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Measurement of void fraction in pipes by neutron backscattering imaging technique

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Void fraction of air-water two phase flow has been investigated using neutron backscatter imaging technique. A series of static measurements have been carried out for pipes having different radii and wall thicknesses. The obtained thermal neutron images successfully discriminate between the pipes having different void fraction. Linear relationship describes the values of backscattered thermal neutrons obtained from the reconstructed images and void fraction with some deviations in case of pipe four when buried at 10 cm depth. The obtained results indicate the reliability and effectiveness of the technique for studying void fraction of air-water two phase flow.

Keywords: Neutron backscattering, Imaging technique, Void fraction, Air-water two phase flow, Static measurements

1 Introduction

The two-phase flow void fraction is an important fluid mechanics parameter in several fields. These include, petroleum, chemical and nuclear industries, oftentimes involving harsh media, strict safety restrictions, access difficulties, long distances and aggressive surroundings. Accordingly, there is a growing interest in the use of nondestructive techniques for measuring the two-phase flow fraction. Nuclear based techniques are being considered as one option for improving our understanding of the details of transient two-phase flow structure. These techniques can give information about the void fraction distribution non-intrusively. Photons (X-ray or gamma-ray) detection is, generally, a little less complicated than neutron detection. Gamma-ray attenuation methods[1-4] are successful but sensitive to changes in density of the liquid, sensitive to solid particles in liquids, and cannot be used in large pipes because of high attenuation. Computerized tomography based on using gamma-ray and X-ray has also been used, as a mean to reconstruct the distribution of a gas/liquid two-phase flow over the cross-section of a pipe. These techniques are well established but these are expensive and complicated. Fast neutron attenuation in pipe walls is negligible because of the small fast neutron cross-section of iron. Attenuation, mainly by elastic scattering, is much higher in low mass number materials especially hydrogen containing materials such as water and oil[1].

Several researchers have used neutron scattering methods. In these methods, fast neutrons are incident on a pipe containing liquid and gas[5,6]. The hydrogen atoms in the liquid slow down the fast neutrons. These scattered slow neutrons are measured as a function of liquid level by slow neutron detectors, such as BF_3 or ^3He detectors. In several of the cited applications nuclear reactors are used for the neutron source but this is impractical in many applications. In such neutron scattering measurements, the signal is not linear with the liquid/gas ratio, and in these applications, the signal reaches saturation if the water level is high in large pipes. Fast and thermal neutron radiography has been applied successfully in recent years to measure the void fraction in two phase flow[7-10]. Although the technique can provide useful information about gas to liquid ratios, it is expensive and relatively complicated. Neutron radiography[11,12] depends on the transmission and attenuation of neutrons in a specimen. Slow neutron attenuation by absorption is mainly successful for a specimen that contains atoms with a high slow neutron absorption cross-section such as B, Cd, Gd, Hf and Dy.

Thermal neutron backscattering is a well established method to show the presence of hydrogen. It is used, among others, for landmine detection[13-15]. The neutron backscattering (NBS) method operates by irradiating the surface under investigation with high energy (MeV) neutrons emitted from point isotopic source/sources. The neutrons lose energy by scattering from atomic nuclei beneath the surface and become thermal after a number of collisions. The thermalization process takes far fewer collisions when scattering from hydrogen as compared to other elements. The concentration of thermal neutrons in regions containing hydrogen-rich materials will, therefore, be relatively high. A thermal neutron detector that monitors the neutron flux coming back from their irradiated surface will show an increased count rate above hydrogenous regions. An important advantage of the NBS method is the high speed of operation[16].

Neutron Backscattering Imaging (NBSI) technique has been used successfully in the detection of buried hydrogenous objects i.e. landmines. The two phase flow void fraction in pipes of different radii and wall thicknesses has been investigated using NBSI technique in the present paper.

1.1 Neutron Backscattering Imaging Technique

In the present work, the NBSI detectors consist of eight ^{3}He proportional counter tubes of 1 m length and 2.54 cm in diameter, with position sensitive readout electronics (charge division) as shown in Fig. 1. The tubes are mounted in aluminium tray in a horizontal plane, next to each other with 2.4 mm space in between. The tubes are perpendicular to the scanning direction, thus forming 2D sensitive detector. The coordinates of a detected neutron are determined from the position of the tube hit and the position of the neutron along that tube. The eight ^{3}He-tubes are grouped into two banks with a total sensitive detectable area of 100×22.5 cm^2. Two identical Pu-Be neutron sources with strength of 5×10^6 n/s for each were used. A wider scanning width is achieved by mounting the two neutron sources at 40 cm apart in combination with specially designed steel scatter blocks underneath the sources and a steel reflector above the sources. An almost homogeneous radiation field is obtained[15].

