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VALIDATION OF AXIAL VOID PROFILE MEASURED BY NEUTRON NOISE TECHNIQUES IN CROCUS

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ABSTRACT

Recently a joint project has been carried out between the Paul Scherrer Institut, the Ecole Polytechnique Federale de Lausanne and swissnuclear, an industrial partner, in order to determine the axial void distribution in a channel installed in the reflector of the zero power research reactor CROCUS, using neutron noise techniques. The main objective of the present paper is to report on the validation of the results against an alternative measurement technique using gamma-ray attenuation and simulations with the TRACE code. For the gamma-ray attenuation experiments, the channel used in CROCUS is installed out of the core in a Plexiglass water tank. The source and detector are fixed and the channel is moved axially to keep the geometry of the source/detector arrangement untouched. This is key to measure the void effect by gamma attenuation due to the low contrast of this technique. The paper compares the experimental results obtained with both techniques, with the outcomes of simulations carried out with the TRACE code. Even though the quantitative void fraction estimations are not consistent, the trends obtained with the simulation and experimental techniques are the same. The discrepancies between the various experimental techniques and the simulation outcomes are related to the heterogeneous distribution of the water-air mixture in the radial sections of the channel.

KEYWORDS: attenuation measurements,two-phase flow, void measurements

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1. INTRODUCTION

The development of more efficient Boiling Water Reactor (BWR) fuel assemblies raises new questions about the critical heat flux and potential dryout conditions towards the top of the core, especially since the local void fraction can only be calculated. A reliable method to measure the local void fraction or even determine the average void content in a fuel bundle of an operating BWR is highly desirable.

The possibility of reconstructing the axial void fraction profile from the measured in-core neutron noise is one of the major interest of neutron noise diagnostics, since the experimental void determination in BWR cores has never been completely resolved due to its complexity. A theoretical method [1] has been developed at the Chalmers University to do so. In the meantime, experimental activities have been carried out at the Ecole Polytechnique Federale de Lausanne (EPFL) to test the method with experimental data. One step required for the validation of the method is the measurement of the gas phase velocity in a water-air mixture by neutron noise technique. This has been carried out successfully and was reported in [2].

The present manuscript summarizes two other steps towards the validation of the method. First, the derivation of the void content in a water-air mixture from gas velocity measurements is discussed. Such process requires the use of the system code TRACE [3] to produce a relationship between gas velocity and void content. Second, an independent experimental technique is used to determine the void content in the water-air mixture directly, through gamma-ray attenuation measurements. Such measurement is made possible by the low flux level encountered in the reflector of CROCUS: the channel containing the water-air mixture used in the noise measurements reported in [2] can be removed from the core and characterized separately allowing for a completely independent experimental characterization of the water-air mixture.

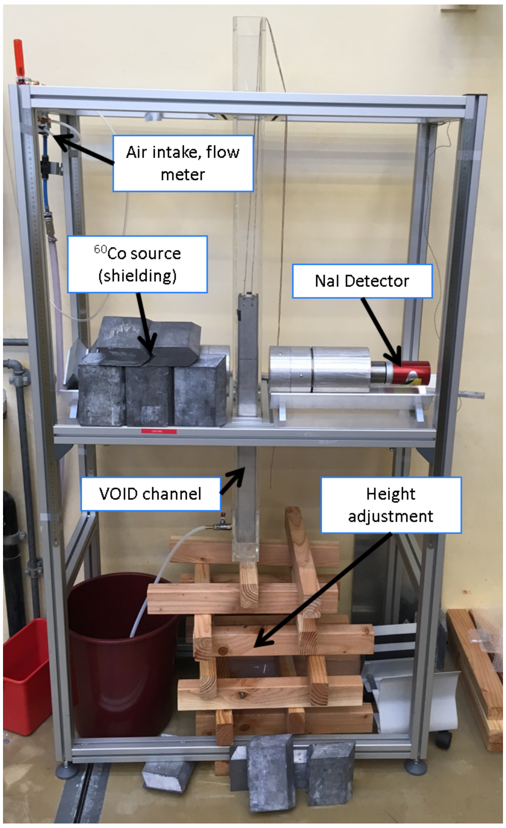
The paper is structured as follows. The second section summarizes the attenuation measurement experimental setup. In the third section, a brief description of the TRACE model used to compute the void fraction in the water-air mixture is provided. The determination of the relationship between velocity profile of the gas phase and the void fraction in the mixture is presented. Finally, in the fourth section, the results of the two experimental methods to determine the void content in the water-air mixture are compared to each other as well as against the TRACE results.

