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Ships and marine technology — Ballast water management systems (BWMS) — Computational physical modelling and calculations on scaling of UV reactors

Navires et technologie maritime — Systèmes de gestion de l'eau de ballast (BWMS) — Modélisation physique computationnelle et calculs concernant les réacteurs UV

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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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) are intended to treat ships' ballast water discharges to comply with applicable standards (Reference [14]). Disinfection using ultraviolet (UV) light is common to many BWMS. 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. A base system (with a low range TRC) is empirically validated through land-based testing, while a unit with a larger TRC (ideally at the highest rating) is validated through shipboard testing. The remaining models that are not empirically tested can 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 BWMS Code (MEPC 72/17/Add.1 Annex 5)[11], adopted as an amendment to the IMO International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004[14]. The BWMS Code specifies that a manufacturer of BWMS must provide technical specifications for any scaling of TRC. Guidance on scaling is provided by the IMO through its 'Guidance on Scaling of Ballast Water Management Systems' (BWM.2/Circ. 33/Rev. 1)[12]. One of the requirements is for validation of the modelling and calculations through comparison of predicted performance to land-based, shipboard, or laboratory test data 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. 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.

Ships and marine technology — Ballast water management systems (BWMS) — Computational physical modelling and calculations on scaling of UV reactors

1 Scope

This document specifies the methodology to conduct computational modelling of ultraviolet (UV) reactor designs for ballast water management systems (BWMS) that incorporate ultraviolet disinfection technology (UVBWMS). The computational modelling is used to calculate the UV reduction equivalent dose (RED) and to compare calculated REDs of the scaled reactor to its base reactor. REDs are determined using organisms with a given dose response.

NOTE   The IMO requires validation of the computational model.

The simulation of a physical UV reactor using a computational model requires that the model be validated (i.e. it performs as intended and reflects the correct physical constraints) and verified (i.e. produces outputs consistent with empirical data). A model developed according to this document is intended to validate the performance of simulated but untested, scaled UV reactors, where the simulation has been verified with test data from base model UV reactors within the product line. As a complete UV BWMS typically incorporates other treatment methodologies such as filters, the impact of changes to external subsystem performance on the overall BWMS is not considered in this document.

2 Normative references

There are no normative references in this document.

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

3.2
base model
ultraviolet ballast water management system (UVBWMS) (3.30) model that has successfully completed land-based testing as defined in the BWMS Code

Note 1 to entry: Typically, a base model is with low range *TRC* (3.28).

3.3
base reactor
UV reactor (3.41) of the *base model* (3.2)

3.4
biodosimetry
measurement of biological response as a proxy for *UV dose* ([3.34](#))

3.5
computational fluid dynamics
CFD
numerical methods and algorithms to solve and analyse problems that involve fluid flows

3.6
detached eddy simulation
DES
computational simulation used to numerically solve the *Navier-Stokes equations* ([3.17](#)), using *RANS modelling* ([3.23](#)) to solve small length scales

3.7
discrete ordinates modelling
DO modelling
development and use of mathematical models to numerically solve the *radiative transfer equation* ([3.18](#)) by discretizing the volume domain and directional vectors

3.8
direct numerical simulation
DNS
computational simulation used to numerically solve the *Navier-Stokes equations* ([3.17](#)) at all length scales

3.9
emission spectrum
relative power emitted by a lamp at different wavelengths

3.10
germicidal range
range of UV wavelengths responsible for microbial inactivation in water (200 nm to 300 nm)

3.11
large eddy simulation
LES
computational simulation used to numerically solve the *Navier-Stokes equations* ([3.17](#)), excluding small length scales

3.12
low pressure UV lamp
LP
discharge lamp of the mercury vapour type, without a coating of phosphors, in which the partial pressure of the vapour does not exceed 100 Pa during operation and which mainly produces ultraviolet radiation of 253,7 nm

3.13
medium pressure UV lamp
MP
medium pressure mercury arc lamp having a polychromatic *emission spectrum* ([3.9](#)) between 200 nm and 400 nm

3.14
model validation
comparison between the output of the calibrated model and the measured data, independent of the data set used for calibration

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

3.15
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.