The NBSI system can work in two modes, stationary mode and dynamic mode. The obtained results of the stationary mode are given in the form of 2D-cross-sectional image. This image represents the backscattered thermal neutrons as they emerge from investigated object. Each image was constructed from 32×16 pixels. Each pixel is of area 3.1×3.1 cm^2 and is given by 256 colours fixed by analyzing code. Each colour indicates a zone with thermal neutrons of average number located within the indicated limits for each colour. Image position is denoted by X and Y values, where the value of X and Y is measured from the vertical axis passes through the geometrical center of the detector array and source position.

In Dynamic mode, the image of the intensity distribution of the backscattered thermal neutrons over the object surface is formed while scanning. The pixel area (3.1×3.1 cm^2) was chosen firstly to depict an object hot spot with a diameter of several tens of cm. The hot spot area depends on the object size and the detector standoff distance. During scanning, each tube spends a time of $3.1/v$ s above a row of pixels, where v (cm/s) represents the scan speed. The total measuring time for all detector tubes to completely measure a row of pixels is, therefore, $8\times3.1/v = 24.8/v$ s. The time for the detector to pass over a pixel row i.e., the pass-over-time, is $(8\times3.1 + 8)/v = 32.8/v$. The detector must pass completely over a position to measure the neutron flux at that position. The real length over which the detector has to move is larger than the effective length of the scan by the detector size[15], ≈ 33 cm.

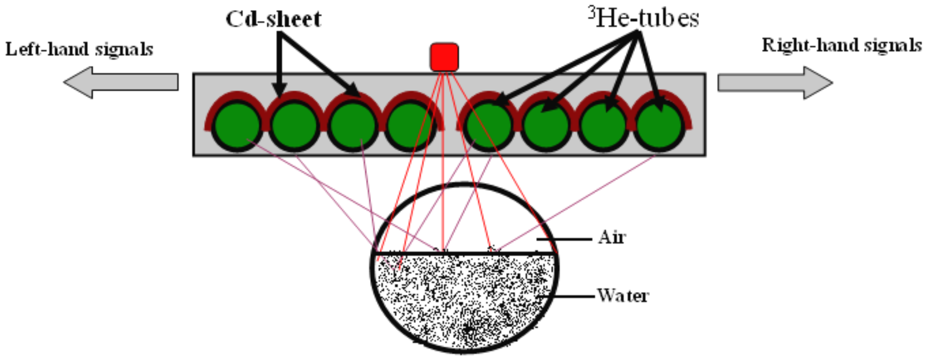

Fig. 1 — Schematic diagram for the experimental apparatus (side view)

2 Experimental Set-up

The experimental set-up is shown in Fig. 1. Polyethylene pipes of wall thickness varying from 0.4 to 0.6 cm and diameters from 4.1 cm to 10.35 cm were used. The specifications and elemental composition of polyethylene pipes used for testing are listed in Table 1. Different levels of water were put inside horizontal pipes and the corresponding backscattered thermal neutrons were measured. The water was static during the whole measurements. The flow regime in this study is of type; stratified smooth flow. The air/water ratio i.e. the void fraction was calculated using the following formula:

$$\alpha = \frac{V_T - V_w}{V_T} \qquad \ldots(1)$$

where α is the void fraction, V_T the total pipe volume and V_w is the water volume. According to Eq. (1), stationary measurements were done for the test pipes (see Table 1) with void fraction varied from 0 to 1. These pipes were shaped to represent water in range of void fractions. Counts were collected with an acquisition time of 120 s. The background count rate was about ≈ 6800 c/s.

