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Three dimensional water and ice quantification using neutron imaging

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Abstract Neutron radiography (NR) and computed tomography (NCT) are important non-destructive testing tools which determine information about an object's interior structure and material properties. Although water quantification using 2-D neutron imaging has been applied to fuel cells for over a decade, the development of an accurate 3-D method has only recently been demonstrated. The 3-D water quantification technique developed at the Pennsylvania State University's Radiation Science and Engineering Center has been applied to the quantification of both liquid and ice phase water. Quantification results of water and ice inside a known small channel test object were accurate to within 2%. This capability allows the quantification of ice within a fuel cell flow field under cold-start conditions.

Keywords Neutron imaging · Neutron computed tomography · Water quantification

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Introduction

Neutron imaging is commonly referred to as neutron radiography because it has many similarities with X-ray radiography. Both radiographic methods are similar in that the attenuation of an initial radiation source's intensity is measured after passing through an object [1]. The measured attenuation creates an image, or radiograph, but the differences between neutron and X-ray interactions with matter result in images with complimentary information. X-ray attenuation is a result of interactions with an atom's orbital electrons, while neutron attenuation occurs through direct interaction with atomic nuclei. Traditionally, the term "radiography" describes techniques that will produce static images on a permanent recording medium, such as film [2], while "radioscopy" describes techniques that will produce images electronically [2].

Since its introduction in the 1960s, neutron imaging has been utilized as a non-destructive qualitative inspection method [3] and, more recently, a quantitative measurement tool [4]. In fields where the quantification of water is extremely important, such as the study of hydrogen powered fuel cells [5, 6] where the amount and distribution of liquid water is key to efficient operation, neutron imaging has proved a valuable tool because of its ability to easily discern minute amounts of liquid water in the presence of other materials. However, radiographic/radioscopic images are 2-D, line integral images that make it difficult to determine the exact "depth" within an object a structure is located. In the case of a hydrogen-powered fuel cell, one cannot determine the amount of liquid water that exists solely within the cathode or anode flow field, which is important in determining hindrances to fuel cell performance.

In contrast, neutron computed tomography (NCT) produces cross-sectional slices that can be used to construct a

3-D volumetric representation of an object and determine the exact spatial location of a structure within it. The mass of the structure can be determined from its voxel count, the interpixel and interslice distances and material density. For example, the water mass residing within a section of a fuel cell flow field can be determined. The acquisition of many neutron radioscopic images, called projections, of the object under investigation at different viewing angles evenly distributed between 0° and 180° is required to perform a reconstruction. The accuracy of the volumetric reconstruction increases with the number of projections taken. However, diminishing returns occur when other factors governing reconstruction accuracy, such as geometric unsharpness or scattering, become dominant.

Experimental

Theory

Because NCT depends on neutron radioscopy, any processing of the 2-D images will have a direct effect on the reconstructed volume. This can have beneficial results. Consider a 2-D radioscopic image, which is comprised of individual picture elements, or pixels, whose gray levels represent neutron attenuation. For an optically thin slab of aluminum where secondary scattering may be neglected, the pixel gray level is given by [7]:

$$G_{\text{dry}} = C * \phi_0 * e^{-\Sigma_{\text{Al}} * t_{\text{Al}}} + G_{\text{offset}} \tag{1}$$

If there were a water-filled cavity within the aluminum slab then the pixel gray level can be described by [7]:

$$G_{\text{wet}} = C * \phi_0 * e^{-\Sigma_{\text{Al}} * t_{\text{Al}}} * e^{-\Sigma_{\text{water}} * t_{\text{water}}} + G_{\text{offset}} \tag{2}$$

where ϕ_0, Σ, and t respectively denote the incident neutron beam flux, the total macroscopic cross section and thickness of aluminum or water. G_{wet} and G_{dry}, represent the gray levels of pixels in images with and without water present while C and G_{offset} represent the gain of the imaging system and the resulting gray level offset. The offset value can result from CCD charge build-up. It is easily removed by subtracting a dark current image, an image captured by the CCD in an absence of light [8]. Dividing Eq. 2 by Eq. 1 removes the attenuation effects of all materials and isolates the water attenuation term in a process called background normalization:

$$\frac{G_{\text{wet}}}{G_{\text{dry}}} = e^{-\Sigma_{\text{water}} * t_{\text{water}}} = G_{\text{water}} \tag{3}$$

