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# Application of Neutron Techniques to the Measurement of Two-Phase Flow Parameters

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SUMMARY The application of neutron beams to the measurement of two-phase flow is reviewed and preliminary experiments are described. Because neutrons are appreciably affected by interaction with hydrogen atoms, techniques based on neutron scattering and transmission are particularly suitable for use with water or other hydrogenous fluids. Atomic 'labelling' of flowing systems by activation with fast neutrons has also been utilised. The important features of these techniques are that the flow is not disturbed in any way and, since the effects of commonly used metals on neutron beams are relatively weak, special materials for pipework are not required. Measurements may be made of phase distribution, mean void fraction and flow velocity. In the experiments reported here, low intensity beams of predominantly low energy neutrons have been used to irradiate polythene test pieces shaped to represent water in a range of void patterns and void fractions. The results are evaluated and the benefits and problems of the methods are discussed.

## 1. INTRODUCTION

Neutrons are appreciably affected by interaction with hydrogeneous materials but less so by metals commonly used in industrial pipework. Hence neutron beams can provide a powerful tool for the investigation of the flow of hydrogenous fluids, particularly steam/water, in thick steel pipes. Such measurements can be obtained by other techniques, but these are usually difficult to perform without interfering with flow conditions, or they may require special pipework. For example, if γ- or X- rays are used, the effect of the steel pipe may be considerably greater than that of the water; therefore either special 'windows' must be installed in the pipe or strong radioactive sources must be used. Because of the relatively weak attenuation of photons by the water, such methods are also unsuitable for short fluid path lengths or high void fractions. In the case of ultrasonic methods, there are difficulties in probing the full depth of a fluid in which large vapour regions exist, such as in annular flow, because of the reflection effects at the phase interface and the poor transmission in vapour.

This paper reviews various neutron techniques for measuring phase distribution patterns and mean void fraction and also notes the use of neutron activation techniques for the measurement of flow velocity. Because it is inappropriate to give an extensive bibliography in a paper of this type, a survey is made of recent work to represent the present state of the art.

Preliminary experiments to obtain design data for a voidage measuring system for an existing high pressure water rig are described. The main project is a pilot experiment with the objective of developing techniques for measurements in larger-scale industrial applications.

## 2. NEUTRON PHYSICS

Most of the background on the use of neutrons in monitoring two-phase flow can be found in the literature on radiation shielding technology (see for example Price et al. (1957)), consequently only the basic concepts will be mentioned here in an attempt to clarify terminology.

Neutron interactions with atomic nuclei can be very dependent on the neutron energy and hence on the neutron velocity. For the present discussion, the term 'thermal neutron energy' will be used to denote energies around 0.025 eV and 'fast neutron energy' for those above 0.5 MeV. Neutron sources produce fast neutrons which have to be slowed down, or moderated, if thermal neutrons are required. When neutrons pass through matter they interact with atomic nuclei to cause scattering, with a change of direction and energy, or absorption (capture), i.e. removal from the beam. The change in energy with scattering is most pronounced with hydrogen, in which the atomic nucleus is about the same mass as a neutron. The parameters describing the probability of such collisions are the microscopic scattering or absorption cross sections (the 'effective' areas) of the target nuclei. These cross sections tend to be larger for low energy neutrons than for high, but sometimes there are also large resonance peaks.

A quantity used in shielding calculations is the total macroscopic cross section, $\Sigma_t$, of a substance; this is the sum of scattering and absorption microscopic cross sections at a particular energy, per unit volume. It can be used to calculate, in a simple case, the number of uncollided neutrons n(z) which would pass through a slab of homogeneous material of thickness z from the incident neutron population n(O) at the particular energy, by the expression

$$n(z) = n(O).e^{-\Sigma_t z}. \qquad (1)$$

where, for single atomic species $\Sigma_t = \frac{\rho . N_A . \sigma_t}{M_m}$,

ρ is density of the material, $N_A$ is Avogadro's number, $M_m$ is the molar mass of the material and $\sigma_t$ is the sum of the atomic scattering and absorption cross sections.

