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Ultraviolet ballast water management systems — Computational physical modelling and calculations on scaling of ultraviolet reactors

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Foreword

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This document was prepared by Technical Committee ISO/TC 8, *Ships and marine technology*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Ballast water management systems (BWMS) that use ultraviolet (UV) are intended to treat ballast water to comply with applicable (IMO D-2 or U.S.) ballast water discharge standards. A key specification for a given model of a BWMS is its treatment rated capacity (TRC), which indicates the unit's rated volumetric flow rate during treatment of ballast water. Typically, a base system (with a low range TRC) is empirically validated through land-based testing, while a unit with a TRC near or at the highest rating is validated through shipboard testing. The remaining models that are not physically tested may be validated through scaling, using a verified numerical approach to predict performance at untested TRCs. Effective 13 October 2019, the type approval of BWMS (both UV and other technologies) requires testing in accordance with the BWM Code (MEPC 72/17/Add.1 Annex 5), adopted as an amendment to the IMO International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004. The BWM Code specifies that a manufacturer of BWMS must provide technical specifications for ny scaling of TRC according to the following criteria:

> "4.14 It shall be demonstrated, by using mathematical modelling and/or calculations, that any up or down scaling of the BWMS will not affect the functioning and effectiveness on board a ship of the type and size for which the equipment will be certified. In doing so, the manufacturer of the equipment shall take into account the relevant guidance developed by the Organization.
>
> 4.15 Scaling information shall allow the Administration to verify that any scaled model is at least as robust as the land-based tested model. It is the responsibility of the Administration to verify that the scaling used is appropriate for the operational design of the BWMS.
>
> 4.16 At a minimum, the shipboard test unit shall be of a capacity that allows for further validation of the mathematical modelling and/or calculations for scaling, and preferably selected at the upper limit of the rated capacity of the BWMS, unless otherwise approved by the Administration."

Guidance on scaling is provided by the IMO through 'Guidance on Scaling of Ballast Water Management Systems' (BWM.2/Circ. 33/Rev. 1). One of the requirements is for validation of the modelling and calculations, and experimental validation to land-based, shipboard or laboratory testing as appropriate. In scaled models, parameters affecting performance must demonstrate equivalence to the base model, identify System Design Limitations (SDL) for each scaled model, and conduct shipboard testing of the most vulnerable model as determined through scaling.

This document is focused on the modelling of UV reactors for scaling purposes, i.e., justifying the applicability of a UV reactor design across a range of TRCs through the use of validated numerical models and calculations. Here, numerical models are used to solve equations governing physical characteristics of a computational domain that represents a model of the physical object (i.e., the UV reactor). This requires numerical representation of the geometry of this system, a discretization of the representation into volumetric sub-elements (meshing), and solving for parameters for various scales. Results are submitted to an Administration to justify the type approval of UV reactors having TRC ratings that have not been validated through type approval testing. Thus, scaling parameters should also include those parameters should also include those parameters associated with SDLs.

Ultraviolet ballast water management systems — Computational physical modelling and calculations on scaling of ultraviolet reactors

1 Scope

This document specifies the methodology to conduct computational modelling of ultraviolet (UV) reactor designs for ballast water management systems that incorporate ultraviolet disinfection technology (UV BWMS). The computational modelling shall be used to calculate UV Reduction Equivalent Dose (RED) and compare calculated REDs of the scaled model to its base model. It should be noted that the IMO requires validation of the computational model. Also, to be noted is that a complete UV BWMS typically incorporates other treatment methodologies such as filters, and the impact of changes to external subsystem performance on the overall BWMS is not considered in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

International Maritime Organization (IMO) G8, Harmonized Implementation of the Guidelines for Approval of Ballast Water Management Systems, BWM Code, Resolution MEPC.300(72)

International Maritime Organization (IMO) BWM, 2/Circ.33 Rev.1, Guidance on Scaling of Ballast Water Management Systems, May 2018

National Water Research Institute, Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse. Third Edition, August 2012

U.S. Environmental Protection Agency, Ultraviolet Disinfection Guidance Manual for The Final Long Term 2 Enhanced Surface Water Treatment Rule. Office of Water (4601), EPA 815-R-06-007, November 2006

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.1
ultraviolet light
UV light
light emitted with wavelength from 100 to 400 nm

Note 1 to entry: Light in the range of 200 to 280 nm is known as UVC and is considered germicidal. UV light in the range of 260 to 270 nm is particularly effective in deactivating the DNA or RNA of bacteria, viruses and other pathogens and thus destroys their ability to multiply and cause disease.