Table 1 — Specifications of polyethylene pipes used for testing

Pipe number	Volume cm^3	Wall thickness cm	wt. of ^{1}H g	Wt. of ^{12}C g	Total wt. g
1	675.97	0.4	11.4	68.3	79.7696
2	1078.8	0.4	14.38	86	100.38
3	3274.2	0.4	27.6	165.6	193.192
4	4080.5	0.6	32.87	245.25	286.125

3 Results and Discussion

The intensity of the backscattered thermal neutrons can be determined as a function of position using the position sensitivity of NBSI system. The resulting images will be blurry because of the scattering of the neutrons in the pipe structures but may still give important information about the air/water ratio. The sensitivity over the image varies strongly as the detector edges get less primary neutrons as compared to the center because of the central position of the sources. Corrections have been applied by subtraction of the background image to remove the impact of the source and the surrounding materials[16]. An example of the net 2D-image, its profiles and the intensity distribution of the backscattered thermal neutrons over pipe number four filled with 3600 cm^3 of water (void fraction = 11.77%), are shown in Fig. 2. The displayed images clearly show the system capability for measuring the void fraction. The peaks appear in the profiles are due to the position of the two Pu-Be sources. Measurements were carried out by the empty pipes to study the linearity of the NBSI technique. The measured backscattered thermal neutrons for

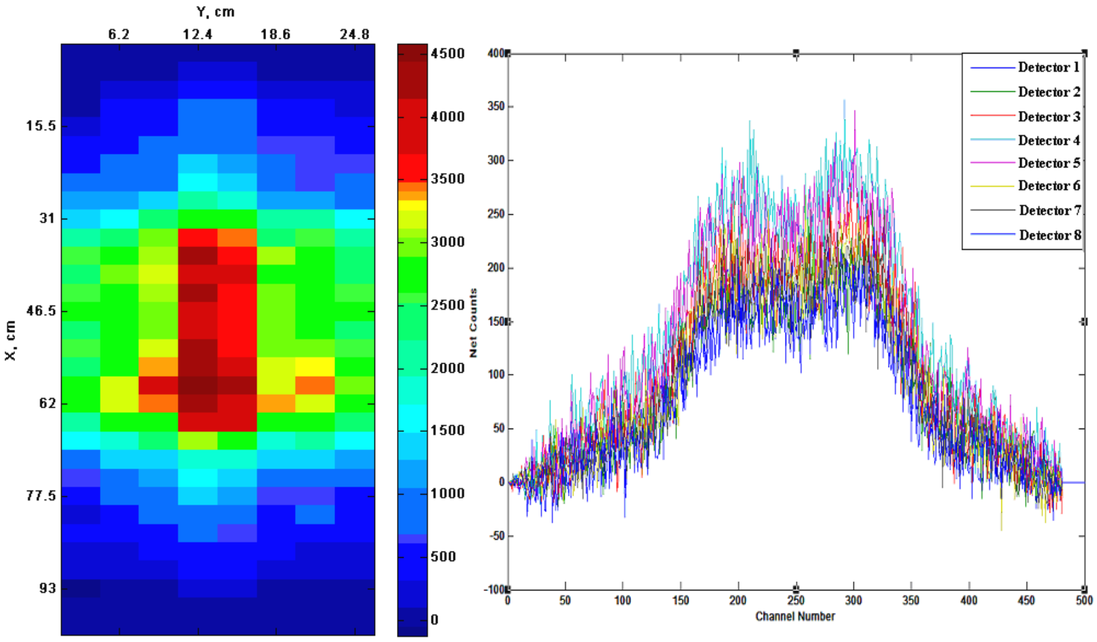

Fig. 2 — 2D-image and its profile for pipe number four with void fraction = 11.77%

these pipes are shown in Fig. 3. The obtained data are distributed along the fitting straight line. This means that the response of NBSI is linear with a correlation factor grater than 0.92.

The geometry used is shown Fig. 1. Although the number of backscattered thermal neutrons depends on several factors, including stand-off distance (~20 cm), sources apart distance = 40 cm, void fraction and the burial depth of the pipe (10 cm at dry sand). The importance of conducting this type of measurements is to check the system workability for measuring the void fraction in the buried pipes. In carrying out all experiments, the same stand-off distance and apart sources distance were used. The number of the backscattered thermal neutrons is almost dependent on pipe wall thickness and pipe diameter for the range of values used in this experiment.

Figures 4-7 show a typical processed 2D-images of backscattered neutron intensity for the test pipes with different void fractions varies in the range 10%-100%. These Figs 4-7 show the relationship between the thermal neutron counts and the air/water ratio i.e. void fraction. The background in these images was removed in two steps: first step by subtracting the background image (empty pipe) from that obtained for a pipe containing certain level of water. Second step; normalizing values of intensity (number of the measured backscattered thermal neutrons) to the maximum value to clarify the difference in contrast in these images. The thermal neutron flux intensity is indicated by coloured columns for neutron counts which vary from-200 to 4500 counts/min. The minimum intensity is indicated by the dark blue colour, while the highest intensity is given by the red one.

