VOID MEASUREMENT IN BOILING WATER REACTOR ROD BUNDLES USING HIGH RESOLUTION GAMMA RAY TOMOGRAPHY

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Abstract

We present a high resolution gamma ray computed tomography (CT) system that can be used for averaged void distribution measurements in sub-channels of fuel rod bundles. This measurement system generates cross sectional void fraction profiles through the pressure vessel for true-to-scale fuel rod bundles operating under typical nuclear reaction conditions and in steady state. Measurements are non invasive, thus the two-phase flow in the bundle is not influenced. The gamma ray CT system consists of a collimated ^{137}Cs isotopic source, a gamma radiation detector arc including 320 single elements and a pulse processing unit. The average spatial resolution of the CT system is about 2 mm in plane and 8 mm axial. The thermal design of the detector arc is optimised to keep the temperature of internal components constant under changing environmental conditions. A specially developed gantry is constructed to realise vertical positioning and continuous rotation of the CT system. To determine the void fraction distribution two different measurement methods are tested. For the two-point calibration method, data sets at zero and one hundred percent void fraction are required. In another measurement, calibration objects filled with reference materials are used. The non superposed slice image is generated using the filtered back projection reconstruction algorithm.

1 INTRODUCTION

The determination of void fraction distributions in sub-channels of fuel rod bundles under real operation conditions is highly important for the analysis of the critical heat flux (CHF) phenomenon as well as dry-out effects and eventually to increase the safety and efficiency of nuclear facilities. There are thermal hydraulic test facilities for boiling water reactors on which the behaviour of newly designed fuel rod bundles can be tested under authentic operating conditions, i.e. at pressures up to 100 bar and corresponding saturation temperatures of up to 311 °C. Different operating scenarios can be adjusted by varying the electrical current that heats the test bundle as well as the coolant flow rate in the test loop. Currently, many efforts are being spent towards CFD modelling of two-phase flows in heated rod bundles (Glück, 2006 and Krepper, 2007). Since two-phase flow modelling is highly challenging for today's CFD codes, the results must be validated by measurements. In the past many measurement techniques were developed to determine void fraction, e.g. needle probes, wire mesh sensors or optical systems. However, applying measurement devices into environments described above is very challenging for the used materials and the system. Furthermore, such measurement systems can only be applied by implementing openings into the housing of the object that has to be analysed. Therefore, measuring solutions operating non invasively are required. A gamma densitometer may be deliver integral information for an alley of sub-channels using a gamma radiation beam that have enough energy to penetrate the vessel and other material respectively and to generate a good void contrast (Leberig, 2006). The new high resolution gamma ray CT device (Hampel, 2007a) can produce 2-D void distribution images in different planes of a test facility. This measurement system was developed for the analysis of the phase fraction distribution in process applications (Hampel, 2007b and Bieberle, 2007b). For gamma ray computed tomography, a collimated isotopic source is placed opposite to a radiation detector arc that measures the radiation intensity weakened by density differences in the object of investigation. The measured density profile is called a projection. By rotating the measuring system around the object a number of projections can be acquired from different angle positions. Using either analytical or algebraic reconstruction algorithms the material distribution of the measured plane can be reconstructed (Kak and Slaney, 1988).

2 THE MEASUREMENT SYSTEM

The gamma CT measurement system was developed by the Forschungszentrum Dresden-Rossendorf and comprises a collimated ^{137}Cs isotopic source, a high resolution gamma radiation detector arc, a pulse processing unit, a measurement PC and a tomography gantry (Fig 1). The high resolution detector arc consists of 320 single contiguously arranged detector elements. They are operated in pulse mode and can to some degree separate scattered from non-scattered gamma photons. Each detector consists of a scintillation crystal (lutetium yttrium orthosilicate) that is coupled to an avalanche photodiode. The active area of each detector is 2 mm by 8 mm and the detection efficiency is about 75% for gamma photons with an energy of 662 keV (Bieberle, 2007a). Avalanche photodiode technology was used to ensure a successful operation in environments with strong electromagnetic fields.

