Biodosimetric Studies for Ballast Water Treatment

H.Y. Li¹, H. Osman², C.W. Kang¹, J. Lou¹ and T. Ba¹

¹Institute of High Performance Computing (IHPC),
Agency for Science, Technology and Research (A*STAR),
1 Fusionopolis Way, 16-16 Connexis, Singapore 138632
²Research & Development, Sembcorp Marine Ltd.,
Admiralty Road West, Singapore 759956

Email: lih@ihpc.a-star.edu.sg

Abstract. Ultraviolet (UV) reactor for ballast water treatment is investigated in this paper. Experimental and numerical simulations are performed for a base reactor named LBW850e. B. Pumilus is chosen as a challenge organism in the experiments. Simulation is carried out based on the commercial software ANSYS FLUENT with user defined functions implemented. The effects of water flow rate and UV transmittance (UVT) on the UV reactor performance in terms of reduction equivalent dose (RED) are studied. The results show that the increase of water flow rate reduces RED. While RED increases with the increase of UVT. The experimental and simulation results show reasonable agreement with each other. With this achieved, the numerical model developed in the current work can be applied to other reactors.

1. Introduction

Ultraviolet (UV) radiation is widely used for both drinking and ballast water treatment [1]. The mechanism for UV radiation for water treatment is that UV light can kill or disable the organisms to function and reproduce them. UV light is known to be able to impair DNA or RNA and cellular structures. When UV light penetrates organisms, the energy is absorbed by DNA or RNA which results in the photochemical damage. Such damage inhibits the enzymes used for nucleic acid synthesis. Under such conditions, the damaged DNA or RNA cannot copy during replication. This inactivates the microorganism. The advantage of UV radiation is that it does not introduce or generate any hazardous chemical material or by-product during the procedure.

UV dose delivered to individual microorganism is one of the important factors used to evaluate the UV reactor performance. It determines the log reduction of the microorganisms. UV dose is the product of the UV intensity to which microorganism population is exposed and the exposure time. Different microbial populations absorb various UV dose as the UV intensity in the reactor is not uniform. This is also coupled with the complex flow trajectories of the microorganism due to the highly turbulent flow in the reactor. Under such a condition, UV reactor must be tested to validate the dose under different operating conditions.

Experimental study of UV reactor for ballast water treatment generally involves two stages, i.e. collimated beam test and full scale test. Collimated beam test is used to get the UV dose response curve of the challenge microorganisms while full scale test can be adopted to evaluate the UV reactor performance through analysis of log inactivation and reduction equivalent dose (RED). In the experimental test, the measurement of UV dose distribution is critical for the evaluation of UV reactor.
performance. The measurement of UV dose distribution can be achieved by using dyed microsphere method developed by Blatchley et al. [2,3] for both bench-scale and large-scale UV reactors. The dyed microspheres was used by Zhao et al. [4] to measure the dose distribution in UV reactors with different inlet pipes including straight and elbow shapes. Their results confirmed that dyed microspheres can be used as an additional test for the UV reactor validation based on the measured UV dose distribution. Shen et al. [5] proposed a Lagrangian actinometry (LA) method based on the application of dyed microspheres to measure UV dose distributions in UV reactor system. Their tests were conducted using coliphage MS2 as the challenge organism. The development of such method is a breakthrough for the experimental study of UV reactor performance as the LA method can provide accurate prediction of the dose distribution for any microorganism. Experimental study of UV reactor for water treatment, although is desirable, it generally involves with sophisticated and high resolution equipment to provide reliable results. Scaled experimental investigation is expensive too. Extreme cautiousness is usually demanded for the hazardous microorganisms. In view of this, theoretical investigations, in particular numerical simulations, play an essential complementary role in understanding the various process involved in the UV reactors.