3.16
MS2 phage
ATCC 15597-B1

non-pathogenic bacteriophage commonly used as a challenge organism in *UV reactor* (3.41) *biodosimetry* (3.4)

3.17
Navier-Stokes equations

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

3.18
radiative transfer equation

mathematical relation describing the variation along a path of the spectral radiance in an absorbing, emitting and scattering medium.

Note 1 to entry: The solution of this equation depends on the radiative properties of the medium: spectral extinction coefficient, spectral albedo and spectral phase function, and on the thermal and optical boundary conditions.

3.19
reduction equivalent dose
RED

UV dose (3.34) derived by entering the log reduction after UV treatment using a collimated beam with the same UV spectrum output as in the reactor testing into the *UV dose-response* (3.36) curve that was derived through collimated beam testing, or the UV dose computed by combining the dose distribution computed in *CFD* (3.5) modelling with the UV sensitivity (dose response) of the organism

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.

3.20
residence time

time period that a particle resides within the boundaries of the *UV reactor* (3.41) during treatment, which varies with flow rate and path

3.21
residence time distribution
RTD

probability distribution of *residence time* (3.20) that microorganisms stay in a flow-through *UV reactor* (3.41), typically shown as a histogram

3.22
Reynolds-averaged Navier-Stokes equations
RANS equations

time-averaged equations of motion for fluid flow derived from *Navier-Stokes equations* (3.17), primarily used to describe turbulent flows

3.23
Reynolds-averaged Navier-Stokes modelling
RANS modelling

turbulence modelling (3.29) conducted by solving the *Reynolds-averaged Navier-Stokes equations* (3.22) at all length scales

3.24
scaled model
ultraviolet ballast water management system (UVBWMS) (3.30) model that is based on the *base model* (3.2) but has been modified to accommodate to a higher or lower *treatment rated capacity (TRC)* (3.28)

3.25
scaled reactor
UV reactor (3.41) of the *scaled model* (3.24)

3.26
spectral output
distribution of wavelength and relative intensity emitted by a UV lamp

3.27
Tetraselmis **sp.**
ATCC 50244
marine phytoflagellate commonly used as a test organism and a representative of organisms in the ≥10 μm and <50 μm size class

3.28
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.

Note 3 to entry: TRC values pertain to stated intake water quality conditions.

3.29
turbulence modelling
development and use of mathematical models to predict the evolution of turbulence in fluid flows

3.30
ultraviolet ballast water management system
UVBWMS
system that uses *UV light* (3.31) to process ballast water, generally in combination with filtration, to remove, render harmless, or avoid the uptake or discharge of harmful aquatic organisms and pathogens within ballast water and sediments

Note 1 to entry: In addition to the *UV reactor* (3.41), 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 can impact UV transmission) and organisms (that can be resistant to UV treatment).

3.31
ultraviolet light
UV light
light emitted with a wavelength ranging from 100 nm to 400 nm

Note 1 to entry: Light in the range of 200 nm to 280 nm is known as UVC and has the capacity to be germicidal. UV light in the range of 260 nm to 270 nm can be particularly effective in deactivating the DNA or RNA of bacteria, viruses and other pathogens at appropriate requisite doses 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.

3.32
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

3.33
UV absorbance

radiant power absorbed within a material

3.34
UV dose

product of *UV intensity* (3.38) and *residence time* (3.20), typically reported in units of mJ cm^{-2} or J m^{-2}

3.35
UV dose distribution

probability distribution of delivered *UV doses* (3.34) that microorganisms receive in a flow-through *UV reactor* (3.41), typically shown as a histogram

3.36
UV dose-response

inactivation kinetics of a microbial species resulting from UV exposure

3.37
UV exposure time

time elapsed between UV radiation initial and final exposures

3.38
UV intensity

intensity of UV radiation at a specific geometric location with respect to the UV source, measured in mW cm^{-2}

Note 1 to entry: UV Intensity measures the "amount" of UV energy actually penetrating through the water being treated.