2. GAMMA ATTENUATION EXPERIMENTAL SETUP

The channel containing the air-water mixture is made of aluminum. It is 650 mm long; it has a square flow section of 46 by 46 mm^2 and a wall thickness of 2 mm. Air is injected at the lower end of the channel at a single axial location. A Plexiglas water tank (1200 x 500 x 50 mm^3) contains the channel. The channel is submerged in the tank with its end 10 mm below the water surface to represent the same conditions than in the CROCUS reflector. The Plexiglas tank is held upright by two perforated shelves. It rests on an assembly of wooden planks. A faucet is located at the bottom of the tank to drain it from the water. The source and detector used for gamma attenuation measurements are located on the lower shelf. The experimental setup is shown in Figure 1.

To move the channel axially, a set of wooden planks of identical widths (75 mm) are used, they are inserted or removed below the setup to change the axial position of the VOID channel with respect to the source/detector assembly. As much as possible, the geometry of the source/detector arrangement is kept untouched through the measurement campaign to avoid changes in the count rate. This is key to measure the void effect by gamma attenuation due to the low contrast of this

(a) **Channel with 20 L.min^{-1} air injection**



(b) Overall view

Figure 1: Attenuation measurement experimental setup

technique. The source is a ^{60}Co one produced by Eckert&Ziegler, with an activity of slightly less than 18 MBq. The source is collimated using 4 perforated 4.5cm long lead cylinders, two between the source and the channel; two between the channel and the detector. The collimator has a diameter of 0.5 cm.
The detector is a NaI crystal (model 51B51/M2 from Scionix). It is used in conjunction with an Osprey® multi-channel analyzer (MCA) tube base, which contains a high voltage power supply, preamplifier and a digital MCA. It is coupled with the Genie 2000 software suite for data acquisition. To reduce the effect of gain shift during the long acquitions (typically around 1000s), the Multi Channel Analyzer mode is used, and the number of counts considered in each measurement is the integral of all the counts under the two photopeaks of ^{60}Co.

2.1. Void measurement by gamma attenuation

The determination of the void content in the channel at a given location is obtained by three different gamma attenuation measurements: a measurement with a given air injection flow rate, for which the recorded number of counts is reported as C^{α}; a measurement where no air is injected in the channel, for which the recorded number of counts is reported as C^{full}; and a measurement where the water tank as well as the channel are empty, for which the recorded number of counts is

reported as C^{void}. Strictly speaking, C^{void} corresponds to a case where the tank is full of water and only the VOID channel is empty. The underlying assumption here is that the effect of the water in the tank on the absorption in the channel is low which is reasonable with respect to the width of the tank: the amount of water between the tank and the channel outer boundary is negligible as shown in Figure 1b.
The void content α inside the channel is determined using Eq 1 [4].

$$\alpha = \frac{C^{\alpha} - C^{full}}{C^{void} - C^{full}} \tag{1}$$

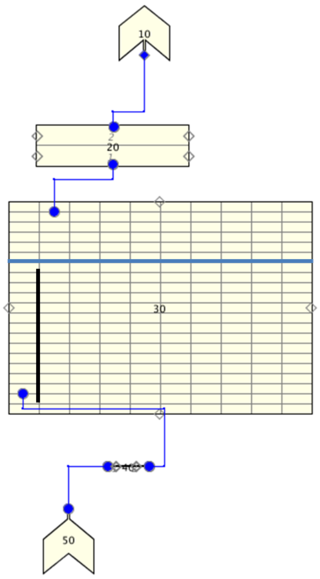
The C's are corrected for deadtime using the estimations provided by Genie2000. The uncertainty for each C quantity is determined as reported in Section 2.2 and the uncertainty of void fraction is determined using the error propagation formula, assuming the various C estimates are uncorrelated.

