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INVESTIGATIONS ON THE BEHAVIOUR OF PARTICULATE MATTER IN DRINKING WATER DISTRIBUTION NETWORKS

BADANIA NAD ZACHOWANIEM SIĘ CZĄSTEK ZAWIESINY W SIECI DYSTRYBUCYJNEJ WODY DO PICIA

Demographic change, increasing prices and technological progress lead to decreasing water demands in Germany and other European countries. Resulting hydraulic variances in established drinking water distribution networks produce quality impairments of potable water, e.g. due to accumulation of particulate matter. Within a cooperative research project, the transport behaviour of amorphous corrosion products in such networks is investigated. The occurring processes are modelled, so particle-related quality aspects of drinking water during distribution can be described as well as the fouling situation of pipes. The models will be included in a pipe modelling software to allow both water quality management and hydraulic optimization. In this work, experimental investigations and the modelling of particle transport in pipe flow using CFD software are introduced.

1. Introduction

1.1. Research objectives

Decreasing water demand in numerous European countries causes varying hydraulic conditions in established drinking water distribution systems. Increased retention times may have an influence on chemical parameters (e.g. chlorine and oxygen depletion), physical parameters (temperature increase) as well as biological parameters (microbial activity) during transportation. Therefore, it is important to understand the natural processes, which generally depend on time, hydraulic conditions and water characteristics, to systematically optimize distribution systems. With new models, describing the occurring processes transport, sedimentation, mobilization and formation of particulate matter in the black box “drinking water distribution network”, the following applications can be offered:

- Established supply networks may be investigated for impairments before consumer complaints occur.
- Occurring quality problems may be isolated easier, so better optimization strategies can be implemented.
- Sanitation with varying planning horizon can be realized, before urgent need for action is required.
- New system sections can be planned with focus on quality aspects.

1.2. Fundamentals

Corrosion of unlined steel and cast iron pipes or pipes with bad or damaged corrosion protection is a main source for particulate matter in drinking water distribution networks [1, 2, 3]. The process of corrosion is discussed by several authors under miscellaneous aspects [3, 4]. However, a general prediction about occurrence and intensity of corrosion processes is not possible to date. In principle, iron from pipe walls is oxidized to ferrous iron due to oxygen and, under normal conditions, further oxidized to different solid ferric iron species, dependent on the corrosion conditions. This results in iron scales (incrustations) on the inner pipe surface and particulate material in the free water body and pipe wall.

Figure 1 shows the total amount of particles, continuously measured at the outlet of a water treatment plant (ground water; rapid sand filtration) and a customer tap (right half of the figure) in the same supply area (working range of the particle counting device: 0.9 to 200 μm). The particle concentration has increased during transport to the supply network. Also, we can see an influence of the treatment process on the measured particle concentration at the treatment plant outlet: directly after back flushing of the rapid sand filters, we can measure an increased solid concentration at the water treatment plant outlet respectively in the filter effluent.

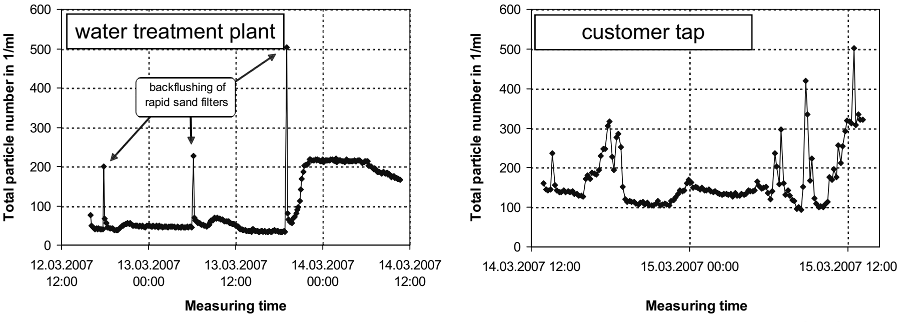

Fig. 1. Measured total particle concentration on a water treatment plants outlet (left) and a customer tap in the same supply area (right diagram)

Particulate matter can be found in distribution systems as suspended material in the free water body, as lose deposit on the pipe bottom and as soft corrosion film on pipe walls over the whole pipe cross section in corroding iron pipe segments. Particulate sediment can be mobilized due to changing hydraulic conditions and leave the distribution system at the customers tap or during flushing events. This is noticeable as brown water. Further particle sources, e.g. by microbial activity in biofilms, are not considered in this work.

