Developments on High Pressure Two Phase Flow Measurement Techniques

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Abstract

AREVA operates a world-wide unique thermal hydraulic platform to ensure high safety standards in the nuclear industries. This platform is operated as an accredited test and inspection body according to ISO 17025 and 17020 to grant a high and independently confirmed quality standard. The accreditation also ensures the independency of the organization and confidentiality to the individual stakeholders, as for example research centers, utilities, components suppliers, engineering companies and vendors. The aim of the tests is to demonstrate the reliability of components and systems – mainly under operational or accidental conditions. In addition to that it is also the aim of the tests to increase the understanding of the fluid dynamic processes. Especially under operational conditions it is very difficult to gain local measurement data. This paper gives an overview of the current developments of these measurement techniques focused on the local void fraction measurements in an annulus as an example for AREVA's strategy in the field of advanced two-phase flow measurement techniques.

With increasing requirements with respect to the local resolutions the efforts for measurement techniques increase as well. For that purpose AREVA has built up a specific test loop to develop measurement techniques and which is therefore not linked to production measurements. Within this loop it is possible to adjust water/steam properties representative for operational and accident conditions of LWRs. This loop has been used to develop a procedure to measure the void fraction distribution in an annulus representing the hydraulic diameter of a typical LWR core sub-channel. This paper describes the process, which has been established to reach reliable local high resolution measurements.

Keywords: local void measurements, advanced two phase flow measurements, components qualification, systems testing

1. INTRODUCTION

AREVA has been operating a worldwide unique testing and qualification infrastructure for more than 35 years, which is mainly delegated to systems and components of light water reactors [1]. AREVA has opened this Thermo-Hydraulic Platform for partners within the power plant industries, among which are authorities, research centers, component-suppliers, utilities and/or engineering companies. To ensure our partners a high quality of test and qualification standards AREVA's platform is accredited as flexible test laboratory according to ISO 17025 and as independent inspection body according to ISO 17020. The International Laboratory Accreditation Cooperation (ILAC) has settled an almost worldwide cooperation agreement, according to which the associated countries accept each other's accreditations. According to this agreement, the accreditation of AREVA's Thermo-Hydraulic Platform is valid not only in each of the countries with AREVA laboratories (which are France, Germany and USA) but also in almost all countries of the world e.g. Canada, India, China, Japan, Korea, Emirates, Russia and all countries of the EU.

The testing and qualification infrastructure is focused on flexible task solutions for power plant applications. Therefore, it is common practice to modify the existing testing infrastructure to fulfill the requirements of a qualification or an inspection task. To avoid new individual accreditations for each task, AREVA has successfully applied for a flexible accreditation based on which the general methods and the applicable range of measurement have been certified, which are given in Table 1:

Table I: Accredited measurement range of AREVA's Thermo-Hydraulic Platform

Parameter	**Range**
Temperature	0°C - 1000°C
Pressure	10 Pa - 40 MPa
Volume flow rate	0,1 l/h – 100 000 m³/h
Mass flow rate	Up to 4000 t/h
Force	Up to 10.000 kN
Momentum	Up to 50.000 Nm
Length	1 µm - 10 m
Velocity	1 mm/s – 100 m/s
Acceleration	0,5 - 1000 g
Electrical power	Up to 20 MW
Active power	Up to 50 KW
Current	Up to 85000 A
Voltage	Up to 420 V

Within a continuous improving process new measurement methods are under development to ensure, that the test capabilities are going to fulfill the requirements of the customers. With increasing relevance of computational fluid dynamics there are clear indicators that local two-phase flow parameters are of increasing relevance. Under the frame of the approach that AREVA operates several facilities under original operation conditions, it is also required to develop such measurement techniques for high pressure and temperature conditions. This paper focuses on the development of a local gamma void measurement technique and indicates how to bring it on the level of an accredited measurement technique.

2. Motivation and background for local void measurements

Applications for the local void measurement techniques can be in the frame of nuclear but also in non-nuclear applications. For example in the development of coal fired power plants based on Siemens's BENSON license it can be of interest to know the local void fraction in so called rifled boiler tubes to understand the mechanisms of the heat transfer enhancements. For that purpose tests have been performed at the BENSON facility as it is shown in Figure 1 [2]. A rifled tube (a cross section of such a tube is shown in Figure 2) has been installed as test section in the BENSON loop. The loop itself has been mainly used to gain critical heat flux data. Therefore, the tube has been directly electrically heated.