3.39
UV irradiance

power passing through a unit area perpendicular to the direction of propagation

Note 1 to entry: UV irradiance is typically reported in watt per square metre (W/m^2). It is also usually reported in mW/cm^2 or µW/cm^2.

Note 2 to entry: Irradiance varies with UV lamp output power, efficiency and focus of its reflector system, and distance to the surface.

3.40
UV light emitting diode
UV LED

semiconductor source, in this context providing narrow wavelength emission at a given wavelength in the UV spectrum

3.41
UV reactor

vessel or chamber where exposure to *UV light* (3.31) 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.

Note 2 to entry: The wavelengths emitted by a UV lamp are dependent on the lamp type (e.g. LED, low pressure [LP], medium pressure [MP]).

3.42
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 (e.g. 1 cm)

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. The UV reactor is considered independently of the complete BWMS, but can be affected by the inlet and outlet conditions imposed by those other system components. Thus, those parameters describing the range of inlet and outlet conditions shall be defined.

In the 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 received by each particle is determined from the hydraulic conditions, the radiative conditions, and individual particle trajectories through the reactor. Multiple particles (usually in the thousands or tens of thousands), each with a unique trajectory, then define the dose distribution. The dose distribution is combined with the UV sensitivity (dose response) of an organism, usually in a separate model, to determine the RED.

In the Eulerian approach, the concentration of viable organisms is determined as the organisms pass through the reactor by calculating the inactivation of organisms in each mesh element. This is done by combining the irradiance and residence time to get the dose applied in that mesh element with the UV sensitivity (dose response) of the organism. Multiple organisms of different sensitivity can be tracked simultaneously through the reactor. The number of viable organisms exiting the reactor divided by the number entering the reactor determines the overall inactivation of the organism and hence RED.

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

a) 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 can be validated by using dyed microspheres[7].

b) UV intensity as measured with a UV sensor, and flow rate measured during validation testing and during operation on a scaled system.

4.2 Modelling best practices

The choice of software and methodology for the modelling effort shall be identified and chosen for capabilities in the flow and radiation domains. Typically, the approach includes computational fluid dynamics (CFD). The modelling approach shall be based on Clause 5, and additional modelling parameters are based on computational modelling best practices as described in the literature (see References [4], [15]).

5 Modelling and calculations

5.1 General

The principle of computational physical modelling and calculations on scaling of ultraviolet reactors is to ensure that all scaled UV reactors demonstrate that the scaled reactors produce a simulated RED that is equal or higher than the base UV reactor. Here the base reactor has been subjected to empirical [dose response] tests to validate the model. The same model base reactor shall also have been used in land-

based type approval testing. The numerical model shall be calibrated to experimental data to validate the modelling method. If calibration shows the model does not represent experimental results, then the model shall be updated to reduce fit error with the experimental data. Additionally, a sensitivity analysis shall be supported with conclusions on numerical model accuracy and the impact of varying parameters between the models.

5.2 Geometric model

Computational models necessitate that the computational domain accurately represent the geometric characteristics of the systems they are intended to simulate. Three-dimensional (3D) computer generated geometric models of all UV reactors should include the fundamental components and features in contact with water that are included in the computational domain (e.g. lamps, baffles, cleaning wipers, UV sensors, support structures). This should also include dimensionally accurate representation of all geometries (e.g. number and position of lamps). Assumptions and exclusions used to create the 3D model such as wall smoothness, baffles, rivets, welds, wiper mechanisms, etc. shall ensure the computational models mimic the physical models. A discussion and justification shall address any components excluded from the geometric model if these components affect the reactor's treated efficacy to ballast water.