In order to understand the reasons for the appearance of turbidity peaks, numerous investigations were performed, describing composition and amount of particulate matter in drinking water pipes, e.g. [4, 6]. Ferric corrosion products, obtained from a small scale pilot plant, are very small on average. Analysis of particles from flushing show a mean particle size ($x_{50,3}$) of roughly 80 nm for this ferric particles. The working range of the used measuring method "acoustic spectroscopy" goes from 0.005 to 100 µm. Because of the low zeta potential, roughly almost varying in the small range of -10 and +10 mV at pH range 6.5 till 9.5, voluminous flocs can be formed. The particles have an amorphous shape and are therefore difficult to describe with geometric shapes. Significant cohesive and adhesive forces can act, due to large specific particle surface area. The primary particle density is 3 to 5/cm³, but agglomerates have a density (dependent on size), which may hardly vary from that of water. Particle investigations on a pilot plant (see chapter 3) brought a density of 3.3 g/cm³.

Other particulate matter has smaller densities with an average of 1.6 g/cm³ [7]. Under normal conditions, the particle volume concentration in drinking water distribution systems is very low and in the range of 1 ppm (10^{-4} Vol.-%) [7]. Mainly algae and other organic material, as well as sand, manganese and abrased pipe material (e.g. plastic, asbestos fibre) can be found. [5, 6] The accurate mixture may vary in wide ranges both within locations in a distribution system and different networks.

Figure 2 shows the particle concentration during a flushing event on a PE pipe section (blue curve, left axis) and the respective total iron and manganese concentrations (red and green curves, right axis). The increased particle/iron concentration in the flush water may result from the steel pipe sections situated in upstream of the PE pipe, from where corrosions products can enter the observed plastic pipe and settle under sediment formation.

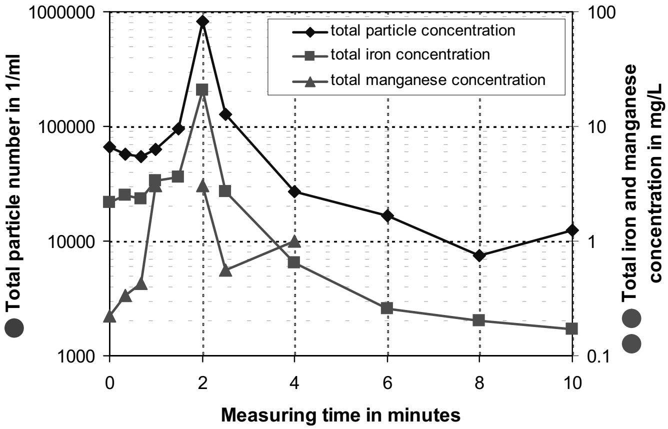

Fig. 2. Measured total particle concentration (0.9 – 200 µm) and appropriate total iron and manganese concentrations during a flushing event in a drinking water distribution system

2. Transportation and settling of particles

Particles enter the drinking water distribution network at the outlet of water treatment plants or are formed due to corrosion in unlined steel pipe sections. Suspended particles subjected to pipe flow are influenced by various hydraulic induced forces. Several authors investigated these forces and the resulting particle or floc behaviour, e.g. [8, 9, 10].

During stagnation, weight and buoyancy act on particles with a density different from that of the surrounding water. Consequently they move normal to the pipe axis of a horizontal pipe. In summary, the resulting force is referred to as sedimentation force. As result, a particle in quiescent water accelerates to a terminal velocity due to gravity or is pushed due to motion of the fluid, because the fluids interior friction acts against the particle motion. The so called drag force depends on the difference of fluid and particle velocity, described as slip velocity. Also it depends on the shape of the particle and the size of the cross section area, which is directed towards direction of motion. For the special situation with very small, spherical particles in a quiescent water body, Stokes equation can be used, to calculate the terminal settling velocity, considering weight, buoyancy and drag force.

