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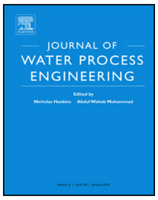

Development of a hydrodynamic static mixer for mixing chemicals in ballast water treatment systems

Jae Hyeong Kwon, Jae Hong Jung, Hai Don Lee, Yong Seok Park, Dae Won Kim*

Techcross, 84 Yenginsan-Ro, Inju-Myun, Asan-Si, Chungcheongnam-Do 336-833, Republic of Korea

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ABSTRACT

The movement of non-indigenous aquatic species (up to about 6000 species) along with ballast water into foreign countries during the shipping process poses concerns to human and environmental health as well as aquatic biodiversity. The International Maritime Organization (IMO) is expected to impose tighter regulations on ballast water discharges in the near future, and consequently, the development of more efficient ballast water treatment processes is required. In this study, the hydrodynamic performance of a static mixer in a ballast system for the complete mixing of injected chemicals and ballast water flowing in the main pipe was numerically investigated. Through several steps (design of mixer shape using numerical methods, CFD simulations, and validation tests), the performance of the static mixer was evaluated. The CFD simulation results showed that the target fluid (water + chemical) was completely mixed at a distance equal to 8 times the pipe diameter downstream of the mixer outlet, and the mixing quality was about 95%. Furthermore, the results of the CFD simulations and the validation tests were in agreement. The results of this study suggest that the use of a static mixer in the disinfection and neutralization system stabilizes the system and minimizes the amount of chemicals consumed.

1. Introduction

Annually, over 10 billion tons of ballast water are transferred between ports [1] as a byproduct of global shipping. When ballast water is moved during the shipping process, non-indigenous aquatic species may be introduced into another country, as a consequence of attaching themselves to ship hulls or being present in the ballast water or other parts of the ship. Over the last several decades, the extent of both oceanic shipping and transport has increased, and hence, the global dispersal and invasion potential of non-indigenous aquatic species have greatly increased. Invasive aquatic species are of concern to human and environmental health as well as aquatic biodiversity. The adoption of a single discharge standard by the International Maritime Organization (IMO) has provided a universal benchmark for the rapid development of treatment systems [2]. Various regulatory bodies have also established additional requirements pertaining to the management of ballast water for vessels operating in their territorial waters. For example, California and New York have imposed ballast water discharge standards that are a 1000 times tighter than the IMO regulations (USCG) SB 497 and CWA 401 [3]. Owners/operators are encouraged to remain current with these regulatory requirements [4].

Consequently, the development of more efficient ballast water treatment processes is required. In order to satisfy the stricter laws for ballast water discharge, many methods for ballast water treatment have been tested. Commercially available ballast treatment processes include ozonation, electrolysis techniques, and importantly, the use of highly concentrated chemicals as disinfectants. According to statistical data in the IMO report and from the California State Lands Commissions, chemical methods (including electrolysis and chemical-disinfectant-injected systems) constitute the highest portion (38%) of all ballast system treatments [5]. When high concentrations of chemicals are used as disinfectants in ballast treatment systems, there can be incomplete mixing of the water and the excess chemical disinfectants. Also, in the case of disinfectants, an additional neutralizing process is necessary during the deballasting step. Controlled disinfection and neutralization systems use many kinds of sensors to measure the TRO (total residual oxidant), FRO (free residual oxidant), and ORP (oxidation reduction potential). Owing to the effects of incomplete mixing, control of the ballast treatment system becomes difficult. In addi-

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Abbreviations: CFD, chemical fluid dynamics; FRO, free residual oxidant; IMO, International Maritime Organization; ORP, oxidation reduction potential; TRO, total residual oxidant.

* Corresponding author. Fax: +82 414209090.
E-mail addresses: kdw@techcross.com, djkjh1109@techcross.com (D.W. Kim).

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tion, the excessive injection of chemical disinfectants leads to high operation costs and has a detrimental effect on the environment.

In this study, a static mixer was developed for application in ballast water treatment systems. Its purpose is to ensure the complete mixing of the ballast water and the added fluids (high concentrations of chemical disinfectants), thereby mitigating the incomplete mixing effects. Fig. 1 provides a schematic illustration of a ballast water treatment system that includes a static mixer.

2. Materials and methods

The performance of the static mixer was evaluated at the "completely mixed point" (D). The mixing rate refers to pre-existing static mixer development data. Generally, the mixing rate is represented by the coefficient of variation (CoV), which is the ratio of the standard deviation to the mean and provides a measure of the relative spread of a distribution [6]. The CoV of the mixing rate was calculated as $(100 - N/100)$, where N is the percentage mixing effect. In other words, a value of 0 for the CoV corresponds to 100% mixing, whereas a value of 0.01 corresponds to 99% mixing.

In this study, the static mixer was developed in four steps, as illustrated in Fig. 2.

First, the static mixer shape was decided based on numerical solutions of continuity and momentum equations for its complex geometry, and the turbulence energy was then calculated based on this shape. In the second step, the static mixer was modeled in three dimensions using SolidWorks software [7], which is capable of expressing 3D shapes. The third step was the simulation of the mixing process using computational fluid dynamics (CFD). It has become possible to numerically solve for various dimensional flows through a static mixer. The complex static mixer geometry was modeled using an appropriate grid generation software package (ANSYS FLUENT, ANSYS Korea), and the completely mixed point and the mixing rate were determined. Finally, validation tests were conducted to evaluate the functioning of the static mixer. Fig. 3 shows the validation test-bed diagram.