The process for mesh generation shall be defined, and shall provide a description of mesh element geometry and methodology to ensure the meshing provides sufficient density and resolution to capture all relevant flow features. Particular importance should be placed on the mesh adjacent to wall boundaries to resolve the boundary layer flow, and in areas around the UV lamps where more resolution in the mesh may be needed. Generally, an iterative mesh convergence study is used to demonstrate that further refinement in the meshing provides no additional resolution of the hydraulic condition.

5.3 Turbulence model

Turbulence modelling is used to simulate flow characteristics in the UV reactor (see Reference [1]). The behaviour of fluid in a flow field is described by the Navier-Stokes equations (NSE). While direct numerical simulation (DNS) can be used to numerically solve the NSE, this can be computationally expensive due to the calculation of the complex turbulence component. Instead, Reynolds-averaged Navier-Stokes (RANS) models are employed that simplify turbulence using time-averaging and save on computational resources. Common RANS models include Spalart-Allmaras, κ-ε, and κ-ω. Other turbulence models numerically solve the NSE at larger scales and use RANS models to simulate smaller scales (detached eddy simulation [DES]) or exclude the smaller scales completely (large eddy simulation [LES]). This is not an all-inclusive list of all turbulence models. New models are continually being developed, therefore it is important that the appropriate turbulence model be selected for the simulation. The turbulence model and basis for selection shall be described and justified in the hydraulic modelling section.

5.4 Radiation model

Radiative transfer modelling is used to simulate light fields in the UV reactor. The radiative transfer equation (RTE) characterizes a traveling beam of radiation, losses to energy absorption, gains from beam emission, and redistribution from scattering. The RTE can be numerically solved using the discrete ordinates (DO) modelling method by discretizing the volume domain and directional vectors. The Monte Carlo (MC) radiation model is a Eulerian method that simulates the paths of individual particles of radiation, or photons, from the source by randomly sampling from the probabilistic distribution functions that govern their interaction lengths, scattering angles, emission, and absorption rates. By simulating a large number of photons and aggregating the end of path characteristics, physical quantities can be calculated with high precision. The MC model is generally more computationally intensive than the DO model. The radiative transfer model should evaluate multiple UV water transmittances to determine the radiation output across the range of expected (or claimed) treatment scenarios that will be encountered by the UV reactor. This is not an all-inclusive list of radiative transfer models. The model and basis for selection shall be described and justified in the radiative modelling section.

5.5 Calculation of the UV dose

5.5.1 General

CFD models for simulating the performance of UV reactors for microorganism inactivation are developed in Lagrangian and Eulerian approaches (see Reference [2]), taking into account hydrodynamics, kinetics and radiation field within the UV reactor. In the Lagrangian approach, microorganisms are treated as discrete particles where the trajectory is predicted by integrating the force balance on the particle. In the Eulerian approach, the conservation equation of species (microorganisms) is solved along with the transport equations as a reacting tracer.

5.5.2 Lagrangian particle tracking

The Lagrangian approach includes the tracking of particles, where a particle tracking study is used to combine the hydraulic and radiation model outputs. The process involves the injection of particles having the same density as water at the inlet into the UV reactor. The particles 'flow' through the UV reactor and are exposed to the UV lamps, in which the output of lamps is simulated by the UV radiation model. A user-defined function (UDF) is used to calculate the cumulative UV dose that each particle in the simulation is receiving. The UDF is based on the amount of radiation that is received, and assumptions and equations used in the model and UDF shall be described.

The lamp output in the simulation software mimics the actual lamp output. For monochromatic systems, the one characteristic wavelength (254 nm for low pressure lamps) is used. For polychromatic systems, the other wavelengths are normalized to one wavelength (usually 254 nm) by multiplying the radiation at each wavelength by the dose response at that wavelength divided by that at 254 nm and summing over all germicidal wavelengths to obtain the equivalent UV_{254} dose. This approach simplifies the mathematics and is common practice. The UV_{254} dose distribution can then be determined from the time and dose that each particle accumulates as it traverses through the reactor. The resulting dose distribution is then combined with the dose response of one or more organisms to determine the RED of each organism.

