DEVELOPMENT OF A POOL-MODEL TO STUDY THE IMPACT OF DIFFERENT TREATMENT PROCESSES ON DISINFECTION BY-PRODUCTS

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ABSTRACT
To assess how the health risk in indoor swimming pools can be minimized by treatment the impact of different treatment methods on the DBP formation potential has to be investigated. As the results of studies at full scale pools always lack in precision due to changing conditions a pool model was developed to ensure appropriate and defined conditions for investigations. This work explains the way of designing a swimming pool model for simulation of real pool water conditions and pool operation. The developed swimming pool model includes a pool basin, a modular treatment section and a cover to simulate indoor conditions. The treatment section was designed to compare two treatment concepts with each other. The first concept includes a conventional coagulation filtration followed by an upstream activated carbon filtration. This is to be compared to a pool water treatment process consisting of an ultrafiltration (UF) unit, a powdered activated carbon (PAC) treatment process and optional upstream UV radiation using low and medium pressure UV lamps, respectively. To investigate DBP formation and release as well as the treatment processes in detail, a complex sampling system was realized. Comprehensive analyses will be performed including DOC fraction analyses by size exclusion chromatography with organic carbon and nitrogen detection (SEC-OCD-OND), trihalomethane (THM) and chloramines (CA) measurements by membrane inlet mass spectroscopy (MIMS) and total organic carbon analysis. These analytical investigations will be carried out both online and offline. The typical introduction of organic matter into a pool by bathers is simulated by dosing a body fluid analogue (BFA) into the pool water. By the time of submitting this paper to the conference proceedings, the pilotscale swimming pool model including the treatment section is completely installed and first runs to verify all functions are carried out.

Keywords	Chloramines, DBP, Swimming pool model, THM

INTRODUCTION
Chlorine is usually chosen for the disinfection of pool water. A major drawback associated with the use of chlorine as disinfectant is its potential to react with organic and inorganic matter to disinfection by-products (DBPs) such as trihalomethanes (THMs), organic and inorganic chloramines (CAs) and other yet difficult to measure chlorinated by-products (Zwiener et al., 2007). The toxicological and genotoxicological risk assessment with respect to these compounds are subject of current research and scientific discussion (Bernard et al., 2008, Hrudy 2009, Müllner et al., 2007, Plewa et al., 2008, Thickett et al., 2002, UBA 2011).

Conventional water treatment processes such as coagulation filtration are insufficient to remove the molecular weight fractions of DBPs with genotoxic potential. This also applies to the single use of ultrafiltration (UF) membranes (Glauner et al., 2005). The benefits of filtration processes are mainly the removal of particles from swimming pool water. Previous studies on the efficiency of coagulation filtration process combinations showed much higher removal efficiencies regarding particulate matter (> 1 µm) in the case that UF membranes were used for filtration as alternative for conventional sand filtration (Müller & Uhl 2009). For the removal of particles as well as DBP-precursors, ultrafiltration can be combined with granular or powdered activated carbon filtration (Champlin et al., 2002, Göksen 2002).

Another approach to remove or at least minimise dissolved DBPs in swimming pool water is the use of oxidation processes (OPs). The main objective is to oxidise precursors as well as their halogenated disinfection by-products. By adding chemical substances known to react as initiators for radical chain reactions OPs are enhanced to so-called advanced oxidation processes (AOPs). Known combinations are O_3/H_2O_2, O_3/UV, H_2O_2/UV, photocatalytic reactions (TiO_2/UV) and the Fenton reaction (Fe^{2+}/H_2O_2). Furthermore, UV radiation on chlorinated water with medium pressure UV lamps could lead to the formation of free chlorine radicals ($^{\bullet}Cl$) and hydroxyl radicals ($^{\bullet}OH$) which then initiate the oxidation of DBPs (Li & Blatchley 2009). All combinations aim to produce reactive radicals as initiators for radical cross-linking reactions to oxidise precursors as well as DBPs (Beyer & Wörner 2005, Cassan et al., 2006, Liu et al., 2006, Glauner et al., 2005, Landsman et al., 2007). Photolytic degradation of inorganic chloramines such as monochloramine, dichloramine and trichloramine (Li & Blatchley 2009) and THMs (Cassan et al., 2006) by middle pressure UV lamps is described in the literature. During UV radiation also partial oxidation products may be formed by oxidising high molecular weight precursors.

In the literature, investigations on the influence of water treatment on swimming pool water quality under known conditions are mainly focusing single processes and are almost exclusively performed using lab-scale systems. There are only few discussions on combinations of water treatment processes modelling a whole pool water treatment system. Lab-scale systems are able to simulate the conditions of water treatment processes. But in cases of long term behaviour, aging and maintenance processes, such as the flushing of membrane filters, lab-scale pilot plants always tend to be improper to reproduce reality. Besides the simulation of back flush behaviour, models must be suitable to correctly reproduce hydraulic conditions. To avoid scale-up problems and to make the results appropriate for large-scale applications pilot-scale models are necessary. Furthermore, investigations have to be performed under exactly defined conditions considering all mass and material flows. This cannot be realized in a large-scale swimming pool system during daily business. All these considerations indicate the need of a pilot-scale swimming pool model to simulate and investigate pool operation and water treatment.

