The Inspection of Tube Fitting Systems in use for Drinking Water Supply by Means of Neutron Imaging Methods

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Abstract: Metallic fittings as the connection between tube ends are heavily applied in domestic, public and industrial buildings where drinking water is distributed. Given by the manufacturing and joining process, there are spaces left between the fitting and the tube, which either can stay empty or filled with residual water amounts over time.

We looked for an efficient non-destructive method which allows measuring the filling of the system as well as the subsequent water exchange in order to evaluate new designs.

It was tried with the help of neutron imaging techniques to detect and to visualise the amounts of such residual water under different conditions in respect to the applied external pressure. Neutrons are preferable for such kind of investigations because they can easily penetrate the metallic structure, while detecting small water amounts with high sensitivity. Due to the performance of the used digital detection system, it was possible to enhance the contrast and the image quality by using a referencing procedure.

The successfully performed investigations at the neutron radiography facility NEUTRA at PSI can now be compared with model calculations based on dedicated diffusion approximations.

1. Introduction – the problem

Metallic fittings as the connection between tube ends are heavily applied in domestic, public and industrial buildings where drinking water is distributed. Given by the manufacturing and joining process, there are spaces left between the fitting and the tube, which either can stay empty or filled with residual water amounts over time. This uncontrolled assembly might have high risk for contamination with bacteria and health damage in the consequence.

A principle scheme of the arrangement is given in Fig.1. In order to inspect such regions by non-invasive methods optical test have been used, where a Plexiglas dummy of the structure has been manufactured and the water is doped with ink type tracers [1]. Although some direct and preliminary results have been obtained, there remain drawbacks of this approach, because the real fitting is made from steel and it is quite differently manufactured (high pressure squeezing) than the dummy. Furthermore, only the outside flow could be inspected and not the full volume.

Therefore, neutron imaging was found as a suitable NDT method at least for comparison and as verification tool with the previous model studies. The main reason to use neutrons for the inspection is their ability to penetrate metallic structures (e.g. stainless steel)

relatively easily and to have high contrast for water. Even thin layers with few tenth of a millimetre thickness can be visualized and measured quantitatively with high accuracy. Normal X-ray methods would fail in both aspects.
Because the dynamic of the water migration and exchange was in the focus of the study, a dedicated test setup was manufactured by Geberit enabling an operation under controlled conditions. Beside an inspection in time sequences, a volumetric investigation was performed by neutron tomography [2].
In the end, it was intended to find a fitting design, which enables a controlled removal and exchange of the "dead" but contaminated volumes in the fitting area. The circulation and pressure conditions of the fluid might play an important role too.

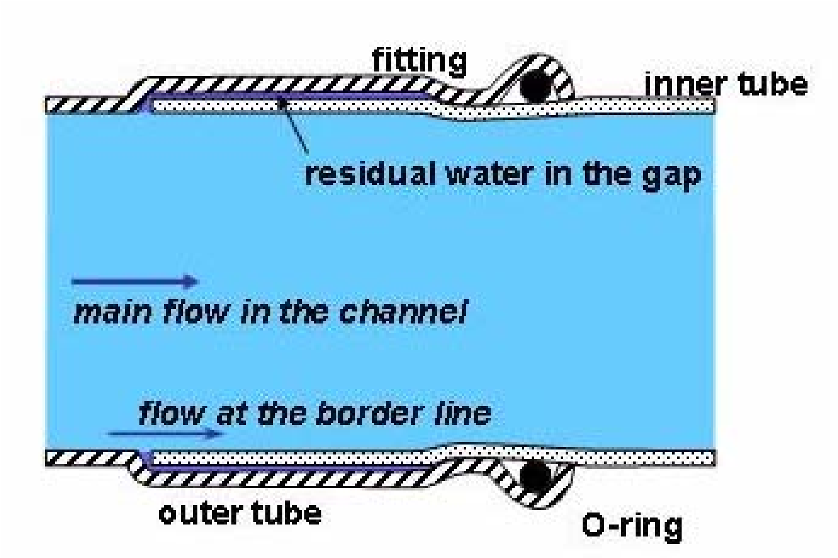

Fig. 1: The problem of the assembly of residual water within the gap between the metallic tubes and the fitting structure was investigated in this study under different experimental conditions

2. Experimental setup

2.1 Test assembly for the fitting structure

Because neutron imaging (details see below) is a locally fixed method due to the size of the neutron source, the test assembly has to be transported to the facility and adapted to the given conditions in respect to beam geometry and detector performance. For this purpose, a design was created as shown as principle in Fig. 2. It contains a pump for a controlled pressure up to 0.6 MPa and diagnostics units for flow rate and pressure. In the upper part the fitting is open for inspection from all sides, which is a requirement for neutron tomography. The real setup is shown in Fig. 3.

