SMaRT-OnlineWDN D4.2: Investigation about the processes of the specified phenomena

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Deliverable 4.2

Investigation about the processes of the specified phenomena

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WP4

Transport Modelling

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WP 4 – Transport Modelling

D4.2 Investigation about the processes of the specified phenomena

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Keywords Imperfect Mixing – Dispersion – Inertia terms – Transport modelling				
Objectives Design of the pilot scales test rig; design of the numerical simulations; experiments for mixing at junctions and contaminant transport in pipes; calibration of roughness and effective diameter; choice of the tracer at both the BWB and TZW test tracks				

Executive Summary

The main objective of the *SMaRT-Online*^{WDN} project is the development of an online security management toolkit for water distribution networks that is based on sensor measurements of water quality as well as water quantity. Pseudo-real time modelling of water quantity and water quality variables is the cornerstone of the project. Existing transport model tools are not adapted for online modelling and ignore some important phenomena that may be dominant when looking at the network in greater detail with an observation time of several minutes.

The aim of this deliverable is to report investigations by the *SMaRT-Online*^{WDN} partners regarding processes of contaminant mixing at junctions and transport in pipes.

Firstly, investigations at the Berliner Wasserbetriebe (BWB) are presented (section 1). The test field is a simple loop with old cast iron pipes representative of old pipes in the BWB network. Chemicals can be injected into the pipe by a pump and three multi-parameter sensors, located at different distances, measure hydraulic and quality parameters (flow, pressure, conductivity pH-value, oxygen,…) during the flow. This network was calibrated for the roughness and the effective diameter of pipes which is reported here. Experiments with salt and its transport under different regimes was also studied. So the transport phenomena like advection, dispersion and absorption can be studied.

Next, a statistic and hydraulic analysis of the Tee and cross-junctions is achieved on the two networks in France (Strasbourg CUS) and Vedif network (demand area of Villejuif)) (section 2). It was found that there are a lot of cases where double tee-junctions are present with a distance inter-tee inferior to 10 diameters which may favour imperfect mixing. A hydraulic analysis was also performed which ensures that every hydraulic regime is well represented. For example, for a double-tee junction with equal 100mm diameter 40% of the Reynolds cases are for laminar flow and 80% are under 10,000. For higher diameters the statistics fall to 20% for laminar flow and 60% under 10,000. The results of this analysis serve to design the new test rig built in Dresden by TZW and supply CFD cases for the numerical simulation.

Finally, in section 3, the new test rig at TZW (Dresden) and all the investigations that were necessary to know which product to inject, the injection system and the experimental setup are presented. First investigations at TZW have been performed applying several colour tracers with different densities under laminar and turbulent flow conditions The experiments were conducted in a straight pipe with velocities in a range of 0.004m/s to 0.5 m/s. The main results under laminar flow conditions are:
1) Dispersion is the main process for spreading and mixing,
2) The behaviour (moving up or down) of the tracer depends particularly on the density of the injected liquid,
3) An injected liquid with a higher or lower density than the water moves at the pipe wall with a lower velocity than the water body.

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1. Experiments at the BWB test track

In this chapter we describe the test track of the Berliner WasserBetriebe, the experiments and the results.

1.1. General Information

The test track had been a part of the drinking water distribution network for about 90 years and is located inside the water works Friedrichshagen in Berlin, as represented in Figure 1. It has a length of 600 m and lies 1.5m under ground level. So it represents a regular pipe in a “normal“ water network.

Figure 1: Aerial view of the experimental location at the BWB test track

1.2. Hydraulic Information

The pipes are made of cast iron and have a diameter of 150 mm. Inside the pipes there is an incrustation layer of 1 cm on average. This is illustrated in Figure 2.

Figure 2: A cut of a segment of pipe to show incrustation

1.3. Experiment Information

According to BWB safety regulations, the test track is separated from the drinking water distrbution network. It will be filled with Berlin drinking water by a bypass. An injection pump is installed at the test track to inject solutions into the pipe. Two additional hydrants and valves have been installed there to simulate different demands and flows. The flow at the beginning of the test track is measured by a flow meter.

NaCl solutions with a maximum concentration of 280 g/L will be prepared in three 100 L tanks. The injection flow depends on the existing pressure in the pipe and is regulated by a flow meter in the injection pump. Due to the normal pressure of 5 to 5.5 bar at the test track, the injection flow will be at maximum 70L/h.

Three multiparameter sensors are installed in the test track (these are located in Figure 3) with a minimum distance of one meter from outlets and measure online hydraulic (velocity and pressure) and some quality parameters (among others conductivity). All three sensors are located centrally to the pipe.

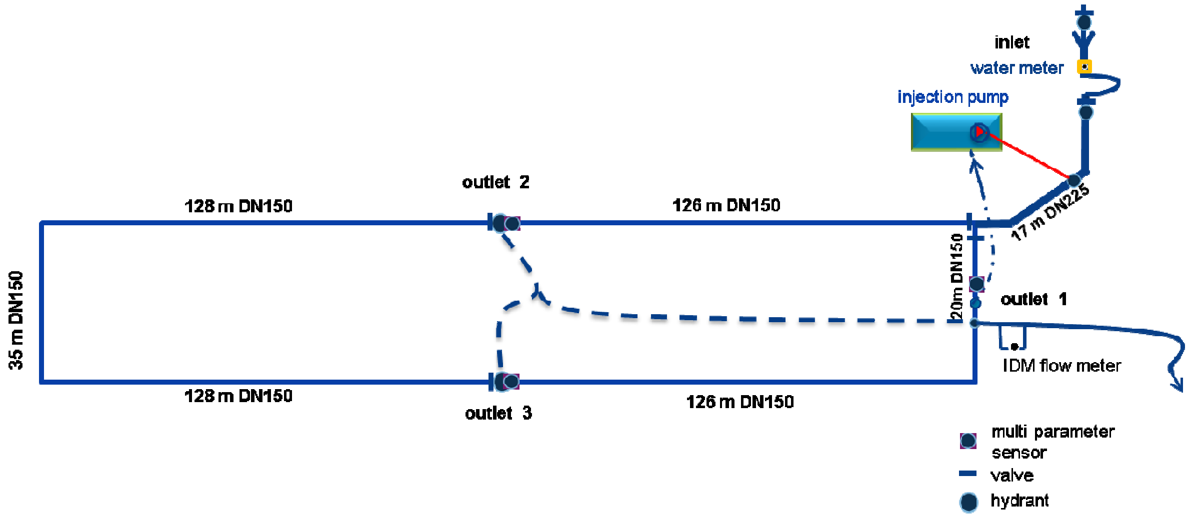


Figure 3: Blueprint of the experimental network at the BWB test track

1.4. Preparation

Leak tests

After having detected leakage at two outlet valves and having repaired them, leak tests were successfully performed (see: Figure 5).

To carry out these, all three outlets were closed and the inlet water meter was read at 3 p.m. 24 hours later the water meter was read again and showed no difference to the value the day before. The pressure data at night show the constant pressure of 4.66 to 4.69. These values are rounded up or down by choosing an accuracy level of two significant digits.

