice plate with 6% hole-area percentage, when the hole-number increased from 1 to 4, a 7.99% decline in inactivation percentage and a 0.48×10⁵ Pa drop in pressure difference were observed. On the other hand, there was a 0.45 m³∙h⁻¹ addition to the flow rate and an AMIJ increase of 0.6×10⁵ cells∙J⁻¹. Hence for multi-hole orifice plates, the effect of increasing the hole-number was similar to that of increasing the hole-area percentage.

Opposite experimental result was obtained by other researcher, in which an increase in hole-number obtained higher cavitational yield (Sivakumar and Pandit, 2002). Theoretically, for a constant hole-area percentage, an exponential increase in hole-number results in an exponential increase in hole-perimeter. According to previous research (Zhao & Zhang, 2008), the hole-perimeter of the orifice plate inversely affected the pressure difference, and consequently was inversely proportional to the inactivation percentage.

The impact of hole-number on *Heterosigma akashiwo* inactivation was further investigated under constant pressure differences (Table 3). For No.2 and 8 orifice plates, an elevation of the pressure difference to 2.16×10⁵ Pa was applied by changing pump frequency so that all three orifice plates could operate on the same pressure difference. Nevertheless, even under constant pressure difference, an elevation of hole-number still causes the reduction in inactivation percentage. E.g.: increasing hole-number from 1 to 16 decreases the inactivation...
percentage by 19.11% (See Table 3). In contrast, using similar experimental conditions plus the adoption of almost constant flow rate, an improvement in cavitation effect (as exhibited by the elevation in iodine liberation) was observed (Vichare et al., 2000).

3.3 *Heterosigma akashiwo* Inactivation by a Conical-hole Orifice Plate

Conical-hole orifice plate was further introduced to inactivate *Heterosigma akashiwo*, and the results are shown in Table 4. In comparison with single- and multi-hole orifice plates, the conical-hole orifice plate not only yielded equivalent inactivation percentages, but also elevated the energy efficiency considerably. E.g.: for No.10 conical-hole orifice plate with 6% hole-area percentage, a maximal inactivation percentage of 51.12% was observed, which was even slightly higher than that of the single-hole orifice plate (No.3, See Fig. 3A, 6% hole-area percentage). Moreover, due to the low pressure difference, AMIJ for No.10 conical-hole orifice plate reached $2.10 \times 10^7$ cells·J$^{-1}$, which was at least 6.35 times higher than that of the single- and multi-hole orifice plates (No.3, See Fig. 3A, 6% hole-area percentage).

The pressure before the conical-hole orifice plate was also low in comparison with that obtained before the single-hole orifice plate. E.g.: the highest pressure before the conical-hole orifice plate was about $2.0 \times 10^4$ Pa (No.10), in comparison with that of $2.55 \times 10^5$ Pa for the single-hole orifice plate (No.3). Low pressure before the orifice plate is desirable, since it allows the use of a low-pressure centrifugal pump to trigger the hydrodynamic cavitation. Moreover, it reduces the pressure-resistance requirement of the pipeline.

In addition, different assembling orientation (hereinafter as orientation) also exhibits different inactivation performance. For example, for No.9 conical-hole orifice plate with 39% hole-area percentage, the inactivation percentage for the small-to-large orientation was 39.26%, which was 165.99% higher than that observed for the large-to-small orientation. Moreover, in terms of energy efficiency, the AMIJ for the small-to-large orientation was $2.01 \times 10^7$ cells·J$^{-1}$, which is only 6.35% higher than that exhibited by the large-to-small orientation.

For a single-hole orifice plate, microalgae inactivation by hydrodynamic cavitation most likely occurs on its downstream side. While for conical-hole orifice plate, higher *Heterosigma akashiwo* inactivation percentage and pressure difference were observed when the conical-hole orifice plate was oriented in the small-to-large direction, in which hydrodynamic cavitation only occurred on its upstream side. Probably the modification in orifice plate shape changed the velocity profile around the orifice plate, thus altered the occurring location of hydrodynamic cavitation, while the exactly reason still deserves further investigation.

3.4 Repeating Inactivation of *Heterosigma akashiwo* by Orifice Plate

Repeating inactivation using orifice plates is tried to elevate the inactivation percentage. Two schemes of repeating inactivation are presented here. Firstly, series-connection of two single-hole orifice plates with the same specification is used to inactivate *Heterosigma akashiwo*, and the representative results are shown in Table 5. With series-connection, due to the elevation in pressure difference, the inactivation percentage increased, while AMIJ and the flow rate decreased. E.g.: for single-hole orifice plates each with 25% hole-area percentage, after series-connection, an inactivation percentage of 49.29% was obtained, which was 16.16% higher than that of a single orifice plate alone. In contrast, the AMIJ decreased to $1.61 \times 10^6$cells·J$^{-1}$, which was 299% lower than that of a single one.