Numerical study of UV reactor performance includes three components, i.e. fluid flow, microorganism transport and radiation transfer. These three components can be carried out sequentially. In the numerical simulation, the microorganisms are generally assumed to be solid particles and they are referred to as “particles” loosely here. Prior to the development of the dyed microorganism method, the UV dose distribution is generally predicted through numerical simulations. Lyn et al. [6] proposed a two dimensional numerical model combined with the random walk approach to predict UV dose distribution. Their simulation results compared with experimental data and reasonable agreement was achieved. Munoz et al.[7] developed a three dimensional numerical model to predict UV reactor performance. The number of particles is studied to establish statistically meaningful results. It is revealed from their study that RED is sensitive to the particle numbers. A Three-step of UV fluence rate and fluid dynamics method (TURF) was developed by Xu et al. [8] to simulate three components including fluid flow, microorganism particle movement and radiation transfer in the UV reactor. Their results showed that the size and shape of the microorganism particles have negligible effect on the UV fluence while water flow rate, reactor size and shape have significant impact on the reactor performance. Further study was done by the same authors [9] on the impacts of lamp arrangement for the UV reactor performance. They found that lamp arrangement has complex effects on the log inactivation of the UV reactor under different flow rates. In the evaluation of UV reactor performance, RED is generally used. The calculation of RED requires a cumbersome procedure to switch back and forth between the fluence and survival microorganism concentration [7]. In view of this, Li et al. [10] proposed a new performance indicator of minimum UV dose to replace RED. Such new minimum UV dose is independent of microorganism dose response curve and it can be easily obtained from the numerical simulation.

Although extensive experimental and numerical studies have been performed with respect to UV reactor for water treatment, there are no general conclusions for UV reactor performance under different designs and operating conditions. Even a specific UV reactor for treating different microorganisms, the performance could be different. The current work makes continuous efforts for the evaluations of UV reactors built at Sembcorp marine in Singapore [11]. The main focus here is to study the effects of different parameters on the UV reactor performance based on RED. This is different from the authors’ previous work which focuses on the UV dose distributions. In this paper, both experimental and numerical simulations are carried out for a base reactor, i.e. LBW850e.

2. Experiments
UV reactor LBW850e consists four parts in general, namely, inlet and outlet pipe, quartz-lamp assemble and two baffle plates. Low-pressure lamps are arranged uniformly at different radial locations of the reactor. These lamps are enclosed by the cylindrical quartz sleeves separating lamps from water. Two baffle plates are used to support the quartz-lamp assembly. They are fixed near the
center and outlet boundary of the reactor, respectively. A UV sensor constructed to the ONORM standard. It is fixed to measure fluence rate at a point approximately 10 mm from the surface of the quartz in the radial direction. Figure 1 shows the geometry of LBW850e in the simulation.

Fig. 1 3D geometry of LBW850e

UV reactor contains two types of experiments including bench-scale test using a collimated beam apparatus and full-scale reactor test. Collimated beam test characterizes the relationship between UV dose and log inactivation and it is called UV dose-response curve of the challenge microorganism. In the experiments, UV light is directly imposed to a collimating tube to dose a sample of challenge microorganisms with known concentration. After a specified exposure time, the sample of challenge microorganisms is analyzed to determine the log inactivation. Collimated beam tests are usually carried out based on a range of doses to generate a UV dose-response curve for a specified challenge microorganism. Full-scale reactor testing is used to determine the log inactivation as well as RED. In the experiments, the challenge microorganisms are injected into the UV reactor. The microorganisms absorbed the UV dose when they pass through the reactor. Log inactivation is obtained by measuring the concentration of the microorganism before and after exposure to UV light in a reactor. Full-scale reactor test can be performed for the test reactors. With log inactivation obtained, RED can be calculated through the dose-response curve from bench-scale test.

3. Simulations

3.1. Simulation methodology
The current simulation involves with fluid flow, radiation heat transfer as well as particle tracking. The problems are governed by Navier-Stokes equation with proper turbulent flow model, discrete ordinates (DO) radiation model as well as discrete phase model (DPM). The following assumptions are made before introducing the mathematical formulations:

1. The flow is incompressible.
2. The effects of lamps as well as the baffle plate on the radiation fields are not included. The baffle plates are treated with opaque walls.
3. Heat transfer is not considered.
4. Walls are smooth and no energy loss is considered when particles collide with walls.
5. Particles are assumed to be spherical and massless with similar properties as water.
6. Particles do not affect the fluid flow.
7. Scattering effect is not considered.

The conservation equations governing the transport of mass, momentum with considering turbulent flow are given by

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0
\]  

(1)
\[ \nabla \cdot ( \rho \vec{u} \vec{u} ) = - \nabla P + \nabla \cdot \left[ ( \mu + \mu_t ) \left( \nabla \vec{u} + ( \nabla \vec{u} )^T \right) \right] - \nabla \cdot \left( \frac{2}{3} \rho \kappa \vec{l} \right) \] (2)