2.2 Neutron imaging method

Neutron imaging methods based on digital detection techniques have been available in Switzerland since 1997 at PSI, when the first such facility (NEUTRA) came into operation at the Swiss spallation neutron source SINQ. It provides a well-collimated beam of thermal neutrons with a diameter up to 40 cm at the end of the beam line. Details about the performance and the layout of NEUTRA are available elsewhere [3, 4]. In a single neutron radiography image, the shadow of the illuminated structure is detected as a data set, containing both direct image information and also numbers for the attenuation by the sample material. Therefore, a quantification of the investigated materials is relatively straightforward.

The detection system during all investigations at NEUTRA consisted of a cooled CCD camera with extremely high light sensitivity and high dynamic range [5]. It observes a neutron sensitive scintillation screen via a mirror and lens over a total optical path of about 1.15 m. The scintillation screen (Li-6 doped ZnS) can be considered as the initial neutron detector.

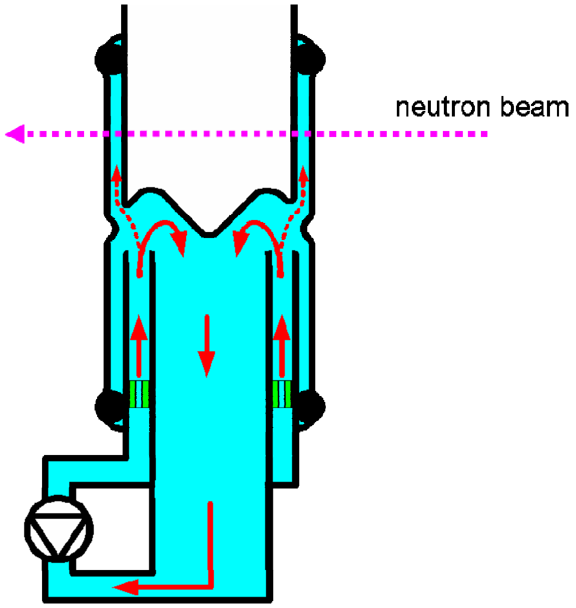

Fig. 2: Principle setup for the study of the streaming conditions of water in the gap between tubes and the fitting under different conditions. The real device is shown in Fig. 3.

Fig. 3: Test facility for the on-site diagnostics of the water flow in the fitting region, based on the scheme in Fig. 2. The dimensions become clear if the tube (on top) diameter of 8 cm is taken into account.

The same setup is used for tomography investigations [2], where the object is rotated around its vertical axis stepwise from 0° to 180° and about 300 projections are produced. Based on this data set, the whole sample volume can be reconstructed with the help of mathematical tools. Only stationary conditions in respect to water flow can be observed because the whole exposure time is in the order of an hour or more.

2.3. Involved materials and their properties in neutron interaction

The main problem to be solved in the inspections was the good penetration of the structure and a high contrast of the fluid at the same time. The attenuation coefficients Σ for the three involved compounds steel, light water and heavy water (explanation later) are summarized in Table 1. As the well-known attenuation law (1) shows, these values contribute in the same way to the beam weakening of the intensities in front and behind the object (I_0 and I, respectively) than the thickness d in beam direction.

$$I = I_0 \cdot e^{-\Sigma \cdot d} \tag{1}$$

This indicates that the two kinds of water differs in Σ by a factor of about 10, where light water gives much higher values than the steel construction whereas heavy water is less attenuating at all.
For this reason, heavy water was used in one experiment as initial filling material, which is more ore less transparent for neutrons, while light water was later applied during a replacement step as a tracer.

3. Experimental program

As indicated above, the distribution of the residual water is assumed to be depending on the flow conditions of the main and boundary stream and the geometry of the fitting itself. While changeable pressure and flow conditions were used to take care for the first aspect, two different manufacturing principles for the fitting were tested for the second one. A "symmetric" and an "asymmetric" fitting design were investigated separately.

1st series

In order to follow the water distribution during filling of a "virgin" connection, an initially dry assembly was observed in time sequences during a stepwise increase of the system pressure. The inspection was done by alternative neutron images for the observation angles "45°" and "135°", where the whole setup was rotated for – and backward.

