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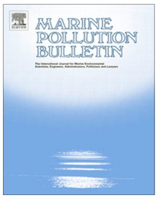

Sample port design for ballast water sampling: Refinement of guidance regarding the isokinetic diameter

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ABSTRACT

By using an appropriate in-line sampling system, it is possible to obtain representative samples of ballast water from the main ballast line. An important parameter of the sampling port is its "isokinetic diameter" (D_{ISO}), which is the diameter calculated to determine the velocity of water in the sample port relative to the velocity of the water in the main ballast line. The guidance in the U.S. Environmental Technology Verification (ETV) program protocol suggests increasing the diameter from 1.0× D_{ISO} (in which velocity in the sample port is equivalent to velocity in the main line) to 1.5–2.0× D_{ISO}. In this manner, flow velocity is slowed—and mortality of organisms is theoretically minimized—as water enters the sample port. This report describes field and laboratory trials, as well as computational fluid dynamics modeling, to refine this guidance. From this work, a D_{ISO} of 1.0–2.0× (smaller diameter sample ports) is recommended.

1. Introduction

In order to meet the discharge standard prescribed in the International Maritime Organization's (IMO) ballast water management convention, ballast water discharged from commercial vessels shall contain few living organisms, for example, <10 living organisms $\geqslant 50\ \mu m$ in minimum dimension per m^3 (IMO, 2004). These numeric limits also correspond to the discharge standard promulgated by the United States (USCG, 2012; EPA, 2013). Most vessel owners will install a ballast water management system (BWMS) that treats ballast water to comply with the standard. Prior to vessel installation, the BWMS needs type approval from a flag state and therefore must undergo land-based and shipboard verification testing to determine its biological efficacy in removing or killing organisms.

Importantly, to quantify the number of living organisms in treated and untreated discharge, representative samples of ballast water are needed (Richard et al., 2008; Lee et al., 2010; Pazouki et al., 2010; Miller et al., 2011; Frazier et al., 2013). To ensure representative samples are obtained, sample ports will be installed to collect samples representative of the volume of interest. The IMO G2 guidelines stipulate using sample ports to facilitate testing of a vessel's compliance with the discharge standard (IMO, 2008). U.S. regulations (USCG, 2012) require vessels with BWMS to install sample ports that allow ballast water to be collected. Guidance for in-line sampling is provided in the Environmental Protection Agency (EPA) Environmental Technology Verification (ETV) program Protocol for land-based verification testing (ETV Protocol, EPA, 2010). In turn, the ETV Protocol is incorporated by reference into the U.S. regulations; thus, the same guidance is used in the U.S. to address both verification and compliance testing. Further, the research that informed the ETV Protocol—choosing the sample port geometry based on computational fluid dynamics (CFD) modeling (Richard et al., 2008)—also serves as the basis for the G2 guidelines.

As a starting point, the CFD modeling assessed the configuration of a sample port having an "isokinetic diameter" (D_{ISO}) of 1.0, that is, a sample port's diameter was calculated to ensure the velocity of water in the sample port was equivalent to the velocity of the water in the main ballast line. By collecting in-line samples with an isokinetic sampling facility, it is possible to obtain a representative portion of the main ballast line (e.g., Soo, 1999). To accommodate likely variations in organism density over time (e.g., due to stratification within a tank; Murphy et al., 2002; First et al., 2013), a time-integrated sample should be obtained over the entire duration of sample collection.

The ETV Protocol recommends using the following equation to determine the isokinetic diameter for the sampling pipe (D_{ISO}) installed in the main ballast pipe, where D_{ISO} is calculated based

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on the diameter of the main pipe (D_M), volumetric flow through the sample port (Q_S), and the main line (Q_M):

$$D_{\mathrm{ISO}} = D_M\sqrt{\frac{Q_S}{Q_M}} \tag{1}$$

The ETV Protocol recommends a sample port diameter of 1.5–2.0× the calculated D_{ISO} for in-line sampling. In effect, increasing the port diameter while maintaining the same volumetric flow in the main ballast line will result in a relatively slower flow velocity within the sample port, also known as a sub-isokinetic sample. The guidance originated from numerical models using CFD that showed sub-isokinetic sampling resulted in lower pressure gradients and turbulence at the sample port entrance (Richard et al., 2008); these conditions could minimize the mortality or organisms entering the sample port.

The overall objective of this work was to reconsider the guidance in the ETV Protocol that the diameter of a sample port should be 1.5–2.0× D_{ISO}, as it has been a recurring topic of discussion within the ballast water testing community. Some members have expressed concern that this size (larger than 1.0× D_{ISO}) can unnecessarily occlude the main ballast pipe (because the outer diameter of the sample port is relatively large compared to the inner diameter of the main ballast pipe). Additionally, it has been suggested that using isokinetic sampling (1.0× D_{ISO}) is not only an easier and more practical approach than slowing the flow velocity in the sample port relative to the main flow velocity, but it will also allow a more representative sample to be collected. This project examined these concerns and set boundaries on the sample port sizes using CFD modeling and empirical studies with natural communities of live organisms.

