Simulating UV disinfection reactor performance

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Introduction

Nowadays, water treatment with ultraviolet (UV) radiation becomes increasingly important. **UV lamps** are employed whose radiation permeates the water flow and deactivates pathogenic micro-organisms.
Currently, reactor disinfection efficacy is judged by means of **biodosimetric measurements**: Water flowing through the reactor is spiked with micro-organisms of known concentration. When determining the concentration of viable micro-organisms after passing through the reactor, a reduction value is obtained, which can be used to calculate the **Reduction Equivalent Fluence (REF)**. The exact procedure of certifying UV disinfection reactors, which is specified in the ÖNORM M 5873-1 [1], is complex and costly.

Aims

- Combine the different aspects of **Ultraviolet Disinfection (UVD)** into an overall simulation of a small UVD reactor (Figure 1). This includes:
  - * **Computational Fluid Dynamics (CFD)** simulation of the water flow
  - * **Particle tracking** of micro-organisms in the water
  - * **Radiation modelling** of the radiation emitted by the UV lamp
- Compare to available data from multiple **biodosimetric certification procedures**

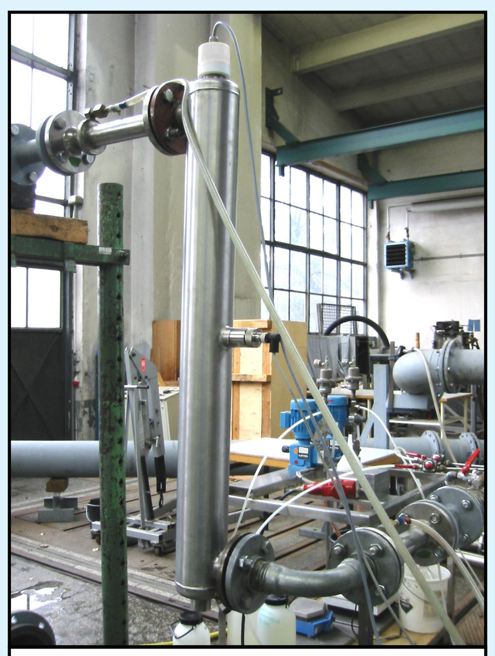

Figure 1: The examined UV disinfection reactor

CFD simulation

A **small single-lamp reactor** was modelled, measuring ~1m along the main axis.
Steady-state calculations have been carried out using the **realizable-k-ε turbulence model**.
Pressure loss data were available from certification reports and additional measurements. CFD pressure loss results are compared to experimental data and to a quadratic fit (R^2=0.9981) in Figure 2.
Compared to the experiment and fit, a **mean accuracy of 5.4 and 3.2%**, respectively, has been obtained.
Significant unsteady fluctuations may occur, but could only be reproduced by computationally too expensive unsteady CFD simulations.

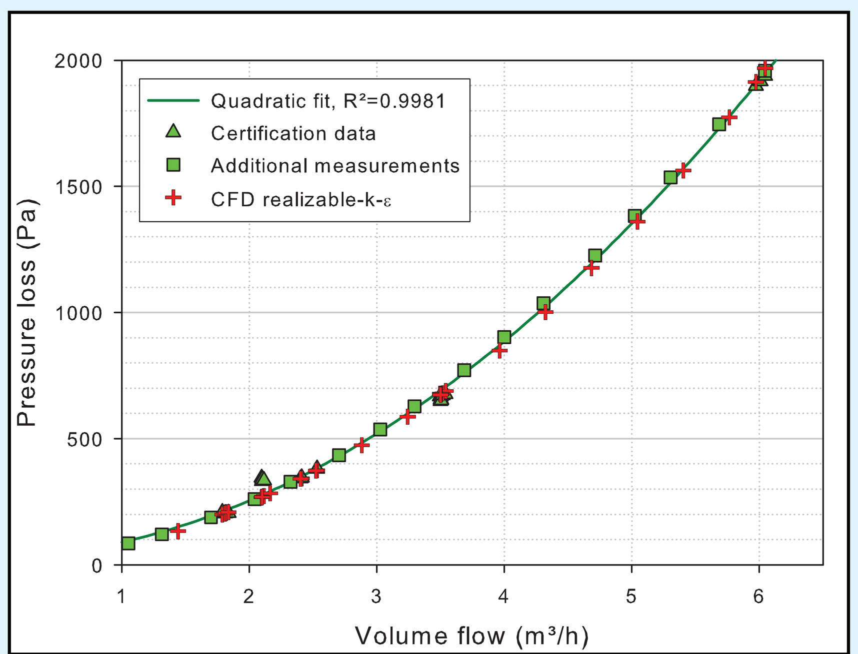

Figure 2: Pressure loss (Pa) of the UVD system vs. volume flow rate (m^3/h). Experimental data for different measurements and their quadratic fit (R^2=0.9981) are plotted. For comparison, CFD results have been added. They show excellent agreement with the experiments.