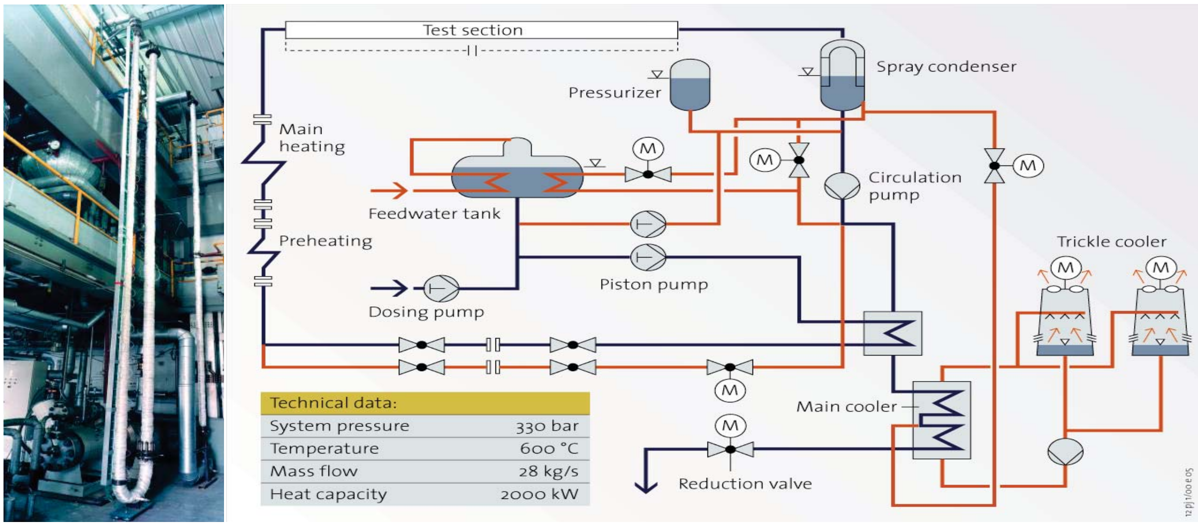

Figure . 1: BENSON Test rig scheme and a photo with integrated test tube

Figure 2 shows an example of the measurements of this void fraction distribution in a rifled tube based on gamma densitometry as it has been shown in [3].

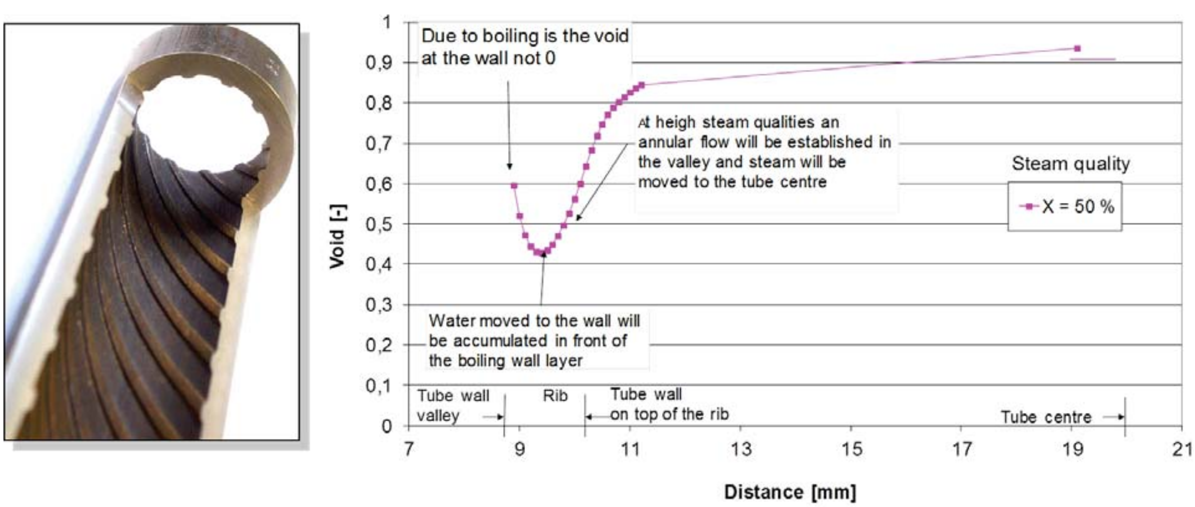

Figure 2: Void fraction distribution in a rifled tube as shown on the left picture

The measurement appeared to be reasonable, but it was one conclusion out of this measurement campaign, that the measurements have to be prepared out of the operational test loops. Possible loops for final applications could be the KATHY loop [4] which AREVA operates to measure the critical heat flux in fuel elements (the loop is shown in the Figure 3). This loop can be operated as a forced circulation loop (left scheme in Figure 3) or as a natural circulation (right scheme in Figure 3). The loop itself is designed in such a way that the rods installed in the test channel (see center top photo of Figure 3) can be electrically heated. Based on related temperature measurement it is possible to detect the critical heat flux.

