DEVELOPMENT OF A SCATTERING PROBABILITY METHOD FOR ACCURATE VAPOR FRACTION MEASUREMENTS BY NEUTRON RADIOGRAPH

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DEVELOPMENT OF A SCATTERING PROBABILITY METHOD FOR ACCURATE VAPOR FRACTION MEASUREMENTS BY NEUTRON RADIOGRAPHY

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ABSTRACT

Recent test results indicated drawbacks associated with the simple exponential attenuation method (SEAM) as currently applied to neutron radiography measurements to determine vapor fractions in a hydrogenous two-phase flow in a metallic conduit. The scattering component of the neutron beam intensity exiting the flow system is not adequately accounted for by SEAM, and this leads to inaccurate results. To properly account for the scattering effect, a neutron scattering probability method (SPM) is developed. The method applies a neutron-hydrogen scattering kernel to scattered thermal neutrons that leave the incident beam in narrow conduits but eventually show up elsewhere in the measurements. The SPM has been tested with known vapor (void) distributions within an acrylic disk and a water/vapor channel. The vapor (void) fractions deduced by SPM are in good agreement with the known exact values. Details of the scattering correction method and the test results are discussed.
INTRODUCTION
Recent test results indicated drawbacks associated with the simple exponential attenuation method (SEAM) as currently applied to neutron radiography measurements to determine vapor fractions in a hydrogenous two-phase flow in a metallic conduit [1-4]. The scattering component of the neutron beam intensity exiting the flow system is not adequately accounted for by SEAM, and this leads to inaccurate results [2,5], e.g., a negative vapor fraction for a pure water region [5]. To properly account for the scattering effect, a neutron scattering probability method (SPM) is developed. The method applies a neutron-hydrogen scattering kernel to scattered thermal neutrons that leave the incident beam in narrow conduits but eventually show up elsewhere in the measurements. The SPM has been applied to a test configuration with known vapor fractions and its use provides improved accuracy of predictions based on the experimental vapor fraction measurement. The development of SPM and its test results are presented below.

SCATTERING PROBABILITY METHOD
Consider a collimated beam of neutrons impinging perpendicularly (in z-direction) on a narrow conduit through a point \((x,y)\) on the flat conduit surface (Figure 1). All planes parallel to the conduit surface are regarded as \(x\)-\(y\) planes. The conduit contains a central vapor layer between two water layers. The thickness of the two-phase flow along the beam path through the point \((x,y)\) is \(T(x,y)\) and the vapor layer thickness is \(b(x,y)-a(x,y)\) where \(a(x,y)\) and \(b(x,y)\) represent the interfaces of the vapor and water regions that are measured from the inner surface (source side) of the conduit. Since the scattering by hydrogen atoms is the dominant interaction, only the hydrogen atom is considered in scattering. The hydrogen densities for vapor and water are \(N_v\) and \(N_w\), respectively. The probability that a neutron will be scattered in the flow is given
where $\sigma_s$ and $\sigma_t$ are microscopic scattering and total cross sections of hydrogen. This formula gives the scattering probability in terms of the vapor fraction $F(x,y)$ measured along the beam path through the point $(x,y)$, where $F(x,y) = \frac{f_i(x,y) - a(x,y)}{r(x,y)}$. Since the absorption by hydrogen is negligible compared to scattering ($<1\%$ of the total interaction at $E=0.025$ eV), the ratio $\sigma_s/\sigma_t$ is assumed to be unity. The vapor fraction $F(x,y)$ is given in terms of the scattering probability $P(x,y)$ by:

$$F(x,y) = \frac{1 + \frac{\ln[1 - P(x,y)]}{\sigma_t N_w T(x,y)}}{1 - (N_v/N_w)}$$

The optical thickness of water, $\sigma_t N_w T(x,y)$, is determined from the scattering probability $Q(x,y)$ when the conduit is completely filled with water and is given by $\sigma_t N_w T(x,y) = -\ln[1 - Q(x,y)]$. The hydrogen density ratio $N_v/N_w$ is dependent only on the temperature and pressure of the system and is readily available for a measurement condition. $P(x,y)$ and $Q(x,y)$ are determined by applying a neutron-hydrogen scattering kernel to scattered neutrons which leave the incident beam of intensity $I(x,y)$. The intensity of transmitted beam, $V(x,y)$, measured at the point $(x,y)$ on the detector is the sum of two components: (i) the uncollided fraction of the beam initially
impinging through the point \((x,y)\) on the conduit surface, and (ii) the cumulative fractions of the entire population of source neutrons that experienced collisions anywhere in the system and eventually ended up at the point \((x,y)\) on the detector. If point \((x,y)\) represents a finite mesh element on the conduit or detector (e.g., a pixel point of a video image), then the measurements defined at the point \((x,y)\) are the measurements integrated over the mesh element. In this case \(V(x,y)\) can be expressed by

\[
V(x,y) = I(x,y)[1 - P(x,y)] + \sum_{\text{all}(x',y')} I(x',y')P(x',y')S(x',y';x,y) \tag{3}
\]

where \(S(x',y';x,y)\) is an angular scattering function, the probability that a scattered neutron, which originally enters into the conduit at the point \((x',y')\) and experiences a scattering in the flow, will appear at the point \((x,y)\) on the detector.