Meanwhile, cycling inactivation of *Heterosigma akashiwo* using a conical-hole orifice plate was also performed, and the results are shown in Fig.6. The inactivation percentage increased with additional inactivation cycles. After 4-cycle inactivation, there was a 7.4% increase in inactivation percentage as compared to 1-cycle inactivation. Additional increasing in cycle
number to 5 only elevated the inactivation percentage by 0.5%. On the other hand, after 4-cycle inactivation, there was a $1.62 \times 10^7$ cells-J$^{-1}$ decline in the AMIJ, which was 338% lower than that of 1-cycle inactivation.

### 3.5 Energy Consumption of *Heterosigma akashiwo* Inactivation by Orifice Plate-generated Hydrodynamic Cavitation

The specific energy consumption under different treatment conditions with inactivation percentages around 50% (except for No.2 orifice plate) were calculated, and the results are shown in Table 6. The specific energy consumption of a No.9 conical-hole orifice plate with small-to-large orientation was 17,225 J-m$^{-3}$, which consumed only 6.84% energy relative to that consumed using the No.3 single-hole orifice plate. Ballast water passing through either a single- or multi-hole orifice plate may be regarded as experiencing treatment using a series-connection of one conical-hole orifice plate with the large-to-small orientation and subsequent another one with the small-to-large orientation. Probably this is the reason why single- or multi-hole orifice plates exhibit much higher energy consumption than conical-hole one.

For repeating inactivation, series-connection elevated the specific energy consumption drastically (See Table 4 No. 5 and 9 orifice plates), which is consistent with the energy efficiency results obtained in Section 3.4. The results indicate that although series-connection treatment and cycling inactivation both can improve the inactivation percentage, the dramatic decline in energy efficiency offsets any advantages offered by repeating inactivation.

The specific energy consumption for currently used type-approved ballast water management systems based on UV treatment technology and the IMO meeting standards is 431,138 to 547,200 J-m$^{-3}$. In comparison, the specific energy consumption for conical-hole-generated hydrodynamic cavitation based on 50% inactivation was about 25 to 32 times lower than previously mentioned ballast water management systems (based on results in Table 6, No.5 Conical-hole S→L). Due to its low specific energy consumption, conical hole-generated hydrodynamic cavitation shows great potential for use in ballast water treatment.

### 4 Conclusions

Orifice plate-generated hydrodynamic cavitation was employed to inactivate viable *Heterosigma akashiwo* in simulated ballast water. For single- and multi-hole orifice plates, increases in hole-area percentage and hole-number each showed negative effects on the inactivation percentage, while exhibiting positive impacts on energy efficiency. In comparison with single- and multi-hole orifice plates, the use of conical-hole orifice plate yielded the highest inactivation percentage of 51.12%, with only 6.84% energy consumption (based on 50% inactivation percentage). Moreover, much lower pressure was needed to trigger the hydrodynamic cavitation, which allowed use of a low-pressure pump. Generally, conical hole-generated hydrodynamic cavitation exhibits excellent performance and shows great potential as a pre-inactivation technique to treat ballast water.

### 5 References


6 Appendix A-Calculation of the Energy Consumed Per Cubic Meter of Sea water

Assuming sea water is incompressible and based on Bernoulli’s equation, total energy per unit mass of sea water (\( \psi, \ J\cdot kg^{-1} \)) is given by:

\[
\psi = \frac{u^2}{2} + \frac{p}{\rho_{s}} + gz
\]  

(A1)

Where:
- \( u \) is the sea water velocity, m\cdot s^{-1};
- \( p \) is the pressure, Pa;
- \( \rho_{s} \) is the sea water density, kg\cdot m^{-3};
- And \( z \) is the height difference between the calculating point of the pipe and the datum level, m.

The energy consumed per unit mass of sea water due to hydrodynamic cavitation is given by:

\[
\Delta \psi = (\frac{u_1^2}{2} + \frac{p_1}{\rho_{s}} + g z_1) - (\frac{u_2^2}{2} + \frac{p_2}{\rho_{s}} + g z_2)
\]  

(A2)

Where the subscripts “1” and “2” denote the position on the pipe just before and after the orifice plate, respectively.