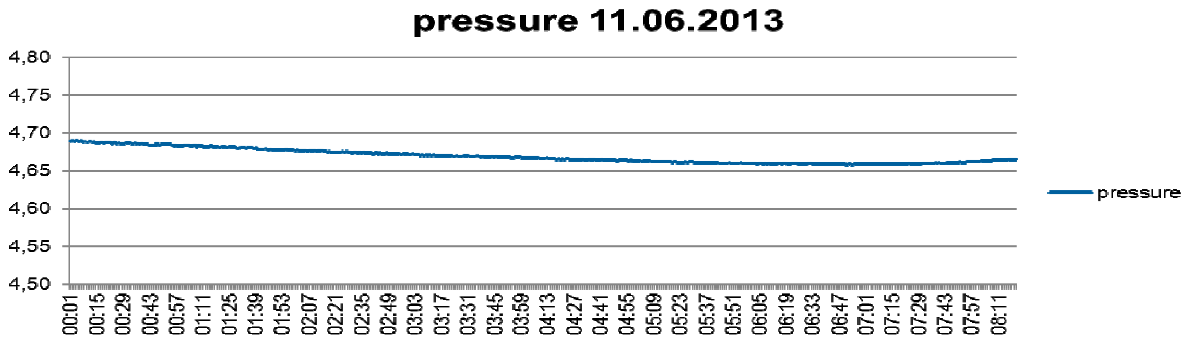


Figure 4: Measurement of pressure in static condition to control leakage

Flow tests

Flow tests were made to calibrate the effective hydraulic dimension of the pipe. Several experiments with different flow regimes were carried out to calibrate the effective dimension and the roughness.

Prior to these experiments, the sensor data for velocity were calibrated by an ultra sound sensor. As shown in Figure 5, two different tests were carried out to calibrate the effective diameter by measuring the velocities. These test should also show that a velocity of 0.7 m/s can be achieved.

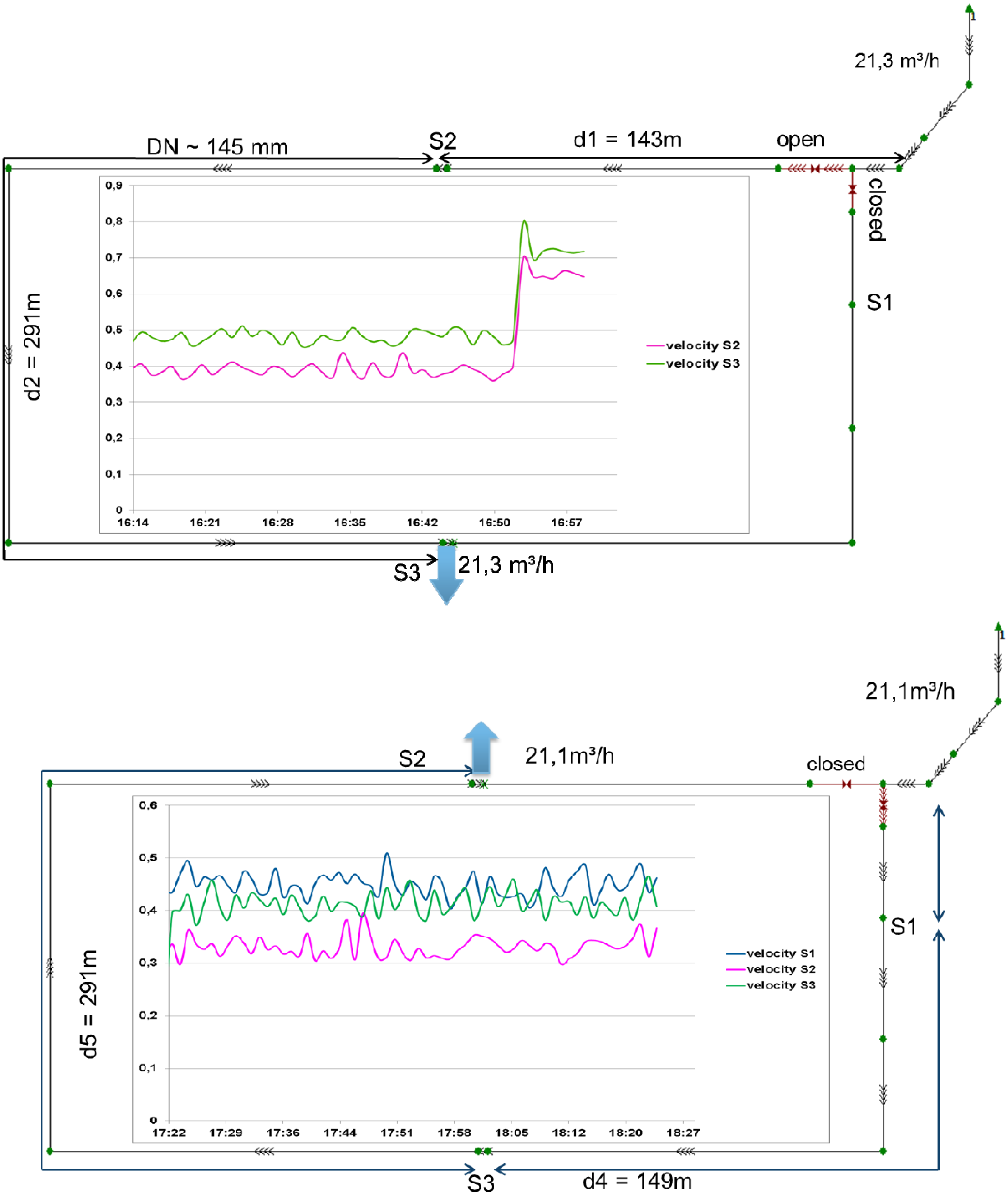


Figure 5: Values of velocities for calibration of diameter and roughness

1.5. Experiments

Each experiment is characterised by a contamination scenario with different configuration of the test track. Flow direction, injection duration and flow at the inlet and outlets were changed. While carrying out experiments, the conductivity was measured online and the concentration was calculated afterwards by the empirical relation between solution concentration and the conductivity is worked out by measurements. A linear regression fits the data well.

Figure 6 shows the relation between conductivity and the concentration of NaCL

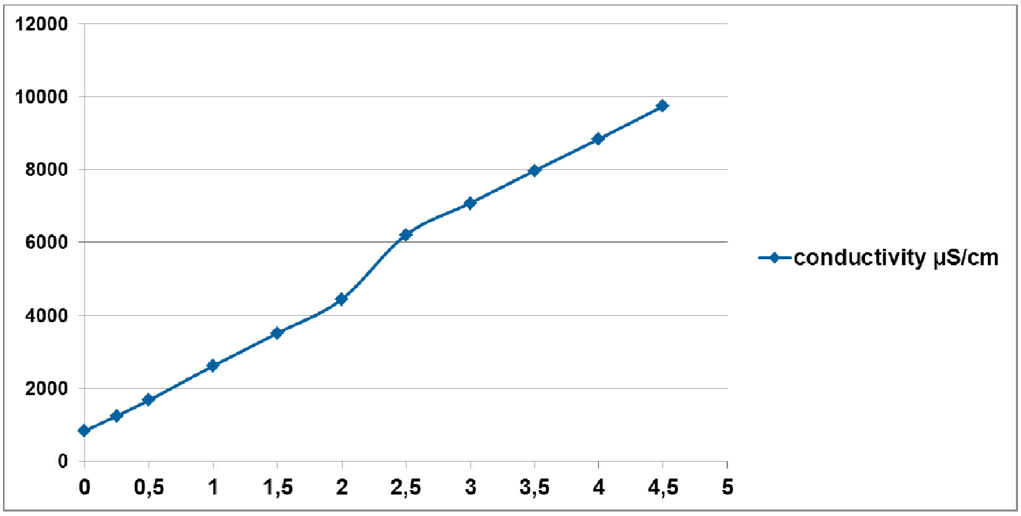


Figure 6: Law to measure concentration with conductivity

The empirical relation is established to be:

$$Cd = 1816 * C + Cd_{initial}$$

Where Cd is the conductivity and C the concentration.