The validation tests were conducted in three steps. During the tests, several chemical reagents, including red channel test dye (Tail Corp.), sodium hypochlorite (12%, Junsei Chemical Co., Ltd., Japan), and sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5H_2O$, 98.5%, Samchun Chemical Corp., Korea), were used. The first validation step was the dye test, in which the mixing quality was determined via UV-spectrophotometry. Prior to the mixing test, the absorbance of the colored dye was measured using a UV–vis spectrophotometer (DR 5000, Hach Inc.) to determine the wavelength absorption

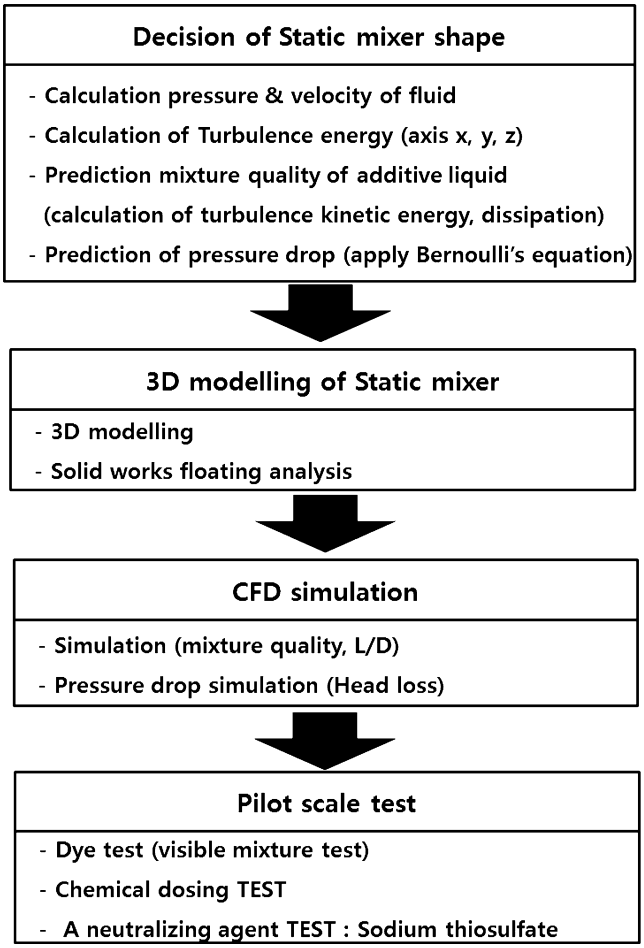

Fig. 2. Steps in the development of the static mixer.

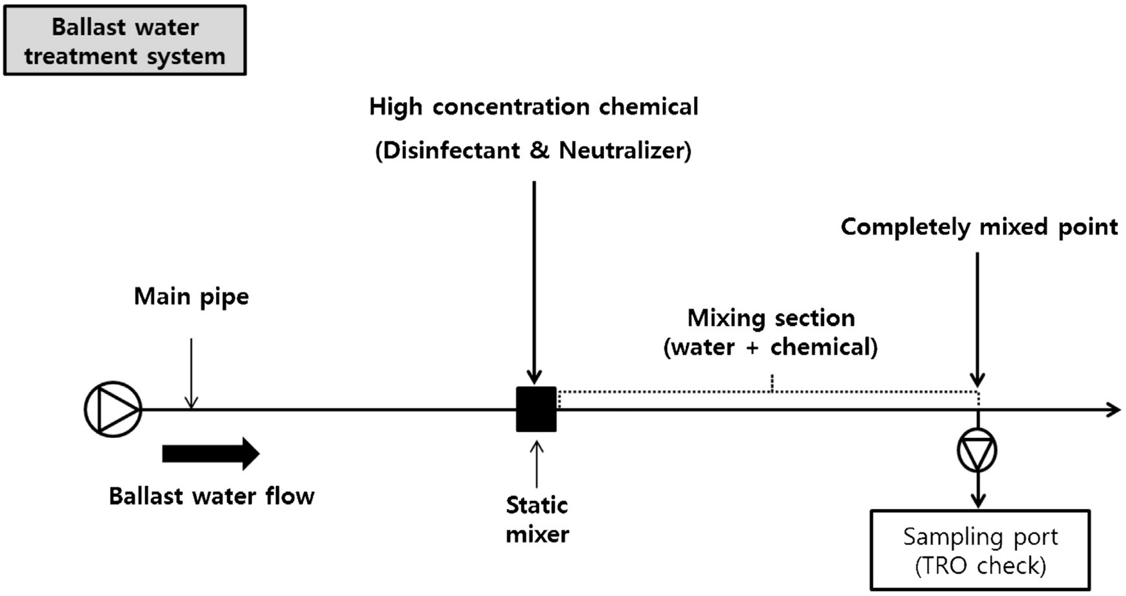

Fig. 1. Schematic illustration of a ballast water treatment system, utilizing a static mixer.