2nd series

After reaching a final status in the water distribution, neutron tomography runs were started in order to visualize the water filling in the gap as precise as possible. Three-dimensional information could be derived und used mainly to distinguish between the two production methods "symmetrical" and "asymmetrical".

3rd series

In a final step, it was intended to see how a new stream of water can change the volume and the distribution of the water in the gap. Therefore, the dry setup was filled first with heavy water (having low contrast for neutrons), than emptied such that only the "death volume" remains filled. Later the whole setup was filled again with light water (providing the high contrast). In this way, mainly the newly ingresses water will be found, visualized and measured.

Table 1. Attenuation coefficients for thermal neutrons (E ~ 25 meV)

material	Attenuation coefficient Σ [1/cm]
Steel	1.1
Light water	3.5
Heavy water	0.37

4. Evaluation procedure

Results from neutron transmission measurements are given in Fig. 4. On the left, the empty structure is shown, indicating that the metallic structure of the fitting is more or less transparent for thermal neutrons. The different parts of the setup are visible, where the O-ring delivers the highest contrast.
If the assembly is filled with normal (light) water, the lower part becomes completely dark due to the neutrons scattered out by the water. Although some changes can be seen in the upper part, no clear information can be derived in this direct transmission image. Therefore, a "referencing procedure" was applied, were the image of the actual status is divided by the image of the empty structure and the result multiplied by a scaling factor N, which considers the dynamic range (16 bits).

$$I_{res} = \frac{I_2}{I_1} \cdot N = \frac{I_0 \cdot e^{-(\Sigma_s \cdot d_s + \Sigma_w \cdot d_w)}}{I_0 \cdot e^{-\Sigma_s \cdot d_s}} \cdot N = e^{-\Sigma_w \cdot d_w} \cdot N \qquad (2)$$

According to (2), this resulting image contains only the required information about the change in the water distribution (index w), whereas the effects by the steel constructions (index s) vanish.

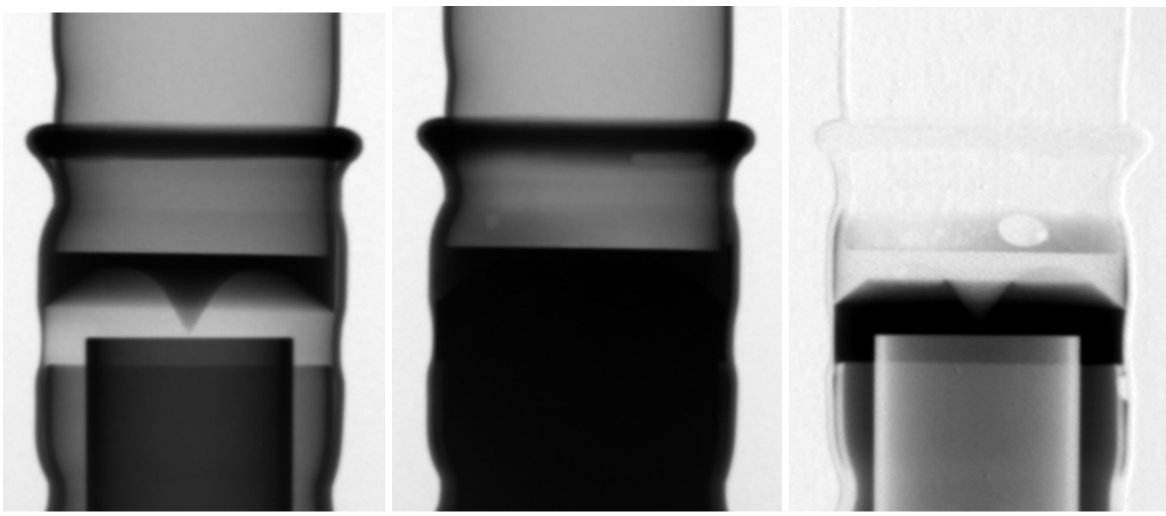

Fig. 4: Neutron images of the inspection zone of the setup in Fig. 3: left – the empty assembly, middle – after water filling, right – after "referencing" according to (2)

As the resulting imaging data (Fig. 4, right) can demonstrate, only after this image processing step an analysis of the water amounts in the small gaps becomes possible. Small lines are visible at the edges in the resulting image because the object could not be stabilized over hours in the same position during the application of the water under high pressure. This mistake is of less importance for the evaluation.