The pipes were flushed properly before the start of the experiments and after each experiment the pipes were flushed again by opening all outlets. So the velocity of approximately 0.7 m/s could be achieved. Only this velocity guarantees that substances in the pipe can be completely washed out.

Every time the flushing lasted at least 10 to 15 minutes until there was no change in conductivity.

Figures representing additional experiments are also presented: The experiments in Figures 7,8 and 9 show the distribution of NaCl concentration along the path by setting different flow directions and different demands.

We can see that the concentration of the injected solution decreases with the distance to the contamination source and is a function of the demand flow, which represents the advection as one of the parameters for transport . The higher the flow rate in the pipe, the more solution will be transported by advection. The result of the calculated mass balance shows the sum of other phenomena, which are absorption, diffusion and dispersion. The mass balance is calculated by the integral of the diagram for concentration. It shows for the experiment below that 54% of the

6,533 g injected solution came out from the outlets and 46% remained in the pipe, which means the sum of absorption, diffusion and dispersion.

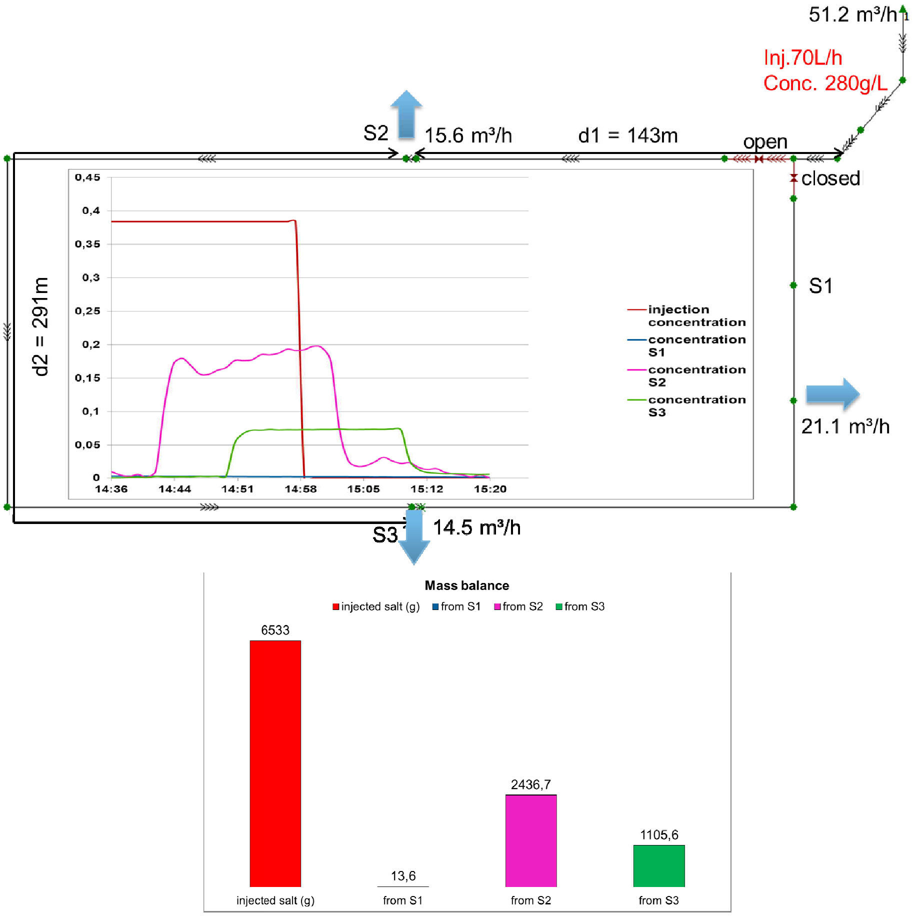


Figure 7: Distribution of the concentration with 1 path from inlet to outlet and 3 demands and also the mass balance