2. Methods

2.1. Overview of computational fluid dynamics modeling

Prior to any experimental work, CFD modeling was performed to ensure experiments could be scaled from a large-scale ballast system to a smaller laboratory-size apparatus. Modeling was performed using Abaqus® modeling software (Dassault Systèmes Simulia Corp., Providence, RI). The CFD models were developed, parameterized, and run to determine the suitability of conducting experiments on a smaller (laboratory) scale than the original Richard et al. (2008) work, which modeled a sample port within a 20 cm (8″) piping system (all pipe sizes reported here are nominal pipe size [NPS]). That is, computer modeling was performed to ensure similarity, or similitude, among the "large-scale" systems (used in the previous modeling effort) and the "small-scale" systems (used in this work). The flow parameters associated with the larger system assumed a main ballast flow rate of 227 $m^3\,h^{-1}$ (1000 gpm) with a sample flow rate of 5.7 $m^3\,h^{-1}$ (25 gpm), resulting in flow velocities of 2.0 $m\,s^{-1}$ (6.6 $ft\,s^{-1}$) for 1.0× D_{ISO} and 0.7 $m\,s^{-1}$ (2.5 $ft\,s^{-1}$) for 2.0× D_{ISO} (data not shown). The flow parameters associated with the smaller system (5.3 cm [2″]) used a main ballast flow rate of 16 $m^3\,h^{-1}$ (69 gpm) with a sample flow rate of 0.02 $m^3\,h^{-1}$ (0.09 gpm). This resulted in the smaller system having the same flow velocities as the larger system of 2.0 $m\,s^{-1}$ (6.6 $ft\,s^{-1}$) and 0.7 $m\,s^{-1}$ (2.5 $ft\,s^{-1}$) (data not shown).

A large-scale system is commonly used at ballast water test facilities, including the facility at the Naval Research Laboratory in Key West, FL (NRL). This system moves large volumes of seawater (i.e., >200 m^3 [52,834 gal]), making it difficult to obtain the accuracy needed when sampling the source and the discharge water. Therefore, the experiments were performed using small-scale systems, with either 2.5 cm (1″) or 5.1 cm (2″) main ballast pipe diameters, and volume transfers of approximately 380 L (100 gal) and 3 m^3 (793 gal), respectively. These small-scale systems reflected more practicable arrangements to examine variations in the sample ports design and their impact on sample representativeness (primarily by assessing the capture efficiency and mortality of live organisms) than large-scale experiments. Multiple small-scale experiments were conducted in one day, as opposed to the large scale where system complexity and large volumes limited the number of trials to two or three per week. Further, the scaled test setups allowed experimental parameters, such as source water volume, homogeneity, and volumetric flows, to be more tightly controlled than large-scale experiments.

2.2. Empirical testing of sample ports with different diameters

Experiments were conducted to assess the effect of sample port diameters on organism recovery (i.e., capture efficiency). These trials were executed at two scales: with a 5.1 cm (2″) main ballast pipe diameter to examine organisms $\geqslant$50 μm in minimum dimension (nominally zooplankton; "field trials"), and with a 2.5 cm (1″) main ballast pipe diameter to examine organisms $\geqslant$10 and <50 μm in minimum dimension (nominally protists; "laboratory trials"). In all trials, the sample ports were in a straight configuration (rather than L-shaped) to reduce the number of variables affecting the sample port's collection of organisms. All trials were conducted at NRL (24.56°N, 81.78°W) using natural communities of ambient organisms from the surrounding oligotrophic seawater.

The laboratory and field trials were conducted to examine whether different sample port configurations yielded samples that were representative of the fluid stream. In all trials, the percent recovery of live organisms collected from the sample port was compared to recovery of live organisms from the discharge; the values of both tanks were normalized to the source. Additionally, organism mortality was evaluated to determine if the sample port configuration resulted in any difference between the Source, Discharge, and the Sample.

2.3. Field trials: experimental design

Field trials examining the recovery and mortality of ambient organisms in the $\geqslant$50 μm size class were conducted using a 3.8 m^3 (1000 gal) capacity, cylindrical tank defined as the Source Tank (Fig. 1). Water was transferred to the Discharge Tank (with the same dimensions as the Source Tank) through a 5.1 cm (2″) polyvinyl chloride (PVC) pipe (i.e., the main line), which was plumbed from the bottom of the Source Tank (Fig. 1). A horizontal centrifugal pump (Pacer Pumps, Lancaster, PA) was used to transfer water at 380 L min^{-1} (100 gpm) to the Discharge Tank. The sample port was installed 244 cm (96″) downstream of the pump, equating to approximately 48 pipe diameters of straight piping from the sample port (to ensure water flow was turbulent and fully developed). Water from the sample port was collected in a small carboy, defined as the Sample Port Tank.

The sample ports for this experiment were constructed using commercially available, smooth bore, seamless, grade 316, stainless steel tubing. Four sample ports—all straight—were tested (Table 1). The tubing inner diameters were calculated to determine the diameters corresponding to 0.75, 1.0, 1.5, and 2.0× D_{ISO} (Eq. (1)). Then, commercially available pipes that best matched the D_{ISO} calculations were chosen, and the flow rate through the tubing was adjusted to obtain the respective 0.75, 1.0, 1.5, and 2.0× D_{ISO} ratios.

2.4. Field trials: sample collection

Each field trial yielded three sample types, which were water from the Source, Discharge, and Sample Port Tanks. The Source