Filtration and UV treatment for ships' ballast water management – water quality challenges and UV-dose requirements

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ABSTRACT

Filtration and ultraviolet treatment is a possible combination for treatment of ships' ballast water. Such systems will be further developed to meet the challenges of ballast water management according to international regulations. UV systems should be designed for inactivation of robust algal species not removed by the filtration step. This study presents the UV dose requirements for one such algae species (Tetraselmis suecica). Other algae species may show even higher UV resistance. Larger organisms, such as Artemia franciscana, exhibit very high UV tolerance and have to be removed or destroyed by filtration or treatment units imposing high hydraulic shear forces.

Reduced ballast water quality (high content of suspended solid and dissolved organic matter) will reduce the transmittance and the performance of the UV system; this has to be taken into account when designing full-scale systems. Ballast water treatment systems should include filtration, or a unit to destroy particles and zooplankton capable of harboring bacteria, before UV disinfection.

Key words: Ballast water, treatment, water quality, UV treatment

INTRODUCTION

The introduction of invasive marine species into new environments by ships' ballast water has been identified as one of the greatest threats to the world's oceans. The International Convention for the Control and Management of Ships Ballast Water & Sediments was adopted by the International Maritime Organization (IMO) in 2004, which implies that the world's fleet must invest in approved technology for treatment of their ballast water before discharge.

Filtration and ultraviolet treatment in the UVC spectral region has become a popular method for management of ballast water. The method is valued because of its effectiveness to inactivate algae, bacteria and viruses (Liltved et al., 1995; Singh, 1975), and by not leaving toxic residues behind after the application of normal UV doses (Oliver and Carey, 1976; de Veer et al., 1994). The principal effect of UVC in microorganisms is damage to the DNA or RNA caused by photo-induced dimerization of opposite pyrimidine units in the nucleic-acid strand. Once the pyrimidine residues are covalently bound together, replication of the nucleic acid is blocked or results in mutant daughter cells unable to multiply (Stover et al., 1986). However, previous work has shown that UVC inactivation of marine vibrios, freshwater bacteria and algae can be temporary, because of the presence of repair mechanisms (Liltved and Landfald, 1996; Sing, 1975). Such repair should be taken into account when assessing the UV dose necessary for efficient UV disinfection of ballast water.

Water quality can influence the effect of physical and chemical disinfectants, including UV treatment.

Particles may provide protection against chemical and non-chemical disinfection agents, depending on the particle type and size, and the nature of association between the microorganism and the particle. Several investigators have reported a correlation between the suspended solids content and the survival of fecal coliforms in UV-exposed wastewater (Whitby and Palmateer, 1993). Qualls *et al.* (1983) observed that bacteria harbored by particles were partially protected, so that UV disinfection was limited to 3 to 4 $\log_{10}$ units reduction. Filtration was required to meet strict bacterial standards. Scattering and absorption of UV light by particle surfaces may reduce the effect of the UV treatment (Qualls *et al.*, 1983). Particles of organic origin absorb more UV than mineral particles. Limited protection of microbes is provided by clay particles, because much of the UV light is scattered. Shading may limit the exposure of individual bacteria, but has not been a problem in well-designed UV disinfection reactors with lateral dispersion.

Dissolved organic carbon (DOC) is defined as total organic carbon (TOC) after filtration through a membrane filter. In freshwater supplies, humic substances originating from the terrestrial environment are often the most significant

contributor to the DOC, conferring a brownish-yellow color to the water. In wastewater, proteins, carbohydrates, lipids and organic amines can elevate the DOC level. Several organic compounds in water (e.g., humic substances, phenols and lignin sulfonates) can absorb UV light, thus reducing the UV dose available for microbial inactivation (Harris *et al.*, 1987). The UV transmittance of good quality seawater is generally high. However, the transmittance may drop in coastal waters and in harbors, particularly during bad weather conditions, in periods of planktonic blooms, etc.