Note 2 to entry: Specifically, UVC light causes damage to the nucleic acid of microorganisms by forming covalent bonds between certain adjacent bases in the DNA or RNA. The formation of such bonds prevents the DNA or RNA from being unzipped for replication, and the organism is unable to reproduce.

3.2
ultraviolet ballast water management system
UVBWMS
system which uses *UV light* (3.1) to process ballast water, generally in combination with filtration, to remove, render harmless, or avoid the uptake or discharge of harmful aquatic organism and pathogens within ballast water and sediments

Note 1 to entry: In addition to the *UV reactor* (3.4), the UVBWMS includes ballast water treatment equipment, all associated control equipment, monitoring equipment, piping, and sampling facilities.

Note 2 to entry: Most UVBWMS include a filter to remove larger particles (that may impact UV transmission) and organisms (that may be resistant to UV treatment).

3.3
base model
ultraviolet ballast water management system (UVBWMS) (3.2) model that has successfully completed land-based testing as defined in the BWMS Code

3.4
UV reactor
vessel or chamber where exposure to *UV light* (3.1) takes place, generally consisting of UV lamps, quartz sleeves, UV sensors, quartz sleeve cleaning systems, and baffles or other hydraulic controls

Note 1 to entry: The UV reactor also includes additional hardware for monitoring UV dose delivery; typically comprising (but not limited to) UV intensity sensors.

3.5
base reactor
UV reactor (3.4) of the base model

3.6
scaled model
ultraviolet ballast water management system (UVBWMS) (3.2) that is based on the *base model* (3.3) but has been modified to accommodate to a higher or lower TRC

3.7
scaled reactor
UV reactor of the *scaled model* (3.6)

3.8
spectral output
distribution of wavelength and relative intensity emitted by the UV lamp

3.9
Reynolds-Averaging Navier-Stokes (RANS) modelling
turbulence modelling conducted by solving the *Reynolds-Averaging Navier-Stokes equations* (3.35, 3.36) at all length scales

3.10
direct numerical simulation
DNS
computational simulation used to numerically solve the Navier-Stokes equations at all length scales

3.11
detached eddy simulation
DES
computational simulation used to numerically solve the Navier-Stokes equations, using *RANS* (3.9) modelling to solve small length scales

3.12

large eddy simulation

LES

computational simulation used to numerically solve the Navier-Stokes equations, excluding small length scales

3.13

discrete ordinance (DO) modelling

development and use of mathematical models to numerically solve the radiative transfer equation by discretizing the volume domain and directional vectors

3.14

treatment rated capacity

TRC

maximum continuous capacity expressed in cubic meters per hour for which the BWMS is type approved

Note 1 to entry: It states the amount of ballast water that can be treated per unit time by the BWMS to meet the standard in regulation D-2 of the BWMS Convention.

Note 2 to entry: The TRC is measured as the inlet flow rate of the BWMS.

3.15

UV transmittance

UVT

fraction of incident light transmitted through a material (e.g., water sample or quartz), measured at specific wavelengths (e.g. 254 nm) and path length

3.16

UV irradiance

UV light power per unit area incident to the direction of light propagation at all angles, including normal

3.17

UV exposure time

time elapsed between UV radiation initial and final exposures

3.18

UV intensity

measured flux passing through a unit area perpendicular to the direction of propagation

Note 1 to entry: UV intensity is used in this document to describe the magnitude of UV light measured by UV sensors in a reactor and with a radiometer in bench-scale UV experiments.

3.19

UV dose

product of UV intensity and residence time, typically reported in units of mJ cm^{-2} or J m^{-2}

Note 1 to entry: The UV dose received by a waterborne microorganism in a reactor vessel; accounts for the effects on UV intensity, residence time, UV absorbance of the water, UV absorbance of the quartz sleeves, reflection and refraction of light from the reactor walls.