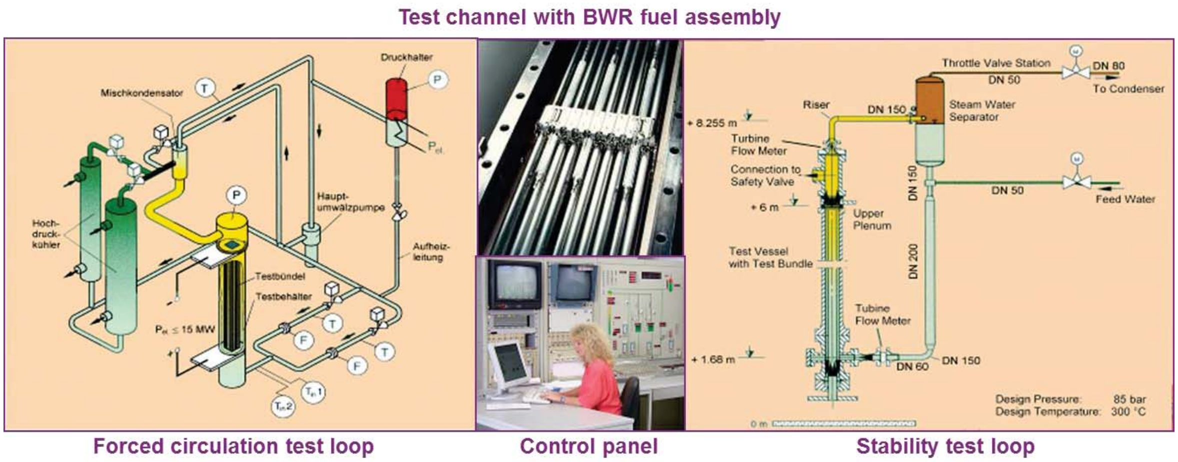

Figure 3: KATHY loop

Another possible position for a local void fraction measurement could be in the PKL loop [5] as it is schematically shown in Figure 4. This loop represents a 1300 MW PWR in the height 1:1 and scaled 1:145 in the cross section as well as in the power supply. The core is modeled by a dummy made of electrical heated rods, whereas the rod geometries and spacer represent the original geometries. The steam generator is made of U-tubes representing the different heights of original U-tubes in the scale 1:1. The loop has more than 1500 measurement positions, which are mainly robust temperature, pressure, pressure drop and flow rate measurements. Different accident scenarios have been and will be investigated. The purposes are for example the investigation of the efficiency of measures in the case of an accident scenario, gaining general information of the transient phenomena and providing a data base for code validation. For that purpose it could be a relevant advantage to have advanced high pressure measurement techniques to get a deeper understanding of the related phenomena.

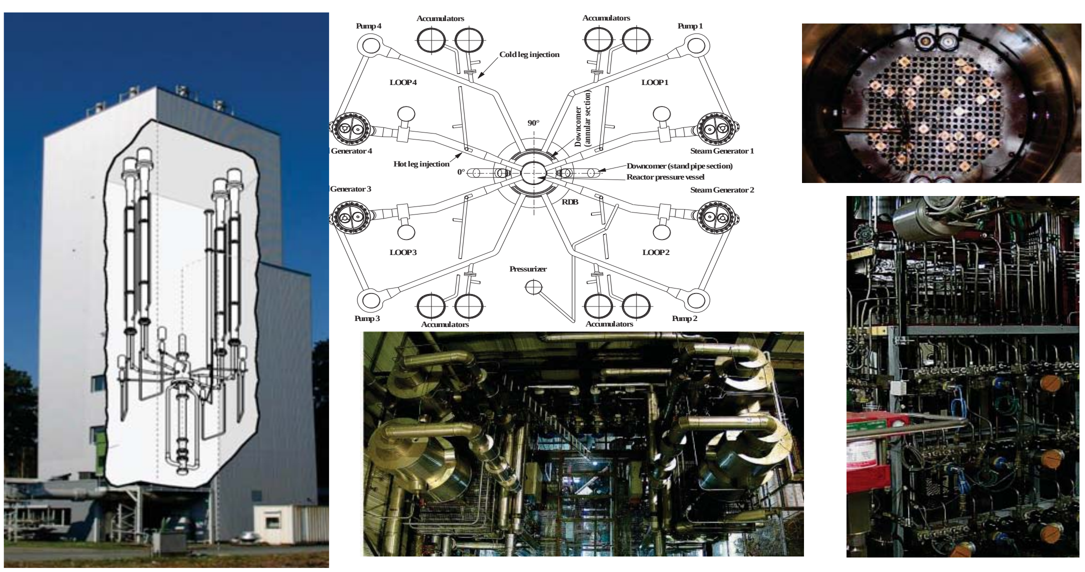

Figure 4: PKL Loop – left: photo of the building with a scheme of the main components – center top: scheme of the arrangement of the main components – center bottom: view into the loop from the bottom right top: photo view in the core mock-up – right bottom: photo of pressure transducer arrangement

3. Development process to validate the local gamma measurement technique

It has been one conclusion of the measurement campaign for the rifled tubes that the measurements are very time consuming and it is very meaningful to optimize the process outside the operational test facilities. Therefore, a test and calibration loop has been build. Figure 5 shows a scheme of the loop and the related measurement technique. The loop is designed in such a way, that water will be pumped via a piston pump into the heater, where the water will be boiled off and superheated. The superheated steam enters a test channel from the bottom. This channel is an annulus formed by an outer tube of an inner diameter of 14,9 mm and an inner tube with an outer diameter of 9,5 mm. The inner tube is arranged in such a way that it could be electrically heated and has therefore an inner support structure to withstand the outer pressure. At the outlet a separator is installed. The water level of the separator will be controlled to such an extent that water will maintain in the test channel and only steam flows through it. Based on the amount of water in the channel, different void fractions can be adjusted. The pressure in the loop will be controlled via a valve behind the separator. Along the channel several pressure drop transducers are installed to measure the pressure drop. As the general flow rates are low, the pressure drop measurements can be used to calculate the cross section averaged void fraction.