Materials of particular interest in the work presented here are water, steel and cadmium. Water, being hydrogenous, produces very rapid thermalisation of neutrons. It has a total macroscopic cross section of about 3.5 $cm^{-1}$ for thermal neutrons. The macroscopic cross-section of iron for thermal neutrons is about one third that of water. Cadmium has a large absorption cross section at energies below about 0.2 eV but a small cross section at energies above that, so it is an extremely useful material for shielding against thermal neutrons.

## 3. VOIDAGE MEASUREMENT WITH NEUTRONS

Various operating modes can be used to exploit the effects of water on neutron beams as techniques for the measurement of void fraction, i.e. the fraction of pipe cross section occupied by vapour. The incident neutron beam may be composed predominantly of either fast or thermal neutrons, and also contain neutrons of intermediate energies. The void fraction may be inferred from the count over a time interval of neutrons transmitted through or scattered by the fluid. The choice depends upon the type of voidage measurement required (whether detailed flow structure or mean void fraction), the size of pipe, and the range of void fraction (whether near zero or unity).

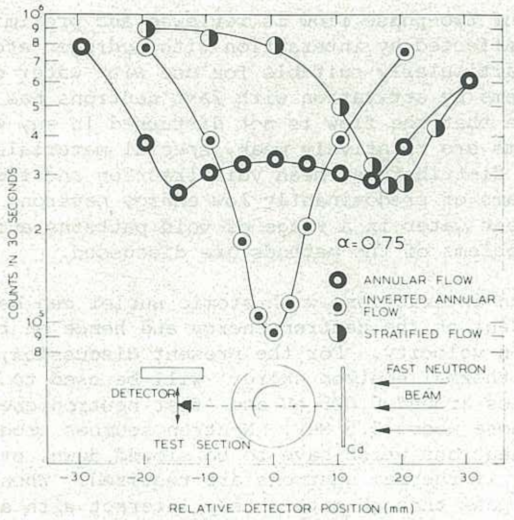


Figure 1 Void pattern detection (ex Banerjee et al. (1978))

### 3.1 Transmission of Fast Neutrons

In this method, a collimated beam of fast neutrons is intercepted by the pipe carrying the fluid and a neutron detector is sited so as to detect neutrons which have been transmitted through the fluid. In particular, this method has been used to determine void distribution pattern because the neutron count rate is affected principally by the liquid along a chord between the neutron source and the detector. A description of the use of this method on 50 mm pipes, exposed to a beam of fast and lower energy neutrons from a nuclear reactor was given by Banerjee et al. (1978). A sketch of their experimental arrangement is given in Figure 1, together with some results from tests on various void patterns made by a combination of water with shaped aluminium blocks to simulate the steam content. For core flow (inverted annular flow), where the liquid is centrally disposed and surrounded by a vapour annulus, the count rate was much less on the central chord than at the edges of the flow path. For annular flow, where the phase disposition is reversed, the count rate was higher on the central chord than halfway to the 'pipe wall'. Near the edges of the flow path, the neutron beam traverses a short span of fluid, consequently the count rate increases again. Similar effects govern the response to stratified flow.

Since a $^{3}He$ detector as used by Banerjee et al. would normally be much more sensitive to thermal than fast neutrons, it is not clear what proportion of counted neutrons was, in fact, transmitted without collision and what proportion was due to scattering, but the general results are consistent with the explanation given. To determine the mean void fraction across the pipe section, the separate transmission counts taken over the pipe diameter segments would have to be suitably averaged.

### 3.2 Scattering of Fast Neutrons

Direct information on the mean void fraction can be obtained by counting the neutrons scattered by the fluid. Detectors are arranged out of the beam path at the side of the test section, and are shielded to ensure that they only receive neutrons which have been scattered within the test section. This method was also investigated by Banerjee et al. (1978) for a 50 mm diameter pipe using the fast neutron source described above. The method is thought to be relatively independent of void pattern because the detected neutrons have undergone several collisions and may have come from any part of the fluid across the section. Two diametrically opposed detectors were used to improve the counts by averaging, particularly for stratified flow where the bulk of the liquid is entirely on one side of the pipe. The count rate was found to be a linear function of void fraction over the whole range.