Additionally, under unsteady conditions with changing flow velocities and directions, the virtual mass effect occurs: The surrounding fluid adheres on the particle surface and the particle motion thereby is hindered, comparable with an increased particle mass.

Especially for small particles ($< 10\ \mu m$) thermodynamic effects cause Brownian diffusion and particles in fluid with concentration gradients experience a force, acting in the direction of lower concentration. Larger particles are not affected by Brownian diffusion but another kind of diffusion, named shear-induced or hydrodynamic diffusion, can be observed. This effect is flow-induced and unlike Brownian diffusion especially appearing at larger particles sizes. A particle moving in a concentrated suspension, hits adjacent particles and as result, we can observe a diffusive nature of the process on large time scales.

In pipes, the fluid flow is influenced by holding the water body on the pipe surface. Due to interior friction and according to Newton's approach for shear stress in viscous fluids, a shear gradient is developed in the pipe cross section. This gradient induces so called lift forces on particles (e.g. Saffman force), on the one side due to the shear gradient itself, and on the other side due to initiated particle rotation. In summary, these forces produce a lateral migration of the particle normal to the mean flow direction and an equilibrium radial position in roughly 60 % distance to the pipe axis.

Especially the behaviour of small particles is also influenced by surface based effects like adhesion and cohesion (e.g. resulting from van der Waals force and surface charge), summarized as particle-particle interaction and particle-wall interaction. Because the particle transport concentration is very low in the range of 10^{-4} percent by volume (1 ppm) these effects will not be considered.

3. Materials and methods

Two identical pipe loops, each with a length of 195 metres and 82 mm inner diameter (DN80, 3.15“), were installed hydraulically independent from each other for transportation and mobilization experiments. One pipe cycle consists of unlined steel pipes, which allows the formation and attachment of corrosion products to be viewed parallel to the transport process. The other system is a PE pipe loop, where the settling behaviour of synthetic particles and corrosion products is observed. Figure 3 shows one of the identical pipe loops.

The pipe water circulates in the pipe loops over the duration of experiments. Turbidity, particle size distribution and pressure are measured at start and end of the pipe loops. Furthermore, flow rate and temperature are continuously logged over duration of the experiments.

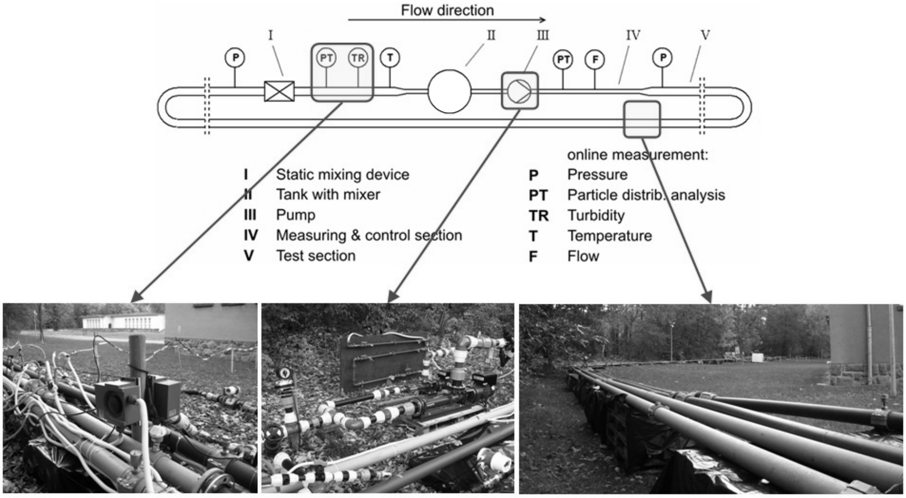

Fig. 3. Scheme of the pilot plant (only one pipe loop shown) used to investigate the behaviour of particles in pipes

For settling experiments in the PE pipe loop, synthetic particles of a PVC powder (Vinnolit E 2078) and formed corrosion products from the steel system are used. Beside a low density of 1,400 kg/m³ and a particle size distribution similar to particles at the outlet of a water treatment plant, the particles of the PVC powder are rounded (not fully spherical). This allows the investigation of their settling behaviour and the comparison with calculations from known force equations based on spheres. The corrosion particles are taken from the steel pipe. They have a density of 3,300 kg/m³ and an amorphous character.