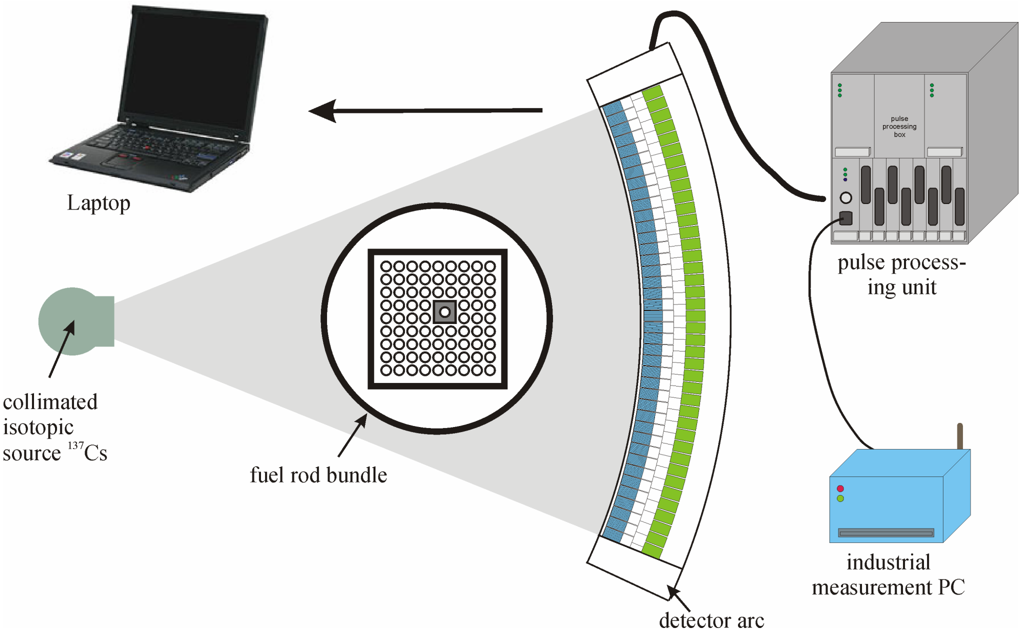

Fig 1: Principle sketch of the gamma tomography measurement system.

The scintillation light from each gamma photon is transformed to a voltage pulse by a charge sensitive preamplifier stage (Fig 2). Here, the signal's amplitude is proportional to the energy of the detected gamma photon. In a separate pulse processing unit pulses are then electrically formed and amplified to an almost symmetrical pulse (Kollar, 2005). A following energy discrimination stage selects those signals whose amplitudes are inside a predefined voltage window. In this way only gamma photons are counted which passed the object of investigation without interaction and deposited their full energy into the scintillation material. The upper and lower threshold voltages are therefore chosen to select the photo peak area out of the interaction spectrum of the used isotopic source. For each approved pulse a 24 bit counter is incremented by one. A 24 bit latch stores the counter values temporarily. The described pulse processing is realised fully parallel. Thus, the pulse count rates of all 320 single detectors can be measured simultaneously, while the data transfer can be accomplished serially. The time needed for a complete data transfer depends on the chosen counter depth. Typically, it takes about 4 ms which is too short to obtain good measurement statistics for the used isotope.