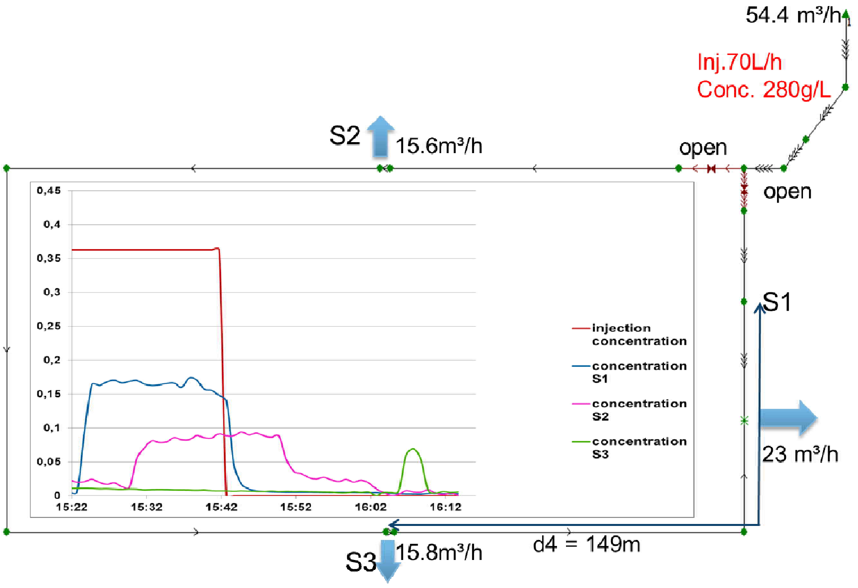


Figure 8: Experiment with 2 paths from inlet to outlet and 2 demands

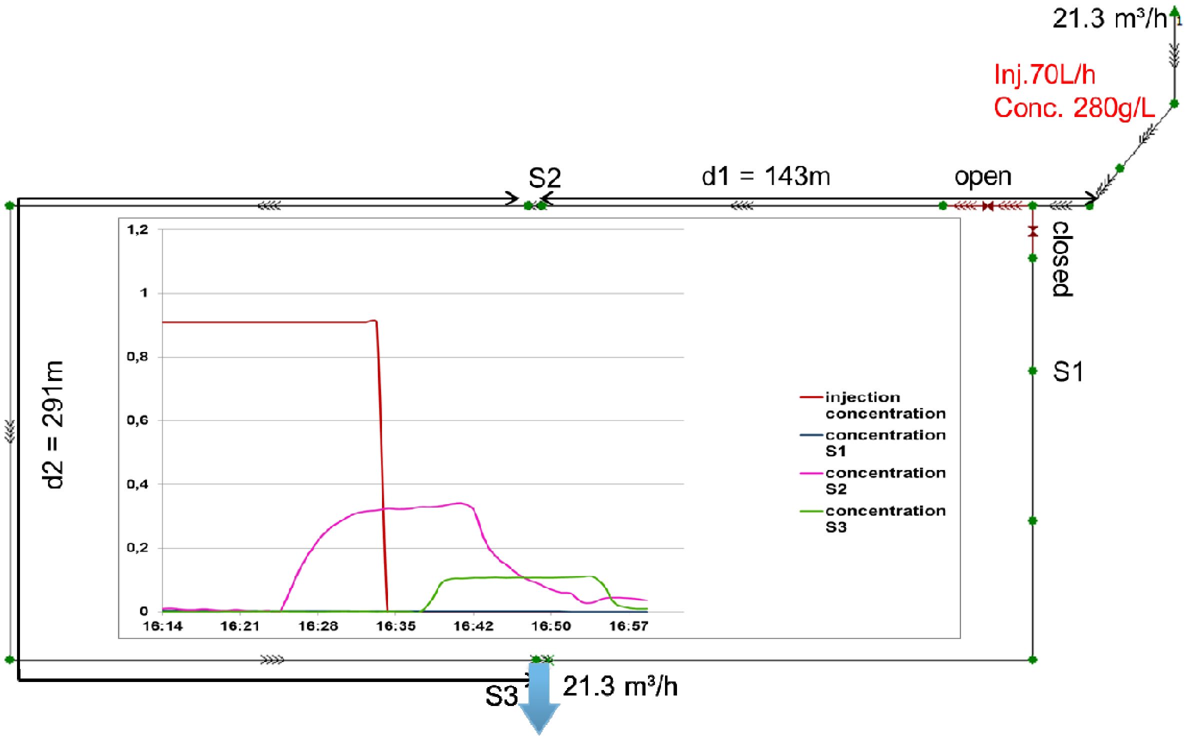


Figure 9: Experiment with 1 path between inlet and oulet and no demand

Additional experiments are necessary to obtain more detailed data for each phenomenom and also to differentiate between them.

It is planned to carry out experiments with the same condition at both the TZW and BWB test field. Since the pipes at TZW test field are new and made of PE they have no incrustation inside. So there will be no significant absorption and the difference of the results will help to define more precisely both of the transport parameters, advection and absorption.

2. Statistical analysis of the Network of Strasbourg (CUS) and Vedif Villejuif

Here we analyse the networks of Strasbourg (CUS) and VEDIF water utlilities in order to understand what cases are representative. Important cases are those that are representative of the network.

This will be used to build and design the geometry and regime cases we want to simulate with CFD and build the more realistic pilot scale at TZW (Dresden).

We explore the statistics of junctions in the two real networks from the partners of the project: CUS (all the network) and Vedif (demand area of Villejuif) in France.

We are interested in knowing the distance between two junctions of the double Tee and the velocities (Reynolds) in each branch, so as to know if we meet real condition cases where the mixing is incomplete. To do that, we create the 1D model in *Porteau* for each network that will be used for real time simulations but with more details for the velocities to be more accurate. We use the same data as in WP3 and WP8, given by the operators CUS and Vedif.

To create models we use the same method: we import the layer of pipes from GIS, we import the layer of demand also from GIS (for CUS it is done by homogeneous area of buildings, for Vedif it is directly derived from the GIS connection points). The rest of the modelling parameters are entered in *Porteau*. Usually, the demand is carried by junction nodes beginning and ending pipes. However, to calculate a Reynolds value representing the real mixing at junctions, we need to have junctions without any demand, to have the sum of all Reynolds equal to zero. To do that we create a special routine that splits the three links in two parts, and move the part of demand of each link to the new node as illustrated in Figure 10.

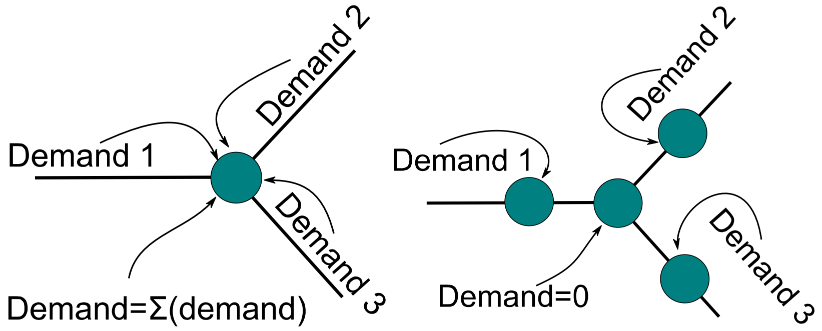


Figure 10: Correction of the model network for Reynolds without influence of nodal demand

1.6. Statistics on CUS network

The complete model of CUS contains 30,512 links, 28,078 junctions for 1,042 km of pipes. We count 53 cross-junctions but only 22 with 100 mm at the four diameters, the others are with different diameters. There is a chance that these are artefacts from the GIS (not real cross-junctions). There are 6,979 simple Tee junctions distributed in 161 classes. Figure 11 shows the 22 more representative classes with the number of junction for each.

