*Int. J. Multiphase Flow* Vol. 14, No. 4, pp. 401–412, 1988
Printed in Great Britain. 

0301-9322/88 \$3.00 + 0.00


# MEASUREMENT OF VOID FRACTION BY A NEUTRON-SCATTERING TECHNIQUE WITH PORTABLE SOURCES: EFFECT OF THE INCIDENT ENERGY SPECTRUM

P. S. L. YUEN,[1]† D. A. MENELEY[2] and S. BANERJEE[3]
[1]McMaster University, Hamilton, Ontario L8S 4M1, Canada
[2]University of New Brunswick, Fredericton, N.B. E3B 5A3, Canada
[3]University of California, Santa Barbara, CA 93106, U.S.A.

(*Received* 1 *September* 1987; *in revised form* 10 *February* 1988)

**Abstract**—When a hydrogenous gas–liquid mixture is exposed to a source of fast/epithermal neutrons, the scattered neutron flux depends on the total amount of hydrogen in the test section, and hence the void fraction. For the technique to be useful in measuring the averaged void fraction, the scattered flux should vary linearly with void fraction and be independent of flow regime. It is shown in this paper that the desirable characteristics of linearity and flow regime independence are only obtained for optimum incident neutron energy spectra. These "optimum" spectra depend on pipe size, pipe wall thickness, neutron shielding and reflection around the experimental setup. The optimum spectra may be obtained in practice by Monte Carlo calculations.

*Key Words:* two-phase flow, void fraction, void fraction measurement, density measurement, non-destructive measurement, neutron scattering, neutron moderation

## 1. INTRODUCTION

Two-phase flows occur in many industrial situations. Examples are flow boiling in nuclear reactor cores and in steam generators, gas–liquid mass transfer in packed beds and fluidized bed reactors. To understand heat, mass and momentum transfer mechanisms, and predict transfer rates in these systems, it is often necessary to know the volume fraction of each phase at the cross-section. Literature surveys (Hewitt & Lovegrove 1976; Lahey 1978; Banerjee & Lahey 1981) indicate that a variety of techniques exist for measurement of this parameter. These techniques include volumetric, electrical, optical, ultrasonic and radioactive principles.

In spite of considerable research on a wide range of void fraction measurement techniques, a need still exists for a non-intrusive method that can be used for two-phase flow through complex geometries and thick-walled pipes. This has led to the use of epithermal/fast neutrons for measurement of void fraction by Rousseau *et al.* (1978) and Banerjee *et al.* (1978a, b, 1979). These neutrons can penetrate considerable thicknesses of metal and are very sensitive to the presence of hydrogenous material which thermalize the incident neutrons. The thermalized neutron flux will vary with the amount of moderating material in the beam path. Preliminary work (Rousseau *et al.* 1978; Banerjee *et al.* 1978a, b, 1979), where the source neutrons were extracted from nuclear research reactors, indicated that the thermalized neutron flux was largely independent of the flow regime and decreased linearly with void fraction. These two properties are important in the practical application of the technique. First, the flow regime is not known *a priori* in such applications, so separate calibrations for each flow regime cannot be used. Second, if the scattered flux does not change linearly with void fraction then a biased void fraction may be obtained due to void fluctuations by measuring the average scattered flux (Harms & Forrest 1971). The technique is also useful in the oil–gas industry and as such, use of portable neutron sources is desirable. Therefore Yuen (1985) has carried out an extensive investigation of their use.

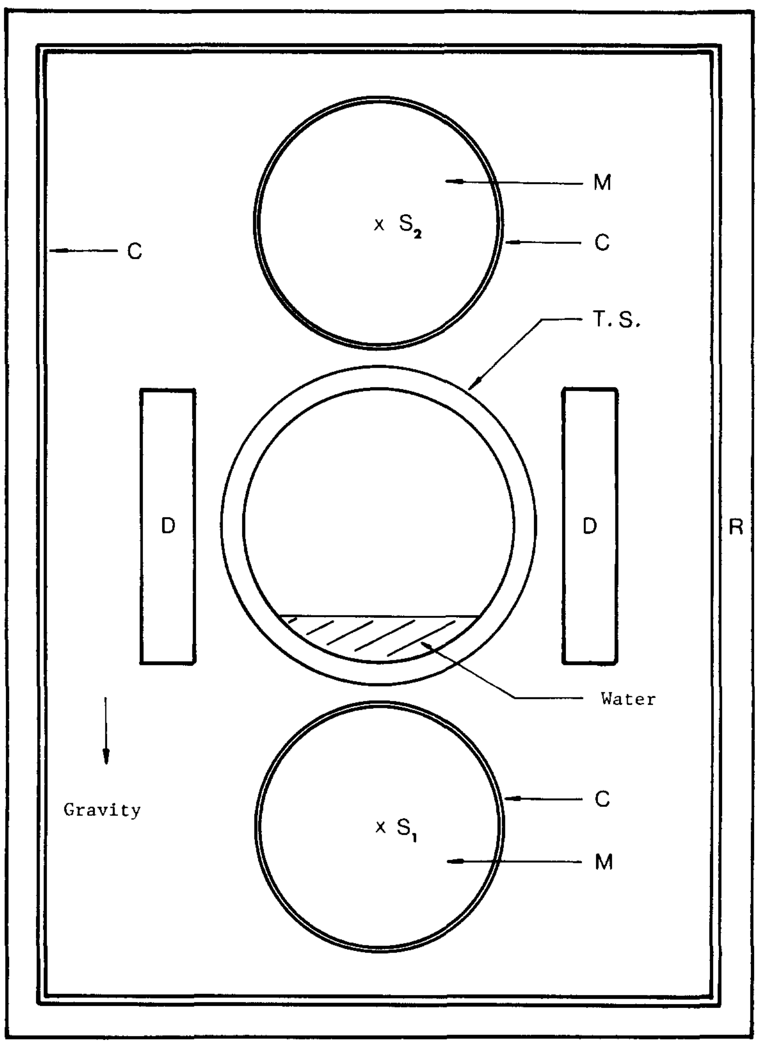
In the present work, the neutron-scattering technique is systematically investigated in situations where the neutrons are provided by portable sources. In particular, the effect of energy spectrum of the incident neutrons on the performance of the technique is examined. As discussed later, this will prove to be the largest effect.