For the case considering turbulent flow, \( \kappa-\varepsilon \) model is adopted and the equations for solving \( \kappa \) and \( \varepsilon \) are:

\[
\frac{\partial (\rho \kappa)}{\partial t} + \nabla \cdot (\rho \vec{u} \kappa) = \nabla \cdot \left( \frac{\mu_t}{\sigma_k} \nabla \kappa \right) + G_k + G_b - \rho \varepsilon \] (3)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \vec{u} \varepsilon) = \nabla \cdot \left( \frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + \frac{\varepsilon}{\kappa} \left( C_{1_\epsilon} G_k + C_{3_\epsilon} G_b - C_{2_\epsilon} \rho \varepsilon \right) \] (4)

where \( C_{1_\epsilon}, C_{2_\epsilon}, C_{3_\epsilon} \) are the constants with values of 1.44, 1.92 and 1.44, respectively. \( \sigma_k \) and \( \sigma_\varepsilon \) are 1.00 and 1.3, respectively. The eddy viscosity \( \mu_t \) is expressed as:

\[ \mu_t = \rho C_\mu \frac{\kappa^2}{\varepsilon} \] (5)

\( C_\mu \) is equal to 0.09. \( G_k \) is the production of turbulence kinetic energy. \( G_b \) is the inclusion of the buoyancy force on the turbulent flow.

The DO model considers the radiative transfer equation is written as: [12]

\[ \nabla \cdot (I \cdot \vec{s}) + a I = a n^2 \frac{\sigma T^4}{\pi} \] (6)

where \( a \) is the absorption coefficient, \( n \) is the refractive index. \( \sigma \) is Stefan-Boltzmann constant. \( I \) is the UV intensity. \( T \) is the temperature. In order to minimize the temperature effect on the radiation field, the flow field is patched to 1K before the simulation of the radiation.

The trajectory of the particles was predicted through the integration of the force balance on the particle based on the Lagrangian reference frame [13]. The mathematical formulation for particle movement is:

\[ \frac{du_{ib}}{dt} = F_D (u_{ib} - u_i) + \frac{g_i (\rho_b - \rho)}{\rho_b} + F_i \] (7)

The subscript \( i \) represents the components of the axis. \( u_{ib} \) and \( u \) are the particle and water velocity, respectively. \( F_D \) is the drag force exerted on water by the particle. \( F_i \) is the other forces involved such as virtual force and pressure gradient force. The mathematical expression of \( F_D \) is:

\[ F_D = \frac{18 \mu}{\rho_b d_b^2} + \frac{C_D \text{Re}}{24} \] (8)

where \( C_D \) is the drag force coefficient and \( \text{Re} \) is the Reynolds number. \( d_b \) is the particle diameter. The expression for \( C_D \) and \( \text{Re} \) are, respectively:

\[ C_D = a_1 + \frac{a_2}{\text{Re}} + \frac{a_3}{\text{Re}^2} \] (9)

\[ \text{Re} = \frac{\rho d_b |u_{ib} - u|}{\mu} \] (10)

\( a_1, a_2 \) and \( a_3 \) are constants which can be applied for spherical particles for all ranges of \( \text{Re} \) [14]. The expressions of these constants are:
In this study, the virtual force and the force incurred by the pressure gradient is included. The mathematical formulation for the combination of these two forces is:

\[
F_i = 0.5 \frac{\rho_i}{\rho_b} \frac{d(u_i - u_{ib})}{dt} + \frac{\rho_i}{\rho_b} u_{ib} \frac{\partial u_{ib}}{\partial x_i}
\]  

(12)

The procedure for simulation of the current problem is divided into three different steps. These are:

1) Simulation of fluid flow in the reactor.

In this simulation, sea water is used for the fluid. \( \kappa-\epsilon \) model with standard wall function is used to simulate the turbulent flow. SIMPLE method is adopted to deal with the coupling of the pressure and velocity [15]. The second order upwind scheme is used to deal with the convection term in the N-S equation. The first order upwind scheme is used for both the turbulent kinetic energy equation and dissipation equation.

A uniform velocity is used at the inlet boundary condition with the volume flow rate known. A constant pressure of 2.2 bar is used at the outlet boundary. The walls are assumed no-slip. Steady state simulation is performed with flow iteration around 20,000 to ensure a converged flow field. The residual for continuity and momentum errors are set to be \( 5 \times 10^{-5} \).

2) Simulation of radiation heat transfer in the reactor.

