The Exploration of Ballast Water Treatment Systems to Reduce Populations of Invasive Species

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Abstract

Invasive species are being transported around the globe daily through the use of ballast tanks. Ships utilize ballast tanks to provide stability over long voyages across the ocean. The introduction of invasive species through ballast tanks is costing communities billions of dollars in damages and health related problems. Through this study, five tested systems of ballast water treatment were examined and their respective effectiveness were compared. Treatment methods included the use of hydrocyclones and UV systems, screens, crumb rubber filtration, deoxygenation tactics, and a continuous microwave system. Each of these systems attempted to remove the largest proportions of phytoplankton, zooplankton, and invertebrate larvae from the water source used. After comparing the effectiveness of each system, a continuous microwave unit proved to be the most viable option for ballast water treatment. This system can be used to successfully kill all potential organisms that are transported in a ballast tank in 200 seconds. The use of a microwave system heats the water to a temperature (55°C), where the organisms cannot survive, and effectively eliminates the threat they pose when they are released.

1. Introduction

Eighty percent of the worlds' commodities are transported via cargo ships (Tang et al., 2005). In order to safely travel across the ocean, ships use ballast tanks to help stabilize their large loads (Tsolaki & Diamadopoulos, 2009). Ballast tanks are expansive storage compartments in the bottom of a ship's hull that store water. The added weight of the water lowers the ship's center of gravity and helps to maintain stability while traveling. Failure to maintain operational ballast tanks can lead to ships breaking in half or capsizing mid-voyage (Tsolaki & Diamadopoulos, 2009). Ballast tanks can hold anywhere between several to one hundred thousand metric tons of water (Sutherland et al., 2001). While water is pumped into the tank, organisms living within the water are also pumped in and stored for the ship's journey. When a ship arrives at its designated port, its tanks contents are emptied into the surrounding water, often permanently dispersing a species, usually cross continental, causing the introduction of new species, to a different biological environment (Tamburri et al., 2001). These introduced invasive species shift natural populations of native organisms due to increased competition for food and habitat (Sutherland et al., 2001), leading to increased rates of marine disease in native species (Waite et al., 2003).

At the Ballast Water Convention in 2016, a set of international ballast standards were created to determine the maximum allowance of organisms remaining in a water source following treatment (Alfa Laval, 2017). For organisms that are 50 μm or larger, only 10 viable organisms are allowed per cubic meter of ballast water. For organisms that are between 10 and 50 μm, there can be 10 organisms per one milliliter. Organisms that are classified as indicator microbes, such as zooplankton that are less than 10 μm, there can be less than 1 colony forming unit per 1 gram of zooplankton samples (Alfa Laval, 2017). These guidelines based on organism size help to target the ability of larger organisms to travel within a ballast tank successfully.

In the United States, over 100 billion dollars are spent every year to manage problems caused by the introduction of non-native species (Tang et al., 2005). In the Great Lakes alone, communities have spent over five billion dollars repairing damages caused by the introduction of Zebra mussels (Tang et al., 2005), which were transported within the internal storage compartments of cargo ships traveling from European ports (O'Neill et al., 1994). Invasive species not only cost communities' money, but also put lives at risk. In the 1990s, a strain of Cholera was transported from South to North America through an untreated ballast water tank. Despite recent attempts to treat ballast water, the rate of invasion world-wide has rapidly increased in the last 200 years (Waite et al., 2001). In 2010, a case of Cholera broke out in Haiti, killing thousands and affecting an additional four hundred thousand people (Tappero & Tauxe, 2011). If this issue is not subsequently tested, the health of an increasing number of ecosystems will be put in jeopardy. The negative impact on human health caused by untreated ballast water will also cost individuals and communities large amounts of money and resources (Bax et al., 2003).