5. Results

1st series

As the results in Fig. 5 can demonstrate, the water can migrate into the fitting structure if sufficient pressure is applied. This process starts relatively early but a complete filling is impossible due to encapsulated residual air which is trapped by the water itself.

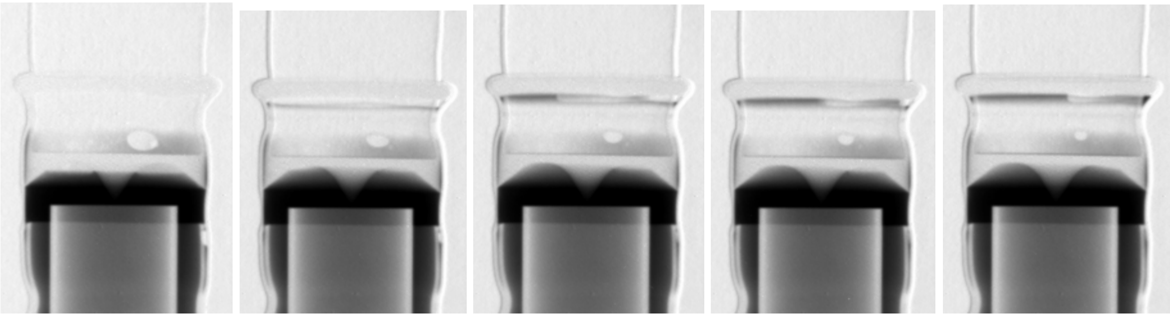

Fig. 5: Filling process of the asymmetric steel fitting with normal water in a sequence of images. Obviously, the residual air content plays a role how and where the water can migrate. The first image was taken directly after starting of the pressure application. The final state was reached after about 15 minutes.

2nd series

This run was undertaken to show the distribution of the water between the fitting structure after removal of pressure and the whole inner water column. The results of this tomography investigation are the three-dimensional volume structure, where some perspective views are selected for Fig. 6.
It becomes clear that sufficient water remains in the fitting also without any applied water to the assembly. This holds for the gap between the two tubes and the space below the O-ring. Compared to the final state of the filling process, the air volumes seem to expand again when the applied pressure comes low.

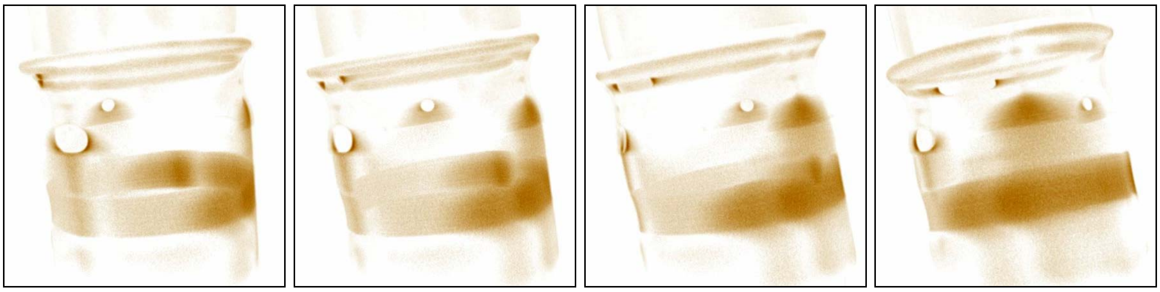

Fig. 6: Water distribution inside the metallic structure of the fitting. Even if only thin films remain, the neutron tomography method has sufficient sensitivity to detect the water.

This remaining water amount is exactly the problem under discussion. First of all, the volume can be determined by the tomography data on demand. In a first estimate, a 60% filling of the total free space was determined. The trapped air delivers a limitation to fill the assembly completely.
Secondly, it was of high interest, in which way the water can be removed practically and more or less completely. This option would be of interest if it is not practicable to avoid any water filling and contamination.

3^{nd} series

As mentioned above, the pictures in Fig. 7 corresponds to a comparison of the state where the assembly is filled with heavy water. We assume a similar distribution of the heavy water as determined for light water in the 2^{nd} series (see Fig. 6). However, due to the low contrast of the neutrons for heavy water, it is impossible to do the inspection in the same quality and contrast.
From this initial but not verified state, the redistribution of water (exchange of heavy water by light water) was studied when the water was applied under high pressure again. The results for both symmetric and asymmetric assemblies are shown in Fig. 7.