Particle tracking

Particle tracks were calculated by solving the **force balance equation** for the particle in question.
The random nature of the used **discrete random walk (DRW)** model allowed the calculation of many particle tracks originating from a single grid cell (Figure 3).
Approximately **26000 particle tracks** were calculated for every case, enabling statistically reliable calculations.

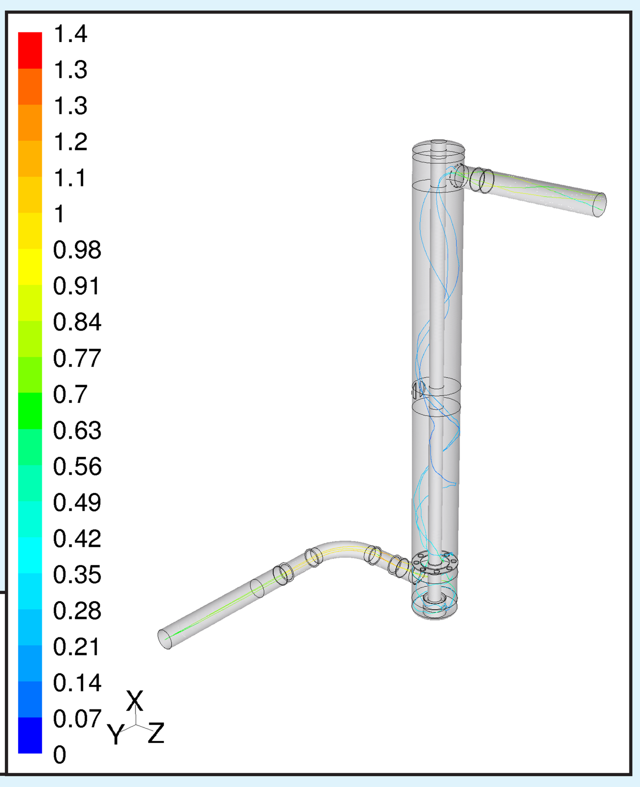

Figure 3: Three tracks originating from a single cell. The impact of random effects leads to non-identical paths. Paths coloured by particle velocity magnitude (m/s).

Radiation modelling

Several radiation models have been implemented, which exhibit different degrees of physical realism:

- Multiple Point Source Summation with Focus effect **(MPSS-F)**
- Multiple Segment Source Summation with and without Focus effect **(MSSS/MSSS-F)**
- Line Source Integration with Focus effect **(LSI-F)**
- Modified LSI **(RADLSI)**

See [2] for a detailed description of these radiation models.

One major limitation of the radiation modelling exists: Due to the unknown **UV conversion efficiency** of the lamp, the radiation models had to be calibrated to fit an available UV sensor reading. Thus, the calculated REF depends on the chosen efficiency value, and the radiation models can only be compared among themselves.

The radiation calculation results in a **fluence rate distribution** for the main reactor volume. As an example, fluence rate results are shown along an axial and radial path in the reactor volume in Figure 4.