The International Marine Organization reports that 10 billion tons of water are exchanged each year (Boldor et al., 2008). The current major ideology for a preventive method that minimizes non-indigenous species transfer is to release port water into the open ocean (Waite et al., 2003). This method anticipates that the species being transported will not be able to survive their release in the open ocean and will limit the influence they have on coastal areas. However, this method of offshore ballast water exchange proved to be only 65% effective at preventing invasive species survival (Sutherland et al., 2001). Additional methods have been tested for ballast water treatment effectiveness. This paper examines six of these different methods and systems of ballast water treatment that use deoxygenation, UV systems, hydrocyclones, screens, crumb rubber filtration, and microwave systems to remove invasive species including zooplankton, phytoplankton, and invertebrate larvae. The National Research Committee of Canada conducted research of this nature in 1996, determining that a screen is the most effective treatment for ballast water (Waite et al., 2003). In a study conducted on the possible transfer of lionfish to the Eastern Pacific Ocean via ships' ballast tanks, it was discovered that the average screen used on vessels is unable to successfully remove the majority of lionfish larvae from the water source (MacIssac et al., 2016). This study helps to promote the need for continued research into new methods of treatment for ballast water that could potentially be more effective than a simple screening process.

The research presented in this paper challenges the notion that a screen is still the most effective water treatment method. This method of treatment is outdated as the creation of other systems such as UV treatment (Sutherland et al., 2001) and continuous microwave systems are proving to be more effective at removing organisms from ballast tanks (Boldor et al., 2008). The studies discussed in this paper were evaluated on their ability to successfully remove zooplankton, phytoplankton, and invertebrate larvae from the water source. The method of evaluation utilized in this paper is a novel development in the establishment of an effective ballast water treatment system as it compares the effectiveness of multiple treatment methods, as opposed to focusing on individual systems. This paper does not focus on self-conducted experiments using each water treatment system, resulting in a restraint on the information available for review. The research is limited by the supply of data available for each test being evaluated. Despite this potential lack of information available for examination, the issue surrounding invasive species being transported via ship ballast water must be resolved, as the health of both humans and marine ecosystems are threatened by the introduction of non-indigenous species (Bax et al., 2003).

2. Systems tested

Six various techniques from five different studies on ballast water treatment systems were compared for effectiveness. Each of these six techniques were effective at removing at least one of three organisms typically found in ballast water, phytoplankton, zooplankton, and invertebrate larvae. These three test groups allow for the effectiveness of each system. The systems tested utilized hydrocyclones, UV treatment, microwave systems, self-cleaning screens, crumb rubber filtration, and deoxygenation techniques.

Two of the five systems examined used combinations of hydrocyclones and UV treatment systems. A hydrocyclone is a device used to separate particles of various size suspended in a liquid. Prior to water's entry to the ballast tank, the water is subjected to a cyclonic motion that propels large particles to the outside of the device and into a separate sample port called "post-solids" (Sutherland et al., 2001). The particles that are too large to pass through the cyclone are released and denied access to the tank. Following the cyclone, the UV system consisting of 20 germicidal UV lamps is applied to the remaining post cyclone stream that has potential bacteria, viruses, and microalgae contaminating it (Sutherland et al., 2001). In one of the two systems tested, a self-cleaning screen was tested in place of the hydrocyclone. This experiment allowed the effectiveness of two primary treatments, a self-cleaning screen and a hydrocyclone, to be compared (Waite et al., 2003).

Similar to the use of a screen, a crumb rubber filtration system was used in one of the studies examined. This system filtered water through tubes filled with pieces of rubber of various depths and medias. The filtration rate was also altered to determine if there was an optimum rate of flow (Tang et al., 2005). The microwave system that was tested raised the temperature of the water and was analyzed to identify the necessary time and microwave strength needed to eliminate organisms from the water (Boldor et al., 2008). Each of these systems were tested for optimal rates of efficiency.

In one study, deoxygenation tactics were tested as a method to not only treat ballast water but reduce corrosion rates of ballast tanks. In this experiment, the oxygen was purged from the tank by continuously pumping in nitrogen (Tamburri et al., 2002).