†Present address: Atomic Energy of Canada Ltd, Whiteshell Nuclear Research Establishment, Pinawa, Manitoba R0E 1L0, Canada.

## 2. EXPERIMENTAL ASPECTS

A typical experimental setup for the present investigation is shown in figure 1. The test-section consists of a section of metal-walled pipe (carbon steel or aluminum) sealed at one end. Inserts with very thin walls are placed in the test-section to partition water from air, simulating different flow patterns with various void fractions. Three flow regimes were investigated, namely, radially symmetric annular, radially symmetric inverted annular and stratified. Test-sections of different inside diameters were used. For each test-section size, experiments were performed with a thick carbon steel wall and with a thin aluminum wall. The thin aluminum walls affect the neutrons very little.

Three neutron sources, $^{241}$Am/Li, $^{252}$Cf and $^{241}$Am/Be, were used. The average energies of the neutrons from these sources are 0.4, 2.8 and 5.1 MeV, respectively. The details of the neutron spectra of these sources may be found in Knoll (1979) and Amersham/Searle (1974/75) and will not be repeated here. Either one or two neutron sources were mounted at opposite ends of the




M - Neutron Moderator
$S_1$ - Neutron Source 1
$S_2$ - Neutron Source 2
D - $^3$He Detector
R - Shielding (Neutron Reflector)
C - Cd Sheet
T.S. - Test Section

Figure 1. Schematic diagram of experimental setup using a portable neutron source and conceptual design of a portable void fraction meter using the technique of neutron scattering.

test-section. The neutron sources were usually covered with cadmium sheets to remove neutrons with subcadmium cutoff energy (0.5 eV). Two $^3He$ detectors were placed on opposite sides of the test-section and at 90° to the axis joining the two neutron sources. The scattered neutrons were collected by these detectors with and without cadmium shields. The scattered subcadmium flux is then obtained by difference.

## 3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Scattered subcadmium neutrons were measured as a function of void fractions in test-sections incorporating different flow regimes. The experimental data were analyzed by firstly defining a dimensionless neutron counting rate $\nu$ as

$$\nu = \frac{N(\epsilon) - N(1)}{N(0) - N(1)} \quad [1]$$

where

$N(\epsilon)$ = subcadmium neutron counting rate at void fraction $\epsilon$,

$N(1)$ = subcadmium neutron counting rate when test-section is empty

and

$N(0)$ = subcadmium neutron counting rate when test-section is full of water.

The significance of the dimensionless neutron counting rate $\nu$ is that, if the scattered subcadmium neutron flux is linear with void fraction $\epsilon$, $\nu$ is related to $\epsilon$ by

$$\nu = 1 - \epsilon. \quad [2]$$

Moreover, $\nu$ is a measure of the interaction between incident neutrons and the hydrogenous material in the test-section. Any contribution to the scattered neutron counting rate through direct impingement of source neutrons is eliminated. This concept is particularly important in cases where the subcadmium component in source neutrons is not removed. Based on previous findings

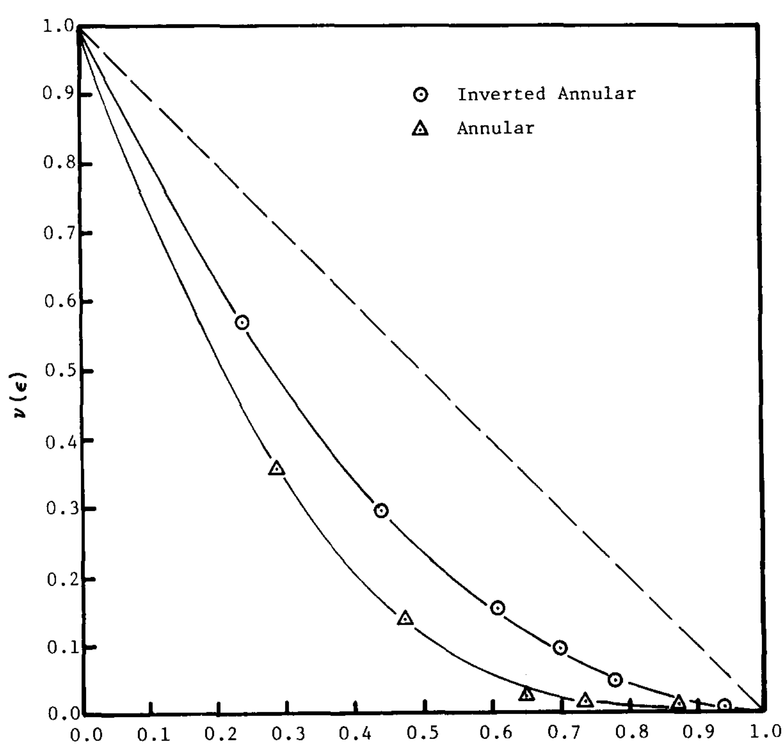



Figure 2. Measured dimensionless subcadmium neutron counting rate, $\nu(\epsilon)$, for a 51 mm dia test-section using an unmoderated $^{241}Am/Li$ neutron source.

(Banerjee *et al.* 1978a, b, 1979), while the source neutrons are in the form of a beam it is this subcadmium dimensionless counting rate $\nu$ that is expected to be reasonably independent of flow regime and roughly linear with void fraction.