### 3.3 Transmission of Thermal Neutrons

A scheme suitable for the measurement of high void fractions in small pipes was described by Frazzoli and Magrini (1979). This work utilised a thermalised neutron beam from a $^{252}Cf$ source and Plexiglas/air test sections. The system nominally detected transmitted neutrons, i.e. those passing through the fluid without collision. The beam width, pipe and detector diameters were all nominally 25 mm so that the arrangement provided a measure of the average void fraction. With this arrangement, it is impossible to distinguish between directly transmitted neutrons and those which have reached the detector by multiple scattering. However, it was apparently possible to fit the measured characteristic of count rate as a function of voidage, for annular flow at void fractions above 0.5, with a relatively simple calculation based on equation (1) and the assumption that any neutron would be lost after a single collision and therefore would not reach the detector. Such an analysis would only apply up to a fluid thickness that is barely greater than the neutron mean free path in the fluid; for water at STP this is about 3 mm. The analysis was used to predict the count rate/void fraction relationship for the annular flow of water/steam mixtures in thermal equilibrium at 7.8 MPa, from the results of the tests with Plexiglas/air.

## 4. FLOW VELOCITY MEASUREMENT WITH NEUTRONS

Neutron activation provides a means for the non-intrusive measurement of flow velocity of a water/steam mixture. A short burst of high energy neutrons is passed into the flow channel to produce a radioactive isotope of nitrogen by the $^{16}O$ (n,p) $^{16}N$ reaction which has a threshold of about 10 MeV. The isotope $^{16}N$ emits gamma radiation with a main spectral peak at about 6 MeV and a half-life of about seven seconds. A gamma monitor at a given distance downstream detects the gamma emission and an average fluid velocity may be found by analysing the time delay between neutron burst and received signal. This technique generally requires a particle-accelerator to produce the short bursts of high energy neutrons. The liquid and vapour are activated and, depending on the velocity and density gradients in the fluid, the count rate versus time signal will be degraded from the initial pulse shape and so special attention must be paid to the method of time analysis. Recent experiments using this technique were performed by Kehler (1978) for use in nuclear reactor safety studies. These tests appear to have been made only with air/water mixtures in pipes of 75 and 125 mm bore.

## 5. EXPERIMENTS

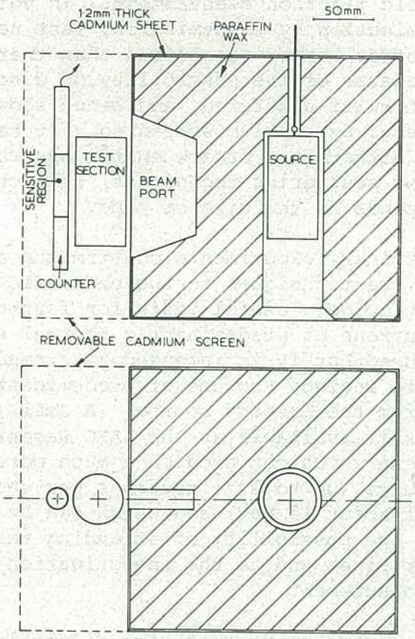


Figure 2 Typical experimental arrangement

### 5.1 Experimental Equipment

The aim of the present work is to measure void pattern and average void fraction in a 50 mm bore pipe carrying a high void-fraction steam/water mixture at a pressure of 1.5 MPa. It is part of a series of assessments of various types of two-phase flow instrumentation. Initial experiments were made using predominantly thermal neutrons; test materials were polythene pieces shaped to represent the liquid phase in various void patterns and air to represent the vapour phase. Polythene is a hydrogenous material which, experimentally, gives similar neutron attenuation and scattering results to water.