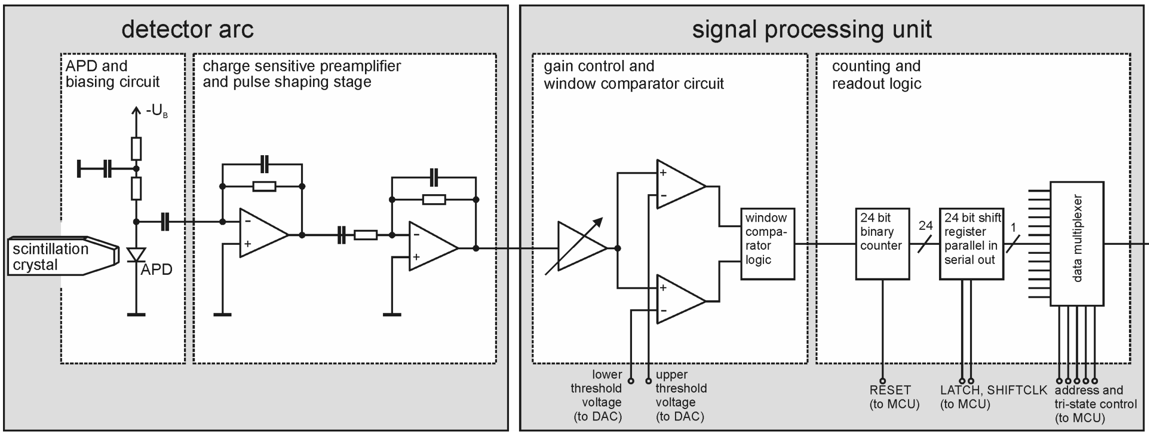

Fig 2: Scheme of the pulse processing electronics.

The thermal configuration of the detector arc was designed to keep the temperature of sensitive components, such as the photodiodes and the scintillation crystals, constant. Therefore, the heat producing amplifier circuits as well as the temperature sensitive devices are placed onto the detector arc's base plate, which was composed of aluminium. An integrated water cooling system maintains the temperature of the base plate's surface and realises an effective as well as homogeneous heat transfer.

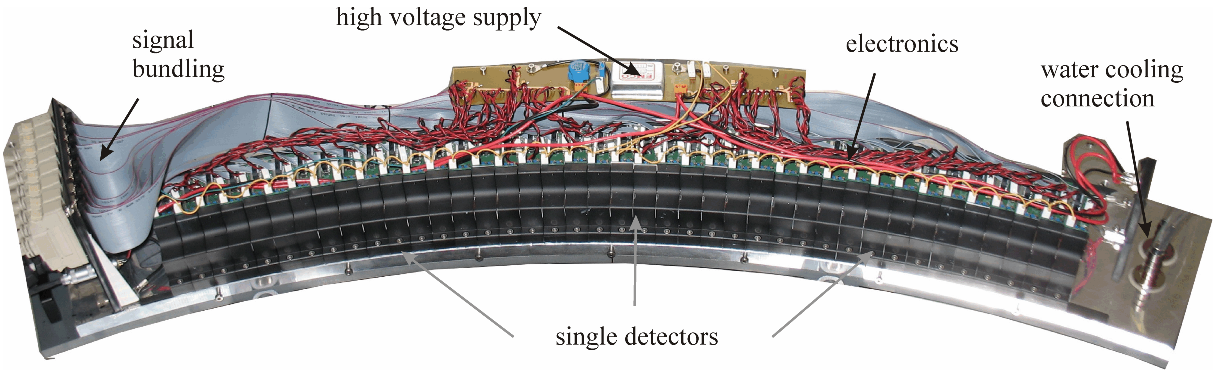

Fig 3: Photo of the opened detector arc.

This allows a nearly drift free operation of the measurement system under varying environmental conditions. For temperature monitoring during measurements 40 temperature sensors are applied, which are homogeneously distributed inside the detector arc. The ^{137}Cs isotopic source which is currently in use has an activity of 165 GBq. The source has a diameter of 5.6 mm and a length of 12.9 mm and is contained in a double welded stainless steel capsule. This capsule is clamped on a chain and is located in a depleted uranium shielding container. The source can be moved outside the shielding container using a bowden cable. To restrict the radiation to a fan beam, a special collimator was fabricated out of the tungsten alloy Densimet^{TM} (Fig 4). The upper face of the collimator has the inverted shape of the shielding container's front to guarantee a tight fixation of the source container to the collimator. This is necessary to keep radiation leakage low. At the front side a 46° wide sector slit forms the radiation fan. The slit height can be varied between 1 mm and 10 mm by additional tungsten plates in order to adjust axial resolution.