The result for an experiment conducted for a 51 mm dia thin aluminum-walled test-section using an $^{241}$Am/Li source is shown in figure 2. The results are for two extreme flow regimes, namely, annular and inverted annular. It is obvious that the scattered subcadmium flux depends on flow regime and deviates significantly from a linear dependence on void fraction. Similar results persist for a $^{252}$Cf source which emits neutrons of higher average energy (Yuen 1985). Both these results are different from the findings of previous investigations (Banerjee *et al.* 1978a, b, 1979) where the source neutrons were extracted from research reactor beam port, and the scattered neutron flux seemed to vary linearly with $\epsilon$ and was quite flow pattern independent. In light of this discrepancy of results, efforts were made to investigate the impact of various parameters on this technique so that the reasons for the dependence on flow regime can be understood. The technique could then be tailored on the basis of this understanding to give measurements independent of flow regime and with the scattered neutron flux varying linearly with the void fraction.

A number of parameters were studied. Results from this study were discussed in detail in Yuen (1985) and will not be repeated here. They showed that parameters of less importance are:

- collimation of incident neutrons
- test-section to detector distance
- placement symmetry of neutron sources around the test-section for radially symmetric flow patterns.

Changing the above parameters result in little improvement regarding linearity and flow regime independence. However, the incident neutron energy spectrum has a very large effect as discussed below.

### *(a) Effect of incident neutron energy spectrum*

In the present study, effort was focused on modifying the source energy spectrum. The neutrons from a given neutron source were "softened" by putting the source in a cylindrical container of water. Experiments were repeated with the moderated source. In particular, for the 51 mm aluminum-walled test-section, the $^{241}$Am/Li source was moderated with moderators of different diameters and experiments were repeated with inserts simulating inverted annular flow. It should be noted that the moderated source was not shielded with cadmium sheets and the incident neutron spectra were expected to include a subcadmium neutron component. The results for this set of comparative experiments are shown in figure 3. From this figure, it is evident that, as the moderator diameter increases and thus the average incident neutron energy decreases, the dimensionless scattered neutron counting rate $\nu$ progressively increases for any given $\epsilon$. This implies that $\nu$ can fall above or below the $\nu = 1 - \epsilon$ line depending on the average incident neutron energy. From the same figure, it is noticed that near-linearity in $\nu$ is observed for a moderator diameter of 110 mm. This suggests that the corresponding incident neutron spectrum is an appropriate one to yield both linearity and flow regime independence. The experiment was repeated with inserts simulating annular flow and the result is shown in figure 4. From this figure, it is evident that both linearity and flow regime independence are achieved.

For the above results and discussion, it is evident that an appropriate incident spectrum is needed to achieve linearity and flow regime independence. This is further substantiated with the comparison of three incident neutron spectra which yielded different results when applied to the same 51 mm test-section. These three spectra are shown in figure 5. The spectrum (a) of an unmoderated $^{241}$Am/Li neutron source (Amersham/Searle 1974/75) is concentrated at an intermediate energy between $10^5$–$10^6$ eV. The energy spectrum (b) of the nuclear reactor beam (McCormack 1975), with which the previous investigation was conducted, consists of a wide range of energies. The spectrum (c) of the moderated $^{241}$Am/Li source with the 110 mm moderator was calculated with Monte Carlo simulation procedures (Yuen 1985). It is not surprising to observe that spectra (b) and (c) are close to each other, and in both cases linearity and flow regime independence was experimentally observed. It is also not surprising to observe that spectrum (a)

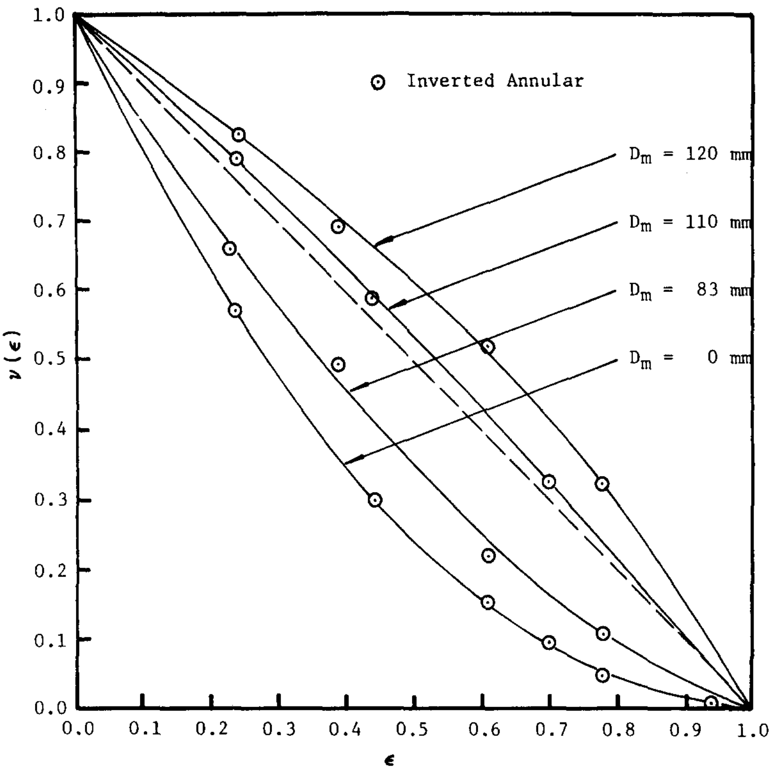



Figure 3. Progressive increase of $\nu(\epsilon)$ as moderation of the $^{241}$Am/Li increases.