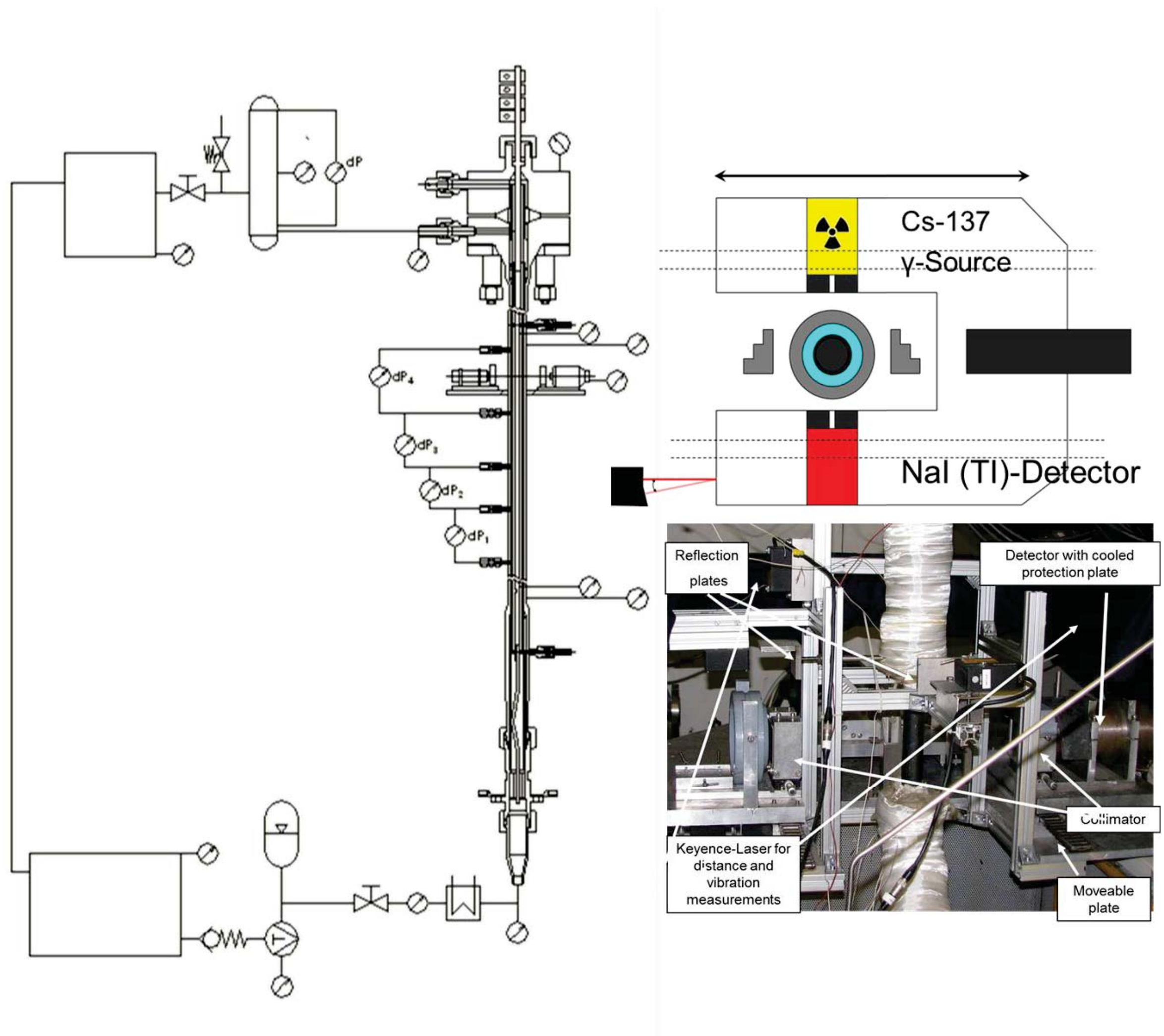

Figure 5: left: scheme of the calibration loop – right top: arrangement of the gamma densitometer – right bottom: photo of an arrangement of a gamma densitometer

In the upper position of the channel (75 hydraulic diameters from the inlet and 25 hydraulics diameters from the outlet) a gamma densitometer has been installed, which is schematically shown in Figure 5. It consists of a Cs – 137 source, which has an activity of about 3,7*10^{11} Bq and a NaI detector. Both, the detector and the source have each an adjustable collimator – to define the thickness of the beam. Both are installed on a plate, which can be moved along the tube. In addition to the tube two steel blocks are installed, which can be used for calibration purposes. Several triangulation sensors are installed to identify the position of the tube and the plate with the gamma source.

The reduction of the gamma beam intensity can be described by eq. (1)

$$I = I_0 \cdot e^{-\sum_{j=1}^{n} \mu_j \cdot \delta_j} \quad (1)$$

with: I as beam intensity, I_0 as the source term beam intensity, μ beam damping coefficient and δ as damping length. The void fraction averaged along a beam in the test channel is:

$$\alpha(h) = \frac{\delta_{Steam}(h)}{\delta_{Total}(h)} \quad (2)$$

with: $\delta_{Steam}(h)$ as cumulated steam length along a beam and the total length $\delta_{Total}(h)$ at position h.
It can be shown that the void can be also described based on three measurements - with saturated steam, with saturated water and the related two phase flow – according to (3).

$$\alpha(h) = \frac{ln\left(\frac{I_{2\,Phase}(h)}{I_{Water}(h)}\right)}{ln\left(\frac{I_{Steam}(h)}{I_{Water}(h)}\right)} \quad (3)$$