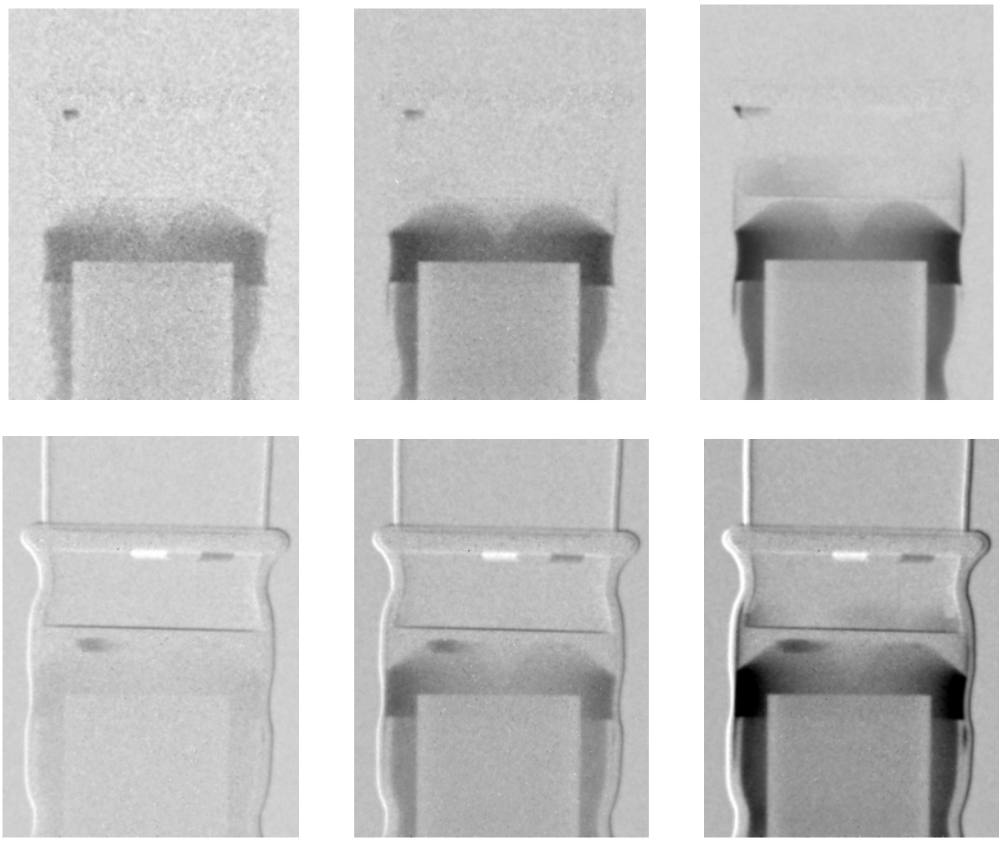

Fig. 7: Water exchange during recirculation of light water replacing heavy water, which was used previously in the initial filling: upper line – symmetric structure, lower line – asymmetric structure. The process is followed over a time interval of up to 30 minutes

The comparison between the two series demonstrates that in the case of the symmetric setup a fast and more homogenous exchange of the two kinds of water happens. However, until the final observation after 30 minutes, no exchange took place in the upper region near the O-ring. The removal of the heavy water looks different in the asymmetric case, where local changes happen more often.
In both test series there was a clear indication that it is impossible to exchange the total amount of residual water in the way to apply another water column. The diffusion inside water is not strong enough to make a full replacement. However, the asymmetric assembly has been filled with "fresh" water much faster, within minutes than hours. This finding corresponds with the previous ink tests.

6. Conclusions

The results of the three test sequences enable the conclusion that the method of neutron imaging has been best suited for the detection of low water amounts within the steel structures of the fittings connecting drinking water tubes. If a suited referencing procedure is applied, the sensitivity for the water determination is further increased. When the water distribution is stable in time, the full water amount can be determined three-dimensionally with neutron tomography.
Using the property of the two kinds of water (H_2O, D_2O) to create very different contrast in neutron transmission, a water exchange was studied between residual and fresh water amounts. It was found out that the obtained results are in good agreement with the labour experiments with Plexiglas dummies.
The described neutronic procedures are useful to inspect similar configurations where the metallic structure has to be transmitted and relatively low amounts of organic material have to be investigated. The facilities for neutron imaging are available for further studies on demand.

References

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