5.5.3 Eulerian reacting tracer

The Eulerian approach involves tracking the concentration of viable organisms as they pass through the reactor. For polychromatic systems, the germicidal (equivalent UV_{254}) dose is calculated at each point in the same way as for the Lagrangian approach. A high concentration of organisms of one or more species is assumed at the inlet and the destruction calculated based on the UV dose-response, germicidal irradiance, and residence time at each point in the reactor. The RED is determined from the mass average concentration of viable organisms leaving the reactor compared to those entering the reactor.

5.6 Scaling procedure

5.6.1 Main steps

The typical scaling procedure shall follow the main steps outlined in Figure 1.
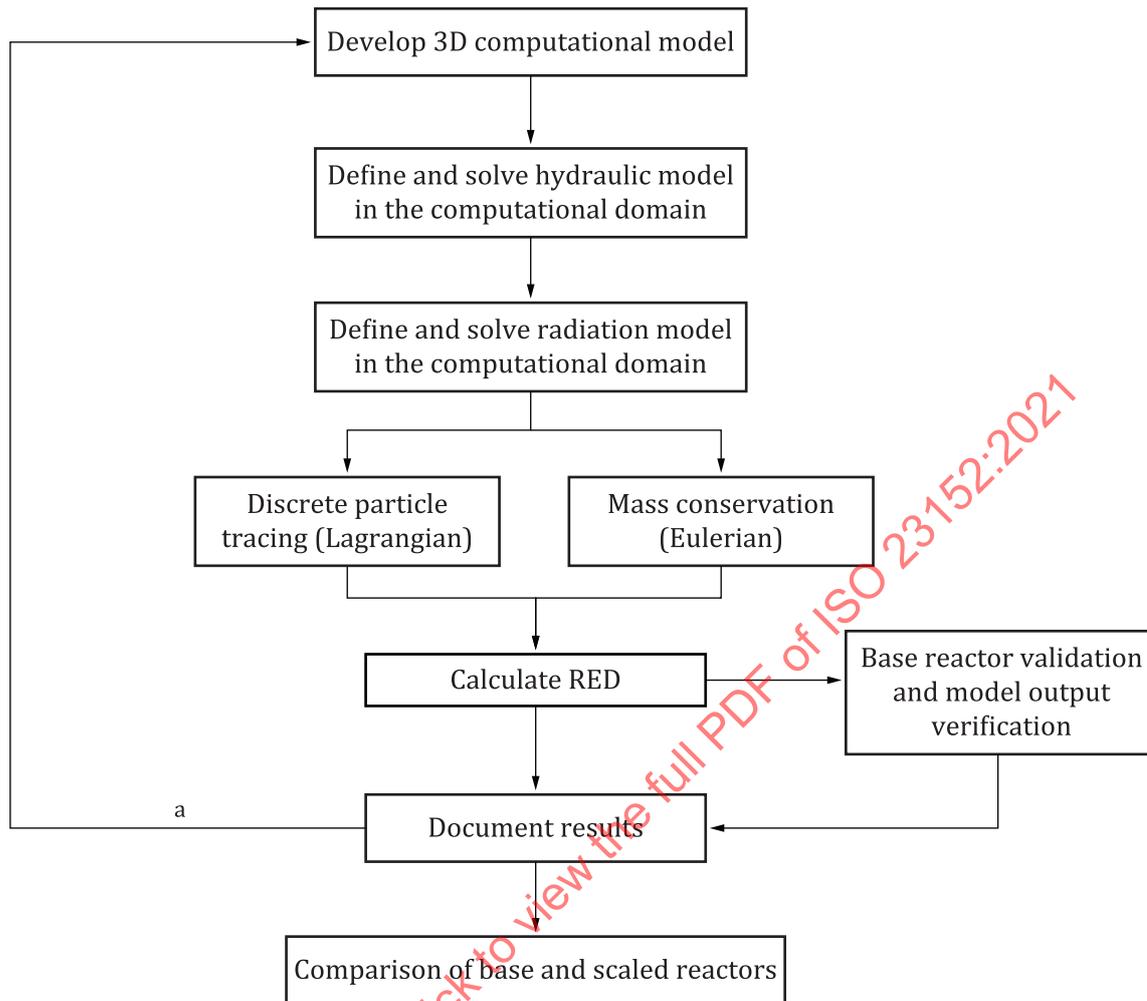
a   Repeat for scaled reactor geometries.