2.2. Uncertainty estimation

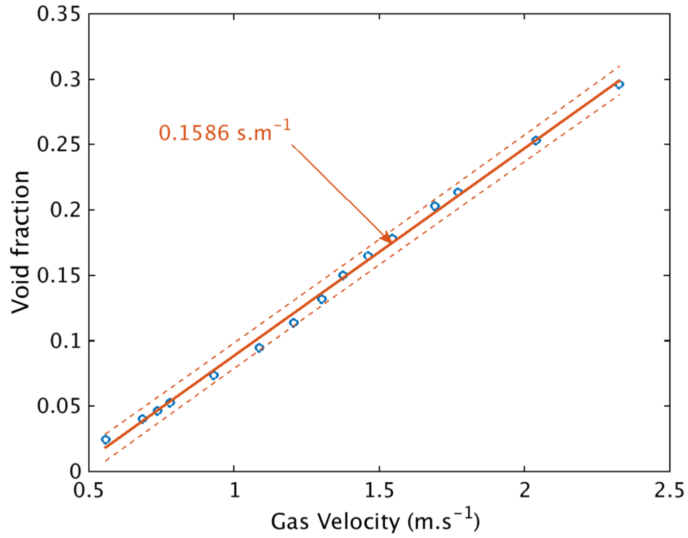
With respect to the random nature of the radioactive decay of the ^{60}Co source, the counting uncertainty has a Poisson behavior. A standard error propagation formula is used to determine the uncertainty on α determined with Eq 1 due to the counting statistics.
As far as the uncertainty related to the axial position of the VOID channel is concerned, all the planks used have the same width with a tolerance of around 1mm, which is negligible with respect to the position uncertainty of the source-collimator-detector arrangement. The latter position is only accurate to around 1cm. Such uncertainty would result in a systematic shift of a given void profile. Consequently, the same setup (set of planks and position of source-collimator-detector) is used throughout the measurement campaign. As a result, the axial uncertainty is of the order of several mm and considered negligible.
Next is considered the uncertainty of air injection rate. According to the manufacturer the accuracy of the flow meter is 5%. However, given the crude graduation (every 5 L.min^{-1}) available on the flow meter as well as the manual nature of the setting, a larger uncertainty of about 10% is assumed. To avoid this source of uncertainty, the air injection setting is kept untouched throughout the various measurements involved in a given axial profile. The main valve of the pressure reducer is used to start/stop the air injection. Large fluctuations ($\sim$10%) in the air injection rates are observed when the injection rate is above 50L.min^{-1}.
The temperature of the water is monitored during the acquisitions and no trend is observed hence no additional uncertainty related to the water temperature is considered in this work.

3. TRACE MODEL

A TRACE model of the channel containing the water-air mixture is established by using SNAP v2.6.01 and TRACE v5.0 patch 3. The experimental setup is simulated using a 3-D vessel component. The channel containing the water-air mixture is represented by cell edges of the vessel component for which both the flow area and the hydraulic diameters are set to 0.0 effectively limiting the flow of the water-air mixture to the z-direction.
The vessel component is modeled with 21 axial levels, 10 cells in the x-direction, and 1 cell in the y-direction. The water level is set to 75 cm, 5 cm above the exit of the void channel, which corresponds to the 15th axial level in the vessel component. The air injection was simulated by the FILL component (50) for which the mass flow rate of air as well as the inlet pressure are fixed



(a) **Model of the experimental setup**



(b) Void fraction vs gas velocity for various mass flow rates for pointwise bubble injections. The dashed lines represent the 95% confidence interval of the fit

Figure 2: Calculation of the void content in the channel with TRACE

to the desired value. The atmospheric pressure in the water tank is simulated by a BRAKE (10) component for which the pressure is fixed at 10^5 Pa. The TRACE model is shown in Figure 2a. The no-flow edges are highlighted in black and the water level is highlighted in blue. With respect to the air injection, the pipe 40 is connected to the first cell of the VOID channel in the negative Z direction. A combination of arbitrary small flow area (10^{-6} cm^2) and hydraulic diameter (10^{-4} cm) is used to keep the pressure high in the pipe 40 and guarantee that no water is flowing out of the system.