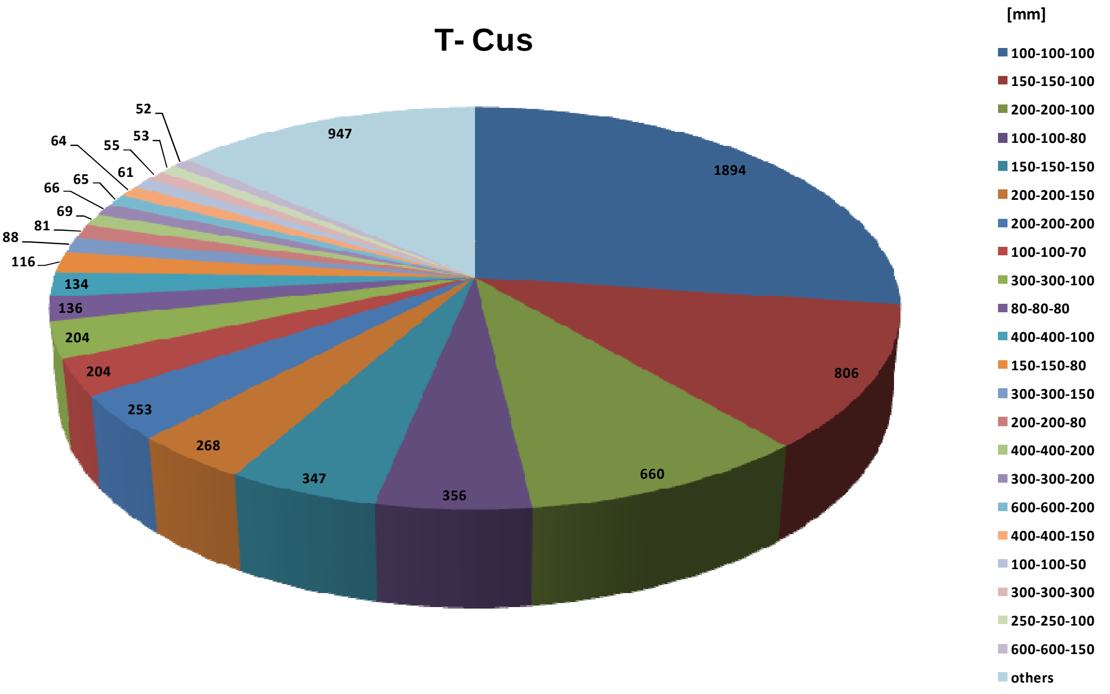
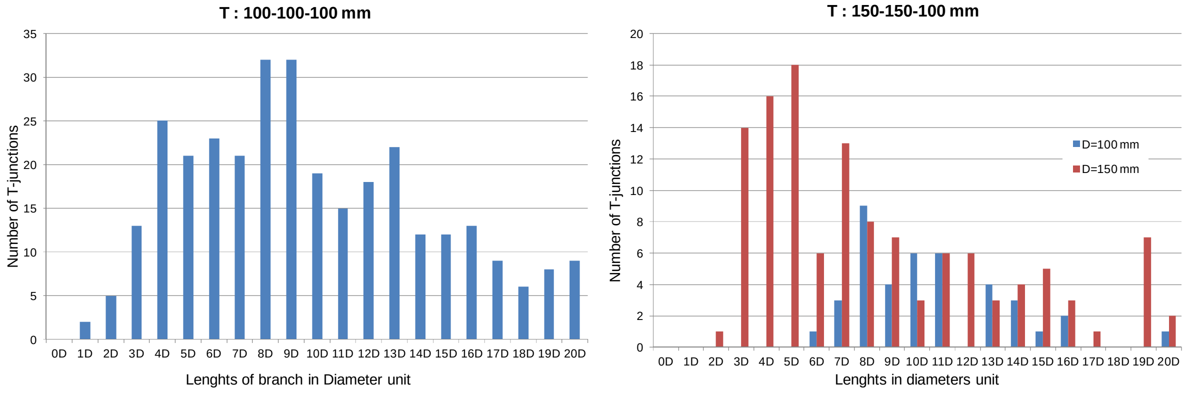


Figure 11: Distribution of Tee-junctions by diameters for CUS network

Junctions with the same diameter equal to 100 mm represent 27% of the total number. More than 48% are contained in the three first classes (100-100-100, 150-150-100, 200-200-100). In the project we study in more details these values by inspecting length to the next junction for each branch.

We can observe in Figure 12 the frequencies of lengths in diameter units (equal length/diameter). The more prevalent diameter 100 mm, as in many networks, have a lot of links with a length smaller than 20D, and some of them are less than or equal to 10D (193). We can also observe a lot of branches with these values of length for the two others Tee junctions, but with a smaller frequency before 10D. This serves as guidance for designing the inter-tee length for a double-tee or N junctions.



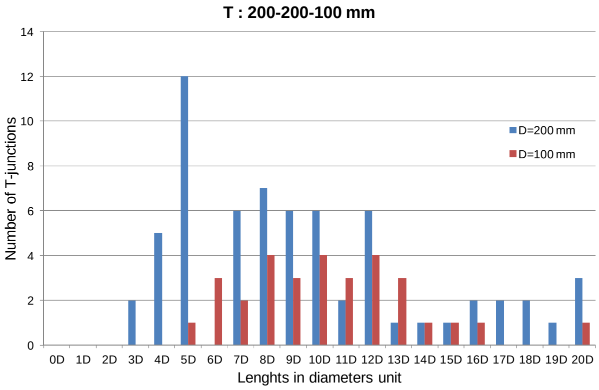


Figure 12: Frequencies of length to the next model node for the three first classes of Tee-junctions

Reynolds values are calculated for a typical day simulated by 15 minute time steps (with the *Zomayet Porteau* Module). With this result, for each junction of a class and each branch, the frequency of Reynolds is created.

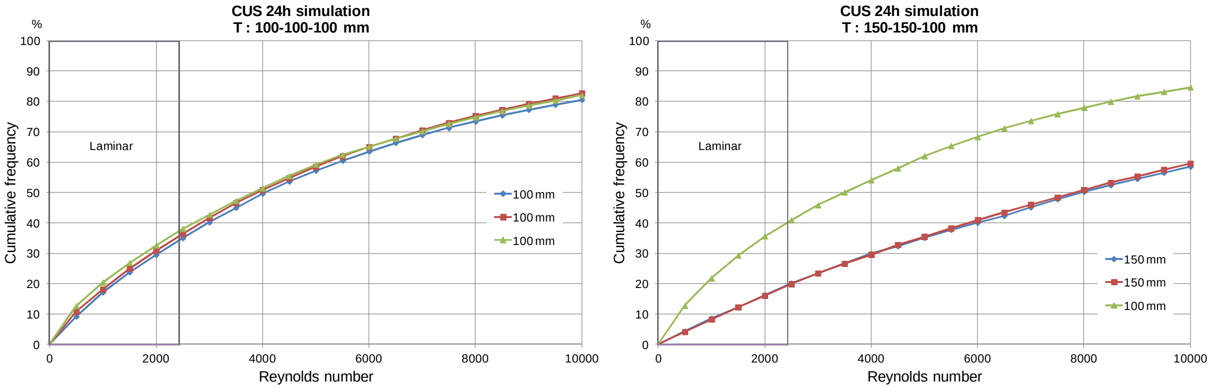


Figure 13: Cumulated frequencies of Reynolds values at 100-100-100 and 150-150-100 mm Tee-junctions for the CUS network

For 100-100-100 mm, more than 80% of Reynolds values are smaller than 10,000 and around 40% are in laminar flow.

For 150-150-100 mm, we obtain the same curve as for 100 mm branches, but for the two 150 mm branches, laminar flow is less present around 20%. Values smaller than 10,000 are more than 60%. We find the same result with 200-200-100, the larger the diameter is, the larger Reynolds value is, and laminar flow is less present.
For these three classes of Tee-junctions in the CUS network, we can conclude that laminar flow is really representative and cannot be ignored. Moreover, values greater than 10,000 are less representative, so we will only simulate and test values less than or equal to 10,000.

1.7. Statistics on the Vedif Villejuif subnetwork

The network of Villejuif area contains 5,196 links, 4,771 junctions for 205 km of pipes. It has just 2 crosses and 1,186 Tee junctions. The Tee-junctions are distributed as represented in Figure 14 with the most representative classes of diameters.

Again, 100-100-100 is the largest class with 353 junctions, around 30%. The second class has also the same 3 diameters 150-150-100 (15%). However the lengths of branches for these three classes are very different. The minimum length is 2.04 meters (maximum 883 m) for 100-100-100, it’s greater than 20D. We have the same results for the two others classes. After discussing with Vedif, we conclude that GIS data don’t correspond to reality. Technicals employees who draw the GIS change the design to make it more readable (with a minimum length between two objects).