With the flow field from the previous step, the radiation from the lamps to the surrounding fluid in the reactor is simulated in this step. Discrete Ordinates (DO) model is used for the simulation. Phi divisions is \( 5 \times 5 \) and the phi pixels is \( 3 \times 3 \)[12]. Increasing the division will increase the computational cost substantially. Phi pixel of \( 3 \times 3 \) is recommended for the semi-transparent boundaries (ANSYS FLUENT, 2012). Therefore, it is chosen in the current simulation. The non-gray DO implementation divides the radiation spectrum into \( N \) wavelength bands, which need not be contiguous or equal in extent. The radiation transport equation is integrated over each wavelength interval, resulting in transport equations for the quantity UV intensity.

The physical properties for different materials are listed in Table 1.

| Material | Density (kg/m³) | Specific heat (J/kg•K) | Thermal conductivity (W/m•K) | Absorption coefficient (1/m) | Refractive index | Internal emissivity |
|----------|----------------|------------------------|------------------------------|-----------------------------|-----------------|--------------------|
| water    | 1025           | 4800                   | 0.6                          | depends on UVT              | 1.372           | 0.8                |
| lamp     | 2200           | 964                    | 1.55                         | 0                           | 1.5             | 1                  |
| steel    | 8030           | 502.48                 | 16.27                        | 40                          | 1.36            | 0.6                |
| PTFE     | 2200           | 1300                   | 0.25                         | 30                          | 1.36            | 0.85               |
(3) Particle trajectory simulation.
In this step, the movements of the particles under the converged flow and radiation fields from steps 1 and 2 are simulated. The trajectory equation of the particle movement, i.e. Eq. (7) is solved by stepwise integration over discrete time steps. The body force is assumed to be constant over each small time interval. The other forces acted on the particles are linearized. A trapezoidal scheme is used for integrating Eq. (7). The integration time used in the simulation is $10^8$ s. Such time step is chosen based on Courant number of 0.25 used in the simulation. The time step size is around $10^{-6}$ if Courant number of 0.25 is used. However, we choose an even smaller time step size of $10^{-8}$ in the simulation for consideration of the high flow rate applied in the other reactors.

3.2. Mesh sensitivity study
Mesh sensitivity study is carried out for LBX850e. Two different mesh sizes are generated using ANSYS meshing software. The numbers of elements after converting from tetrahedral to polyhedra mesh in ANSYS FLUENT are 8.29 million and 12.9 million, respectively referred to as medium mesh and fine mesh thereafter. Boundary layers are used in order to capture the flow features near the walls. The numbers of boundary layers for the two meshes are fixed at 5. The mesh structures are shown in Figs. 2 and 3 for the medium and fine mesh, respectively.

![Fig. 2](image1.png)
**(a)** Medium and, **(b)** zoomed mesh for LBX850e.

![Fig. 3](image2.png)
**(a)** Fine and, **(b)** zoomed mesh for LBX850e.

Note here that all the key parameters below is dimensionlessed with the RED under flow rate of $338\text{m}^3/\text{h}$ and 60% UVT. The subscript of $*$ is used to represent the dimensionless parameters. The velocity and fluence rate profiles at $x = -3.5$ m are chosen to compare the distributions under the two meshes. The line is selected to pass the center of the UV reactor cross sectional area. Shown in Fig. 4, generally, the two meshes can produce close results in the aspect of velocity as well as the fluence rate. Therefore, medium mesh is able to get the mesh independent results.
Particle number sensitivity study is performed based on the two meshes with UVT 70%. Three different particle numbers are chosen, i.e. 5000, 10000 and 20000, respectively. Tables 2 and 3 show the non-dimensional UV dose under different particle numbers. A further comparison of RED for the three different particles is calculated. Such calculation can be achieved using the UV dose inactivation model. The inactivation model is usually described by the first-order model. The inactivation of the microorganism is defined by the log inactivation of \( N \). It is expressed as:

\[
-\log_{10}\left(\frac{N}{N_0}\right) = kD
\]  

(13)

where \( N_0 \) and \( N \) represent the number of microorganisms alive in the reactor before and after exposure to UV dose. \( k \) is the inactivation constant. \( D \) is the UV dose received by the individual microorganisms. It is calculated by:

\[
D = \int_0^T E dt
\]

(14)

where \( E \) is the local fluence rate. The calculation procedure to get the RED is listed below [7]:

1. Use Eq. (13) to calculate \( N/N_0 \) using \( D \) obtained from simulation.
2. Use \( N/N_0 \) obtained from step (1) to get the overall survival ratio of the microorganisms using the following equation:

\[
\frac{N}{N_0} = \prod_{i=0}^{i=\infty} \frac{1}{n_p \left( \frac{N}{N_0} \right)_{i}}
\]

(15)

3. Substitute the results from Eq. (15) to Eq. (13) to get RED.
4. log inactivation is calculated from the overall survival ratio of the microorganisms.