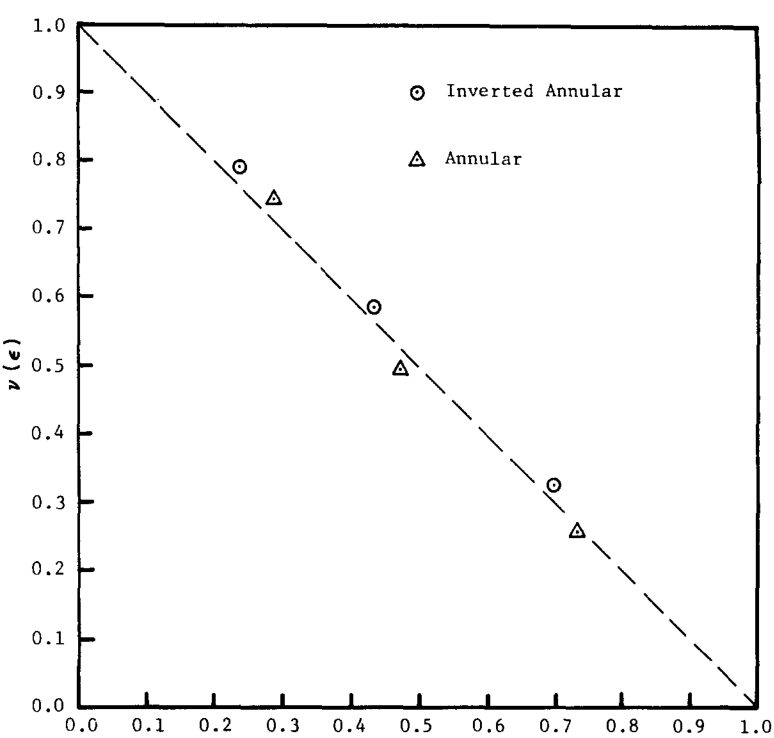



Figure 4. The achievement of linearity and flow pattern independence for the 51 mm dia test-section with an appropriate incident neutron energy spectrum which resulted from the moderation of the $^{241}$Am/Li source with a moderator diameter of 110 mm and consisted partly of subcadmium neutrons.

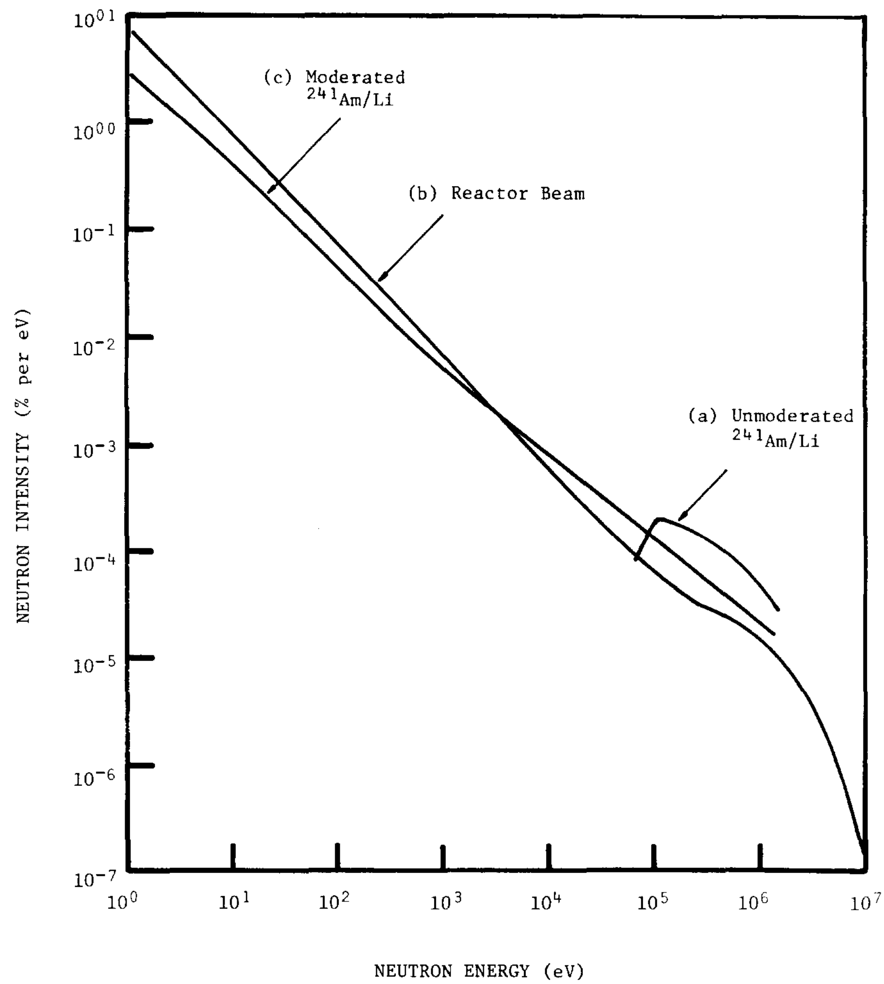



Figure 5. Incident neutron spectra of: (a) unmoderated $^{241}$Am/Li neutron source; (b) McMaster Nuclear Reactor neutron beam; and (c) moderated $^{241}$Am/Li neutron source with a moderator of 110 mm.

is considerably different from the other two and yields a high degree of non-linearity and flow regime dependence, as discussed previously.

This neutron scattering technique was further tested against flow regimes lacking radial symmetry, i.e. stratified. Experiments were conducted with inserts simulating stratified flow regime. For each $\epsilon$, the water phase was situated in two positions with respect to an appropriately moderated neutron source which yields linearity and flow regime independence for the radially symmetric flow regimes, namely annular and inverted annular. In position 1, the water phase is close to the moderated source and in position 2, it is away from the moderated source. The results are shown in figure 6. The dimensionless neutron counting rate $v$ is observed to fall consistently above and below the ideal linear line for positons 1 and 2, respectively. At position 1, the water phase is subjected to a higher incident flux because of the divergence of the source, resulting in a higher scattered neutron flux at the detectors. For positon 2, the incident neutron flux is lower because the water phase is further away from the neutron source, resulting in a lower scattered neutron flux. Referring to figure 1, a water phase distributed in position 1 with respect to source 1 is equivalent to a water phase distributed in position 2 with respect to source 2 because of the mirror-reflection symmetry about the axis joining the two detectors. Since the average for positions 1 and 2 with respect to the same single neutron source falls on the ideal linear line, it is envisaged that, in practical situations, two identical moderated sources placed diametrically opposite to each other at equal distances from the pipe would also yield a measurement independent of flow regime lacking radial symmetry with respect to the pipe axis. It is then evident that once an appropriate incident neutron spectrum is selected, linearity and flow regime independence can be