Precise data on the UV-dose requirements to accomplish inactivation of typical ballast water model organisms are essential for establishing a firm basis for design of ballast water management systems (BWMS), and for better operation and control of such systems.

The objective of the present study was to provide UV dose/response data for two important model organisms (*Tetraselmis suecica* and *Artemia franciscana*) from laboratory experiments, and to show how an increased particle content can influence the survival of UV-treated test organisms, including heterotrophic bacteria.

MATERIALS AND METHODS

Water quality

In the experiments reported here, natural seawater, with and without additives, was used. High salinity test water (>32 PSU) was pumped from 60 m depth in the Oslofjord. For the low-salinity brackish test waters, surface water from 1 m depth was used. In order to adjust the concentrations of dissolved organic carbon (DOC), particulate organic carbon (POC) and total suspended solids (TSS) to fulfill the IMO requirements, soluble lignin, starch and kaolin, respectively, were added.

Chemical analyses

The dissolved and total organic carbon (DOC and TOC) levels were measured by accredited methods based on Norwegian Standard NS-ISO 8245 (NIVA method G5-3): The TOC was measured on the whole sample, and the DOC was measured after filtering the sample through a GF/F filter (0.7 μm).

Particulate organic carbon (POC) was calculated as the difference between the TOC level in the sample, as measured on a non-filtered sample, and that measured after the same sample was filtered. The POC was also measured as the amount of organic matter accumulating on a GF/F filter (0.7 μm) when a known amount of sample was filtered (NIVA method G6).

The total suspended solids (TSS) level was measured using the NIVA gravimetric method B1/2 in accordance with NS-EN 872 and NS 4733.

Test organisms

Tetraselmis suecica was grown autotrophically in a seawater growth medium with added nutrients. The seawater was disinfected by membrane filtration before use. The algae culture method used was the 'growing culture volume' technique for isolated algae strains available from NIVA's algae culture collection.

Artemia franciscana was obtained by hatching of resting cysts. Approximately 0.1 g of cysts was incubated with 1 litre of 20% salinity seawater with a bright light source at a temperature of 22–26 ˚C with good aeration. Naturally occurring heterotrophic bacteria associated with newly hatched Artemia franciscana were used in the filtration and UV-treatment experiments. Particles for the filtration and UV treatment experiments were obtained by fragmenting Artemia into smaller particles by the hydraulic shear forces of a centrifugal pump and a semi-closed valve.

UV treatment

The test-water samples (50 mL at 20 ˚C with added test organisms) were kept on slow stirring in Petri dishes during the UV treatment. Samples (2 mL) were withdrawn by a sterile pipette at given time intervals. The UV lamp used was a 15 W (3.5 W of 254 nm UV output) low pressure germicidal lamp (Philips Ltd, Eindhoven, The Netherlands) mounted in an apparatus that provided a collimated beam (Qualls and Johnson, 1983). The irradiance (mW/cm^2) at 254 nm at the liquid surface (E_0) was measured by a calibrated UVX-25 sensor coupled to a UVX radiometer (Ultraviolet Products Inc., San Gabriel, CA, USA). The average irradiance (E_{avg}) in the suspension was calculated by the following equation (Morowitz, 1950):

$$E_{avg} = E_0(1 - e^{-a\ell})/a\ell$$

where a is the absorption coefficient of the suspension (cm^{-1}) and ℓ is the path length (cm) in the water. The absorbance at 254 nm was measured with a spectrophotometer. Non-uniform distribution of irradiance across the top of the Petri dish was taken into account by using the average irradiance of several measurements. In addition, the small effects of reflection from the water surface (Reflection factor) and divergence of the beam (Divergence factor) were calculated by the method of Bolton and Linden (2003). The UV dose, defined as the average irradiance in the water in the Petri dish times the exposure time (s), was varied by varying the exposure time.