According to TRACE simulation results, the void fraction in the water-air mixture and air velocity are constant axially. Plotting void fraction against velocity for various flow rates shows a clear linear relationship between void fraction and gas velocity when the flow rate changes as shown in Figure 2b. A linear fit (ordinary least squares) returns a slope of 0.1586 ± 0.0024 s.m^{-1} with a determination coefficient of 0.9975. Such relationship allows to translate the velocity measured through neutron noise in [2] into estimates of the void content in the water-air mixture. Specifically, the Eq 2 is used for this purpose:

$$\alpha^{NM} = a.v_{NM} + b \tag{2}$$

where a and b are the coefficients of fitting the TRACE results shown in Figure 2b; v_{NM} is the velocity of the gas phase measured through neutron noise techniques and α^{NM} is the resulting experimental void fraction. The results labeled as "Noise Measurements" in the comparison of simulations with measurements in section 4 are obtained using this approach. The effect of the fitting coefficients uncertainty on the final experimental uncertainty for the water-air mixture void content, is estimated using a Monte Carlo method.

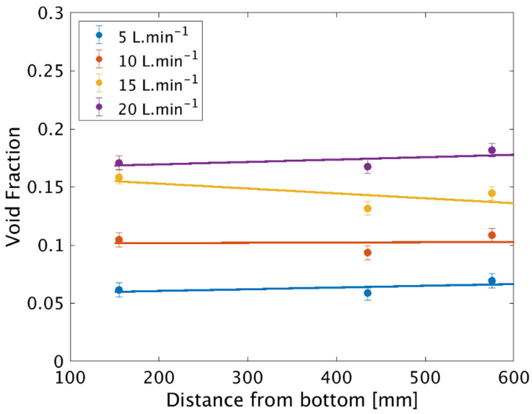


Figure 3: Axial evolution of the void fraction in the channel using attenuation measurements

4. EXPERIMENTAL RESULTS AND COMPARISON WITH SIMULATIONS

The experiments have been performed on June 22^{nd}, October 18^{th}, 29^{th} and 30^{th} 2018. On June 22^{nd}, attenuation measurements are performed at three different axial locations respectively 155, 435 and 575 mm from the bottom of the channel, for volumetric flow rates ranging from 5 to 20 L.min^{-1}. Each measurement is 1000s long to reduce the experimental uncertainty. The detector deadtime is 1%. The deadtime is slightly larger when the channel is voided, but the difference is not significant. The void fractions are determined experimentally using Eq 1 and plotted in Figure 3. A linear fit is performed for each gas mass flow rate, considering the uncertainty of each point in the fitting. A slope of zero cannot be rejected with a 95% confidence level for any of the air injection rate. The void fraction is indeed constant throughout the channel. On October 18^{th} and 29^{th}, additional volumetric flow rates have been investigated with flow rates ranging from 2 to 55 L.min^{-1} at a single axial location since the void fraction is constant throughout the channel. To investigate the reproducibility of the measurement, a final acquisition has been done on October 30^{th} where the source and detector are translated sideways by 4 mm towards the side of the channel. A reduced set of the flow rates considered on October 29^{th} was acquired again. The behavior of the void fraction in the channel with respect to the air injection flow rate is depicted in Figure 4 for the various measurement dates. Void fractions up to 45% are obtained for the largest air injection rate of 55 L.min^{-1}. For a given measurement date and flow rate, the spread between the repeated attenuation measurements corresponding to a specific injection rate is explained by the uncertainty listed in Section 2.2. It seems that the measurements are reproducible at first. However, very large discrepancies are observed between the acquisition of Oct 18 and 30^{th}: for the same volumetric flow rate, the amount of void measured in the channel can differ by up to 45% for large injection rates. Such a large discrepancy would be unexpected for a homogeneous mixture in the channel. However, attenuation measurements only provide information about the average void content along the cord between the source and the detector. Shifting the source detector setup by 4 mm toward one side of the channel led to a large reduction of the air content along the cord which suggests that the mixture in the channel is far from homogeneous. Such phenomenon is well known in the fluid mechanics community and has been reported many times, see for example [5,6]. It shows the limitation of the attenuation techniques for the determination of global void content in a channel.