Assuming the pipe diameter is constant and the pipe is mounted horizontally, it follows that \( z_1 = z_2 \), \( u_1 = u_2 \), and the following expression applies:
\[ \Delta \psi = \frac{(p_1 - p_2)}{\rho_s} \]

Thus the energy consumption per cubic meter sea water \( (W_s) \) is:

\[ W_s = \Delta \psi \cdot \rho_s = \frac{(p_1 - p_2)}{\rho_s} \]

(A3)

Since the pressure value obtained by pressure transducer is in PSI, equation A4 is modified as:

\[ W_s = 6.89 \times 10^3 (p_1 - p_2) \]

(A4)

(A5)

Where \( p_1 \) and \( p_2 \) are the pipe pressures just before and after the orifice plate, respectively, PSI.

### 7 Appendix B - Calculation of the Amount of Microalgae Killed Per Joule

The amount of microalgae killed per cubic meter is given by:

\[ \Delta n = (n_1 - n_2) \times \frac{10^6 \, \text{cm}^3}{\text{m}^3} \]

(A6)

Therefore, the amount of microalgae killed per joule (AMJ, \( A_s \), cells\cdot J^{-1}) is:

\[ A_s = \frac{(n_1 - n_2) \times 10^6}{6.89 \times 10^3 \times (p_1 - p_2)} = \frac{1.45 \times 10^7 (n_1 - n_2)}{(p_1 - p_2)} \]

(A7)

Where:

\( n_1 \) and \( n_2 \) are the concentrations of viable microalgae before and after treatment, respectively, cell\cdot mL^{-1}; \( p_1 \) and \( p_2 \) are the pipe pressures just before and after the orifice plate respectively, PSI.

#### Table 1 Parameters of experimental single-and multi-hole orifice plates

<table>
<thead>
<tr>
<th>No.</th>
<th>Number of holes</th>
<th>Hole diameter (mm)</th>
<th>Total hole area percentage (%)</th>
<th>Total hole area (mm²)</th>
<th>Total hole perimeter (mm)</th>
<th>Cavitation number (Cv)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>8</td>
<td>25</td>
<td>200.96</td>
<td>100.53</td>
<td>0.945</td>
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<td>4</td>
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<td>6</td>
<td>50.24</td>
<td>50.27</td>
<td>0.098</td>
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<td>6</td>
<td>50.24</td>
<td>100.53</td>
<td>0.080</td>
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Note: The inner pipe diameter is 32mm.
Table 2 Parameters of experimental conical-hole orifice plates

<table>
<thead>
<tr>
<th>No.</th>
<th>Small-hole diameter (mm)</th>
<th>Small-hole area (mm²)</th>
<th>Hole area percentage (%)</th>
<th>Large-hole diameter (mm)</th>
<th>Length h (mm)</th>
<th>Assembling orientation</th>
<th>Cavitation number (Cv)</th>
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<td>9</td>
<td>20</td>
<td>200.96</td>
<td>39</td>
<td>32</td>
<td>34</td>
<td>L→S</td>
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<td></td>
<td></td>
<td></td>
<td>S→L</td>
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</tr>
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<td>10</td>
<td>16</td>
<td>314</td>
<td>25</td>
<td>32</td>
<td>45</td>
<td>L→S</td>
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<td></td>
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<td></td>
<td>S→L</td>
<td>1.918</td>
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</table>

Note: The inner pipe diameter is 32mm.

Table 3 Impact of hole number on the inactivation of *Heterosigma akashiwo* under constant pressure difference

<table>
<thead>
<tr>
<th>No. of holes</th>
<th>Number of holes</th>
<th>Total hole perimeter (mm)</th>
<th>Microalgae inactivation percentage (%)</th>
<th>The amount of microalgae inactivated per joule (10⁶ cells∙J⁻¹)</th>
<th>Flow rate (m³∙h⁻¹)</th>
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<tr>
<td>3</td>
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<td>8</td>
<td>16</td>
<td>100.53</td>
<td>30.56</td>
<td>0.684</td>
<td>3.417</td>
</tr>
</tbody>
</table>

Note: The pressure difference before and after the orifice plate was kept constant at 2.16×10⁵ Pa.