It is clear that 10000 particle numbers under medium mesh is sufficient to produce a particle and mesh independent solution. The error is well within 1%.

Table 2 Particle effect on UV dose based on medium mesh

| No of particles | 5000  | 10000 | 20000 |
|-----------------|-------|-------|-------|
| Minimum Dose*   | 0.31  | 0.28  | 0.29  |
| Maximum Dose*   | 19.63 | 21.22 | 19.95 |
| Average Dose*   | 1.83  | 1.95  | 1.93  |
| RED*            | 1.72  | 1.71  | 1.71  |
Table 3 Particle effect on UV dose based on fine mesh

| No of particles | 5000 | 10000 | 20000 |
|-----------------|------|-------|-------|
| Minimum Dose    | 0.30 | 0.30  | 0.30  |
| Maximum Dose    | 12.62| 19.49 | 19.15 |
| Average Dose    | 1.94 | 1.96  | 2.16  |
| RED             | 1.63 | 1.71  | 1.70  |

4. Results and discussions

4.1. The inactivation constant of B. Pumilus
The current numerical model is validated against the biodosimetric test data for B. Pumilus bacteria. The inactivation constant $k$ of B. Pumilus is derived from the B.Pumilis response curve as shown in Fig. 5. The average value of $k$ is 0.00148 and such value is used in the calculation of RED.

4.2. Comparison between simulation and experimental results
In order to evaluate the uncertainty involved in the experiments, the standard uncertainty analysis and error propagation is used to check whether CFD prediction fall within certain level of confidence about the measured data.

At a 95% confidence level the uncertainty for the LBX 850e validation data set is 0.46284 log.
For B. Pumilus, at RED of 1239 J/m², log $i$ is around 2. Therefore, DL = RED/log $i$ = 620/log $i$.

Under such a condition, the interval where in 95% of the cases the true mean value lies can then be constructed with $2.0 \pm 0.46284\times62/123.9 = 2.0 \pm 0.23$ (or the respective doses: 1239 ± 14.4 mJ/cm²). This translates to experimental uncertainty of around 12%.

Figure 6 shows the comparison of non-dimensionlized RED between experiments and simulation under different flow rates with the variation of UVT. Generally, the results from CFD simulation have reasonable agreement with the experimental data. The maximum discrepancy between simulation and experiments is 13.4% for the parameters studied. The increase of flow rate decreases the particle residence time in the reactor, resulting in the reduction of RED.

Figure 7 shows the variation of non-dimensionlized RED with UVT under the non-dimensionlized flow rate of $Q^* = 0.45$. The increase of UVT increases the fluence rate exposure of the particles. The UV dose absorbed by the particle then increases which accordingly increases RED.

Figure 8 shows the non-dimensionlized predicted RED versus the experimental RED. The line with $y = x$ is also superimposed in the graph. The error bars are from the experimental test. Most of the error bars cross $y = x$ line which indicates a reasonable agreement between the simulation results and the experimental data.
Fig. 6 Variation of RED with flow rate under (a) 60% UVT and, (b) 70% UVT

Fig. 7 Variation of RED with UVT under $Q^* = 0.47$
5. Conclusions
This paper has studied the UV reactor for the ballast water treatment experimentally and numerically. The effects of UVT and flow rates on the reactor performance are analyzed. Comparisons between experiments and simulation results show reasonable agreement. With the validation of the numerical model, it can be applied to other reactor performance analysis in future.