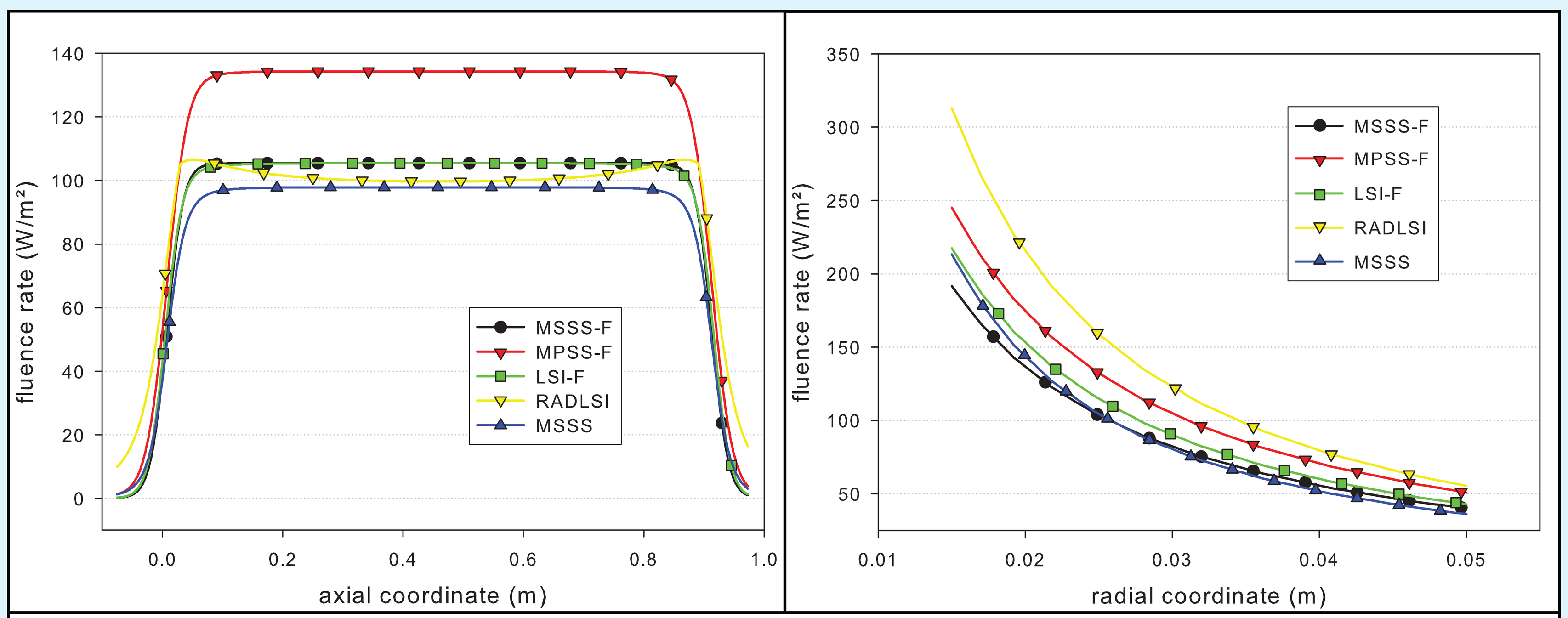

Figure 4: Two examples of the fluence rate distribution for the different radiation models along an axial (left) and radial (right) path in the reactor volume.

Numerical integration of **fluence rate** along **particle tracks** yields a **received fluence** value for every particle track

Results and Conclusions

Fluence results for the whole set of particles can be arranged into a **fluence histogram** (Figure 5). A REF value is easily calculated from the fluence distribution.
The resultant REF values were compared to experimental data for **23 sets of operational parameters**.
A plot of the error for the different radiation models is shown in Figure 6. Mean and standard deviation of the error have been computed (Table 1).
For the different implemented radiation models, **mean errors between 7 and 25% have been found**. The standard deviations are relatively high, ranging from 8.9 to 15.4%.

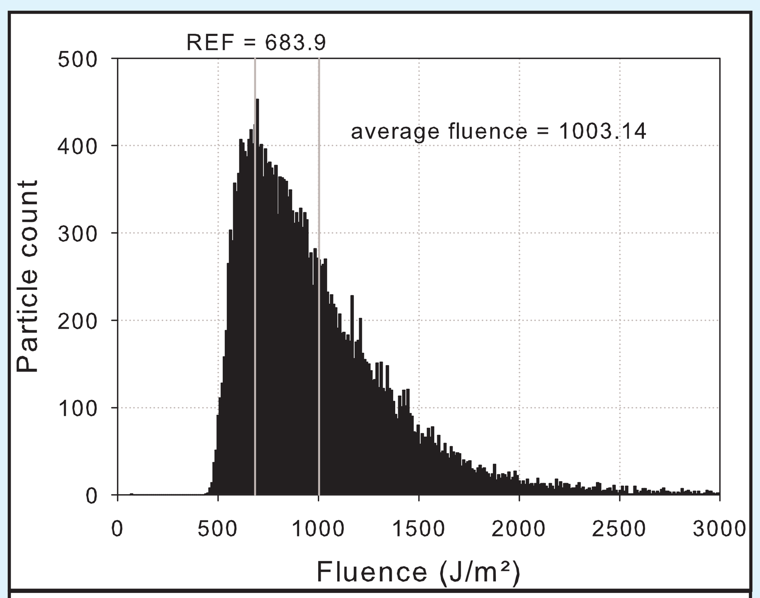

Figure 5: An example of a fluence histogram. The resultant REF and arithmetic mean of the fluence distribution are indicated.