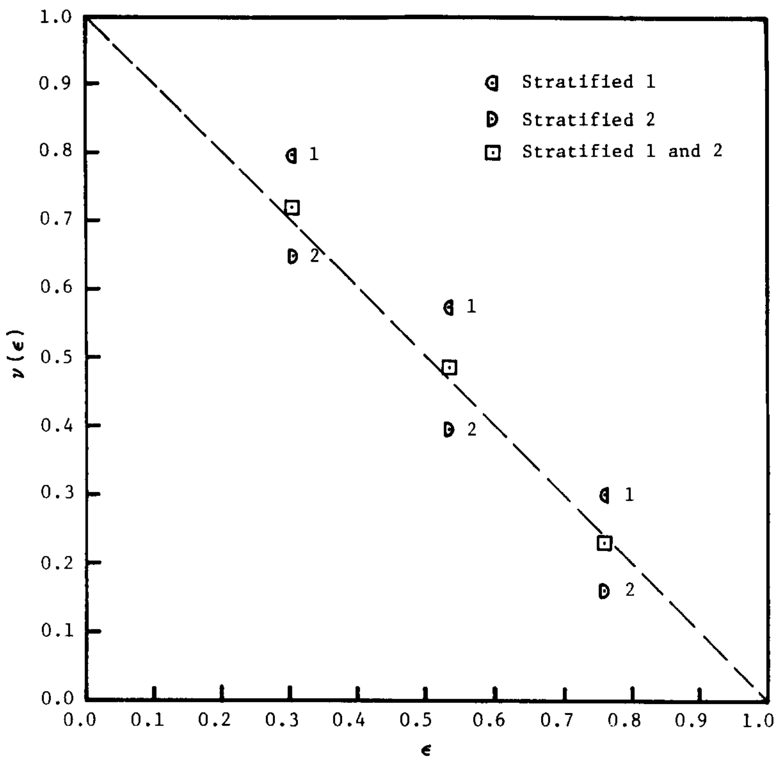



Figure 6. Perturbation caused by the water phase distribution in stratified flow regime with a moderator achieving linearity and flow regime independence for radially symmetric flow regimes.

achieved provided that two detectors and two identical moderated sources are used. Thus, it is suggested that a setup similar to that shown in figure 1 should be used to implement this technique.

The present study proceeded with the investigation of other parameters on the appropriate incident neutron spectra. These parameters include the test-section inside diameter, test-section wall thickness and the presence of neutron-reflecting material around the test-section.

*(b) Effect of neutron-reflecting material around test-sections*

Since shielding is always necessary in an actual void fraction meter setup and shielding of neutrons invariably consists of moderating material, it is of interest to investigate the effect of shielding material around the test-section on the incident energy spectrum. Experiments with the 51 mm thin aluminum-walled test section and moderated $^{241}$Am/Li source with 110 mm moderator were repeated. However, the incident neutrons were "hardened" by wrapping the moderator with cadmium sheets to remove the subcadmium neutron component. The result is shown in figure 7. Non-linearity and flow regime dependence are now observed. Subsequent experiments were conducted with wax (neutron-reflecting material) surrounding this experimental setup (Yuen 1985). The result is shown in figure 7, where both linearity and flow regime dependence are "restored". This result suggests that a harder incident neutron spectrum is needed in the presence of neutron-reflecting material around the test-section. This phenomenon can be explained as in the following.

The subcadmium neutron flux is given by incident neutrons thermalized in the test-section. The probability of an incident neutron being thermalized decreases with the incident neutron energy but increases with the number of collisions inside the liquid phase. The number of collisions normally increases with the amount of water or liquid fraction. A fast neutron may not have suffered enough collisions before escaping from the test-section and therefore would not contribute to the subcadmium neutron counting rate. This results in $\nu$ falling below the ideal linear line. However, in the presence of a neutron reflector, this neutron can be slowed down first by the neutron reflector and reflected back to the test-section to be further slowed down to the subcadmium energy. This additional component raises $\nu$ towards the ideal linear line.

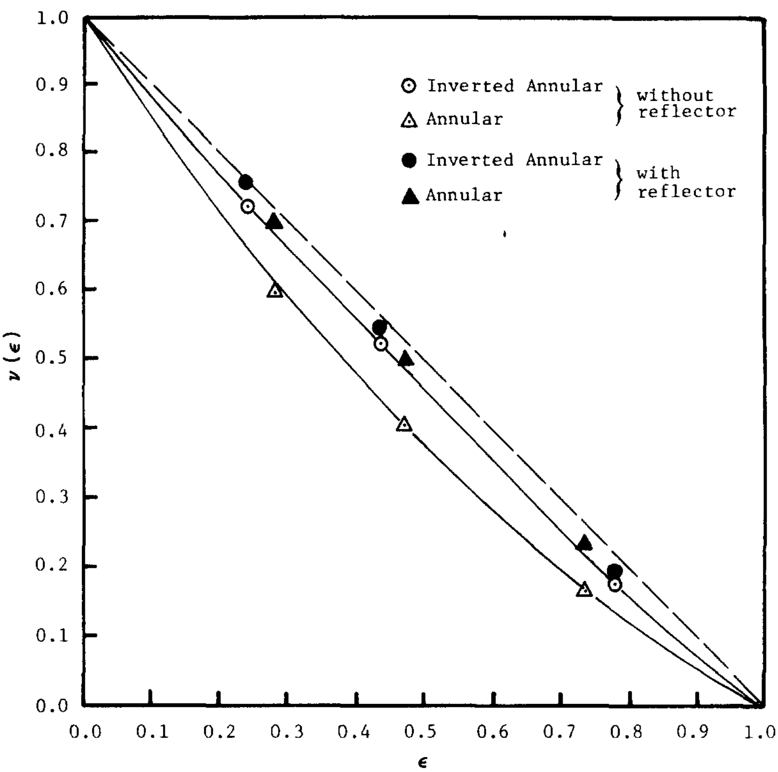



Figure 7. Requirement of a harder incident neutron spectrum in the presence of neutron reflectors to yield linearity and flow regime independence in $\nu(\epsilon)$.