Figure 1 — The typical scaling procedure of base and scaled UV reactors by CFD

The main steps for scaling are as follows.

1) Develop a 3D computational model.

   a)   Identify the reactor parameters:

      —   TRC: the TRC of the base model and the scaled model(s), in m^3h^{-1}; model number as tested.

      —   Define the range of flow parameters in the reactor design and as validated in the land-based testing.

      —   UVT: the UVT range of ballast water, in percentage (%); and how is the UVT measured.

      —   UV power: the UV_{254} (254 nm) output power of the UV lamps, in W; the type and spectral output of the lamps; the radiation characteristics.

      —   UV reactor: dimensional information, including the volume of UV reactor, the distance between UV lamps, and other arrangement parameters of UV reactor.

   b)   Develop the geometric 3D computational model of the base reactor.

  c) Mesh the geometric 3D computational model of the base reactor.

    — The UV reactor geometry of the base model is meshed in high quality. Increased resolution should be used at key areas, e.g. discretization of UV lamps and perforated plates. Similarly, a dense hexahedral mesh should be used along surfaces to resolve hydrodynamic boundary layers and around the perimeter of UV lamps to capture exponential decay of UV intensity.

    — Quality checks of the meshing should be performed (e.g. convergence analysis, sensitivity analysis, element proportion checks, angle checks, etc.). Typically, 1 to 2 million mesh elements are required to achieve mesh independence.

2) Define and solve the hydraulic models in the computational domain (see Reference [10]).

  — A turbulence model shall be selected appropriate to the reactor hydraulic conditions as described in 5.3 and according to computation modelling best practices.

  — Initial and boundary conditions shall define the range of inlet flow rates, wall roughness, outlet pressure, turbulence length (list all fluid parameters), and the intended range of flow rates.

  — Solve the flow domain: perform a steady-state CFD simulation by solving governing flow equations. This results in a prediction of point velocities across the interior of the UV reactor for the specified inlet flow rate.

3) Define and solve the radiation model in the computational domain.

  — A discrete ordinate (DO) radiation model calculates radiation intensity as a function of, e.g. the absorption of water and the emissivity of wall surfaces. Alternatively, a Monte Carlo (MC) radiation model can be used.

  — Radiation models shall define UVT (UV transmissivity within the reactor) range based on manufacturer's claimed data, where the reduction in intensity is defined over a 1 cm path length.

Boundary conditions for the radiation model shall consider.

  — The emissivity of reactor walls based on best practice. Describes the amount of radiation reflected/absorbed at wall surfaces.

  — Diffuse fraction defined as 0. Describes a fully specular reflection of radiation at wall surfaces (distributed equally in all angles).

  — Refractive index (lamps, sleeve, and fluid).

The model is then solved to calculate the radiation intensities in the computational domain.

4) For the Lagrangian approach, solve discrete phase particle paths inserted at inlet of the computational domain. The discrete phase model simulates the path of particles through the unit using the combined numerical flow/UV intensity field. A random walk or particle physics model may be employed. Particles are randomly "injected" at the model inlet and their x, y, z-coordinates are predicted as a function of time. The requisite number of particles added is evaluated using a particle sensitivity test. The result is a predicted path line for each injected particle, which represents a random organism path through the reactor. Massless particles are used, which follow the velocity fields of the continuous phase (water).

  a) Turbulent dispersion should be used to assign random fluctuations to the velocity component, based on the local turbulence.

  b) A number of "tries" are used. Each particle track is repeated to account for the random fluctuation, and provides a representative average result. This accounts for both eddy lifetime and eddy size.

c) Calculate the estimated UV dose for each injected particle by summing the cumulative UV dose along the predicted particle path. The result is a UV dose distribution. The number of particles should be sufficient to define the dose distribution. The results file should contain the cumulative particle doses (mJ cm^{-2}).