A typical experimental configuration using simple, easily constructed equipment, is shown in Figure 2. The 0.37 TBq, $^{239}$Pu-Be neutron source produces 1.7 x $10^7$ neutrons per second at around 5.5 MeV. This source is raised from its storage flask into an assembly comprising blocks of paraffin wax fully enclosed by, except for the source entry channel and neutron beam emission port, 1.2 mm thick cadmium sheets. The experimental test section is placed in front of the port and a 12 mm $BF_3$ neutron detector (mainly sensitive to slow neutrons) is placed according to the type of experiment discussed below. The configuration is, in general, based on that of Frazzoli and Margrini (1979). Neutrons from the source are substantially thermalised by the paraffin wax and then absorbed by the cadmium. Cadmium sheets surround the experimental chamber to shield the experiment from stray scattered neutrons and minimise the background counts. All neutron counts were taken over 100 second intervals. The neutron beam from this arrangement will be predominantly at thermal energies.

Three experiments have been performed with this equipment, each experiment having a different configuration. The effect of void pattern has been tested by simulating annular and core flows. The latter is expected to occur only with heated pipes but it was used in this experiment as a contrast to annular flow.

### 5.2 Void fraction Measurement by Transmitted Neutrons

The scheme for the measurement of mean void fraction by the detection of transmitted neutrons is shown in Figure 3, together with experimental results. In this case, the test section is located at right angles to the position shown in Figure 2; the total test section diameter is thus irradiated by predominantly thermal neutrons for about 16 mm of the test section length. Since the sensitive region of the detector is about 50 mm long, the detector is placed at right angles to the test section to enable it to count over the whole test section width.

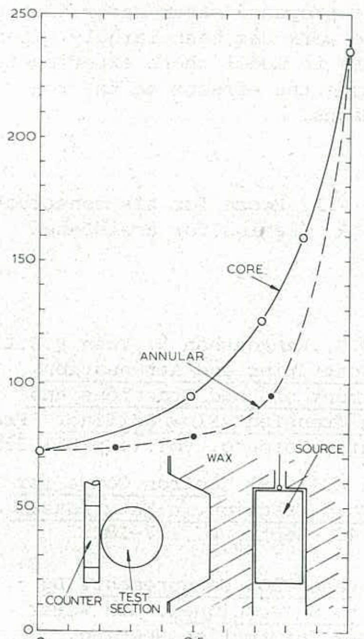


Figure 3
Void fraction by transmission

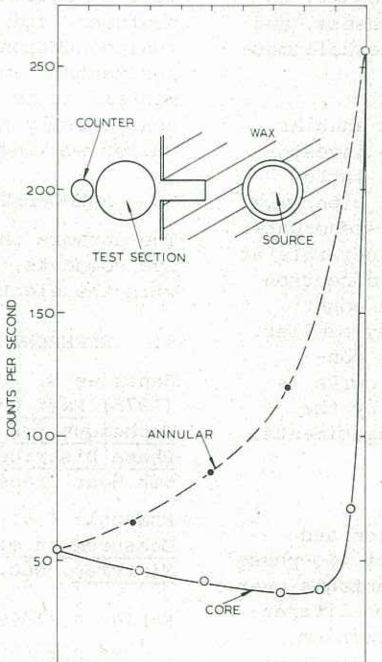


Figure 4
Narrow beam transmission

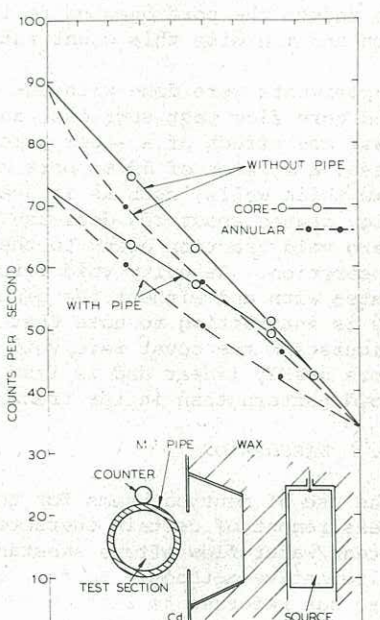


Figure 5
Void fraction by scattering

The results show an increasing count rate with increasing void fraction, as fewer neutrons interact with the progressively decreasing number of target nuclei. There is a noticeable difference between the simulated annular and core flow patterns, the annular flow giving a highly sensitive characteristic above a void fraction of about 0.7 but a much less sensitive characteristic below this value.