The particles are suspended in drinking water. Then the suspension is homogenized and filled in the PE pipe loop. A constant flow rate is adjusted and the measuring program started. An experiment takes one to two days, dependent on the settling behaviour of the particles.

Mobilization experiments consist of a lasting several days period with constant flow rate of drinking water, where particulate attachments consisting of corrosion products are formed in the steel pipe. Prior to each mobilization experiment, the pipe is flushed with drinking water. In a second step, different velocities and velocity changes in defined time steps are used to investigate the mobilization behaviour of the formed attachments. Due to high particle load, on-line particle counting isn't possible. The solid load is rather measured with on-line turbidity meters and the obtained measuring results are converted to mass load (e.g. mg/L) with a determined turbidity/iron concentration relationship.

4. Experimental results

In the transportation experiments the settling rate of particulate matter is directly measured with an on-line particle counting device. With each taken data set we obtain the physical parameters temperature, flow rate and pressure and a discrete particle size distribution. Even if a measuring range of 0.9 to 200 μm is possible, the focus is on particles up to 10 μm.

The suspension is circulating in the pipe loop. Starting at the pumps, the suspension is homogenized. A particle has then a pipe distance of 195 m to settle and approximately a settling distance in the pipe cross section of 3.5 cm (8.2 cm inner diameter). Before measuring the particle concentration at the end of the pipe, the suspension is homogenized in the pipe cross section with a static mixing device.

Over the duration of a transportation experiment, settling curves like in figure 4 are logged.

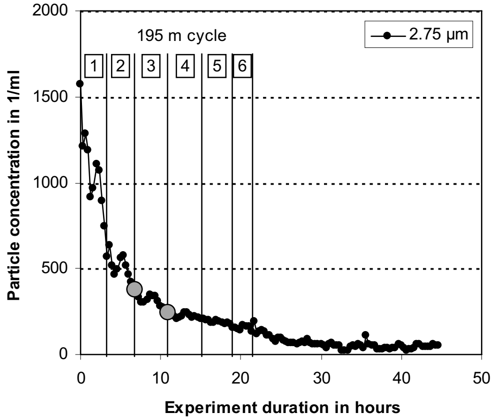

Fig. 4. Development of particle concentration in a typical transportation experiment at the pipe loop in the particle size class from 2.5 to 3.0 μm; Vertical lines margin the cycle times; Mean flow velocity is 0.02 m/s.

It shows the change in particle concentration of corrosion products of the particle size class from 2.5 to 3.0 μm with a mean particle size of 2.75 μm. The mean flow velocity during the experiment was 0.02 m/s (laminar flow). By measuring the flow rate, we can calculate the transport time for the 195 m pipe loop and then compare the ingoing particle concentration (left orange point in figure 4) with the outgoing particle concentration (right orange point). The difference between both measuring values is then the amount of settled particulate matter in the observed particle size class, written as settling grade. This method is applied for all used particle size classes.

Of interest is in the next step the correlation between settling grade on the one side and particle characteristics (size, shape, density) as well as hydraulic conditions (flow velocity, viscosity) on the other side. Figure 5 shows therefore the correlation between Reynolds number (respectively flow velocity in small boxes) and settling grade of corrosion particles with a mean diameter of 2.75 μm.