5) For the alternate Eulerian approach, solve for the concentration of organisms as they pass through the reactor. The fluid-dynamics and photo-statics are calculated in each mesh element with the CFD program reading the irradiance at the mesh points. The mass conservation equation of live microorganisms (species mass conservation equation) is solved separately based on the calculated velocity field. The density of the species is assumed equal to the density of the ballast water.

The log inactivation of each organism in each volume element as the water passes through the reactor is determined by first calculating the dose applied obtained by multiplying the irradiance by the residence time in that element, and then dividing by the UV sensitivity (dose per log) obtained from the dose response at the concentration of the organism in that volume element.

$$\text{Logi} = I \times t/D_L \tag{1}$$

Where, in each volume element:

Logi   is the log inactivation;

I is the irradiance (mW cm^{-2});

t is the residence time (seconds);

D_L is the UV sensitivity or dose required per log inactivation obtained from the dose response (mJ cm^{-2} logi^{-1}),

6) Calculate the reduction equivalent dose (RED).

a) For the Lagrangian approach, calculate the destruction of organisms using dose distribution and dose response of the organisms. Annex A provides an example to calculate RED for the Lagrangian approach.

b) For the Eulerian approach, the ratio of microorganism concentration at the reactor outlet to the inlet yields the log inactivation. From that, the RED is read from the dose response.

7) Document the results, providing (at a minimum) the following parameters:

a) examples of the flow field and flow trajectories;

b) Reynolds number vs. flow;

c) examples of the radiation field at different UVTs;

d) statistical analysis of particle dose (e.g. dose histogram, low dose particles) for the Lagrangian approach, or the concentration distribution at the outlet for the Eulerian approach;

e) RED as a function of UVT and flow rate.

8) Validate the CFD model of the base reactor through empirical testing. Validate that the base reactor simulation reflects base reactor criteria (see checklist Annex B). Then verify that the simulation predicts performance consistent with empirical test data as described in Annex B.

9) Repeat steps 1 to 7 for the scaled reactor(s).

   a) Ensure similitude between scaled models (spectral output range, consistent orientation, turbulence model, density of particle traces, density of the species, fluid parameters).

10) CFD analyses for all UV reactors (base and scaled) shall be used to demonstrate the following.

   a) All scaled UV reactors apply an equal or higher RED than the base reactor over a range of flow rates (for example, 20 % to 110 % TRC) and UVT's (from the minimum tested/approved to 95 %T).

   b) Models shall include RED assessments with at least two organisms having UV sensitivities that represent the lower and upper UV sensitivities of organisms encountered during type approval testing.

6 Scaling metrics

6.1 General principles

Use simulated (predicted) RED as a metric to compare base and scaled UV reactors to confirm that all UV reactors are under the same physical or environmental conditions, as follows:

a) UV lamp: scaling shall account for the impact of the UV lamp on the measured UV Intensity and that scaled minimum UV intensity should be used to ensure adequate treatment during operation;

b) UV transmittance: at least three different UVT values, for example 49 %, 74 %, 95 % (because ballast water clarity (UVT) can vary from port to port).

If all scaled UV reactors apply an equal or higher simulated RED which relates to challenge organisms (e.g. MS2 phage and *Tetraselmis* sp.) than the base model, then this demonstrates that any parameters of the scaled reactors that would affect the reactor performance are equivalent to those of the base reactor.