Determination of viable organisms after treatment

The counts (CFUs) of viable *Tetraselmis suecica* after UV treatment were determined by plating on agar plates after serial dilutions in distilled saline water. 100 μL samples were spread on a seawater agar growth medium and incubated in constant light for 120 h at 20 ˚C. Colonies of *Tetraselmis sp.* were observed by viewing agar plates in a stereo microscope at 160x magnification.

Viable *Artemia franciscana* after UV treatment were determined by inspection using a stereo loupe at 10-40x magnification within 6 h after sampling. Viable organisms were counted and identified based on motility and integrity according to OECD (1985): OECD Test Guideline for Testing of Chemicals 202, "*Daphnia sp.* acute immobilization test

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and reproduction test". Since it may take several hours for the lethal actions of the UV to show effect on motility, treated samples with observable live organisms were recounted after 24 h.

Heterotrophic bacteria were determined as CFUs after various treatments by serial dilutions in distilled water supplemented with 0.9% (w/v) NaCl and spreading of aliquots on tryptone soy agar (Oxoid, Basingstoke, UK) supplemented with 0.5% (w/v) NaCl and by the membrane technique (American Public Health Association, 1989). Samples were plated in duplicate, and colonies were counted after 2 and 5 days of incubation in the dark at 20 ˚C.

RESULTS AND DISCUSSION

Test water quality

During testing of BWMS in land-based tests, the test water should fulfill the IMO-requirements shown in **Table 1**. To obtain these concentrations, soluble lignin, starch and kaolin need to be added when conducting land-based tests at NIVAs test facility located in Solbergstrand, Oslofjord, Norway. In **Table 1**, typical concentrations of dissolved organic carbon (DOC), particulate organic carbon (POC), total suspended solids (TSS) and UV transmittance for a 1 cm water depth (UVT) after addition of additives are shown. Measurements of the UV transmittance (UVT) in the test water varied between 62% and 66% for the brackish water and between 88% and 93% for the seawater. It is essential that the UV treatment system be designed to administer the required UV dose at the reduced water quality and the lowest UV transmittance.

In **Table 2**, the relative contributions of the various additives to the water quality parameters (brackish water) are shown. As indicated, both kaolin and lignin are the principal reducers of UV transmittance.

Table 1: IMO requirements and the concentration ranges of dissolved organic carbon (DOC), particulate organic carbon (POC), total suspended solids (TSS), salinity and UV transmittance (UVT) in land-based tests with brackish water and seawater.

	Salinity [PSU]	DOC[mg C/L]	POC {mg C/L]	TSS [mg/L]	UVT %
Brackish water					
IMO requirements	3–22	>5	>5	>50	-
Range measured	21-22	5.0-5.5	5.0-5.8	50-54	62-66
Seawater					
IMO-requirements	>32	>1	>1	>1	-
Range measured	32-33	1.9-2.8	2.7-3.0	13-20	88-93

Table 2: Relative contributions of different additives to the water quality parameters (brackish water).

	Kaolin (TSS additive)	Maizena (POC additive)	Lignin (DOC additive)
% of TSS	90	10	0
% of UVT	55	10	35
% of turbidity	85	15	0

UV Dose/response studies

To investigate the UV doses required to inactivate the model microorganisms (*T. suecica* and *A. franciscana*), laboratory experiments were conducted with pure seawater without additions. The results of this study are presented in **Figure 1**.The number of surviving cells (logarithmic scale) versus the UV dose is shown. A long initial lag phase, with no response to increasing UV dose, was observed. After a UV dose of 70–80 mJ/cm^2, a linear inactivation was evident, fitting first order kinetics reasonably well.

The UV resistance found in *T. suecica* was high. An UV dose of 100–150 mJ/cm^2 was required for 90% inactivation. Such a high UV resistance in algae species (and higher than for other studied non-algae microorganisms, such as parasites, bacteria and viruses), is in accordance with data found in the literature. In general, larger microorganisms are more resistant than smaller ones, which also is evident for *A. franciscana*. In **Figure 2**, percentage inactivation of *A. franciscana* versus UV dose is presented. An UV dose of approximately 2000 mJ/cm^2 was required for 90% inactivation of *A. franciscana*.