3. Removal of Phytoplankton and Zooplankton

Populations of phytoplankton and zooplankton were tested in four of the five studies examined. The study testing deoxygenation methods did not test to remove zooplankton or phytoplankton populations due to their additional focus on corrosion control, limiting their sampling to corrosion control and invertebrate larvae. The concentration of phytoplankton and zooplankton varied greatly from treatment to treatment. In each study examined, phytoplankton appeared to be easier to remove than zooplankton populations.

Phytoplankton concentrations were tested following the use of UV treatment and a hydrocyclone in an experiment completed by Sutherland et al. (2001). The concentration of phytoplankton was highest in the post-solids checkpoint and lowest following UV treatment (Sutherland et al., 2001). The post-solid checkpoint consisted of the waste formed from the hydrocyclone, supporting the effectiveness of a cyclonic system. This combination of the UV treatment and hydrocyclone proved to be the most effective method of removing initial phytoplankton populations. However, following this treatment, a collection of phytoplankton was subjected to three months of dark storage to determine their ability to survive and regrow without light. It was discovered that phytoplankton can regenerate despite being stored in darkness for three months (Sutherland et al., 2001). Despite the inability to kill phytoplankton populations completely, the effect of UV treatment included a 100% deactivation rate of auxospores, a cell required for normal physiological processes to occur in phytoplankton, eliminating their ability to reproduce (Sutherland et al., 2001). The use of a screen in place of a hydrocyclone followed by a UV system conducted by Waite et al. (2003) appeared to have practically no additional impact on the water treatment (Waite et al., 2003).

In an experiment conducted by Tang et al. (2005), it was determined the use of crumb rubber filtration was only 58% effective at removing phytoplankton at its optimum settings, with a filter depth of 1.2 meters, a filtration rate of 24.4 $m^3/h\ m^2$, and a media size of 0.5-1.2 mm (Tang et al., 2005). The optimal settings of the crumb rubber filtration tested initially in the experiment were the deepest filter depth, the slowest filtration rate, and the smallest media size evaluated. Following the conclusion of the crumb rubber experiment, it was determined that the optimal size for the most effective crumb rubber filtration system would be too large for practical ship application due to the necessary surface area and depth of media needed to obtain a slow filtration rate for optimum flow (Tang et al., 2005). A ship that has a ballast tank flow of 5000 m^3/h would require a 70 m^2 surface area with a 2 meter deep crumb rubber layer to be at its highest removal effectiveness, a size too large for shipboard application (Tang et al., 2005). Crumb rubber filtration does not ensure that the phytoplankton populations admitted to the tank will not be able to regrow following reintroduction to light.

The studies that examined zooplankton populations revealed lower removal rates for zooplankton than phytoplankton. Zooplankton concentration was virtually unaffected following the use a hydrocyclone and UV treatment in the study by Sutherland et al. (2001). The replacement of the hydrocyclone with a screen to this process by Waite et al. (2003) did not increase the effectiveness of removing zooplankton populations (Waite et al., 2003). Crumb rubber filtration was only 50% effective at removing populations of zooplankton (Tang et al., 2005). However, in an experiment by Boldor et al. (2008), zooplankton nauplii were subjected to a continuous microwave system. After being subjected to this treatment, the concentration of zooplankton nauplii were diminished by almost 100% in 150 seconds (Boldor et al., 2008). The microwave system was the only treatment method that was able to effectively remove a large majority of zooplankton populations.

4. Removal of Marine Invertebrate Larvae

Systems that included deoxygenation techniques, a screening process, or a microwave system, proved effective at removing the large majorities of invertebrate larvae typically transported in ballast tank systems. Deoxygenation tactics conducted by Tamburri et al. (2001) resulted in death rates of 79-97% for three species examined (Tamburri et al., 2001), but the test was only run for 72 hours, so long-term impacts were not calculated. It is hypothesized that if the organisms had been left in a deoxygenated environment for two to three weeks, they all would have been killed (Tamburri et al., 2001). In order to contrast the effectiveness of removing oxygen from a tank, a similar test was run with organisms left in an open-air container. In this test, less than 26% of the organisms tested were killed (Tamburri et al., 2001), supporting the effectiveness of deoxygenation tactics.