References
[1] Hijnen, W.A.M., Beerendonk, E.F., Medema, G.J., 2006. Inactivation credit of UV radiation for viruses, bacterial and protozoan oo)cysts in water: a review. Water Res. 40(1): 3-22.
[2] Blatchley III, E.R., Shen, C., Naunovic, Z., Lin, Z. L., Lyn, D.A., Robinson, J.P., Ragheb, K., Grégori, G., Bergstrom, D.E., Fang, S., Guan, Y., Jennings, K., Gunaratna, N., 2006. Dyed microspheres for quantification of UV dose distributions: photo-chemical reactor characterization by Lagrangian Actinometry. J. Environ. Eng. ASCE 132(11): 1390-1403.
[3] Blatchley III, E.R., Shen, C., Scheible, O.K., Robinson, J.P., Ragheb, K., Bergstrom, D.E., Rokjer, D., 2008. Validation of large-scale, monochromatic UV disinfection systems for drinking water using dyed microspheres. Water Res. 42 (3): 677-688.
[4] Zhao, X., Alpert, S.M., Ducoste, J.J., 2009. Assessing the impact of upstream hydraulics on the dose distribution of ultraviolet reactors using fluorescence microspheres and computational fluid dynamics. Environ. Eng. Sci. 26(5): 947-959.
[5] Shen, C., Scheible, O.K., Chan, P., Mofidi, A., Yun, T.I., Lee, C.C., Blatchley III, E.R., 2009. Validation of medium-pressure UV disinfection reactors by Lagrangian actinometry using dyed microspheres. Water Res. 43(5): 1370-1380.
[6] Lyn, D.A., Chiu, K., Blatchley III, E.R., 1999. Numerical modeling of flow and disinfection in UV disinfection channels. J. Environ. Eng. 125(1): 17-26.
[7] Munoz, A., Craik, S., Kresta, S., 2007. Computational fluid dynamics for predicting performance of ultraviolet disinfection-sensitivity to particle tracking inputs. J. Environ. Eng. Sci. 6(3): 285-301.
[8] Xu, C., Zhao, X.S., Rangaiah, G.P., 2013. Performance analysis of ultraviolet water disinfection reactors using computational fluid dynamics simulation. Chem. Eng. J. 221: 398-406.
[9] Xu, C., Rangaiah, G.P., Zhao, X.S., 2015. A computational study of the effect of lamp arrangements on the performance of ultraviolet water disinfection reactors. Chem. Eng. Sci. 122: 299-306.
[10] Li, W.T., Li, M.K., Bolton, J.R., Qiang, Z.M., 2016. Configuration optimization of UV reactors for water disinfection with computational fluid dynamics: feasibility of using particle minimum UV dose as a performance indicator. Chemical Eng. J. 306: 1-8.
[11] Li, H.Y., Osman, H., Kang, C.W., Ba, T., 2017. Numerical and experimental investigation of UV disinfection for water treatment. Appl. Therm. Eng., 111: 280-291.
[12] ANSYS Manual, 2012, ANSYS–FLUENT 12.0, Theory Guide.
[13] Cundall, P.A., Strack, O.D.L., 1979. A discrete numerical model for granular assemblies, Géotechnique 29(1): 47-65.
[14] Moris, S.A., Alexander, A.J., 1972. An investigation of particle trajectories in two-phase flow systems. J. Fluid Mech. 55(2): 193-208.
[15] Patankar, S.V., 1980. Numerical Heat Transfer and Fluid Flow. Hemisphere Publisher, New York.

Nomenclature

- \( a \) - absorption coefficient \((1/m)\)
- \( c_1, c_2, c_3 \) - constant
- \( C_D, C_{1e}, C_{2e} \) - constant
- \( d_p \) - particle diameter \((m)\)
- \( D \) - UV dose \((J/m^2)\)
- \( E \) - fluence rate \((W/m^2)\)
- \( F \) - force \((N)\)
- \( \bar{g} \) - gravity vector \((m/s^2)\)
- \( G_x \) - production of turbulent energy \((kg/m^3/s^3)\)
- \( I \) - radiation intensity \((W/m^2)\)
- \( n \) - refractive index
- \( N \) - number of microorganisms
- \( P \) - pressure \((Pa)\)
- \( Q \) - flow rate \((m^3/s)\)
- \( \text{Re} \) - Reynolds number
- \( \text{RED} \) - reduction equivalent dose \((W/m^2)\)
- \( \bar{s} \) - direction vector \((m/s)\)
- \( t \) - time \((s)\)
- \( T \) - temperature \(^{°C}\)
- \( \bar{u} \) - velocity vector \((m/s)\)
- \( \text{UVT} \) - transmittance
- \( x, y, z \) - Cartesian coordinate

Greek Symbols

- \( \mu \) - dynamic viscosity \((kg/m/s)\)
- \( \sigma \) - Stefan Boltzmann constant \((W/m^2-K^4)\)
- \( \kappa \) - kinetic energy \((m^2/s^2)\)
- \( \varepsilon \) - energy dissipation rate \((m^2/s^3)\)
- \( \sigma_{so}, \sigma_e \) - empirical constant
- \( \rho \) - density \((kg/m^3)\)
Subscripts

\[ p \quad \text{particles} \]
\[ r \quad \text{reference} \]
\[ t \quad \text{turbulent flow} \]
\[ * \quad \text{dimensionless} \]