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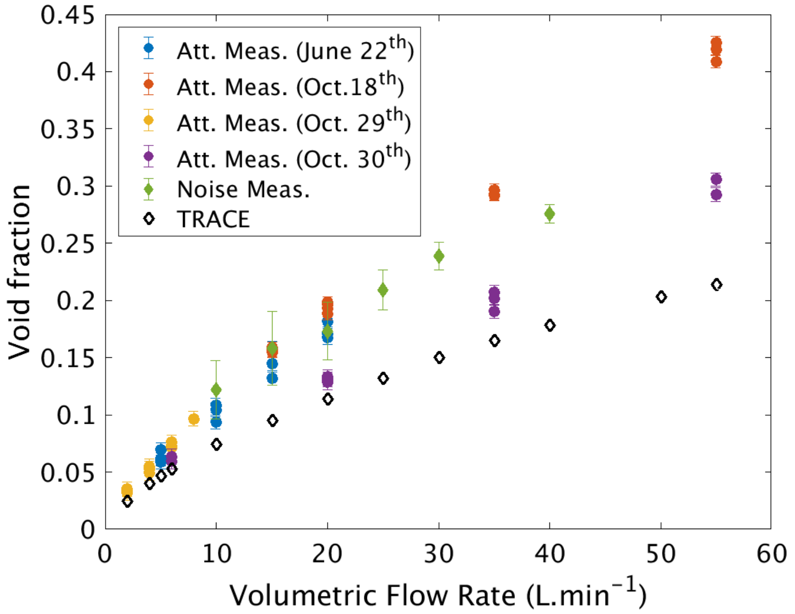

Figure 4: Comparison of void fraction produced through simulation (TRACE) and measurements in the VOID channel through gamma attenuation (Att. Meas.) and neutron noise (Noise Meas.)

The void fraction estimates derived from the gas velocity measurements obtained by noise techniques are also shown in Figure 4 (green diamonds) as well as the TRACE simulation results (black diamond).
Even though the noise measurement based void estimates appear consistent with the early attenuation measurements, such agreement is most likely fortuitous due to the limitation of the attenuation technique stated above. Moreover, even though the detectors used in the noise based estimates are large and sensitive, they may not be able to "see" the full section of the channel either. As such the gas velocity measurement reflected in Figure 4 may not be representative of an "average behavior"; hence it may not be consistent with the quantity computed with TRACE.
Nonetheless, the trends of void content of the water-air mixture in the channel with the air injection rate are similar, which suggests that both measurement techniques are sufficiently sensitive to resolve differences in the void fractions for the air injection rates considered. As shown in Figure 4, those air injection rates correspond to void content between 5 and 40% range.

5. CONCLUSIONS

This paper summarized recent experimental activities carried out at EPFL towards the validation of a theoretical method to reconstruct the void profile in a BWR channel using neutron noise measurements. Specifically, alternate measurements of the void content in the channel through a gamma-ray attenuation technique are reported. The paper also reports on the comparison of the results obtained with both experimental techniques (gamma-attenuation and neutron noise related measurements) and with the system code TRACE. Even though the quantitative void fraction estimations are not consistent, the trends obtained with the simulation and experimental techniques are the same. The discrepancies between the various experimental techniques and the simulation outcomes are related to the heterogeneous distribution of the two-component mixture in the radial sections of the channel. Based on the outcomes of the measurements reported in this work, the following improvements are envisioned for the experimental setup with the objective to produce quantitative estimates of the void content in the channel. For the direct measurements, wire mesh sensors [7] could be used to obtain an accurate characterization of the average as well as local void content inside the channel. A technique making use of thin collimated X-ray beams with high intensity could be tested as well [8]. With respect to the noise measurement technique, a detailed characterization of the field of view of the detectors is required. A potential characterization for such field of view could be done through analog Monte Carlo calculations [9] where the response function of the detector to various patterns of local void content are calculated.

6. ACKNOWLEDGMENTS

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