The effect of multiple scattering by hydrogen is neglected since the thickness \(T(x,y)\) of the two-phase flow under consideration is assumed to be sufficiently small. \(P(x,y)\) shown in Eq. (3) can thus be determined by solving the following system of linear simultaneous equations.

\[
P(x,y) = 1 - \frac{V(x,y)}{I(x,y)} + \sum_{\text{all}(x',y')} \frac{I(x',y')}{I(x,y)}P(x',y')S(x',y';x,y) \tag{4}
\]

Solving these equations by direct inversion is prohibitive since the number of equations can easily exceed 100,000 when each point \((x,y)\) or \((x',y')\) is represented by a video image pixel, and an iterative method is developed for this circumstance. The initial guess of \(P(x,y)\) at every point \((x,y)\) is made with the summation term in Eq. (4) unaccounted for, which is equivalent to neglecting the contributions made by the neutrons scattered elsewhere that reach the point \((x,y)\).
In subsequent iterations, the latest known value of \( P(x', y') \) is used to determine the summation term and consequently to solve for a new \( P(x, y) \) until a convergence criterion is satisfied. \( Q(x,y) \) can be solved for in an analogous manner with measurements obtained for a conduit completely filled with water.

**ANGULAR SCATTERING FUNCTION**

An accurate angular scattering function can be expressed by the double differential scattering cross section formulated in terms of the momentum and energy transfer function. The incident neutrons, however, are approximated to be monoenergetic, and a single differential scattering cross section of water integrated over the thermal energy range in a Monte Carlo transport calculation represents the angular scattering function \( S(x', y'; x, y) \). \( S(x', y'; x, y) \) is then formulated in an \( n \)-th order polynomial of the polar scattering angle of the neutron that scatters at the point \((x', y')\) in the flow and reaches the point \((x, y)\) on the detector as follows:

\[
S(x', y'; x, y) = \left( s_0 + \sum_{m=1}^{n} s_m \theta^m \right) \delta \theta
\]  

(5)

where

\[ \theta \] = the polar scattering angle of the neutron that scattered at \((x', y')\) on a plane in the channel and reached at the point \((x, y)\) on the detector surface,

\[ \delta \theta \] = the solid angle about \( q \) subtended by the detector surface element containing the point \((x, y)\) on the detector, and

\( s_0 \) and \( s_m \) are expansion coefficients to be determined from Monte Carlo simulation of neutron scattering with a water drop.
Use of a Monte Carlo simulation with detailed energy description can have the angular scattering function effectively account for the energy change of the neutrons that have experienced collisions. The energy dependency of the detector response is not taken into account because a gadolinium converter is considered to be a black absorber to the thermal neutrons.

We have considered only a simple neutron scattering problem where the conduit wall and other support structures were not accounted for. There are numerous auxiliary structures that are required to maintain the temperature, pressure, and integrity of the experimental arrangement. Therefore, the hypothetical measurements $I(x,y)$ and $V(x,y)$ are not directly measurable quantities. These quantities should be expressed in terms of measurable quantities that can account for the effect of the additional materials present in the experiment. A systematic normalization method is developed in which measurable quantities, including the background measurement determined experimentally with the conduit empty, are used to normalize the incident beam $I(x,y)$ and the transmitted beam $V(x,y)$.

**TEST RESULTS**

To provide assurance that the neutron radiography technique could be used to obtain accurate quantitative data for vapor fraction measurements, a set of acrylic disks (simulating water) containing holes of various diameters (simulating vapor) were radiographed [5]. Acrylic (polymethyl methacrylate), which contains hydrogen as a major constituent, closely resembles the property of water as seen by a thermal neutron beam. Each hole was partially drilled into the acrylic in order to represent a steam region of 14 percent of water density where water was saturated at 2,000 psia.
The SPM has been tested with a known vapor (void) distribution within an acrylic disk. The measured void fractions deduced by SPM from digitally imaged neutron radiographs are in good agreement with the known exact values as shown in Figure 2. Negative void fractions resulting from SEAM and illustrated in Figure 2 have disappeared except for a few data points which are attributed to experimental uncertainties, and large errors (up to 15%) observed in the SEAM result have been reduced to a few percent when the scattering probability method was used.

A computer simulation to determine what the "measured" vapor fraction across a water/vapor channel would be with an assumed vapor fraction distribution shown in Figure 3 was performed using the Monte Carlo program RCP01 [6]. By calculating the "measured" response of a detector to neutrons passing through the channel and assuming a simple exponential attenuation (SEAM) through the water and water/vapor regions, the "measured" vapor fraction distribution is shown in Figure 4.a. Again we see negative vapor fractions using the SEAM methodology. Employing the scattering probability method (SPM) to correct for scattering, results in a significantly improved "measured" result as illustrated in Figure 4.b.

In summary, the neutron radiography technique for measuring vapor fractions was validated, and the application of the scattering probability method improved the accuracy of the experimental vapor fraction measurements.
REFERENCES


Figure 1

Schematic of Water-Vapor-Water Flow in a Channel

- neutron beam
- inner wall of channel
- detector element

<table>
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inner wall of channel
inner wall of channel
Figure 2

Void Fractions Measured for an Acrylic Disk with Holes

The positions 41 and 148 correspond to the inner and outer radii of the acrylic disk, respectively.
Figure 3

Vapor Fraction Test Arrangement of an Oval Channel

(neutron source)

(aluminum plate)

(stainless steel wall)

(3 Δ water)

(3 Δ vapor)

(Δ vapor)

(0.018"

(1.000"

(0.673"

(not in scale)
Figure 4

Measured Vapor Fraction Distributions in an Oval Channel

a. Simple Exponential Attenuation Method (SEAM)

b. Scattering Probability Method (SPM)