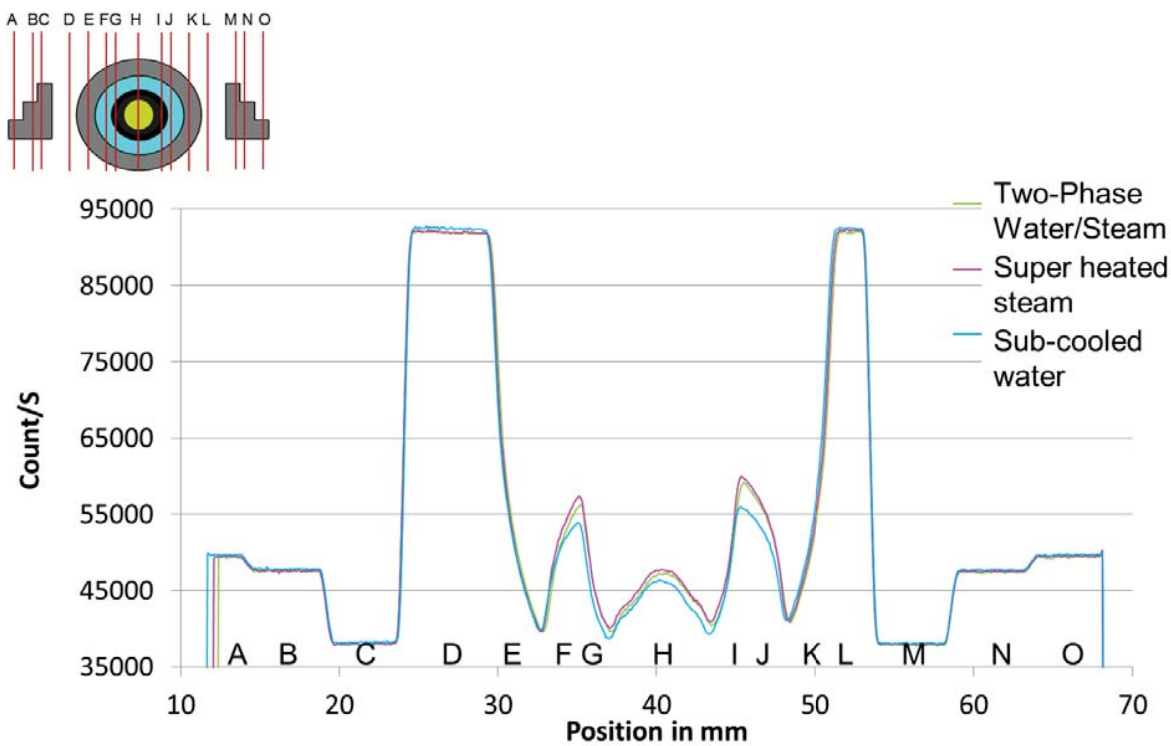

Figure 6: Beam intensity along the test channel and the related calibration blocks

Figure 6 shows as an example a beam intensity reduction measurement of steam, water and two phase flow along the test object. It is obvious that the general changes of the geometry will be represented. As industrial components have been installed, the profile is not totally symmetric. In addition are the differences between the three related tests not very significant. In order to apply eq. (3), it was necessary to develop an evaluation process as it is shown in Figure 7 and described in the following text.

