Report by UWI doctoral researcher Katharina Teuber (T3)

Project number: T3
First and last name of doctoral researcher: **Katharina Teuber**
(Working) title of doctoral project: **Three-phase simulation model for odour and corrosion in sewer systems**
Name of supervisors: Prof. Dr.-Ing. Reinhard Hinkelmann, Prof. Dr.-Ing. Matthias Barjenbruch, Prof. Dr. rer. nat. Gunnar Nützmann

2. Description of doctoral project and research results achieved to date:

Motivation

Every year damages of sewers due to corrosion cause high costs for sewer maintenance. In 1998, the restoration costs for corroded sewers in Germany were estimated to be in a range of billions of US $. At the same time, high hydrogen sulphide (H_2S) concentrations in the sewer atmosphere are a health risk for sewer workers. The processes leading to odour and corrosion as well as the empirical and conceptual description of these processes have been investigated since more than 70 years resulting in different model approaches [1;2]. But so far, existing model approaches [2] are one-dimensional, neglecting three-dimensional flow effects in sewage and air. This project aims to develop a three-dimensional model approach which will be able to verify these assumptions and can be an extension of these models in respect to a more detailed analysis of hydraulic aspects.
The main processes leading to odour and corrosion are illustrated in Figure 1. Under anaerobic conditions in sewage, sulphate present in the wastewater can be reduced to sulphide by sulphate-reducing bacteria (SRB). Sulphide is diffused from the biofilm into the water phase as H_2S. Described by the air-water equilibrium, emission of H_2S from the water into the air phase can occur. This process depends on factors such as the air and water phase velocities, pH value, temperature and the concentration of oxygen and nitrate. The air-water equilibrium for a volatile compound such as H_2S can be described by Henry's law. The temperature dependency of Henry's law can be described by different equations for example, the van't Hoff equation. Another process taking place at the air - water interface is reaeration which is the transfer of oxygen across the air - water interface [2]. At moist concrete pipe walls, H_2S can lead to the corrosion of concrete and other cement-bound materials.
These aspects show why it is important to understand and to be able to estimate transformation processes in sewers. At this point a three-phase simulation model can serve as a decision support system and planning tool. In this dissertation project, the work focusses on a correct description of processes occurring at the water- air interface.

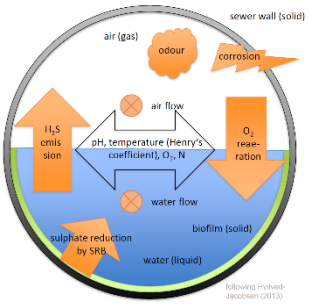

Figure 1: Overview over flow processes in sewer

The focus of this dissertation project lies in the use and extension of the three-dimensional model OpenFOAM to describe water-air flow and H_2S emissions across the air-water interface in closed conduits. Therefore, existing approaches are applied and extended to describe three-dimensional water (single phase) and water-air flow (two phases) and conservative tracer transport (e.g. H_2S). Additionally, a validation of the chosen multiphase solver (interFoam, volume of fluid method) is being performed. An existing mass transfer solver (interHarounFoam) which accounts for mass transfer depending on the Henry coefficient will be extended to describe the temperature dependency of the Henry coefficient.
As a result, a three-dimensional implementation of parts of an in-sewer model will exist and the interHarounFoam solver will be extended to temperature dependency.

Model Concepts

Surface water and air flow is calculated by using the two-phase flow solver interFoam based on a volume of fluid approach for one- and two-phase flows as it is implemented in the open source model OpenFOAM. Both phases are considered as one fluid with rapidly changing fluid properties, therefore one set of Navier-Stokes-equations is solved. The phases are distinguished by an additional transport equation for the volume fraction which is used as a marker to describe the distribution of the phases throughout the domain. The governing equations can be found in [3]. A standard advection-diffusion equation would lead to a non-

physical spreading across the water surface which is why the approach introduced by [4] as it has been implemented by [5] is being used for transport simulations. The same solver is also able to describe mass transfer processes.