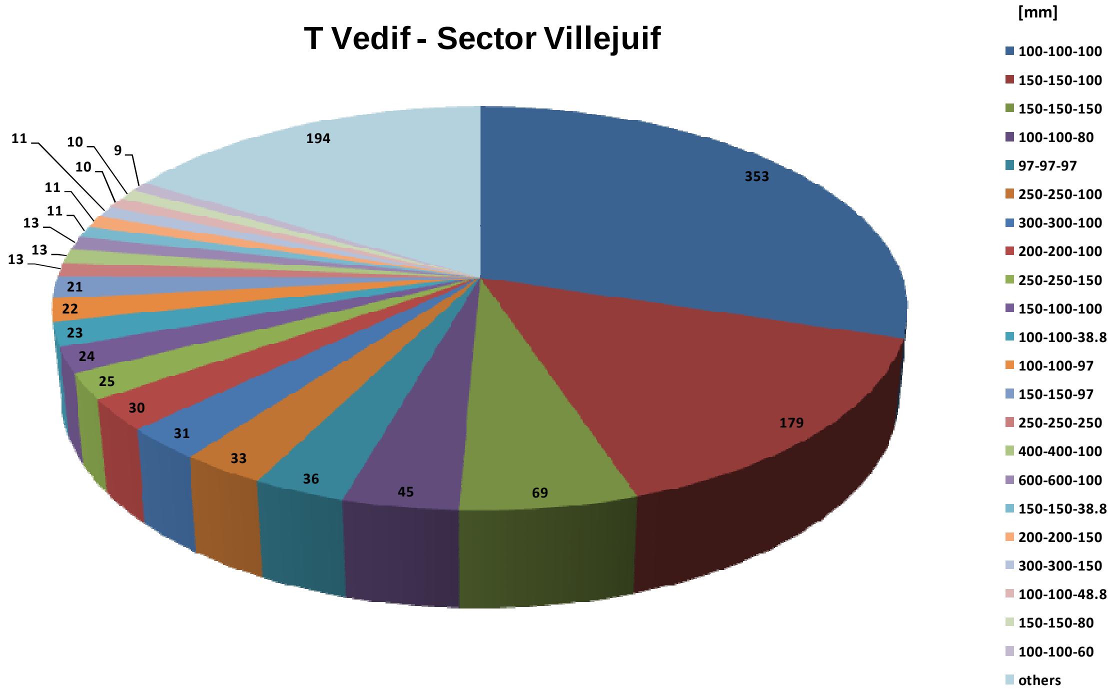
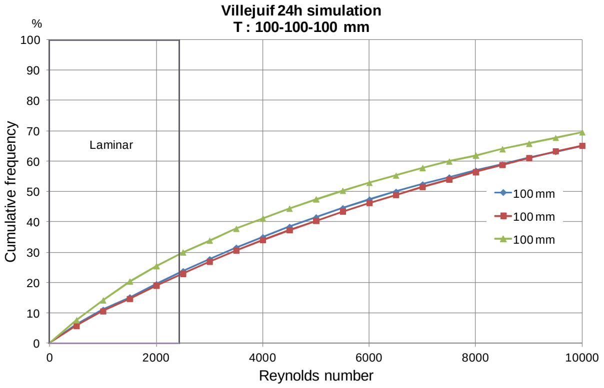
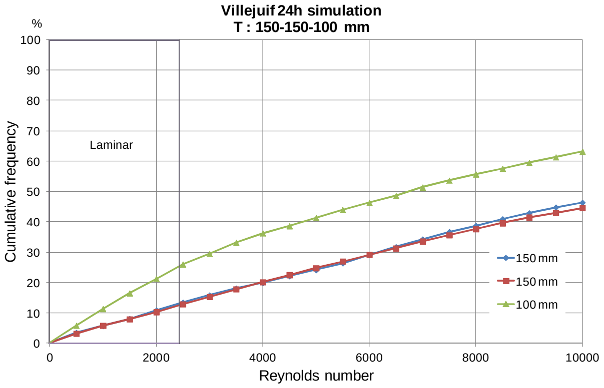


Figure 14: Distribution of Tee junctions by diameters for the Vedif Villejuif subnetwork





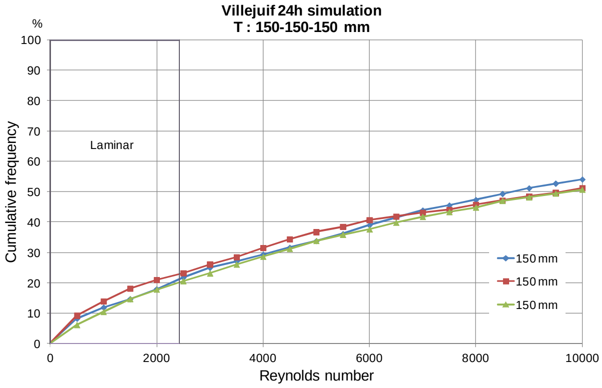


Figure 15: Cumulated frequencies of Reynolds values for the three first classes of Tee-junctions for the Vedif Villejuif subnetwork

With simulations performed by *Porteau*, we observe the distribution of Reynolds values. They are a little bit different than from CUS: The Reynolds level is higher. We think it's because the buildings in the Villejuif area are bigger than in CUS as well as the flows. Another reason may be that near Paris flows are more homogeneous during the day, night values are larger and the laminar flow is not so representative.

<ins>In conclusion</ins>, for the two operator's test networks we observe distances between Tee junctions less than 20D and a cumulated frequency of Laminar flow between 20 and 40%. This means that it is important to model double-Tee-junctions considering imperfect mixing. With these values we decide in accordance with TZW to investigate double Tee junctions of the same diameter D-D-D: 57 mm in pilot scale in TZW and of course in CFD model. We will calculate mixing for some values of Reynolds number (1,000, 5,000, 1,0000) observed between the two junctions. We will do these tests for different distances: 5, 8, 10, 20 D. The last parameters are the ratio of flow given by each branch, one for inlet, one for outlet.

3. Preliminary experiments at test facilities from TZW (Dresden)

As a result of WP 1 the question arose, if it would be more effective to build a new model network instead of modifying the existing one to achieve all the necessary criteria for this project. Because the existing network was situated above ground outside a building, investigations during winter would not be possible. Furthermore, the existing network had to be modified extensively to enable all the necessary experiments for the evaluation or calibration of the modules such as the alarm generation, the optimal sensor location, the transport model, the online model, etc. After discussing the pros and cons, a new above ground network was built in the basement of the TZW building (Figure 16). The network which includes already all modifications for the necessary investigations will enable weather independent tests. The structure of the model network is designed according to the statistics of Tee and Cross-junctions in the drinking water distribution network of Strasbourg and Vedif (cf. previous chapter).

Transparent pipe material is used and one cross- and one Tee-junction was made by hand from clear material for the better viewing of the mixing processes which should be recorded and evaluated via videos and photographs. The entire network is constructed to be as flexible as possible in the sense of sensor placement and flow properties. The setup of the network can be changed quickly and an automatic control is installed as a PLC (Programmable Logic Controller). Via the PLC, the outflow valves can be varied and also the data of the conductivity, flow velocity, pressure, differential pressure, temperature and turbidity sensors are recorded online.

Figure 16: New indoor model network of TZW (Dresden)

Conducted experiments and results:

- <u>Tracer defining experiments:</u>
  After a very short flow distance, the pure NaCl-solution and the water (which were mixed completely at the injection point) separate and create two different density phases in the pipe. Due to this problem, a suitable tracer had to be found with the same density as water.