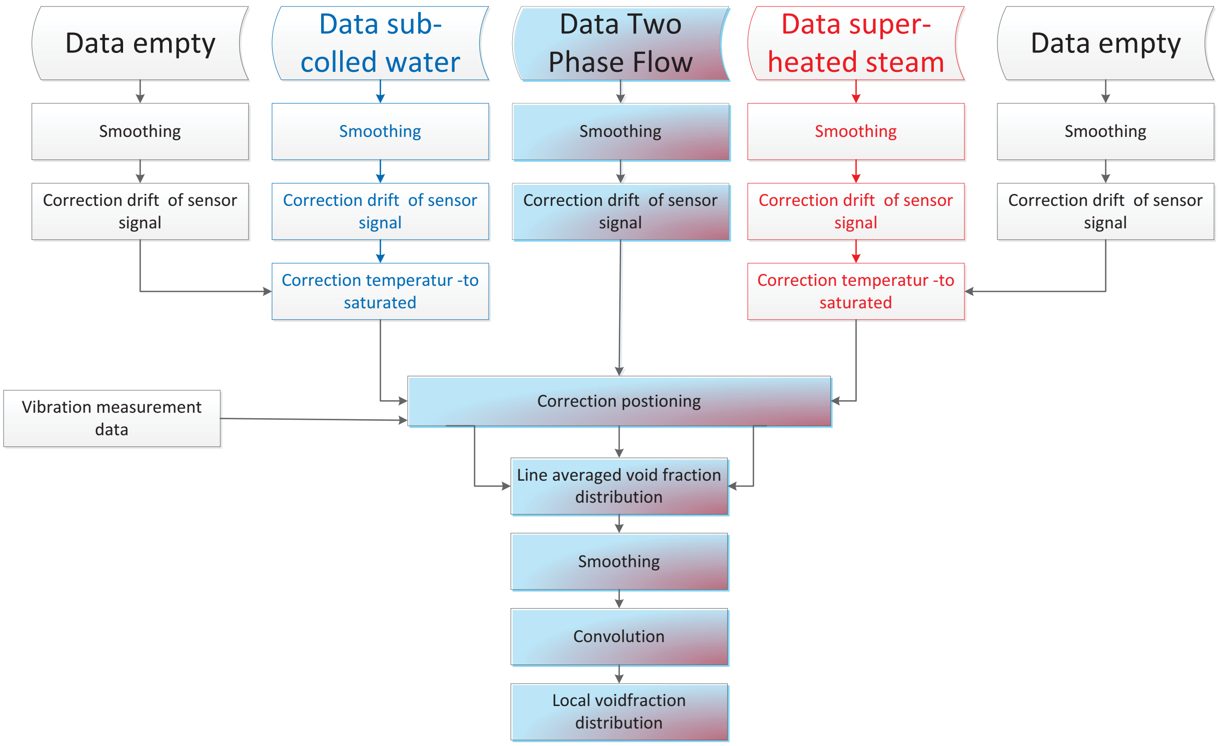

Figure 7: Evaluation process to determine the local void fraction distribution

The tests have shown that there is a slight drift of the sensor signal between different days. Although, the drift is less than 1/1000 of the sensor signal in air, it is necessary to consider this effect, as the three measurements (in steam, in two phase flow and in water) with relative low differences will be used to get the final result. Therefore, calibration measurements have to be performed before each test run and after each test run – to confirm that there has been no drift during the test. Figure 8 illustrates that the inclination of the different levels of the calibration blocks are not totally normal to the beam. In addition to that the accuracy of the positioning can not be totally assured during the different measurements. Therefore, it is necessary to gain a linear regression line and use the related constant for further signal adjustments.

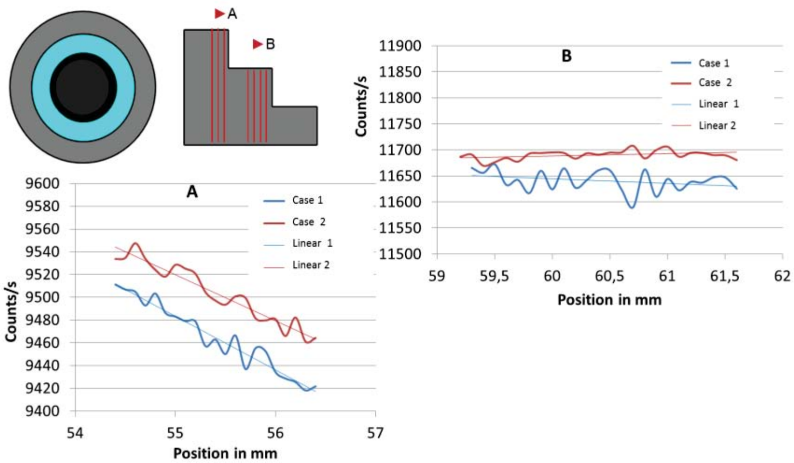

Figure 8: Beam intensity measurements along calibration blocks

Furthermore it is necessary to correct the related single phase flow test signals as they have to be gained out tests with sub-cooled water respectively superheated steam conditions – to ensure, that really single phase flow conditions have been established. The difference in the temperature to the saturation conditions lead to a difference to the density of the related two-phase flow test. This has to be taken into account in the final evaluation. In Figure 9 the relative errors are plotted for the case, that the sub-cooling would not be corrected and one would apply the sub-cooled water condition values in eq. (3). Based on that one can define a relative temperature error as:

$$E = \left(1 - \frac{ln\left(\frac{I_{2\,Phase}(h)}{I_{Water\,subcooled}(h)}\right)}{ln\left(\frac{I_{Steam}(h)}{I_{Water\,subcooled}(h)}\right)} \Big/ \frac{ln\left(\frac{I_{2\,Phase}(h)}{I_{Water\,saturated}(h)}\right)}{ln\left(\frac{I_{Steam}(h)}{I_{Water\,saturated}\,(h)}\right)}\right) * 100 \quad (4)$$

Especially, at lower void fraction this error increases significantly and this causes already at relative low sub-cooling conditions high errors. To perform the corrections, tests with an empty tube have been performed in addition to the single phase flow test. Based on this additional measurement it is possible to extract the contribution of the test channel out of the entire beam reduction signal, which can be used to define the effect of the temperature difference to the saturation conditions.

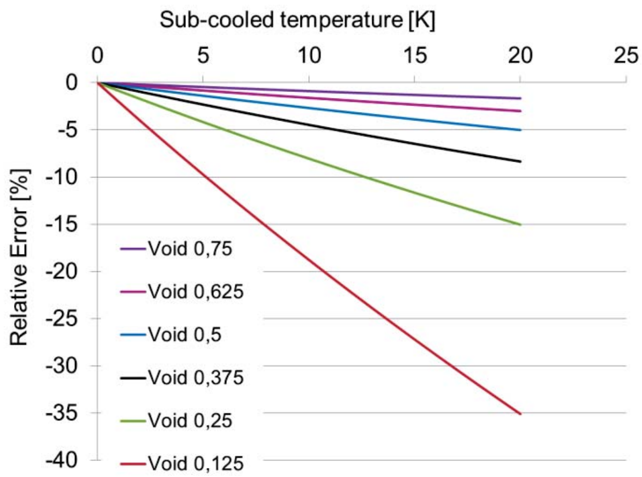

Figure 9: Error without considering the sub-cooling in the evaluation process at 70 bar

Although the movements of the plate have been established with very small steps and have been controlled via triangulation systems, it became obvious that there is a very small lateral drift of the three signal profiles, as they all have to be a minimum signal at the same position of the inner wall. (Hint: This is no effect of thermal expansions of the wall as the measurements are on the same temperature level). Therefore, these three signals have to be moved in lateral direction as shown in Figure 10 – especially, if one is interested in the void distribution near to the wall.