Current State of Work

The work carried out in this project divides in three different parts. The first step is a validation of the water phase described by the numerical model concerning different hydraulic conditions, the consideration especially focuses on flow in closed conduits. A validation was performed as follows: validation of the water phase under consideration of different turbulence models (flow over a hill), validation of the water-air interface (flow over a ground sill). Additionally, a complex sewer geometry (Figure 2) [6] has been analysed to investigate the stability of the simulations using the setup of a closed duct and the overall accuracy in such a complex model domain. A comparison with results of an existing CFD model as well as measured results from a 1:20 scale model (Figure 3) shows a good agreement of the new model with the existing results. Summing up, the CFD simulations were found to produce stable and reliable results. The work of this step resulted in a journal paper which is currently under submission [7].

Figure 2: Flow in complex sewer geometry

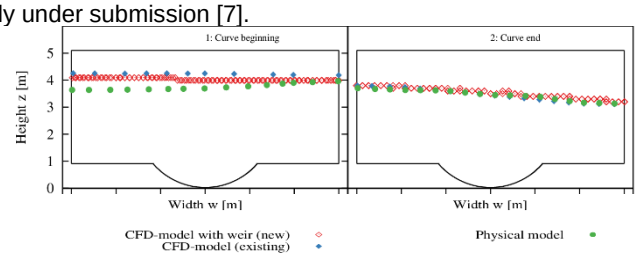

Figure 3: Comparison of water depths in complex sewer

The two remaining working steps are the validation of the air phase behaviour in closed systems and the implementation of transport as well as mass transfer processes depending on factors such as Henry's law to describe H_2S formations.

For the validation of the air phase behaviour, water-air flow in a rectangular duct [8] has been analysed and compared to experimental data provided by the Aalborg University. The results show a good agreement between simulation and experimental data (Figure 4). Additionally, air flow around concrete probes has been simulated using tracer transport simulations. This study has been part of the DAAD WISE internship of Shibashish D. Jaydev (Figure 5). The results can help project T2 in interpreting possible differences in corrosion depths at the concrete probes which are installed in the sewer pilot plant.

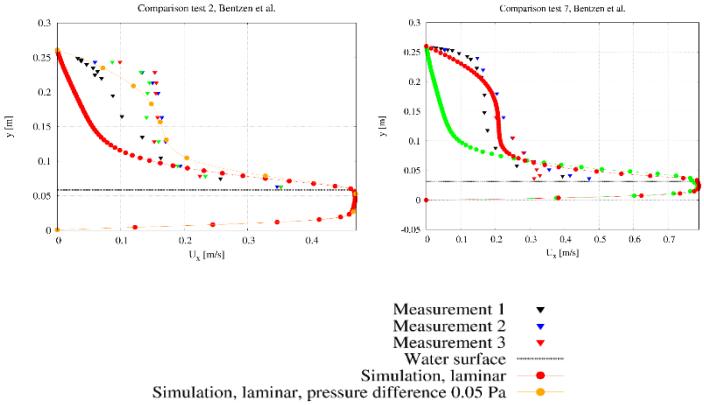

Figure 4: Comparison of simulated air phase velocities to experimental measurements

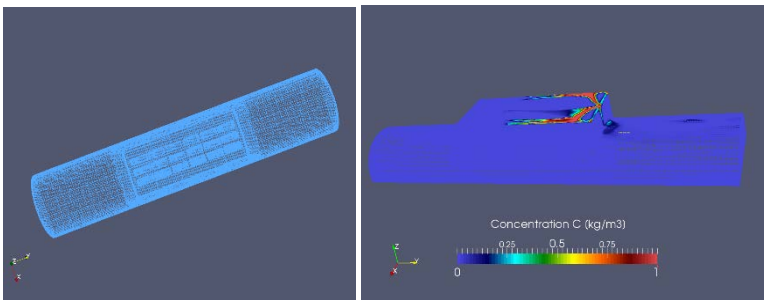

Figure 5: Transport simulations of flow around concrete probes (left: model domain with concrete probes; right: resulting tracer concentration)

Future Work planned

The correct description of the air phase behaviour will be tested in one additional example describing pipe with a semi-circular cross section. Experimental data has been kindly provided by the University of Aalborg. Additionally, the mass transfer solver will be analysed regarding its capability to describe transport and mass transfer processes and the temperature dependency of the Henry coefficient will be implemented. The experimental results gained from the sewer pilot plant will help to define different parameters influencing the mass transfer. The results of the air phase analysis and the mass transfer simulations will be subject to journal papers 2 and 3.