  The experiments included substances like acids, salts, organic compounds and mixing installations. As a result a NaCl-solution (NaCl has the best effect on the conductivity which can be measured easily in the pipe) diluted with methanol to the same density as water was prepared. For a sufficient mixing of the tracer with the water in the pipe a static mixer was necessary.

- <u>Adsorption experiments:</u>
  To identify the eventual interactions of the used materials, the adsorption of the tracer on the inner pipe surface was investigated. For the experiments, the velocity in the network was set to a constant and stable flow before starting the trials. The tracer was completely mixed directly in the pipe via a static mixer. The dosing time for every experiment was 30 seconds. The distance between sensor 1 and 2 was 26 m (Figure 17). For every test series 5 trials were conducted and afterwards the network was cleaned intensely using a pig (foam ball). The conductivity at sensor 1 and 2 was measured and the recovery rate of the injected freight of salt was calculated by the integration of the area of the conductivity peak. The experiments were carried out under turbulent flow conditions (Re=10,000).

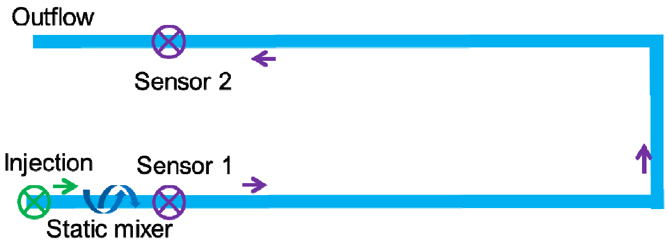


Figure 17: Scheme of the experimental set up

The results of the 5 test series are shown in Figure 18. Based on the inflow concentration, the recovery rate of the trials of every test series was in the range of 90 to 99%. The fluctuation of the trials and the test series were in the same range. From these results, it can by derived that there is no measurable adsorption of the salt tracer on the inner pipe surface.

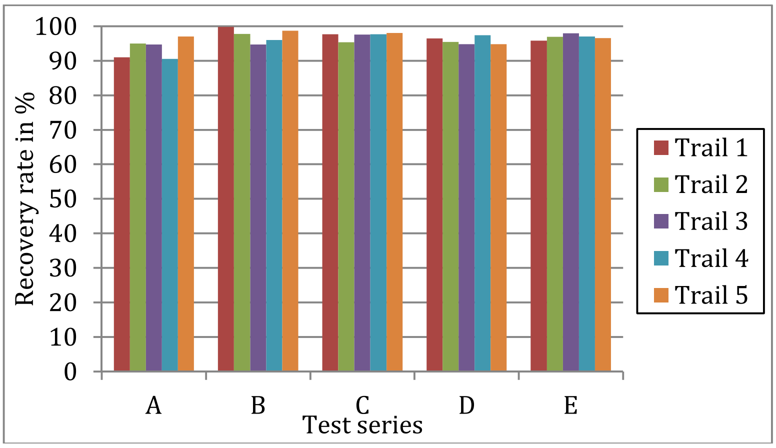


Figure 18: Recovery rate of the salt tracer based on the inflow concentration

- Mixing in cross-junction with 2 inflows and 2 outflows:
  Due to the assumption of no complete mixing at junctions, the real mixing process had to be investigated. One constellation which is very interesting under practical aspects is the pipe cross with 2 inflows and 2 outflows. For the experiments, the flow velocity in both inflows was identical and in a turbulent range. 10 trails were conducted with the identical flow velocity of the outflows. The results showed that 86 % of the tracer freight moved to outflow 4 (Figure 19) and only 14 % to outflow 3. For a second test series the velocity of outflow 3 was doubled compared to outflow 4. The results of the 10 trials were almost equal to the first test series. 78 % of the tracer freight moved to outflow 4 and only 22 % to outflow 3. The experiments showed very clearly that a very incomplete mixing occurs at cross junctions.

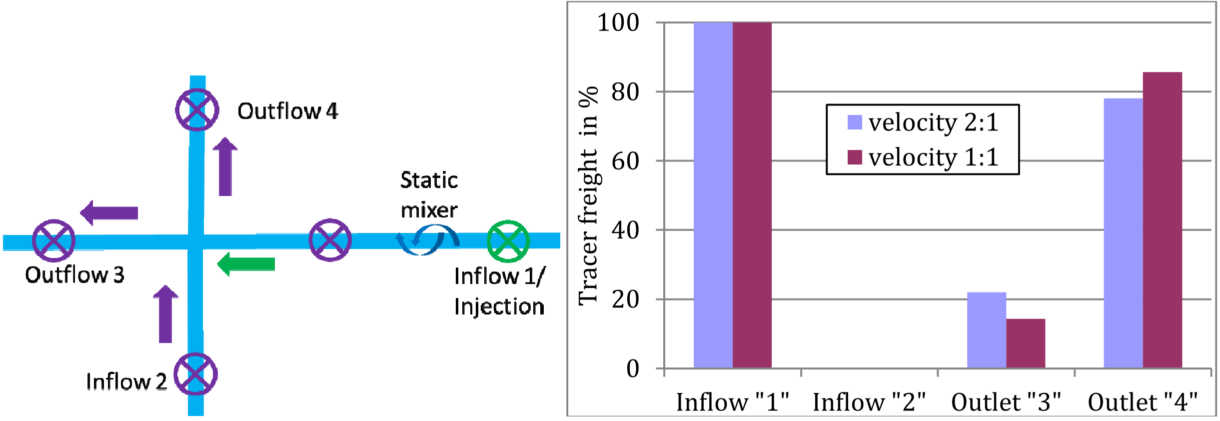


Figure 19: Schema of the pipe constellation for investigating mixing in a pipe cross (left) and the results of the two test series (right)

- Mixing at double Tee-junctions:
  Because double Tee-junctions are used very often in practice, a number of experiments were conducted for this kind of network component. The distances of the Tee-junctions used were 5, 8, 10 and 20 D (D is inner diameter of the pipe system). Two separate approaches the peak (0.5 minutes) and the plateau (3-5 minutes) injection of the tracer were investigated. Using the peak dosing, it is possible to analyse the dilution effect on the travel time and the shape of the peak. For the detailed investigation of the mixing processes in the junctions the plateau injection is a suitable approach. For the CFD modelling of the mixing process, the data of the plateau approach are more relevant. Therefore these results are explained as follows:

Before starting the experiments the velocities in the inflow and outflow pipes were adjusted to a stable and constant level. Two test series with 5 trials were conducted using a Reynolds number of 2,500 and 5,000. For the evaluation of the mixing, the plateau level of the stable conductivity was considered. The tracer was injected at inflow 2 (Figure 20).