Table 1: REF simulation statistics: Mean value and standard deviation of the REF errors (in %) are given for different radiation models.

	MSSS-F	MPSS-F	LSI-F	RADLSI	MSSS
mean	11.58	24.65	11.71	14.64	7.54
std. deviation	9.9	15.37	9.97	9.06	8.93

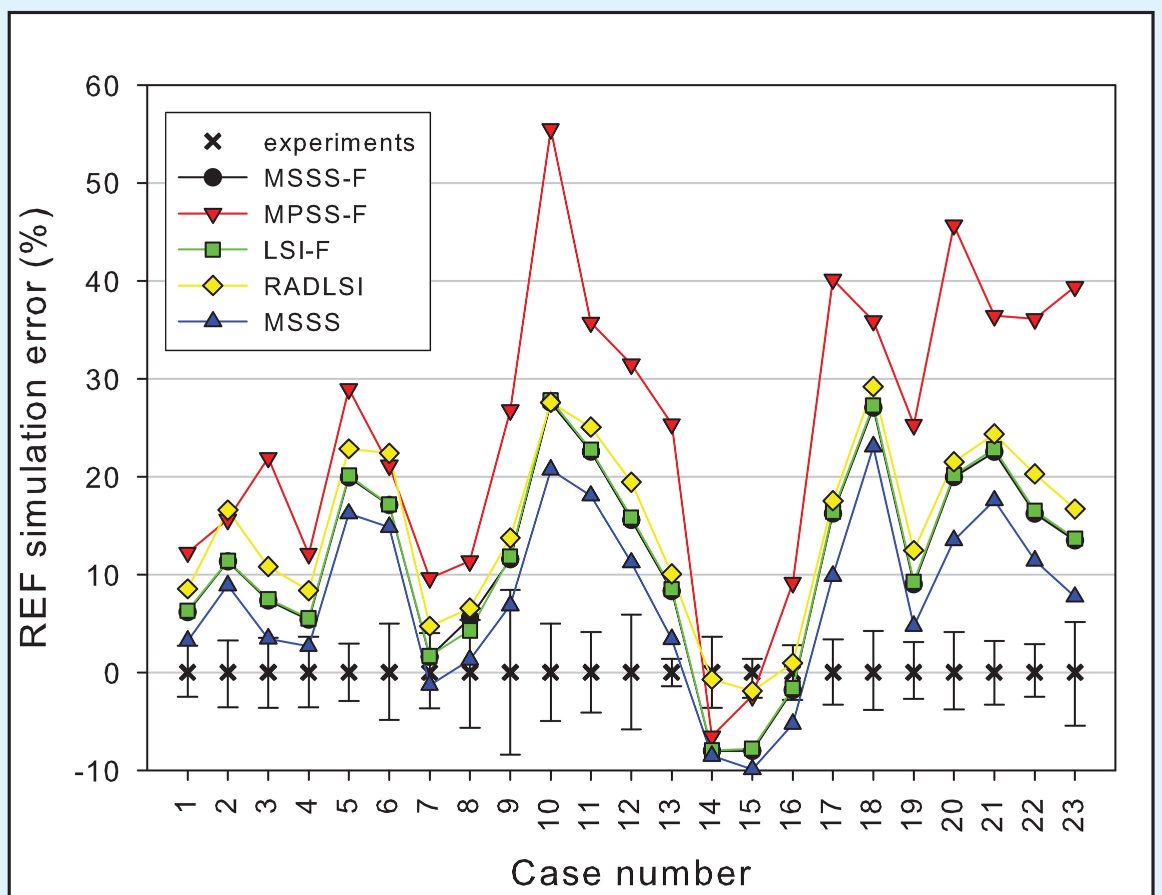

Figure 6: Disinfection simulation results: The relative error is plotted for the different cases. Connecting lines have been added to ease analysis.

Considering the limited amount of available experimental data for the flow field and fluence rate distribution, good predictions of the REF were obtained. The potential use of this method for designing and improving UVD reactors has been demonstrated.

Literature cited

[1] Österreichisches Normungsinstitut. ÖNORM M 5873-1: Anlagen zur Desinfektion von Wasser mittels Ultraviolett-Strahlen - Anforderungen und Prüfung - Teil 1: Anlagen mit Quecksilberdampf-Niederdruckstrahlern, March 2001.

[2] Dong Liu. Numerical Simulation of UV disinfection reactors: Impact of fluence rate distribution and turbulence modeling. PhD thesis. North Carolina State University, 2004.

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For more information

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