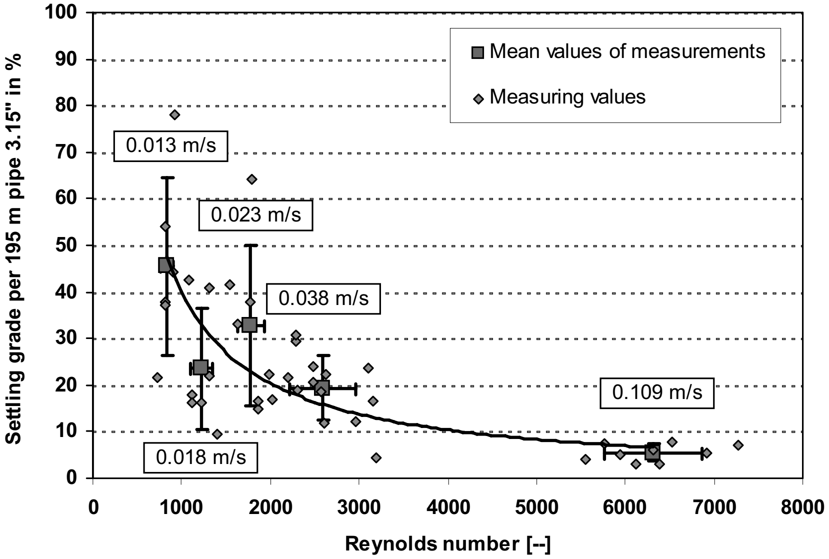

Fig. 5. Settling grade of corrosion particles with 2.75 μm mean diameter dependent on the flow conditions, calculated as Reynolds number; Error bars show standard deviation

The orange dots well illustrate the scattering of the measuring results because of varying system conditions (fluid viscosity and flow rate) during the experiments. The blue squares with black error bars for standard deviation show the mean values of the measurements series at mean flow velocities 0.013 m/s, 0.018 m/s, 0.023 m/s, 0.038 m/s and 0.109 m/s.

We can see an increasing settling grade with decreasing Reynolds number respectively flow velocity in the direction of 100 %. At the other border case, settling grade tends to zero, when Reynolds number respectively flow velocity increase. This can be explained with an increased transport range and influenced settling due to hydrodynamically induced forces acting on the particle in fluid flow.

5. Modelling the transport behaviour with CFD software

The pilot plant is modelled in the CFD software package Comsol. CFD is under single-phase fluid conditions the generic term for numerical methods to solve the Navier-Stokes equations.

The pipe is hydraulically modelled as vertical 2D longitudinal section along the pipe axis in Comsol in full length. The physical conditions (fluid viscosity, flow velocity) are the same as operated in the experiments. Under turbulent flow (beginning roughly at Reynolds number 2300), the k-ω-model is used to describe the additional randomly occurring flow velocities in all directions. This turbulence model is necessary to solve the Reynolds-averaged Navier Stokes equations (RANS), an approach to numerically solve turbulent fluid flow. The acting forces on particles in pipe flow are described by force balances and are based on the (hydraulic) simulation results of the Navier-Stokes equations.

A typical result for a particle tracking simulation with the model is given in figure 6. It shows the velocity profile of the pipe for a mean velocity of 0.012 m/s.

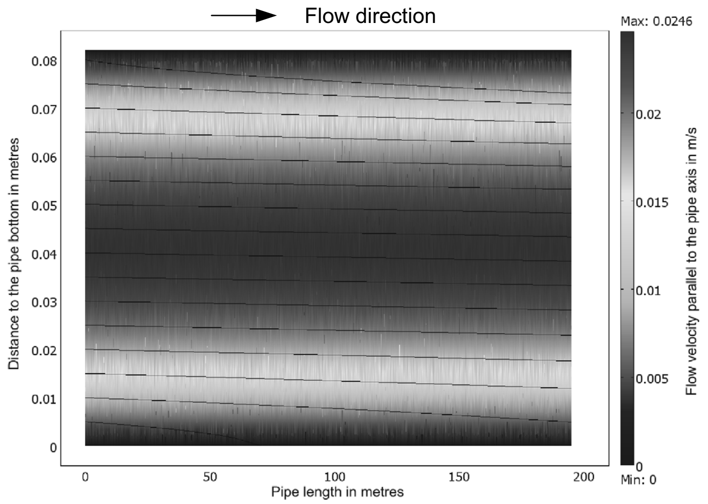

Fig. 6. Plot of the pipe illustrating the developed velocity profile (colours) under laminar flow conditions with mean flow velocity of 0.012 m/s; the black lines show tracks of particles entering the pipe on the left-hand side for flow direction from left to right

The x-axis shows the length (195 m) and the y-axis the hight (0.082 m). The black lines mark the tracks of particles entering the pipe on the left side in different hights and leaving the pipe on the right side, if not settling on the bottom. By varying the starting hight of the particle on the left side, we can – under assumption of full mixing at the start of the pipe – ascertain the part of the pipe cross section, which will be particle-free due to settling. Figure 7 shows an example for a PVC particle fraction with a measured equivalent diameter of 5.5 µm in pink colour.