3.20

Residence time distribution

RTD

probability distribution of residence time that microorganisms stay in a flow-through UV reactor; typically shown as a histogram

3.21

UV dose distribution

probability distribution of delivered UV doses that microorganisms receive in a flow-through UV reactor; typically shown as a histogram

3.22
User defined function
UDF
function provided by the user of a program or environment, in a context where the usual assumption is that functions are built into the program or environment

3.23
model validation
process used to substantiate that outputs of a model provide an accurate prediction of performance

Note 1 to entry: Typically, the model outputs are compared to empirical results of real world experiments at different scales to determine the accuracy of the prediction matches design requirements.

3.24
model verification
process of confirming that a model is correctly implemented with regard to specifications and assumptions of the design

Note 1 to entry: Typically, verification ensures that analysis logic follows the model design, checks for reasonable outputs over the acceptable range of model parameters, and that the model can be run without errors.

3.25
computational fluid dynamics
CFD
an analysis that simulates the fluid flow of ballast water through a *UV reactor* (3.4) to solve fluid interactions with boundary conditions and characterize the flow properties and operating range

3.26
Reduction equivalent dose
RED
UV dose (3.19) derived by entering the log inactivation measured during full-scale reactor testing into the *UV dose-response* (3.31) curve that was derived through collimated beam testing

Note 1 to entry: RED values are always specific to the challenge microorganism used during experimental testing and the validation test conditions for full-scale reactor testing.

3.27
biodosimetry
measurement of biological response as a proxy for UV dose

3.28
emission spectrum
relative power emitted by a lamp at different wavelengths

3.29
germicidal range
range of UV wavelengths responsible for microbial inactivation in water (200 to 300 nm)

3.30
UV absorbance
transmitted radiant power through a material

3.31
UV dose-response
inactivation kinetics of a microbial species resulting from UV exposure

3.32
American Type Culture Collection
ATCC
repository of cell lines and cultured organisms used for research

3.33

MS2 Bacteriophage (ATCC 15597-B1)

non-pathogenic bacteriophage commonly used as a challenge organism in UV reactor validation testing

3.34

Tetraselmis sp. (ATCC 50244)

marine phytoflagellate commonly used as a test organism and a representative of organisms in the ≥10 and <50 µm size class

3.35

Navier-Stokes equations

equations derived from the conservation equations to describe the motion of viscous fluid substances

Note 1 to entry: RED values are always specific to the challenge microorganism used during experimental testing and the validation test conditions for full-scale reactor testing.

3.36

Reynolds-Averaged Navier-Stokes

RANS

time-averaged equations of motion for fluid flow derived from *Navier-Stokes equations* (3.35); primarily used to describe turbulent flows

3.37

turbulence modelling

development and use of mathematical models to predict the evolution of turbulence in fluid flows

3.38

radiative transfer equation

equation that characterizes a traveling beam of radiation, losses to energy absorption, gains beam emission, and redistribution from scattering

4 General requirements

4.1 General principle

Numerical modelling and calculations are used to demonstrate that any parameters of the scaled UV reactors that affect reactor performance are equivalent to those of the base reactor. Here the UV reactor is considered independently of the complete BWMS, but may be affected by the inlet and outlet conditions imposed by those other system components. Thus, those parameters defining the range of inlet and outlet conditions must be defined. One Lagrangian approach of modelling the efficacy of the UV reactor is determined by the UV dose received by particles traversing the reactor. The UV dose is determined from the hydraulic conditions, the radiative conditions, and the particle residence time within the reactor. These are modelled separately and the results are used to calculate to UV dose. Alternately, the efficacy could be modelled using a Eulerian approach.

The key internal and external performance parameters required to assess the UV reactor efficacy are identified as follows:

1. UV dose distribution as a function of UV transmittance and flow rate,

NOTE UV dose distribution can be validated with testing of the base UV reactor using standard test organisms with a known spectral and dose response, or may be validated by using dyed microspheres (Shen et al., 2009).

2. UV sensor irradiance and flow rate measured during validation testing and during operation on a scaled system.

NOTE Consider flow rate measurement uncertainty in models.