OBJECTIVES AND APPROACH

The work to be presented is part of a research project with focus on health-related optimization of pool water treatment with the objective to minimize exposure of bathers and swimming supervisors to disinfection by-products. To minimize the health risk in indoor swimming pools the impact of different treatment methods on DBP formation potential has to be investigated. For these investigations simulations of real pool water conditions are necessary. Therefore, the main objective of the work to be presented is to describe the planning and construction of a pilot-scale swimming pool model including a treatment section and a complex sampling system. Using this pool model, investigations of different treatment process combinations under defined conditions and their impact on DBP formation shall be possible.

The German standard DIN 19643 regulates besides water quality parameters such as maximum concentrations for THMs and CAs also the dimensioning of pools and their treatment systems. Currently, possible applications of four treatment combinations including coagulation, sand filtration, adsorption, oxidation and disinfection are described in detail.

The main dimensioning parameters for pools and their treatment system are the nominal bather loading N and the effectiveness of the treatment step applied, defined by the capacity factor k (DIN 19643 Part 2-5). All dimensions of the swimming pool model such as flow rates and retention times, chemical dosing, air conditioning and filter design have therefore to be in accordance with DIN 19643 assuming a conventional treatment combination of coagulation – sandfiltration – GAC-filtration – chlorination (DIN 19643 part 5). To investigate new alternative treatment combinations the pool model is also equipped with an ultrafiltration module including an upstream PAC dosing and an UV module where an upstream H202 dosing can optionally be performed. Fig. 1 shows the different treatment processes that shall be investigated and compared. The comparison will be between conventional coagulation sand filtration in combination with PAC dosing and coagulation ultrafiltration in combination with PAC dosing as well as UV treatment or UV/H_2O_2 treatment, respectively. The implementation of these treatment processes is shown in Fig. 2.

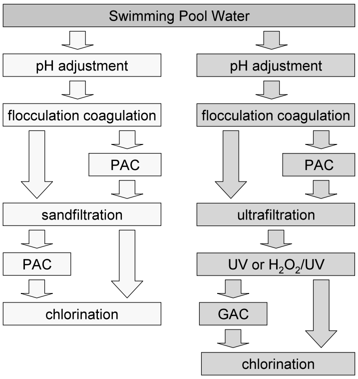

Fig. 1 Treatment combinations which can be applied at the pool model.

To transfer real pool hydrodynamic situations to a pilot-scale pool model, dimensionless similarity-parameters have to be applied. Furthermore, it has to be taken into account that the transfer of linear expansions to pilot scale requires the adjustment of other physical parameters like fluid density or time. This issue is quite difficult when at the same time chemical reactions like formation of disinfection by-products have to be studied. Therefore, the transformation of hydrodynamic parameters from large-scale to pilot-scale is only considered in transversal direction (over the pool depth). With regard to these considerations, the resulting dimensions of the model pool are 1600 mm length x 800 mm width and 2100 mm depth.

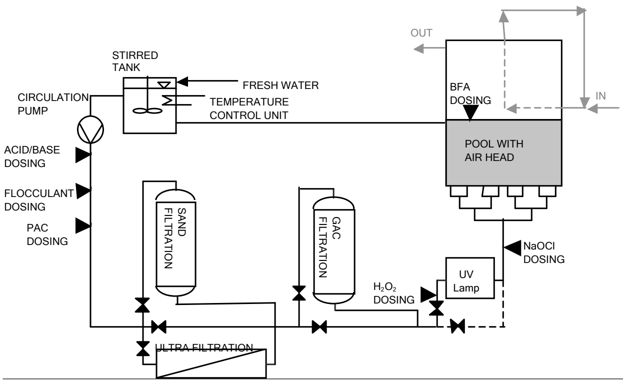

Fig. 2 Flow chart of the pool model's treatment section.

MATERIALS AND METHODS

SWIMMING POOL MODEL

The model pool flow will be from bottom to top. Circulation is realized by a single stage pump. The pool is made of stainless steal 1.4304 and 1.4401 with a nozzle collecting system over the bed depth. The pipe system is constructed of PVC-U pipes allowing flow rates of 1 m s^{-1}. Fresh water supply causing pool water circulation is realized by 48 injection nozzles at the pool bottom dispersing water from a tempered double walled balance tank being fed with overflow water which is subsequently passing respective treatment steps (Fig. 2). The fresh water inflow velocities are determined by the individual design of the injection nozzles. An inflow velocity mean value from experience of 2.4 m s^{-1} is applied for the model pool investigations. Further operation parameters are given in Tab. 1.

Tab. 1 Model pool operation parameters.