Table 4 Inactivation of *Heterosigma akashiwo* using conical-hole orifice plates

<table>
<thead>
<tr>
<th>Orifice plate number</th>
<th>Assembling Orientation</th>
<th>Flow rate (m³∙h⁻¹)</th>
<th>Pressure before the orifice plate (Pa)</th>
<th>Pressure difference before and after the orifice plate (Pa)</th>
<th>Inactivation percentage (%)</th>
<th>The amount of microalgae inactivated per joule (10⁷ cells∙J⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>L→S</td>
<td>3.866</td>
<td>7,579</td>
<td>5,512</td>
<td>14.76</td>
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<td></td>
<td>S→L</td>
<td>3.679</td>
<td>16,536</td>
<td>13,780</td>
<td>39.26</td>
<td>2.01</td>
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<td>10</td>
<td>L→S</td>
<td>3.684</td>
<td>9,646</td>
<td>7,579</td>
<td>18.67</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>S→L</td>
<td>3.672</td>
<td>19,981</td>
<td>17,225</td>
<td>51.12</td>
<td>2.10</td>
</tr>
</tbody>
</table>

Note: The initial viable *Heterosigma akashiwo* concentration was 7.06×10⁵ cells∙mL⁻¹.

Table 5 Inactivation of *Heterosigma akashiwo* using two series-connected single-hole orifice plates with the same specification

<table>
<thead>
<tr>
<th>Orifice plate number</th>
<th>Flow rate (m³∙h⁻¹)</th>
<th>Pressure difference before and after the orifice plate (10⁵ Pa)</th>
<th>Inactivation percentage (%)</th>
<th>The amount of microalgae inactivated per joule (10⁶ cells∙J⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.874</td>
<td>2.232</td>
<td>49.29</td>
<td>1.61</td>
</tr>
<tr>
<td>6</td>
<td>0.394</td>
<td>3.348</td>
<td>41.81</td>
<td>7.61</td>
</tr>
</tbody>
</table>

Notes: The initial viable *Heterosigma akashiwo* concentration was 1.71×10⁶ cells∙mL⁻¹.
Table 6 The specific energy consumption for hydrodynamic cavitation under different treatment conditions

<table>
<thead>
<tr>
<th>Orifice plate number</th>
<th>Treatment conditions</th>
<th>Inactivation percentage (%)</th>
<th>Specific energy consumption (J·m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Single-hole</td>
<td>49.24</td>
<td>251,660</td>
</tr>
<tr>
<td>2</td>
<td>Multi-hole</td>
<td>40.44</td>
<td>215,440</td>
</tr>
<tr>
<td>5</td>
<td>Single-hole, double series-connection treatment</td>
<td>49.29</td>
<td>223,207</td>
</tr>
<tr>
<td></td>
<td>Conical-hole S→L</td>
<td>51.12</td>
<td>17,225</td>
</tr>
<tr>
<td>9</td>
<td>Conical-hole S→L, 3-cycle inactivation</td>
<td>57.65</td>
<td>51,690</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic of hydrodynamic cavitation setup

Fig. 2 Pictures of single-, multi- and conical-hole orifice plate
Fig. 3 Impact of single-hole orifice plate hole-area percentage on inactivation percentage and the amount of microalgae inactivated per joule (A), and the flow rate and pressure difference before and after the orifice plate (B). The initial viable *Heterosigma akashiwo* concentration was $9.45 \times 10^5$ cells·mL$^{-1}$. The increased hole-area percentages presented in X axis each correspond to No.3 to No.7 single-hole orifice plates.
Fig. 4 A typical enumeration result of *Heterosigma akashiwo* stained with Guava® Viacount® by cytometry. A: without treatment; B with hydrodynamic cavitation treatment; No.3 single-hole orifice plate was used. Treatment condition: flow rate 2.685 m³·h⁻¹, pressure difference before and after the orifice plate 2.55×10⁵ Pa, and the initial viable *Heterosigma akashiwo* concentration was 9.45×10⁵ cells·mL⁻¹.

![Fig. 4](image1)

Fig. 5 Impact of orifice plate hole-number on inactivation percentage (A), the amount of microalgae inactivated per joule (B), pressure difference before and after the orifice plate (C) and flow rate (D). The initial viable *Heterosigma akashiwo* concentration was 9.8×10⁵ cells·mL⁻¹.

![Fig. 5](image2)
Fig. 6 Impact of cycling time on inactivation percentage (A) and the amount of microalgae inactivated per joule (B). A No.9 conical-hole orifice plate was used with small-to-large assembling orientation. Initial viable *Heterosigma akashiwo* concentration was $1.69 \times 10^6$ cells·mL$^{-1}$.