*(c) Effect of test-section wall thickness*

Experiments were conducted with a thick carbon-steel-walled test-section (o.d. = 70 mm, i.d. = 51 mm) to investigate the effect of test-section wall thickness on the appropriate incident spectrum. Using the moderated $^{241}$Am/Li source with 110 mm moderator, "overmoderation" was observed. Linearity and flow regime independence could be restored only with a smaller neutron moderator of 105 mm (Yuen 1985). This result indicated that a harder incident neutron spectrum is needed for a test-section of the same inside diameter but with a thicker metal wall. The explanation is similar to that in the case of a neutron reflector. The metal wall reflects escaping neutrons back to the test-section to increase the thermalization probability although the escaping neutron suffers little loss of energy upon reflection by the metal.

*(d) Effect of test-section inside diameter*

This parameter probably has the most significant effect on the selection of appropriate incident neutron spectrum. A thin aluminum-walled test-section of 127 mm i.d. and the unmoderated $^{241}$Am/Li source were used in an experiment to investigate the effect of test-section inside diameter. The result is shown in figure 8 in comparison with that obtained with the 51 mm thin-walled test-section using the same unmoderated neutron source. For the 127 mm test-section, the higher $\nu$ values for any given $\epsilon$ suggest that even an unmoderated $^{241}$Am/Li source is too "soft" for this larger test-section. Experiments were repeated with a neutron source with a harder spectrum, namely, $^{241}$Am/Be source. Moderation of this source and removal of subcadmium incident neutrons were applied. At a moderator diameter of 83 mm, results similar to those shown in figure 4 were obtained, i.e. both linearity and flow regime independence were achieved. This finding indicates that the necessary average incident neutron energy increases with the inside diameter of the test-section. A possible explanation for this phenomenon is given in the following.

For a test-section of inside diameter $D_1$ and an incident neutron of energy $E_1$, the probability of this neutron being registered at the neutron detector depends on whether this neutron is thermalized before escaping from the test-section. The probability of this neutron being thermalized

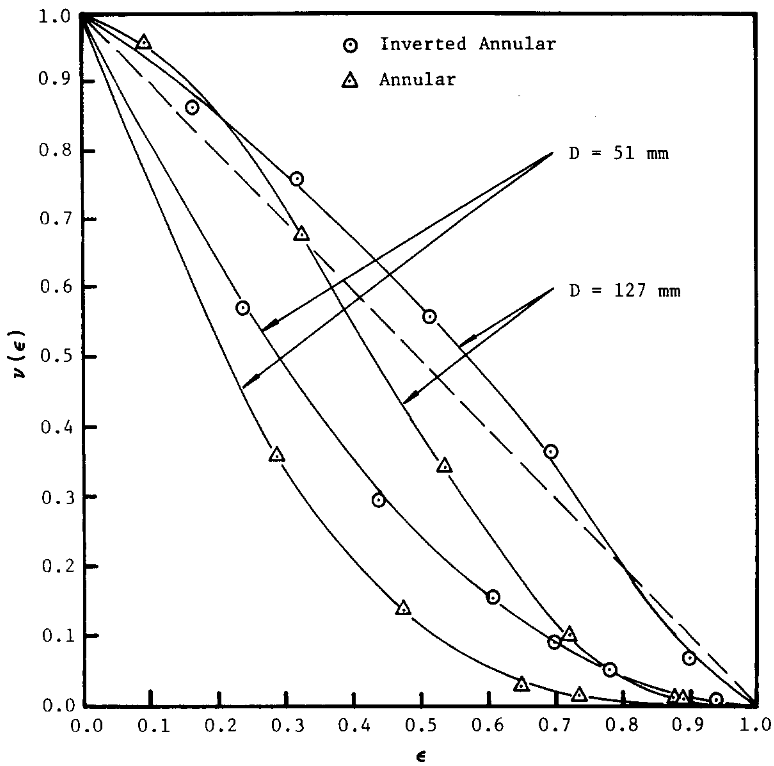



Figure 8. Comparison of $\nu(\epsilon)$ with an unmoderated $^{241}$Am/Li neutron source for test-sections of 51 and 127 mm i.d.

depends on the number of collisions suffered in the water phase and thus the void fraction. Suppose $E_1$ is such that $\nu$ varies fairly linearly with $\epsilon$. If the same incident neutron is used in a test-section of a larger inside diameter $D_2 > D_1$, the number of collisions will increase for a given liquid fraction, resulting in an asymptotic increase of probability of thermalization towards unity. This implies that $\nu$ will fall above the ideal linear line. The only means of lowering $\nu$ is by increasing the incident neutron energy to $E_2 > E_1$ so the probability of thermalization is far away from unity for the same number of collisions. The means incident neutrons of higher energy are needed for an increase in the test-section inside diameter.

## 4. MONTE CARLO SIMULATIONS OF EXPERIMENTS

From the experimental results, it appears that the performance of this neutron-scattering technique relies on the selection of an appropriate incident neutron energy spectrum. This in turn depends on the pipe size, pipe wall thickness and the presence of a neutron reflector (shielding material). To understand the physics of the problem, the experiments were simulated with a Monte Carlo neutron-scattering code. Aspects of the code have been described previously by Banerjee *et al.* (1978a, b). The geometry of a selected experiment was simulated. The calculations of scattered flux were done with sources containing only one energy group at at time. The neutron energy groups were varied from the cadmium cutoff energy (0.5 eV) to 14 MeV. The scattered flux was calculated for each group. For illustration, the results of two groups of energy for a 51 mm test-section with a thin aluminum wall are shown in figures 9 and 10. In figure 9, the incident neutron energy is 0.8 eV. It is interesting to note that, for both the annular and inverted annular flow regimes, the scattered flux deviates from linearity and lies above the linear line joining the two end points $\epsilon = 0$ and 1. The decrease in gradient towards the low void fraction region is due to saturation of thermalization probability, caused by the low energy of the incident neutrons. The sharper decrease in the flux in the high void region is due to the decrease in thermalization probability with less water in the test-section. In figure 10, the incident energy is 4 MeV. It is noticed that the behavior is opposite to that of low-energy incident neutrons. The scattered flux for the