Parameter	Value
Pool volume	2.7 m³ (l x w x d, 1.6 m x 0.8 m x 2.1 m)
Water temperature	30 °C
Flow rate	0.57 m³ h-1
Retention time	4.5 h
Air space	2.6 m³
Air temperature	30 °C
Humidity	4.3 g kg-1
Flow rate	appr. 60 m³ h-1 (depending on humidity)
Balance tank volume	0.2 m³

To make investigations of the air space possible, the pool model is equipped with a lid. The air supply can be run both top-down and bottom-up. The air is supplied by two fans and can be heated. Air samples can be taken from two sampling ports being situated 300 mm and 1500 mm above the water surface, respectively.

POOL WATER TREATMENT

The sand and GAC filters are identical in construction and are both operated with a flow rate of 32 m h^{-1}. The filter columns have a diameter of 150 mm and measure 2000 mm in height. The filter bed depth is 1000 mm. For the sand filter quarz sand with a grain size distribution of 0.63-1.0 mm is used. The GAC filter is filled with DONAU Carbon Hydraffin CC 8/30 activated carbon. The filters are made of glass and include an air release assembly and sampling points located along the bed depth. Running the columns in by-pass mode, extensions of the coagulant retention time before entering the column and bottom-up flushing according to the German DIN 19643 are possible.

Ultrafiltration with upstream PAC dosing is performed using an Inge dizzer S 1.5 4.5 multibore membrane module being run with a flux of 120 L m^{-2} h^{-1} in dead end mode and the Norit SAUF PAC. Normal back flush, forward flush and chemical enhanced flushing with NaOH, H_2SO_4 and NaOCl of the membrane is possible. The PESM membrane's molecular weight cut off is given at 100 kDa. There is a possibility to extend PAC and coagulanat contact time before entering the membrane as well as to change the velocity gradient G.

A low pressure and a medium pressure UV lamp, respectively, are applied for UV treatment. In case of applying the low pressure UV lamp, treatment can be optionally run with or without H_2O_2 dosing.

All chemicals (chlorine, acids, bases, coagulant, H2O2 and synthetic bather load) are dosed by peristaltic pumps with PTFE tubing. Several injection points being situated from 300 to 500 mm under the pool water surface are implemented to dose the body fluid analogue (BFA) which simulates the organic matter release of bathers into the pool water.

CHEMICALS AND MEDIA

Aluminiumhydroxychloride ($Al_2(OH)_5Cl$) and Polyaluminiumchloride ($Al(OH)\ (OH)_{2,1}ClO,_8(SO_4)_{0,1}$) are used as coagulants.

To simulate the organic matter release of bathers, body fluid analogues (BFA) are used. These BFAs are mainly composed of organic and amino acids as described in the literature (Goeres et al., 2004, Borgmann-Strahlsen 2003, Judd & Bullock 2003, Putnam 1971). The components of the BFA stock solution used for the investigations are listed in Tab. 2.

Tab. 2 Body fluid analogs components (according to Judd & Bullock 2003)

Component	Dosage in mg L^{-1}
urea	14,800
creatinine	1,800
uric acid	490
citric acid	640
histidine	1,210
hippuric acid	1,710

Kanan (2010) states, that the BFA might result in a lower THM formation potential because of the presence of natural organic matter (NOM) under real conditions which contributes to an additional DBP formation. To simulate the NOM content of the filling water a Sigma Aldrich humic acid (HA) is used as background component. Both the BFA and the HA are dosed simultaneously from one stock.

Drinking water pre-treated by a GAC filtration is used as raw water and for flushing. The GAC filtration pre-treatment is used to reduce the TOC concentration to max. 0.1 mg L^{-1} but without changing the buffer capacity and the ionic strength. Thus, the organic load can be adjusted precisely by the BFA and HA dosing. This makes an exact analysis of DBPs possible for the reaction pathways of the defined organic pool water components (BFA and HA) being known.

ANALYTICS

Conductivity, pH, amperometric free and combined chlorine and redox potential are measured online using appropriate electrodes. The residual H_2O_2 concentration after UV/H_2O_2 treatment is analyzed according to an improved titanium oxalate method (Sellers 1980, Brandhuber 2009). Aluminum concentrations are determined by atomic adsorption spectroscopy (AAS) using a nitrous oxide/acetylene flame. TOC analytics are performed by catalytic oxidation at 680 °C using an online TOC-analyzer. The THM concentration in the liquid and gas phase of the pool model is analyzed by online measurements using a membrane inlet mass spectrometer (MIMS). For this the basic MIMS system as described by Kristensen (2009) was expanded by the possibility to analyze THMs from the gas phase. For the determination of the DOC-composition liquid chromatography in combination with organic carbon and nitrogen detection (LC-OCD-OND) is performed as described by Huber (2011).

OUTLOOK

Currently, the pool model including the treatment section is completely constructed and first runs to verify all functions are carried out. Upcoming the analytical devices have to be installed, calibration has to be performed and reliability performance has to be tested. First results from the experiments are expected to be published in about a year.

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