A transmission experiment with a narrow beam of neutrons shows the effect of void pattern on a local measurement. The configuration is that shown in Figure 2. Nominally the beam is 16 mm wide across the test section diameter. The detector is aligned to be within the beam. The simulated core flow results, given in Figure 4, show that the counts decrease sharply as the void fraction is reduced from unity to about 0.95 because, in this case, the mass of material is completely within the beam and, at about 0.95 void fraction, the core fills the full width of the detector. As the core increases beyond this, with void fraction approaching zero, the counts increase slightly, presumably due to scattering of the imperfectly collimated beam. For the annular flow pattern, the material is spread around the test section periphery, so the narrow beam only passes through thin layers at high void fractions. With decreasing void fraction the change in count rate is therefore more gradual.

### 5.3 Void Fraction Measurement by Scattered Neutrons

To investigate the detection of mean void fraction by measuring scattered neutrons from an incident neutron beam, the equipment was arranged as shown in Figure 5; this figure also gives experimental results. The test sections were again placed in the beam so that the whole width was irradiated for a short distance along the axis. In this case, the detector was placed at the side of the test section, out of the direct beam. Nominally, only neutrons scattered by the test section reach the detector; in practice, the count rate with unit void fraction is finite because of imperfect collimation and screening and from the contribution from neutrons scattered within the experimental chamber. For this experiment it was necessary to cover the beam port sides with cadmium sheets, and to reduce the port opening to improve the collimation and minimise this count rate.

Experiments were done with the simulated annular and core flow test sections, and also to investigate the effect of a steel pipe. In the latter case, a section of 50 mm bore mild steel pipe with 4mm thick walls, such as is used in the steam/water rig, caused about 20% decrease in the count rate at zero void fraction owing to the increased neutron absorption. At unity void fraction, the count rates with and without the pipe were very similar. It is interesting to note that with this configuration the count rate/void fraction curve is more nearly linear and is less affected by the void pattern than in the transmission experiments.

## 6. DISCUSSION

The use of neutron beams for the detection and measurement of certain characteristics of two-phase steam/water flow offers substantial advantages over alternative methods. So far, most of the literature has referred to tests with water/aluminium, hydrogenous plastics/air or water/air to simulate water/steam. These generally provide reasonable models of the fluid at low temperature and pressure conditions but they become less applicable when temperature and pressure rise, with an accompanying fall in water density and increase in steam density. Seemingly, transmission methods are suitable for void pattern determination; scattering methods, being more independent of void pattern, are better for mean void fraction measurement. In void pattern determination by transmission, fast neutrons appear to offer better resolution than thermal neutrons because of the possibility of discriminating against multi-scattered, and hence slowed down, neutrons, e.g. by cadmium screening. It has been shown that either fast or low energy neutrons are suitable for scattering techniques; the choice largely depends on the size of pipe.

These preliminary experiments confirm the applicability of the techniques to two-phase flow measurements and provide a useful basis for further work. So far, neutrons of predominantly thermal energies have been used but it is intended to extend the experiments to include the use of predominantly fast neutrons from the present source. A small particle accelerator is available at the AAEC Research Establishment which can produce a much more intense neutron source (up to $10^{11}$ neutrons per second at energies of about 15 MeV) and which can be pulsed. This gives the possibility of extending the work to much larger pipes and to the investigation of flow velocity measurement.

The use of neutrons presents some difficulties:
(a) It is difficult to calculate the response of the system in any but the simplest of cases.
(b) Neutron beam characteristics determine the optimum pipe sizes and void fractions for which the methods may be used effectively.
(c) There are biological hazards in the use of neutrons. Care must be exercised in the design and placement of shielding. Residual radioactivity induced in the pipework, etc., must also be considered.

## 7. CONCLUSIONS

Neutron beam techniques are a useful addition to available techniques for measurements in the two-phase flow of water and other hydrogenous fluids. They have particular advantages for high pressure systems in small pipes and for high void fractions. To complete this initial investigation, the work must be extended to include tests with beams of fast neutrons, and also to simulate more closely the actual conditions of the proposed steam/water flow experiments. So far the work has been largely experimental; it is necessary to model these experiments analytically to estimate the effects at the required working conditions.

## 8. ACKNOWLEDGEMENTS

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