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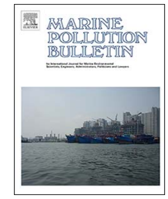

Feasibility of potable water generators to meet vessel numeric ballast water discharge limits

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ABSTRACT

Ballast water is taken on-board vessels into ballast water tanks to maintain vessel draft, buoyancy, and stability. Unmanaged ballast water contains aquatic organisms that, when transported and discharged to non-native waters, may establish as invasive species. Technologies capable of achieving regulatory limits designed to decrease the likelihood of invasion include onboard ballast water management systems. However, to date, the treatment development and manufacturing marketplace is limited to large vessels with substantial ballast requirements. For smaller vessels or vessels with reduced ballast requirements, we evaluated the feasibility of meeting the discharge limits by generating ballast water using onboard potable water generators. Case studies and parametric analyses demonstrated the architectural feasibility of installing potable water generators onboard actual vessels with minimal impacts for most vessel types evaluated. Furthermore, land-based testing of a potable water generator demonstrated capability to meet current numeric discharge limits for living organisms in all size classes.

1. Introduction

Ballast water discharges are a major source of aquatic invasive species (e.g., Bailey, 2015; Carlton, 1985; Ruiz et al., 2015). Some species (e.g., zebra and quagga mussels) have caused significant economic and ecological harm (Pimentel et al., 2005) and have the potential to endanger public health by transporting and introducing cyanobacteria (e.g., Doblin et al., 2007; Hallegraeff, 2015) and human pathogens (e.g., Cohen et al., 2012; Ruiz et al., 2000). International, national, and state/regional regulatory efforts (e.g., IMO, 2004) have established numeric ballast water discharge limits and other management requirements to reduce the risks posed by ballast water discharges (Albert et al., 2013; Gollasch et al., 2007; Gregg et al., 2009). The requirements to meet these discharge limits are gradually being mandated; for example, the International Maritime Organization's (IMO) Ballast Water Convention enters into force in August 2017 (IMO, 2017; Lymperopoulou and Dobbs, 2017) while other national-level discharge limits are currently being implemented (e.g., U.S. EPA, 2013; USCG, 2012). Typically, these regimes are designed to reduce propagule pressure (i.e., quality, quantity, and frequency of living organisms that are introduced into the aquatic environment), which reduces the probability of invasion into a receiving water body (Briski et al., 2012; NRC, 2011). United States and international requirements provide numerous ways for vessels to meet ballast water limits, including the use of combinations of onboard ballast water management systems (BWMS), potable water from onshore treatment facilities, onshore treatment, or cessation of ballast water discharges (Albert et al., 2013; David et al., 2015). Use of ballast water management systems that meet numeric discharge limits should reduce the total number of organisms discharged compared to discharges under current ballast water management regimes (Davidson et al., 2017), which should reduce propagule pressure and invasion risk. While many technology developers and vessel operators have explored the use of BWMS to meet regulatory limits (ABS, 2014; David and Gollasch, 2015; Stehouwer et al., 2015), other approaches for meeting or exceeding those limits for various vessel classes or vessel routes are also being actively explored (Briski et al., 2015; King and Hagan, 2013; Pereira and Brinati, 2012; Paolucci et al., 2015).

The magnitude of a given vessel's ballast water discharge depends primarily upon its size and cargo operations. Typical ballast capacities for large vessels range from 1200 to > 200,000 m^3 (NRC, 1996; NRC, 2008). In contrast, smaller vessels (e.g., pushboats, fishing vessels, small cruise ships and research vessels) may have ballast water capacities of only a few cubic meters (Madaeni, 1999). Large cargo-

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carrying vessels are equipped to fully load or discharge their ballast tanks within a fixed time period, typically 12 to 24 h, to facilitate rapid turnaround times at port (ABS, 2014). Smaller non-cargo-carrying vessels, however, are not typically equipped to handle full ballast loads/discharges on a regular basis and instead must transfer onboard ballast between internal tanks or, as needed, incrementally load or discharge ballast to compensate for continuous changes in vessel loads (e.g., sewage generation or fuel consumption) (King and Hagan, 2013). Given these differences, ballast water management practices on large vessels may not translate to smaller vessels and vice versa. The current market of BWMS are generally designed for vessels with substantial pumping rates (i.e., > 200 m^3 per hour), thus favoring ballast water management practices typical of large vessels (U.S. EPA SAB, 2011). The economics of scaling down these systems has thus far precluded industry from pursuing the market for smaller vessels or vessels with reduced ballast requirements, leaving them with limited options for onboard treatment (MEPC, 2009a).

One possible treatment approach for vessels with reduced ballast requirements is to generate ballast through an onboard potable water generator (PWG) (MEPC, 2009b). A PWG is typically a composite system comprising both a water purification and a disinfection system. The system purifies water from fresh, brackish or saltwater sources using distillation or reverse osmosis (RO) technologies. The purified water is then treated by disinfection technologies that use chemicals or ultraviolet radiation to neutralize any remaining living organisms and pathogens.