Collaboration

Simulation efforts stand in close collaboration with research project N7 (Tabea Broecker).
The thematic work related to in-sewer processes stands in close collaboration to project T2 (Maria Sielaff) and collegiate Daneish Despot, the collaboration efforts have been addressed in [9;10].
The research project is part of the common topic groups “Interfaces in sewer systems“ and “Modelling“.
Internationally, the work stands in close collaboration to research carried out at the University of Valencia, Spain. A personal contact is existing to the researcher Arnau Bayón. Furthermore, experimental data of air phase velocity measurements has been provided by Thomas Ruby Bentzen from Aalborg Universitet, Denmark.
From March to August 2017, the work has been supported by Shibashish D. Jaydev, who joined the project as a visiting student researcher within the framework of the Working Internships on Science and Engineering (WISE) program of the German Academic Exchange Service (DAAD).

References

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7. Teuber,K., Broecker,T., Bayón,A., Nützmann,G. & Hinkelmann,R. (2018): CFD-modelling of free-surface flows in closed conduits. *Progress in Computational Fluid Dynamics*, accepted
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9. Teuber,K., Grüneberger M., Despot,D., Dietmar,S., Barjenbruch,M. & Hinkelmann, R. (2016): Urban Water Interfaces: Interfaces in Sewer Systems. *The 6th German-Russian Week of the Young Researcher*, Moscow, Russia
10. Teuber,K., Grüneberger,M., Despot,D., Dietmar,S., Barjenbruch,M. & Hinkelmann,R. (2017): Modeling and Measuring of Interfaces in Sewer Systems. *37th IAHR (International Association for Hydro-Environment Engineering and Research) World Congress*, Kuala Lumpur, Malaysia

3. Comments on the qualification programme and supervision strategy:

The courses – especially the core courses – which I attended helped me in gaining a deeper understanding of research projects closer connected to the field of natural sciences as civil engineering graduate. The very well organised events broadened my horizon and offered inspiration for my work. The women-only courses especially helped my personal development. The time management and self-organisation course as well as the negotiation course gave useful advice to successfully finish my PhD in time. The yearly summer school as well as the interim workshop were great opportunities to connect with the other doctoral students and to exchange scientifically as well as interpersonal. It also gave me an opportunity to compare the current stage of my PhD to the work of others and get advice to solve the problems I was facing.

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As one of the doctoral student speakers I got deep insights into the great efforts that are conducted by the speakers and the associated members to improve the Research Training Group steadily. At every point our opinion as student representatives found an open ear and we received help when we needed it (examples: internships and family, scholarships as funding after UWI).

Participation in the following Research Training Group events:

1. Core courses
   - I – Urban interface processes – fluxes, transport, interactions (3 ECTS)
   - II – Modelling and measuring concepts of interface processes (3 ECTS)
   - III – Urban freshwater ecology (3 ECTS)
2. Elective courses
   - Oral and poster presentation (IGB Berlin, 23.11.2015 - 24.11.2015)
   - Proposal writing
   - CFDe (Introduction to OpenFOAM) (5 ECTS)
3. Gender courses
   - Time is honey – the new approach to time, self and workload organization
   - Self positioning
   - Negotiation
   - Project management
   - Single coaching (2 sessions)
4. UWI lectures and Colloquium Hydrosciences: Participated in all UWI lectures as well as in the Colloquium Hydrosciences of the Chair of Water Resources Management and Modeling of Hydrosystems (3 ECTS)
5. Other UWI events
   - Orientation Seminar and UWI Opening Ceremony (08. – 09.09.2015)
   - Exposé Talks (08.12.2015)
   - Summer School (13. - 14.09.2016)
   - Kollegiate Seminar (22.09.2016)
   - Interim Meeting (19.05.2017)
   - Student Research Council (17. – 18.03.2017)
   - Summer School (18.-20.09.2018)

Research stays or internships at other research institutions both at home and abroad. --