Annex A
(informative)

RED calculation

A.1 Background

This Annex provides an example calculation to link model findings to actual, well-characterized organism responses. The test organism is exposed to 254 nm UV radiation; other germicidal UV wavelengths are also encouraged. A test organism is chosen and its response to UV_{254} radiation is verified in a series of empirical, laboratory-scale tests using collimated beam UV_{254} light. The organism is remains fully mixed with the water for the base UV reactor, and its response to treatment is measured in samples collected downstream of the reactor.

A.2 Reduction equivalent dose

A.2.1 General

The organism's response is measured by change in concentration due to treatment, or by the reduction equivalent dose (RED). For a given treatment, an organism's response to UV_{254} should be independent of the treatment regime (whether a collimated beam in a laboratory setting, or a UV reactor in a BWMS).

Therefore, as a certain dose experienced by the organism yields a reduction in concentrations (e.g. 2-log reduction), this response can be matched to a dose-response curve determined for that organism using known UV_{254} fluence and exposure times.

The organism used to model the dose in the UV reactor is not specified, although the MS2 phage (see Reference [9]) and *Tetraselmis* sp. (ATCC 50244) have been suggested for freshwater and marine water, respectively.

The benefits of MS2 phage (e.g. ATCC 15597-B1) include (see Reference [13]):

— tolerance to water characteristics used in testing the base unit (e.g. if high salinity water is used in verification testing, the organism should be tolerant so that factors other than the UV_{254} dose do not affect its survivability in culture);

— high resistance to UV;

— nearly first order inactivation kinetics over the range of UV_{254} dose typically used for disinfection;

— ease of seeding and enumerating;

— consistent and reproducible assay results;

— non-pathogenicity to humans;

— inability to photoreactivate.

Also, the benefits of *Tetraselmis* sp. (e.g. ATCC 50244) include:

— the organism class of *Tetraselmis* sp. is 10 μm to 50 μm;

— ubiquitous in the marine environment;

— relatively easy to culture and assay;

— relatively resistant to UV radiation.

A.2.2 Appropriate dose-response curve

Use the appropriate dose-response curve to calculate the survival ratio (N/N_0) for each particle.

From the CFD simulation, each inserted particle leaves the domain having received a specific dose (mJ cm^{-2}). Convert these data into a RED via a dose-response curve. The dose-response curve relates to a challenge organism, in this document MS2 phage (see References [3], [6]) and *Tetraselmis* sp. (see Reference [8]).

Expose these two challenge organisms to different UV_{254} doses (minimum of 4 plus a blank dose, see best practices in Reference [16]), yielding the relationship between UV_{254}-dose and survival rate of the organism. The log inactivation can then be plotted as a function of UV_{254} dose as shown below:

MS2 phage:

$$-\log_{10}\left(\frac{N}{N_o}\right) = -0,0001D^2 + 0,0519D + 0,1107 \tag{A.1}$$

Tetraselmis sp.:

$$\ln\left(\frac{N}{N_o}\right) = -0,0792D \tag{A.2}$$

where

N_0 is the challenge organism concentration in influent sample (cells ml^{-1});

N is the challenge organism concentration in corresponding effluent sample (cells ml^{-1});

D is the UV_{254} dose of challenge organism in volume of ballast water before and after exposure to UV_{254} radiation (mJ cm^{-2}).

A.2.3 Cumulative survival ratio

Sum particle survival ratios and divide by total number of particles to yield cumulative survival (and inactivation) ratios.

Calculate the survival ratio for each particle, $(N/N_0)_i$, using these two dose-response curves, where i denotes each particle. Then calculate the cumulative survival ratio by summing the individual particle survival ratios and dividing by the total number of particles, n_p (assuming each particle has equal weighting or probability) (see Reference [5]):

$$\left(\frac{N}{N_o}\right) = \frac{1}{n_p}\sum_{i=1}^{n_p}\left(\frac{N}{N_o}\right)_i \tag{A.3}$$

A.2.4 Calculate RED

Use the dose-response curve to calculate the RED.

Calculate the RED using the cumulative survival ratio in the appropriate dose-response curve and solving for dose.