In prior studies, it appeared as though screening processes were the most effective at removing invertebrate larvae from ballast water. With the use of a screen prior to a UV system seen in the experiment conducted by Waite et al. (2003), 90% of larvae were effectively removed from the water entering the tank (Waite et al., 2003). The use of a hydrocyclone instead of a screen with a UV system effectively killed all copepods in the tank (Sutherland et al., 2001), but only reduced the combined total organism count of larvae and copepods admitted into the tank by less than 15% (Waite et al., 2003). In a similar examination of mesh screens conducted by the researchers who tested the effectiveness of crumb rubber filtration, it was determined that if two mesh screens were used to filter the water before it entered the tank, the effectiveness of removing these species would be over 90% (Tang et al., 2005).

The microwave system proved to be extremely effective at killing invertebrate larvae, as well as all other organisms within the water. With a system set with the initial test intervals, the microwave system successfully killed 80% of the species subjected to treatment (Boldor et al., 2008). The microwave system killed organisms due to the temperature increase of the water. It was determined that there is an optimum temperature and exposure time for water treatment. If water was subjected to microwave treatments that raised the water temperature to 55°C for 200 seconds, it is predicted that 100% of the marine invertebrates, as well as phytoplankton populations, will be effectively killed and removed from the system (Boldor et al., 2008). The microwave system's nearly complete removal of all organisms examined was the greatest of the six treatment methods reviewed. The cost of implementing this continuous microwave system on a ship was determined to be approximately $2.55/m^3 without a heat exchanger and $1.09/m^3 for a ship with a heat exchanger (Boldor et al., 2008). The cost of this system must be explored even further to determine whether this system is practical and affordable for implementation on all commercial ships in use today. The use of deoxygenation tactics were hypothesized to be just as effective, yet these methods would require a ship to be traveling for at least 2-3 weeks (Tamburri et al., 2008), whereas a microwave system is 100% effective within 200 seconds (Boldor et al., 2008).

5. Conclusion

Ballast tank water treatment is a pressing issue. Failure to properly treat ballast water can lead to disruptions in marine ecosystems and can cost communities billions of dollars. With the discovery that offshore ballast water exchange is not a viable method for effectively treating ballast water (Sutherland et al., 2001), it is clear that additional treatment methods must be explored. In 1996, the National Research Committee of Canada (NRCC) determined that a screening process was the most effective method of treating ballast water. With the conclusion of this study, it is clear the NRCC's conclusion is outdated, and a screening process is no longer the best system available. The use of a microwave system is the most effective ballast water treatment practice of those examined in this study. UV treatment and hydrocyclones only successfully removed one specific type of organism, whereas a microwave system effectively killed all species in the water sample. Crumb rubber filtration only worked at a 50% effectiveness at its optimum settings. Deoxygenation tactics seem to be viable only if a ship is traveling for 2-3 weeks, whereas the microwave system is 100% effective within 200 seconds.

Although a continuous microwave system was determined to be the most effective system of ballast water treatment, there is still research that needs to be conducted. An optimum temperature and time for treatment was identified, but the viability of this treatment aboard a ship must be researched. This system was extremely effective at removing species from the water samples tested, but in order to optimize the effectiveness of a continuous microwave system, the properties of the individual water source on which this system will be used must be further researched and interpreted (Boldor et al., 2008).

The further study of continuous microwave treatment systems should prove to be an extremely effective method of ballast water treatment. The assessment of the cost and viability of this system will determine whether a continuous microwave unit is practical for the use on vessels. The approval of this system as a viable option for ballast water treatment will likely lead to decreased rates of invasive species spread and increased biodiversity.

Resources

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