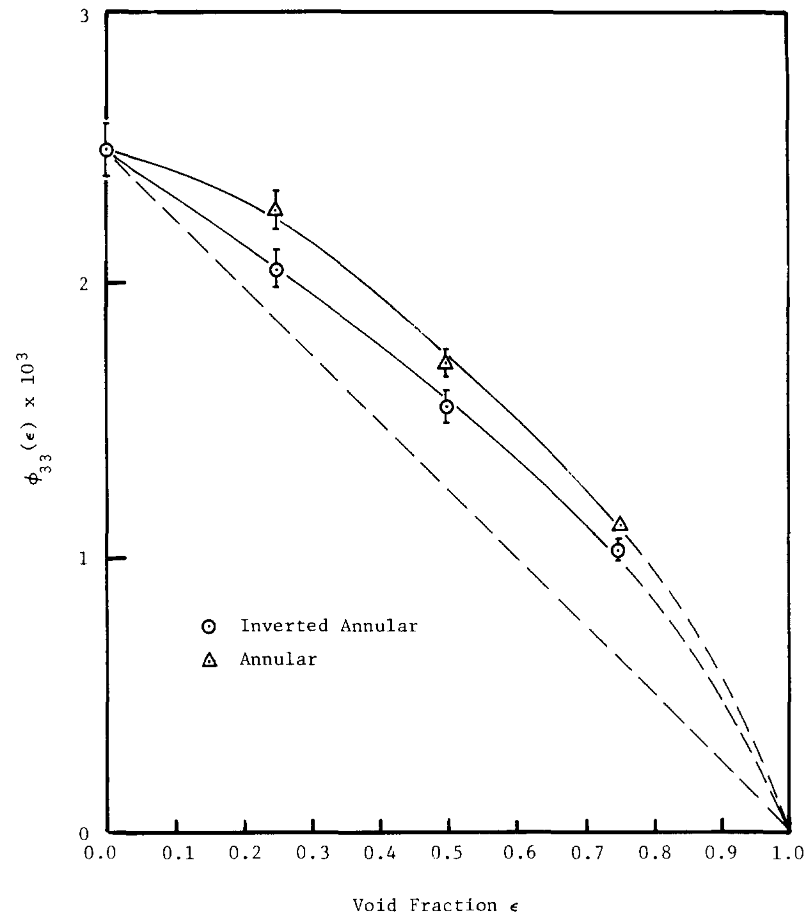



Figure 9. Scattered subcadmium neutron fluence, $\phi_{33}(\epsilon)$, by the 51 mm test-section calculated with Monte Carlo for 0.8 MeV incident neutrons.

two flow regimes is below the ideal linear line. The leveling of scattered flux in the high void region is due to the insufficient number of collisions suffered in the test section. The neutrons are therefore not thermalized before escaping from the test-section. The thermalization probability only starts to pick up in low void regions where the amount of water is large.

It is not difficult to envisage that, for each flow regime with an appropriate weighting of different energy groups, the scattered flux curve can be tailored to a linear line between the two end points, with the scattered neutron fluxes for the high- and low-energy incident neutrons compensating for each other. The experimental results obtained already suggest that there is an optimum set of weights such that the scattered flux for each flow regime is reasonably linear between the two end points, and thus independent of flow regime. The experimental results in figures 2–4 can be explained by the Monte Carlo results. The "sagging" behavior of the scattered flux curves in figure 2 is due to the dominance of high-energy groups. The "bulging" behavior in figure 3 is due to the dominance of low-energy groups, and the $^{241}$Am/Li source is overmoderated. Figure 4 shows a good balance between the high- and low-energy source neutrons at an appropriate moderation. Monte Carlo calculations were done for test-sections of different diameters to determine the optimum neutron energy spectrum (Yuen 1985). The general trend is that the average energy increases with pipe size. For example, the spectra required for the 51 and 127 mm test-sections have spectrum weighted average energies of 0.3 and 2.1 MeV, respectively. A rough relationship between the average energy $E_n$ of an incident neutron spectrum and test-section inside diameter $D$ can be obtained by a linear interpolation through these two data points, yielding

$$E_n = -0.908 + 0.0237\,D, \qquad [3]$$

where $E_n$ is in MeV and $D$ in mm. Using [3], the upper and lower bound on pipe diameter $D$ for