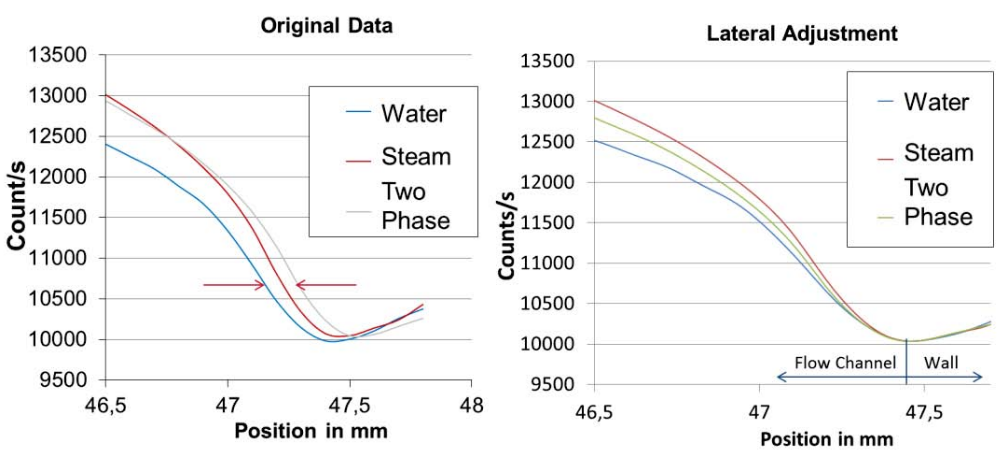

Figure 10: Adjustment of the water, steam and two phase flow profiles to inner wall position

Considering the related corrections it is possible to apply Eq. (3) to get the line averaged local void fraction distribution. The gained profile is too rough for the conversion into a local void fraction. Therefore, the results of applying Eq. (3) have been smoothened as shown in Figure 11. In a last step the linear averaged profile has been transferred to a local void fraction distribution. This has to be done in a numerical convolution process. The assumption is that the void distribution is rotational symmetric. Therefore, one can search a local void fraction profile, which has to be transferred to the measured and smoothened beam averaged void fraction profile. Figure 11 shows the beam averaged void profile and the derived local void fraction profile.

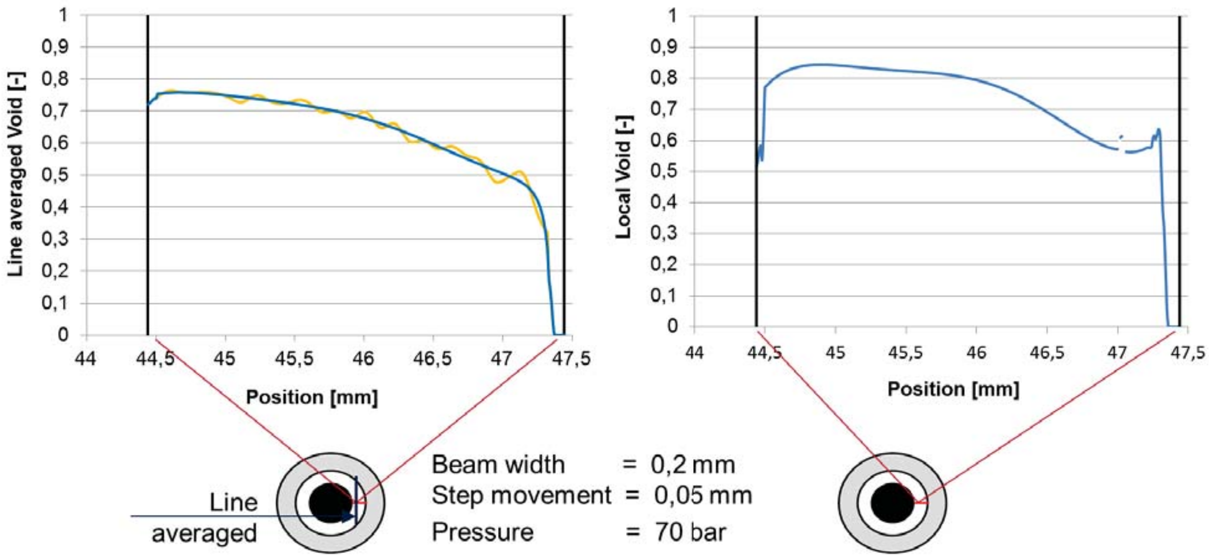

Figure 11: Local and line averaged void fraction distribution in a water column with steam supply

The local void profile appears to be reasonable, as a comparison with a cross-section averaged void gained out off a pressure drop measurement is in the range of the accuracy of this method of about 5%. The profile indicates that the walls (both the outer tube and the inner rod) are wetted, which is expected for unheated walls. In addition, the local maximum of the void in front of the tube wall appears to be reasonable as a kind of drift effect may occurs. In general the profile looks like a kind of an annulus flow, with some droplets in the steam flow (as the void is not 1 in the core). This appears to be also meaningful for a high void fraction.