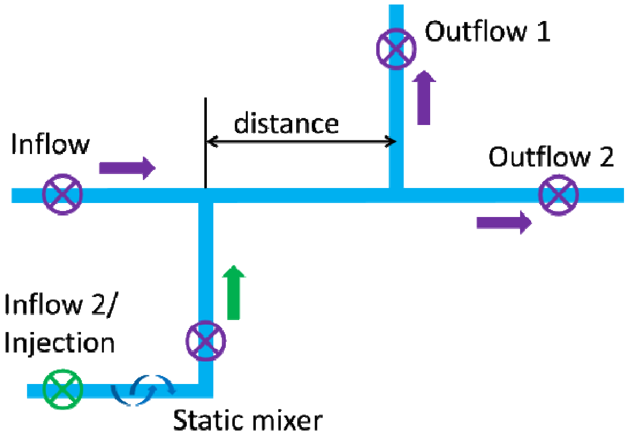


Figure 20: Schema for the investigation of double Tee-junctions

Representative results for a trial with a Reynolds number of 5,000 for the distance of 5 D are depicted in Figure 21. The shape of the conductivity plateau of the three measurement points is almost the same but there are differences in the plateau level of the two outflows. For this constellation the concentration of outflow 1 was higher than of outflow 2.

Figure 22 comprises the results of the two test series. For the Reynolds number 2,500, the concentration of the tracer in pipe outflow is higher than in outflow 2. Using a Reynolds number of 5,000 the proportion inverted. The results showed, according to the investigation of crosses, that the flow velocity has an impact on the mixing processes in fittings but there is also a strong influence of the form of the component (cross or Tee-junction).

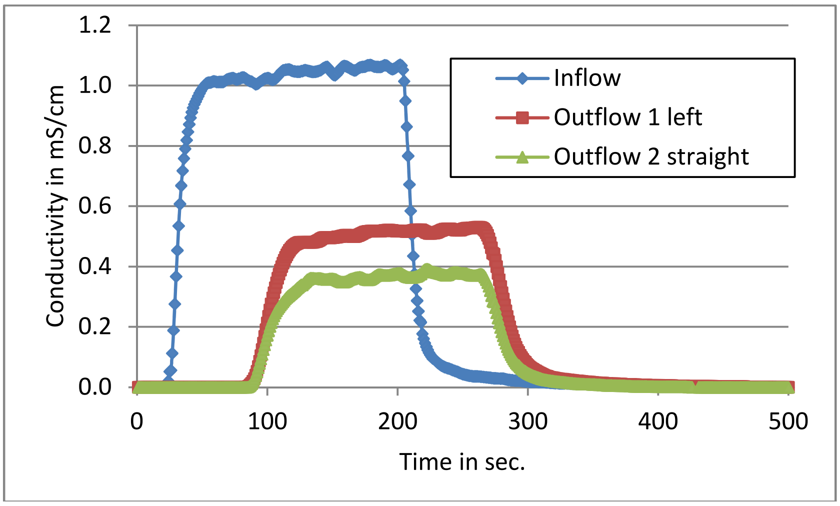


Figure 21: Representative conductivity curves for the constellation double-T D5 / 2 inflows + 2 outflows / Re 5,000

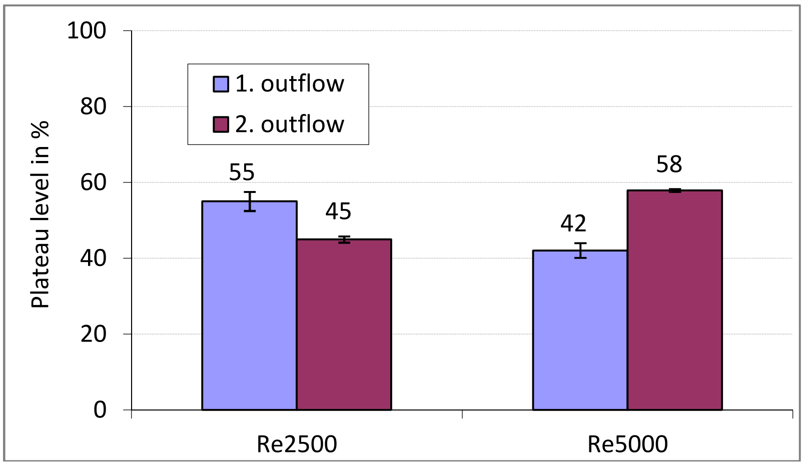


Figure 22: Partition of the tracer for different Reynolds numbers

- Optimal sensor position in the pipe:
  The aim was to identify the influence of the sensor position on the detection of the injected tracer (Figure 23). Experiments were performed by varying the position of the sensor in the pipe (top, side, center and bottom). For this approach, the tracer had a higher density than water. For every set up 5 trials were conducted. During laminar flow the sensor positions top, side and center detected just a small concentration of the tracer. In contrast the sensor at the bottom showed a higher peak maximum and a longer detection time. This effect is caused by the transport of the tracer mainly on the bottom of the pipe. For turbulent conditions there was no difference in the detection between the different sensor positions because of the complete mixing of the tracer.

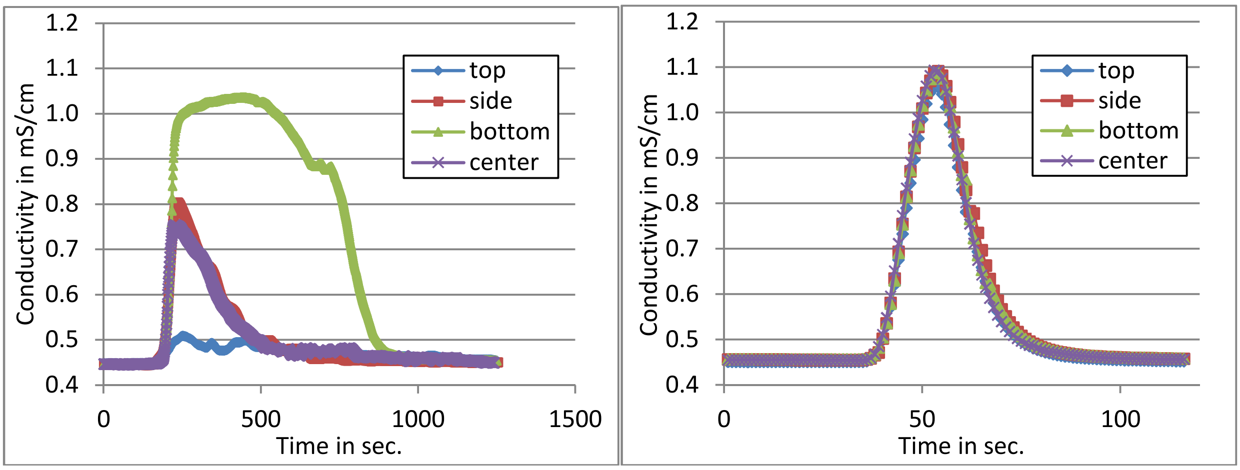


Figure 23: Effect of the position of the sensor on the detection under different flow conditions (left: laminar, right: turbulent).

The software of the alarm generation module was installed on the server of the test model. The functionality was tested successfully.

Currently, tests are in progress to calibrate and to improve the applicability of the software. For this different scenarios will be defined to reduce false alarms.

4. Future investigations

- Mixing: Transport model will be modified to take into account in 1D the results of pilot scale in TZW and CFD in 2D/3D of IOSB and Irstea.

- Roughness/Calibration: BWB small network experiments will be used to test the calibration of the hydraulic parameters and the mixing models.

- It is planned to carry out experiments with the same conditions at both the TZW and BWB test fields. This will help to define more precisely transport parameters, advection and absorption.