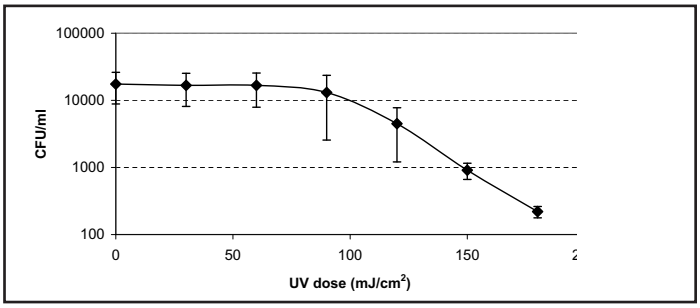

Figure 1: UV Dose-survival curves of UV treated *Tetraselmis suecica* in pure seawater.

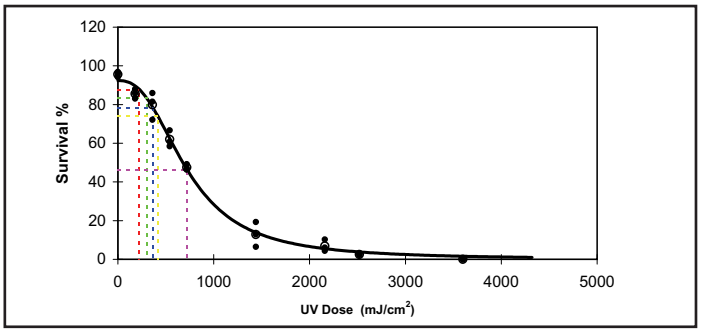

Figure 2: UV Dose-survival curve of UV treated *Artemia franciscana* in pure seawater, observed 24 hours after treatment. Dotted lines indicate EC_{50}, EC_{25}, EC_{10} and EC_5 respectively from right to left.

Effect of pre-filtration

In a test to determine the effect of filtration before UV treatment, seawater without chemical additives, but with natural particles and *Artemia* fragments, was used. Particle size analysis revealed particles in the size range of 10 to 240 μm. The mean particle concentration was 456 per mL. Despite the large number of particles at the lower end (10–20 μm) of the size range, the cumulative particle size and volume distribution showed that larger particle-size classes dominated with respect to the total particle volume.

The particle-protection mechanism was indicated for UV treated bacteria associated with the fragments because of the lack of an UV dose dependent inactivation in the dose range of 10–22 mJ/cm^2 in unfiltered water (**Figure 3**). The results obtained suggest a possible transmission of bacteria to ballast-tanks if proper pre-filtration is not applied. It was demonstrated that pre-filtration substantially improved the overall bacterial removal. Mesh sizes of 50 μm resulted in an efficiency of more than 5 $\log_{10}$ removal, indicating that ballast water should be filtered to remove crustacean fragments and other particles capable of harboring bacteria before UV disinfection.

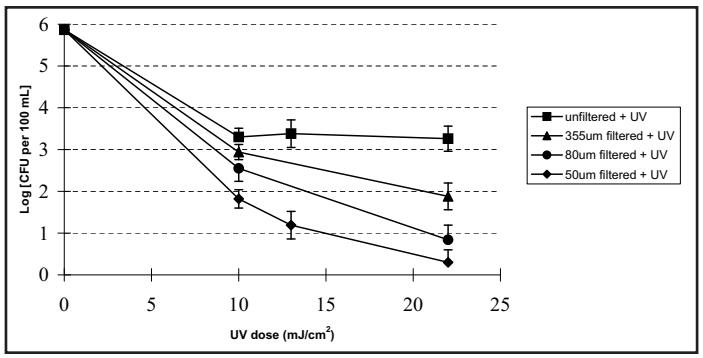

Figure 3: The effect of pre-filtration on survival of aerobic bacteria in UV treated water containing particles.

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