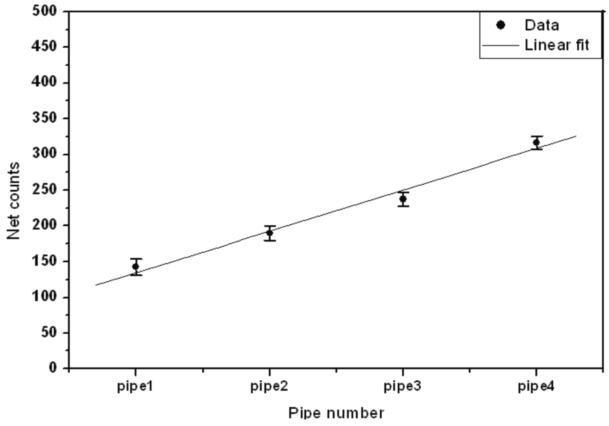

Fig. 3 — Linearity response of neutron backscattering imaging technique

The processed images clearly indicated that, the detected backscattered thermal neutron counts increase sharply with the decrease of void fraction in pipe. These images also show that, the NBSI is very sensitive to small change in air/water ratio. Moreover, Figs 4-7 show that the number of the backscattered thermal neutrons not only depends on the air/water ratio but also on the thickness of liquid column and the exposed surface area. This fact leads us to say the importance of the use of NBSI method in many important applications, such as measuring the leakage rate of oil pipelines.

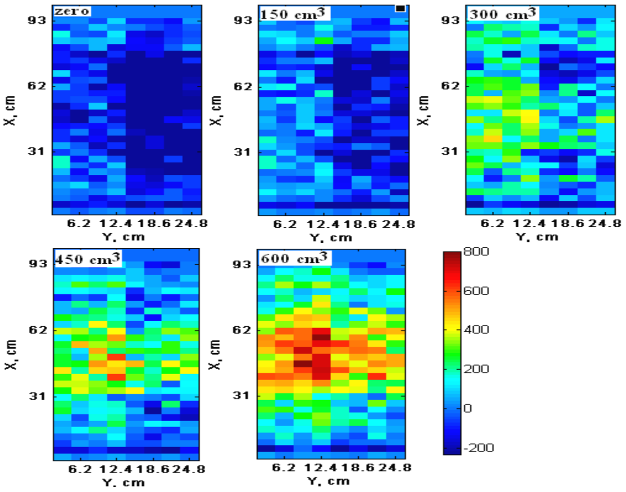

Fig. 4 — 2D images of the intensity distribution for the backscattered thermal neutrons over pipe # one

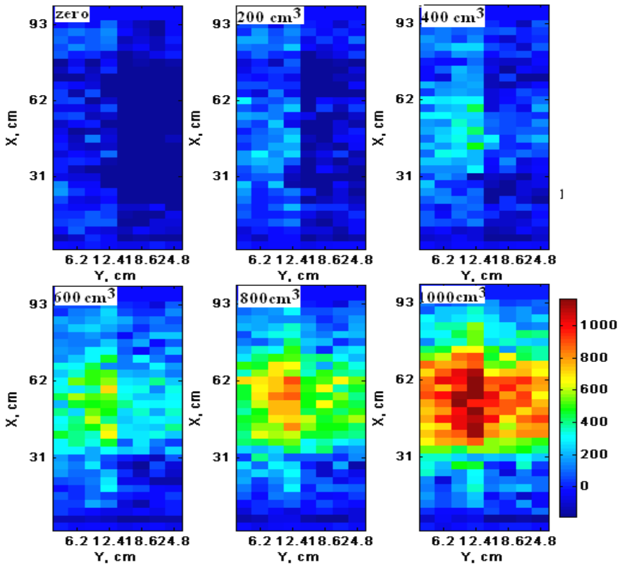

Fig. 5 — 2D images of the intensity distribution for the backscattered thermal neutrons over pipe # two