We can see that, for the hydraulic conditions investigated, the model overestimates the settling grade by roughly 10 – 30 %. The difference between modelled and experimentally obtained data can be corrected by applying an additional constant correction factor 0.62 as shown in the red curve, which fits now better to the experimental values (blue curve). The reasons for the deviations are under further investigation.

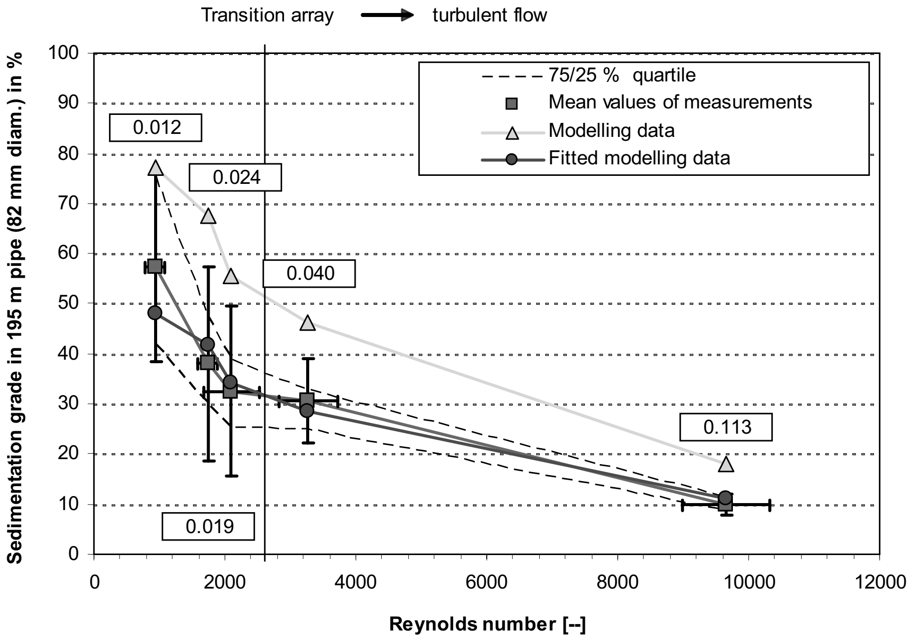

Fig. 7. Comparison of measuring values (blue, with standard deviation), simulation results (pink) and fitted simulation results (red)

6. Summary and conclusion

Various forces act on particles transported in pipe flow. The effect of most forces normal to the pipe axis on particles varies with the position of particles in the pipe cross section respectively the velocity field. This results in changing settling velocities dependent on the position of the particles in the pipe cross section. For transportation experiments a pipe loop with 195 metres length and 82 millimetres inner diameter was installed. Settling experiments with corrosion products and synthetic particles are performed. Physical parameters, turbidity and particle size distribution are measured. The comparison of the concentrations at inlet and outlet of the pipe allows the calculation of settling grades for different particle sizes and particle systems over the pipe distance dependent on the flow rate. With a model describing the force balance on a particle in pipe flow, the experimental results could be described. However, yet an adjustment of the model results to measured data was necessary.

7. Outlook

Further experiments will be performed to enhance the existent database and investigate the scattering of measuring results. The model will be used now for generalization of settling behaviour of the observed particulate matter on different hydraulic and system conditions (pipe diameters, pipe length). For usage in pipe modelling software, the mathematical description of the mentioned relations is necessary. Especially, it is important to consider a practicable usability with focus on easy computing. As a result, it shall be possible to simulate the formation of particulate deposit in pipes of drinking water distribution networks, so that the water supplier can guarantee quality of drinking water at the customers tap.

8. Acknowledgment

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