4. Outlook

Although the local void fraction profile appears to very reasonable and the averaged void fraction across the cross section has been in the range of the measurement accuracy of the measured values of the pressure drop measurement method, it can not be concluded that the method is on such a level that it could be accepted as an accredited measurement technique. To bring the method on such a high level one would have to establish at least a second method validating these results.

Such a validation could be reached by an impedance method. For that purpose several tests have been performed to investigate the general possible arrangement of probes mainly focused on the film thickness identification in water/air tests [6]. These tests also indicate that it appears to be possible to combine different probes to identify the distribution of the water phase. To transfer the sensor design from ambient operational conditions to high pressure applications, endurance and reliability tests have been performed with such a probe in the BENSON loop. Therefore, one individual probe has been manufactured and installed at the end of an evaporator tube, which has been tested during an evaporator test campaign. Figure 12 shows the set-up of the probe and the related installation position. These tests demonstrated the robustness of the design of the probe for harsh pressure and temperature conditions as well as the related gradients.

Such a high pressure impedance tomography like set-up can be used to validate - as a second independent method - the local gamma densitometry method. This would be the basis to finalize the development of the local gamma method which consequently could be accredited according ISO 17025. Both methods are designed to be installed at the existing loops.

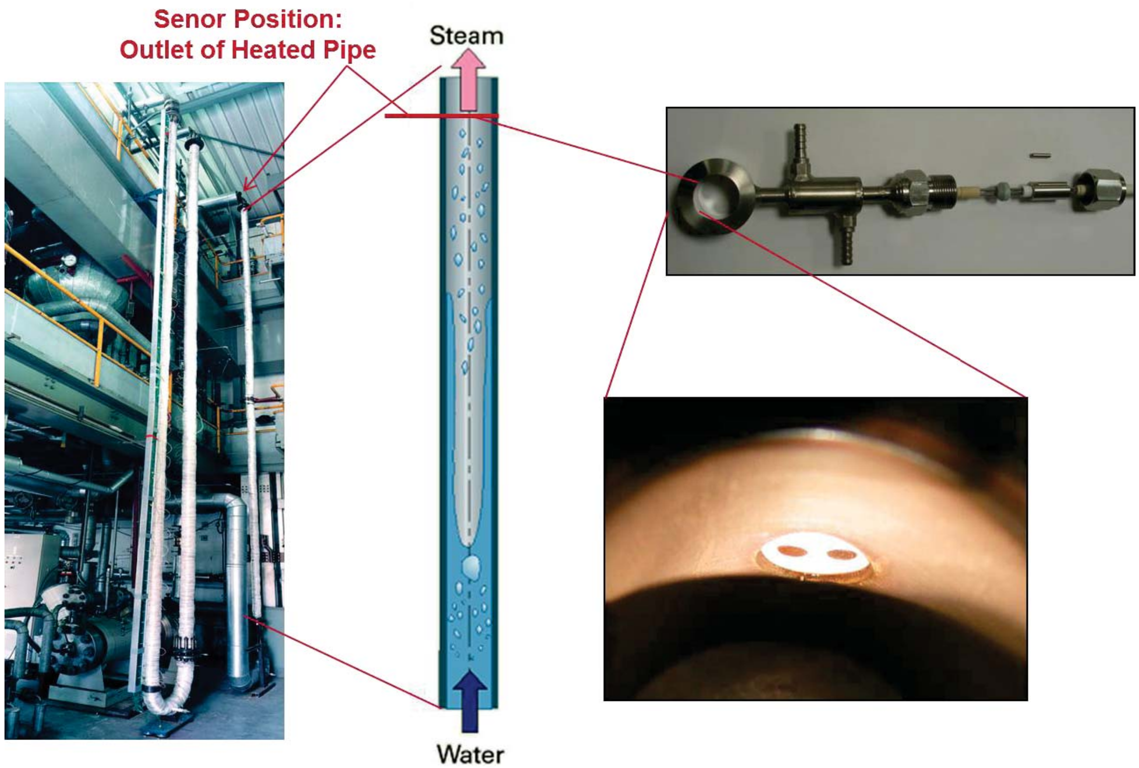

Figure 12: Arrangement of a high pressure impedance probe

Summary

AREVA operates a worldwide unique testing and qualification infrastructure. Due to the accreditation as test- and inspection body according ISO 17025 and 17020 it ensures high quality standards. The different applied measurement methods are under regular review of the related governmental accreditation body. Due to the world wide harmonization of these standards via the ILAC the different locally performed accreditations are valid worldwide. To increase the measurement techniques in the field of local void measurement techniques AREVA has developed two independent methods. The functional qualification process of both methods is finished. These both methods are currently ready to be applied and to deliver reasonable results. But they are currently not established on the level of the accreditation. For that purpose it is the strategy, to cross validate both methods.

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