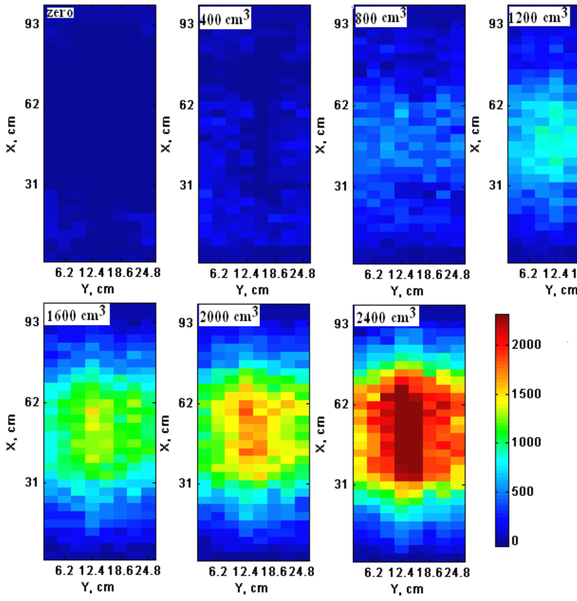

Fig. 6 — 2D images of the intensity distribution for the backscattered thermal neutrons over pipe # three

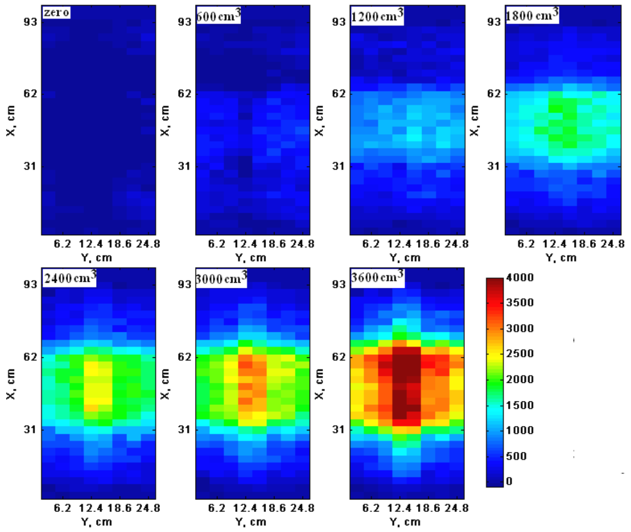

Fig. 7 — 2D images of the intensity distribution for the backscattered thermal neutrons over pipe # four

Figure 8 shows the results of the pipe number four mounted at 10 cm depth. These experiments have been carried out to check the system efficiency for measuring the two-phase flow in the subsurface pipes. There is a sharp decrease in backscattered thermal neutron counts with the pipe depth (Fig. 8). A small amount of addition of water is used in the pipe. In addition, Fig. 8 clearly shows that the statistical fluctuations are relatively high. This could be because of the fact that the relaxation length of the thermal

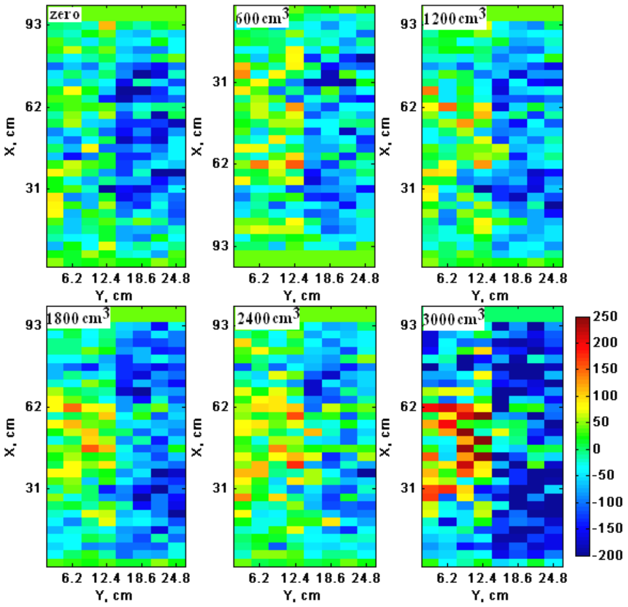

Fig. 8 — 2D images of the intensity distribution for the backscattered thermal neutrons over pipe # four buried at 10 cm depth