Participation in conferences, congresses, etc., at home and abroad:

2015:
- Aqua Urbanica (07. – 08.10.2017, Stuttgart, Germany)
- HSGSim meeting (29. – 31.10.2015, Antwerp, Belgium)

2016:
- HSGSim meeting (28. – 30.04.2016, Gelsenkirchen, Germany)
- XXI International Conference Computational Methods in Water Resources (CMWR), Toronto, Canada (20. – 24.06.2016, Toronto, Canada)
- Python & Matlab Software for Surrogate Global Optimization Toolbox in Water Resources (CMWR Short Course) (21.06.2016, Toronto, Canada)
- 6th German-Russian Week of the Young Researcher (12. – 16.09.2016, Moscow, Russia).
- 12th International Conference on Hydroscience & Engineering (ICHE) (6. – 10.11.2016, Tainan, Taiwan)

2017:
- Wasser Berlin International, Berlin (28. – 31.03.2017)

2018:
- 11th International Conference on Urban Drainage Modelling (23.09.2018 – 26.09.2018, Palermo, Italy)

4. Individual publications:

I. Articles:

- Broecker,T., Elsesser,W., Teuber,K., Özgen,I., Nützmann,G. & Hinkelmann,R. (2018): High-resolution simulation of free-surface flow and tracer transport over streambeds with ripples. *Limnologica* 68: 46-68
- Teuber,K., Broecker,T., Bayón,A., Nützmann,G. & Hinkelmann,R. (2018): CFD-modelling of free-surface flows in closed conduits. *Progress in Computational Fluid Dynamics*, accepted

II. Conference, poster presentations etc.:

- Teuber,K., Broecker,T., Elsesser,W., Agaoglu,B. & Hinkelmann,R. (2016a): Investigation of flow around a ground sill using OpenFOAM. XXI International Conference Computational Methods in Water Resources (CMWR) (20. – 24.06.2016, Toronto, Canada), abstract and oral presentation
- Teuber,K., Broecker,T., Barjenbruch,M. & Hinkelmann,R. (2016b): High-resolution numerical analysis of flow over a ground sill using OpenFOAM. In Proceedings of the 12th International Conference on Hydroscience & Engineering (ICHE) (6. – 10.11.2016, Tainan, Taiwan), reviewed paper and oral presentation

- Teuber,K., Grüneberger,M., Despot,D., Stephan,D., Barjenbruch,M. & Hinkelmann,R. (2016c): Urban Water Interfaces: Interfaces in Sewer Systems. In Proceedings of the 6th German-Russian Week of the Young Researcher (12. – 16.09.2016, Moscow, Russia), paper and oral presentation
- Broecker,T., Teuber,K., Elsesser,W. & Hinkelmann,R. (2017): Multiphase Modeling of Hydrosystems using OpenFOAM, SimHydro, Nice, France. Reviewed paper and oral presentation
- Teuber,K., Broecker,T., Elsesser,W. & Hinkelmann,R. (2017a): Beyond shallow water flow: Navier-Stokes simulations with OpenFOAM. BIMoS-Day Shallow water flow Simulations (22.05.2017, Berlin, Germany), abstract and oral presentation
- Teuber,K., Grüneberger,M., Despot,D., Stephan,S., Barjenbruch,M. & Hinkelmann,R. (2017b): Modeling and Measuring of Interfaces in Sewer Systems. In Proceedings of the 37th IAHR (International Association for Hydro-Environment Engineering and Research) World Congress (13 – 18.08.2017, Kuala Lumpur, Malaysia), reviewed paper and oral presentation
- Broecker,T., Teuber,K., Ladwig,R., Nützmann,G. & Hinkelmann,R. (2018): Impact of small-scale riverbed topography on stream flow and surface detention of a tracer, EGU 2018. Oral presentation
- Teuber,K., Broecker,T., Jaydev,S., Goitom,G., Sielaff,M., Despot,D., Stephan,D., Barjenbruch,M. & Hinkelmann,R. (2018): Multiphase CFD-Simulation of Transport Phenomena in Sewer systems. International Conference on Urban Drainage Modelling (UDM), Palermo, Italy. Reviewed paper and oral presentation