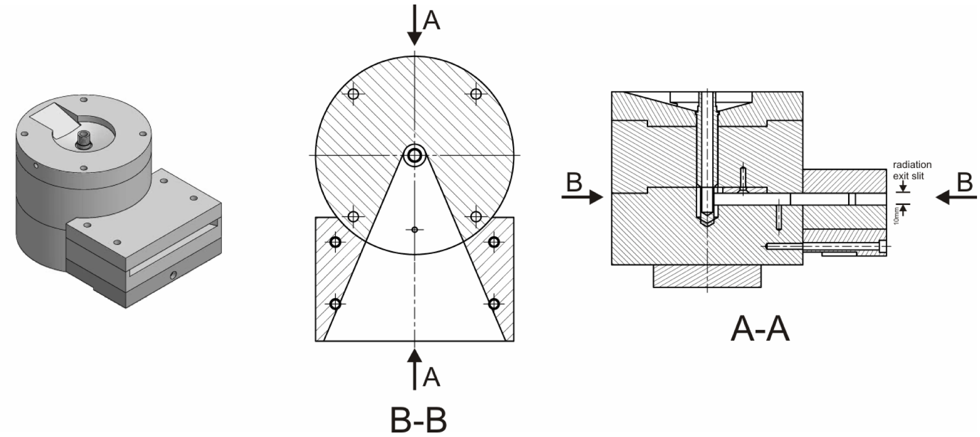

Fig 4: Design and sketch of the isotopic source collimator.

The measurement system resides on a gantry (Fig 5) that realises a vertical and a rotational positioning. Vertical positioning is possible within a range of 2200 mm. The rotating unit consists of a separable ring table on which source, detector arc and electronic components are placed. The ring table is fixed on a gear ring with an external tooth system guided in a roller bearing. A servo motor realises a continuous rotation of the ring table. Electrical slip rings mounted underneath the ring table drive deliver the electrical power to the ring table.

The pulse counters of the detector electronics are completely read out after each angle sensor signal and the counter values are transferred via USB2.0 interface to an additional measurement PC, which is also placed on the ring table. After each tomography measurement the data can be transferred to a second, stationary PC via wireless LAN. An incremental angle sensor with 1000 steps per revolution provides angle signals to synchronise data acquisition with rotation. The rotational speed can be adjusted up to 2 rpm in small intervals. Typically, the rotational speed is set to 0.25 rpm to generate projection acquiring times of 240 ms and more than one revolution are achieved to obtain good measurement statistics.