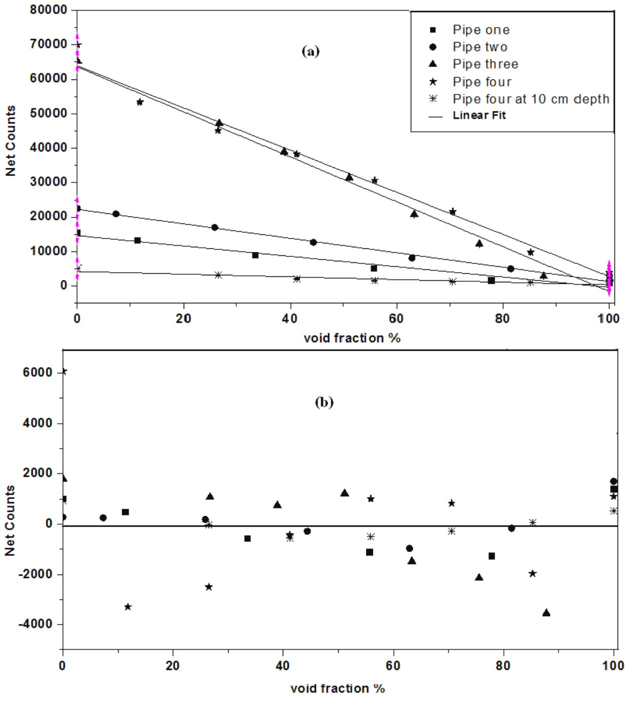

Fig. 9 — (a) Measured backscattered thermal neutrons in pipes of different wall thicknesses and diameters. (b) Deviation from linearity

neutrons is limited by 30 cm in dry sand. Another reason is the relatively large stand-off distance.

Figure 9 shows the cross-sectional averaged void fraction profiles for the same images and somewhat sharper linear response of the thermal neutron counts

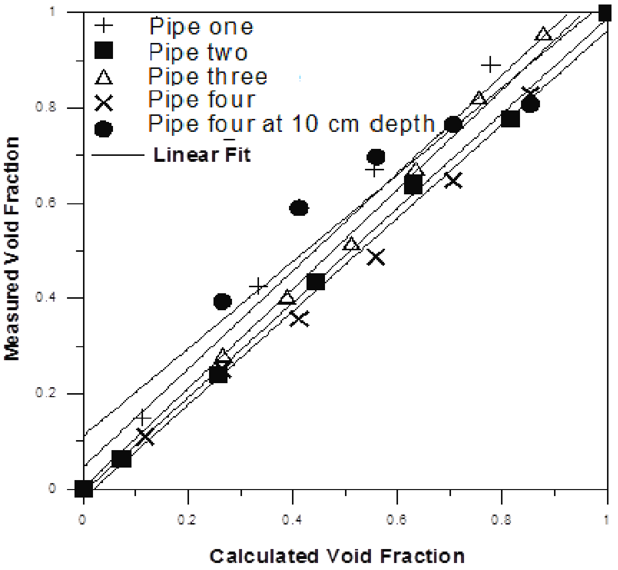

Fig. 10 — Measured void fraction versus calculated void fraction

with the pipe water content. The deviation is relatively large only on the small pipe and the pipe at 10 cm depth. The slope of the line is an indication for the sensitivity of the method to the presence of void fraction.

The measured void fraction was obtained from the following equation:

$$\alpha = \frac{C_{w(i)+a(j)} - C_a}{C_f} \quad \ldots(2)$$

Where $C_{w(i)+a(j)}$ is the count rate of the pipe containing the mixture of water and air by $w(i)$ to the volume of water and a(j) to the volume of air; C_a is the count rate for empty pipe and C_f is count rate when the pipe filling with water i.e. void fraction = 0.

Figure 10(a) shows the relation between the measured void fraction which obtained according to Eq. (2) and the calculated void fraction. The data are distributed equally around the fitting straight line. This means that, the deviation between the measured and calculated void fraction is less than 7% for all the test pipes as shown in Fig. 10(b). The deviation value increases up to 13% only for the pipe four which was buried at 10 cm depth. This can be attributed due to the statistical fluctuation. Figure 10 indicated the sensitivity and reliability of the proposed system to apply successfully for two-phase flow void fraction measurements.

4 Conclusions

The objective of this investigation was to establish a NBSI technique to non-destructively measure the void fraction. The technique was tested by performing a series of measurements to determine the void fraction in pipes. Preliminary experimental results demonstrated that the NBSI technique is sensitive in detecting void fraction in surface and subsurface pipes. The detected thermal neutron count increases sharply with addition of a small fraction of water. Although water was static (no flow), the result should not be different from flowing water as the average volume fraction. The NBSI accuracy was examined by comparing the experimental and calculated results. Compared to neutron radiography, NBSI is much simpler, portable, easily used in field measurements, is much less expensive and can measure flow in many pipes in relatively short time. As well as, NBSI technique is more suitable for horizontal and vertical pipes since this technique is using one sided image approach. Further, investigation should be done for different pipe types and at different stand-off distance. More measurements should be made to test the effect of pipe depth at different environment conditions.

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