Under existing international and U.S. domestic regulatory regimes, all BWMS are subject to a testing and approval process to test the ability of the system to kill or remove organisms to demonstrate the system can meet discharge standards (Tsolaki and Diamadopoulos, 2010; U.S. EPA SAB, 2011). This type of testing is commonly referred to "type-approval" testing. For signatories of the IMO (2004) ballast water convention, type-approval testing is conducted under the G8 guidelines developed by the MEPC for evaluating compliance with that convention's Regulation D-2 discharge standards (MEPC, 2008). In the case of United States, that type approval testing is mandated by the United States Coast Guard and systems must meet the requirements found at 33 CFR Part 151, Subparts C and D (USCG, 2012). Under existing international and domestic regulatory regimes, use of a PWG to manage ballast water should be allowed under international and U.S. domestic, provided those systems were type approved consistent with the IMO G-8 guidelines and/or U.S. Coast Guard type approval testing standards, as applicable (MEPC, 2009b). However, use of PWGs would likely not be considered potable water from onshore public water systems for purposes of regulatory compliance.

PWG capacities range from 2 to up to 80 m^3 per hour (m^3/h). The vast majority of the systems we surveyed (> 85%) produce water at or below 7 m^3/h, suggesting that the application of PWGs would best suit vessels ballasting at rates of 7 m^3/h or less (or the use of more than one PWG). The remaining 13% is evenly distributed across the 7 to 80 m^3/h range. Disinfection system capacities have little bearing on the overall potential for onboard treatment, as their capacities (2 to 36,000 m^3/h) meet and far exceed those of any accompanying water purification systems. Purchase costs for 0.25 to 7 m^3/h PWGs currently range from approximately $40,000 to $170,000. Operating and maintenance (O & M) costs depend on a vessel's overall water production volume and frequency, and thus are highly vessel specific. However, worst case O & M costs for 0.25 to 7 m^3/h PWGs (assuming continuous, non-stop operation over the course of a year) currently range from $2000 to $60,000 per year (U.S. EPA, 2015).

Performance data for organism removal efficacy by PWGs is limited, as vendors' technical specifications typically do not consider micro-organism removal. RO-based purification systems have been reported to provide 4- to 7-log reductions for coliform bacteria and 2.7- to 6.5-log reductions for the MS2 bacteriophage (Madaeni, 1999). Disinfection approaches used in ballast water management systems have generally been shown to be effective in reducing the number of living organisms from multiple genera that would be taken into ballast tanks (First et al., 2016). Ballast water management systems use many of the same disinfection approaches used by PWG systems (e.g., chlorination). We are unaware of other published data evaluating the efficacy of PWGs in removing both zooplankton and other organisms greater or equal to 50 μm or phytoplankton and other organisms in the size range of greater or equal to 10 to 50 μm; however, based on the treatment techniques utilized in PWGs, we would expect high removal efficacies of these "larger" organisms.

The key factors to the successful application of onboard PWGs as a ballast water management alternative include their ability to satisfy vessel ballasting requirements, feasibility of installation, and ability to meet numeric discharge limits. The following summarizes the results of our proof-of-concept study, where we evaluated the extent to which PWGs satisfied each of the above listed criterion by analyzing typical vessel ballasting requirements and PWG capacities, evaluating the feasibility of placing PWGs onboard vessels, and conducting land-based performance testing of a PWG.

2. Materials and methods

The proof-of-concept study involved three phases. The first phase was to evaluate which PWGs, if any, would satisfy vessel ballasting rate requirements. To determine the extent to which PWGs can accommodate vessel ballasting requirements, we gathered ballasting data for vessels of various sizes (see Table 1). Ballast rate requirements on a vessel range from the minimum ballast rate required to compensate for fuel consumption (i.e., continuous ballasting) to the maximum ballast rate equal to the rated capacity of the ballast pump (i.e., intermittent ballasting). Continuous ballasting assumes continuous, non-stop operation of a PWG sized to satisfy the minimum production rate to continuously compensate for fuel consumption (i.e., a smaller, less expensive system). In contrast, intermittent ballasting assumes intermittent operation of a PWG sized to satisfy the maximum production rate equal to the ballast pump rate (i.e., a larger, more expensive system). While potable water generation using a PWG is generally not a continuous operation (because potable water demand is not continuous), PWGs can also reliably accommodate continuous operation, if desired.

The second phase evaluated the feasibility of installing appropriately sized PWGs onboard vessels. For the second phase, we conducted architectural feasibility case studies on a research vessel, an inland river

Table 1
Ballast pump and fuel consumption rates for various vessel sizes.

Length (m)	Breadth (m)	Gross tonnage (GT)	Gross registered tonnage (GRT)	Ballast pump rate (m^3/h)[a]	Fuel consumption rate (kg/h)[b]
26 to 59	–	138 to 839	232 to 1415	5 to 57	770 to 1000
28	8	265	–	39	68
29 to 44	–	82 to 199	139 to 280	57	770 to 4100
35	8	–	261	45	68
46	10	648	–	41	–
54	12	292	–	32 to 34	660 to 770
64	15	2218	–	40 to 80	320
68	6	1914	–	35 to 407	–
68	13	1914	–	40	340
142	22	13,574	–	80 to 120	–
–	–	10,000 to 32,000	–	180	–

[a] Intermittent ballasting rate.
[b] Continuous ballasting rate.