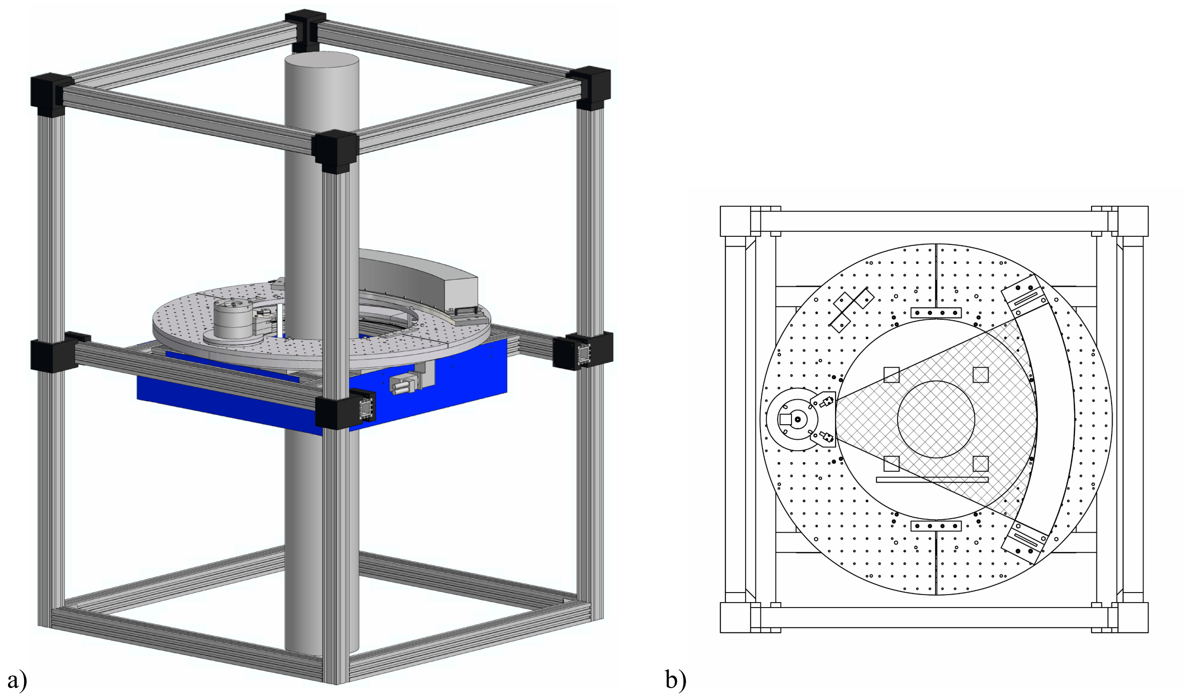

Fig 5: a) 3D CAD drawing of the CT gantry and b) measurement's arrangement on the ring table.

3 IMAGE RECONSTRUCTION

For a complete tomographic scan a count rate data set $\mathbf{N} = \{N_{i,j}\}$ is acquired from $n_p = 1000$ angular measurement intervals, whereas i is the number of detectors ($0 \le i < 320$) and j is the index of the projection angle α with ($0 \le j < n_p$) and $\alpha = 2\pi \cdot j / n_p$. To calculate the extinction sinogram $\mathbf{E}$, there is generally a reference data set $\mathbf{N}^0$ required, which may be obtained from a single projection measurement with no object in the radiation fan or alternatively a complete scan of an object in a reference state, such as a vessel that is either empty or completely filled with a homogeneous substance. The extinction can then be calculated as

$$E_{i,j} = \ln\left(\frac{N^0_{i,j}}{N_{i,j}}\right). \tag{1}$$

The sinogram is used as input for the reconstruction of the cross sectional image $\mu(x,y)$ of the gamma ray attenuation coefficient. One possibility to determine the void fraction distribution in the cross sections of the heated bundle quantitatively is the two-point calibration method. Here, additional scans must be obtained with 0% void ($\mathbf{N}^e$) and with 100% void ($\mathbf{N}^f$) in the bundle. Then the data sets can be scaled according to

$$E'_{\mathrm{i,j}} = \ln\left(\frac{N^{\mathrm{e}}_{\mathrm{i,j}} - N^{\mathrm{f}}_{\mathrm{i,j}}}{N_{\mathrm{i,j}} - N^{\mathrm{f}}_{\mathrm{i,j}}}\right), \tag{2}$$

where $\mathbf{E}'$ is the extinction sinogram which is used to reconstruct a cross sectional void distribution μ(x,y) within the current measurement plane. There are two different types of computed tomography reconstruction algorithms. Analytical reconstruction algorithms aim at the inversion of the Radon transformation. For example, an algorithm called filtered back projection projects each extinction value back onto the image space according to the acquiring conditions. Afterwards, the image is filtered to compensate the error due to the transfer function of the back projection. This reconstruction technique is often used because of its short process time. Algebraic reconstruction algorithms solve the inverse Radon transformation on a discrete basis. Most of them are iterative techniques that construct a sequence of approximate solutions from an initialisation matrix. After each iteration step, the deviation with respect to the original extinction distribution is decreased. Because of the iteration steps algebraic techniques are slower compared to the analytical reconstruction algorithms. But it offers some advantages, such as implementation of a-priori knowledge or single area reconstruction.