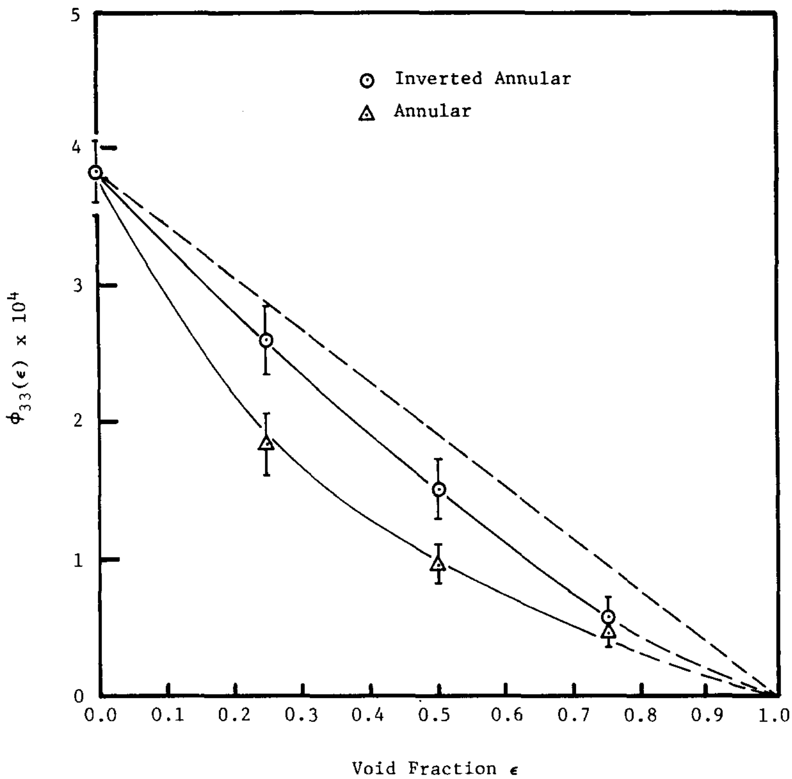



Figure 10. Scattered subcadmium neutron fluence, $\phi_{33}(\epsilon)$, by the 51 mm test-section calculated with Monte Carlo for 4 MeV incident neutrons.

this technique to be applicable, can be estimated. Taking 14 MeV as the maximum energy of neutrons, the corresponding upper bound on pipe diameter is 600 mm. Taking 0.025 eV as the minimum energy (thermal neutrons), the lower bound on $D$ is 38 mm. The Monte Carlo simulations can thus be considered a powerful tool for understanding the technique as well as a design tool.

In spite of the rough guideline given in [3], a standard procedure as outlined below is necessary in selecting a spectrum in the design of a void fraction meter using this technique. The specific geometry of a design is set up for the Monte Carlo code, taking into consideration the specific pipe size, pipe wall thickness and geometry of shielding. Several calculations have to be done for the scattered flux using single groups of source neutrons of varying energies. The source groups are then weighted until a reasonably linear scattered flux vs void fraction is obtained for the major flow regimes. This weighted spectrum is called the reference spectrum. A chosen neutron source is then moderated with an appropriate moderator thickness, and the spectrum of emergent neutrons from the moderator is estimated with the Monte Carlo code. The computed spectrum is then compared with the reference spectrum. This process is repeated until a moderator thickness is obtained such that the spectrum of the moderated source neutrons is close to the reference spectrum. This procedure is laborious but gives good results. The cost of the Monte Carlo runs are small in comparison with the cost of the device, therefore this procedure is worth following when a new system is being designed.

## 5. CONCLUSIONS

1. The energy spectrum of the incident neutrons on a test-section is a key factor in the neutron-scattering technique for void fraction measurement. It affects both the flow regime independence and linearity (with regard to void fraction) of the technique. For a given pipe size, metal wall thickness and shielding material thickness, there are "optimum" incident neutron

spectra which give flow regime independence and linearity for the variation of scattered thermal flux with void fraction.
2. In general, a larger pipe diameter needs a harder spectrum, and a softer spectrum is required for a smaller pipe.
3. A pipe with a thick pipe wall needs a slightly harder spectrum.
4. In the presence of neutron-reflecting material a harder spectrum is needed compared to cases with no shielding material.
5. The appropriate design can be effected by first calculating the scattered flux for groups of monoenergetic neutrons using Monte Carlo techniques. Proper weights for each energy group can be obtained from these calculations by requiring that the scattered flux be independent of flow regime and linear with void fraction. The thickness of moderator around a neutron source is then determined such that the spectrum of the moderated source neutrons is close to the reference spectrum.

*Acknowledgements*—The authors deeply appreciate the enlightening discussions with Professor E. Hussein of the University of New Brunswick on the Monte Carlo work and the support from Ontario Hydro in the Monte Carlo calculations.

## REFERENCES

AMERSHAM/SEARLE CORP. 1974/75 *Radiation Sources for Laboratory and Industrial Use*, p. 48.

BANERJEE, S. & LAHEY, R. T. 1981 Advances in two-phase flow instrumentation. In *Advances in Nuclear Science and Technology*, Vol. 13. Plenum Press, New York.

BANERJEE, S., CHAN, A. M. C., RAMANATHAN, N. & YUEN, P. S. L. 1978a Fast neutron scattering and attenuation technique for measurement of void fractions and phase distributions in transient flow boiling. *Proc. 6th Int. Heat Transfer Conf.* **1,** 351–355.

BANERJEE, S., HUSSEIN, E. & MENELEY, D. A. 1978b Simulation of a neutron scattering method for measuring void fraction in two-phase flow. *Nucl. Engng Des.* **53,** 393–405.

BANERJEE, S., YUEN, P. S. L. & VANDENBROEK, M. A. 1979 Calibration of a fast neutron scattering technique for measurement of void fraction in rod bundles. *J. Heat Transfer* **101,** 295–299.

HARMS, A. A. & FORREST, C. F. 1971 Dynamic effects in radiation diagnosis of fluctuating voids. *Nucl. Sci. Engng* **46,** 408–413.

HEWITT, G. F. & LOVEGROVE, P. C. 1976 Experimental methods in two-phase flow studies. Electric Power Research Institute Report EPRI NP-118.

KNOLL, G. F. 1979 *Radiation Detection and Measurement.* Wiley, New York.

LAHEY, R. T. 1978 A review of selected void fraction and phase velocity measurement techniques. Presented at *Short Course on Two-phase Flow Measurement Techniques*, Dartmouth College, N.H.

MCCORMACK, G. R. 1975 Investigation of neutron spectra. M.Sc. Thesis, McMaster Univ., Hamilton, Ontario.

ROUSSEAU, J. C., CZERNY, J. & RIEGEL, B. 1978 Void fraction measurements during blowdown by neutron absorption and scattering methods. In *Proceedings of the 1978 OECD/NEA Specialist Meeting*. Hemisphere, Washington, D.C.

YUEN, P. S. L. 1985 Development of an epithermal/fast neutron scattering technique for void fraction measurement in two-phase systems with portable neutron sources. Ph.D. Thesis, McMaster Univ., Hamilton, Ontario.