The accuracy of the measured void distribution depends on the measurement time, the spatial resolution of the detector arc, the measured object as well as the positioning accuracy and the repeat accuracy of the measurement system. The latter is defined by the thermal stability of the system, whereby the measurement system achieves a counting deviation of lower than 1% for varying temperatures and humidity. The measurement time is limited by the time needed to keep the test facility in steady state. Thus a statistical error occurs. Depositions inside the vessel are also problematic. Due to the fact that rods can change their position i.e. by thermal dilatation, they are no more locally invariant and thus the void determination inside the sub channels is influenced articulately.

4 RESULTS

First measurements showed that both calibration data sets accomplished at 25 °C (100% void) and 270 °C (0% void) offer local invariant parts which lead to inacceptable void measurement errors. Thus, another method was developed. Laboratory experiments with a mock-up, containing the original geometry as well as the material distribution of a typical fuel rod bundle were arranged. Fig 6 shows three reconstructed cross sectional images of the test section filled with gas, water and hexane respectively. To increase the radiographic efficiency, bags were reamed into the outer wall of the test bundle for each measurement plane. The pressure tank section was filled with water and therein four gas filled reference absorbers were placed adjacent to the milled-out portion. Hence, the attenuation coefficient of water and gas can be determined during the void measurement and thus, the calibration measurements can be cancelled. Another advantage of this method is that all required data may be accomplished at the same temperature and therefore density or length chances caused by temperature variations did not occur. Furthermore, a new developed scattering correction method that simulates the first gamma photon's interaction with the object of investigation was executed onto the data to increase the measurement's accuracy. The filtered back projection algorithm was used to reconstruct non superposed cross sectional images of the gas, hexane and water filled rod bundle as shown in Fig 6. As you can see the absorption within the sub channels increases (decreasing brightness). Eventually, the hexane inside the sub channels was determined with a standard deviation of about 2%.

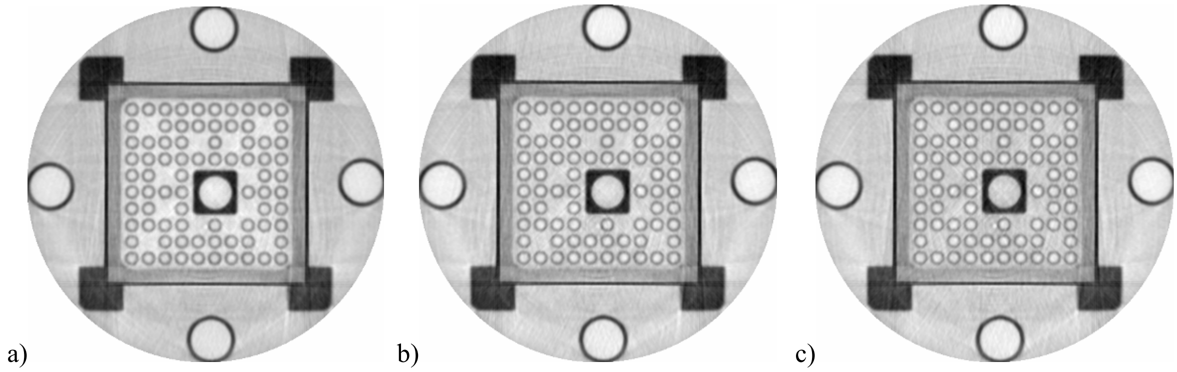

Fig 6: Reconstructed cross-sectional images of the test section of
a) gas filled, b) hexane filled and c) water filled.

5 CONCLUSION

Recently, a sophisticated high resolution gamma ray tomography measurement system was developed to determine void fraction distributions in different planes of thermo hydraulic test facilities for analysing new designs of fuel rod bundles. Therefore, a special gantry was designed to perform tomographic scans in different heights. The 2-D cross sectional void fraction distribution in the bundle can be determined using computed tomography reconstruction algorithms. Laboratory tests have shown that the CT system measures a given test substance in an authentic phantom with a standard deviation of 1.9%. In the future we will attend to optimise data evaluation and the acquiring time.

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