Because the lack of water is ideally the only difference between the image without water present and the image with water present, the division of the one into the other will result in an image of water alone. Isolation of the water attenuation term is the means by which water quantification in radioscopic images is performed [6, 7]. PSUMagic is Penn State's neutron radioscopic 2-D water quantification software, which performs water quantification by comparing pixels of water attenuation, G_{water}, to a look-up table relating pixel gray level to water thickness [7, 9]. Because the accuracy of this quantification technique has been determined [7] it can be used to gauge the accuracy of the NCT water quantification technique.

NCT produces a 3-D volumetric reconstruction, which is comprised of individual volume elements, or voxels. While each voxel occupies the same small volume in the reconstruction, a voxel may represent a volume of space only partially filled by a material: a partial volume. A precise water quantification result requires the inclusion of the water masses represented by these partially filled voxels.

The gray level of a voxel represents the combination of total macroscopic cross sections, Σ_t, of the various materials present at the voxel's spatial location [10, 11]. The influence on voxel gray levels from materials other than water must be removed such that voxel gray levels represent only water. This can be accomplished through background normalizing each projection via Eq. 3. Removing the attenuation effects of materials other than water in the 2-D projection data will yield a 3-D reconstruction with water alone. Two sets of projections for the object being investigated are then needed: one without the presence of water and one with the presence of water.

In NCT a linear dependence between a voxel's gray level and the total macroscopic cross section of the material it represents is expected [12]. Because of the gray level linear dependence, one may say:

$$G \propto \Sigma_t = \frac{m * A_g}{V * M} \sigma_t \tag{4}$$

where G is the gray level value of a voxel, Σ_t is the total macroscopic cross section of water, m is the water mass, V is the water volume, A_g is Avagadro's number, M is the molecular weight of water, and σ_t is the total microscopic cross section of water.

A voxel that represents a volume only partially filled with water will have a gray level value different than that of a voxel that represents a volume completely filled with water. Assuming the presence or absence of water is the only difference between the two sets of projections of the object being investigated, background normalization ensures differences in gray level must result from differences in water mass.

If the gray level, G_U, of every voxel containing an unknown water mass, m_U, is normalized by the gray level, G_R, of a voxel with a known water mass, m_R, then the unknown water mass can be determined:

$$\frac{G_U}{G_R} = \frac{\Sigma_{t_U}}{\Sigma_{t_R}} = \frac{m_U * V_R}{V_U * m_R} \tag{5}$$

The voxel with gray level G_U and the voxel with gray level G_R have equal volumes in the reconstruction, but may contain different water masses. Therefore:

$$m_U = \frac{G_U}{G_R} * m_R \tag{6}$$

In practice, the value used for the reference gray level G_R is the gray level of a voxel with a volume filled with water. The water mass is calculated on a voxel-by-voxel basis; multiplying each voxel by the reference voxel's water mass as determined from the imaging system's pixel mapping and assuming a water density of 1 mg/mm^3. Summing the individual voxel water masses will yield the total water mass.

Setup

This approach to NCT water quantification was tested using a cylindrical aluminum test sample shown in Fig. 1 and the NCT system installed at the Penn State Radiation Science and Engineering Center (RSEC). The 1 MW TRIGA Breazeale Nuclear Reactor, housed at Penn State's RSEC, produces a beam of thermal neutrons with an L/D $\sim$ 150 and an approximate flux of 2.2×10^7 n cm^{-2} s^{-1} at 800 kW.

The installed NCT system consists of a Retiga 4000RV Peltier cooled 12-bit 2048 $\times$ 2048 pixel CCD camera with integration times of 10 ms to 18 min, a 25.4 cm $\times$ 25.4 cm (10 inch $\times$ 10 inch) square scintillation screen, a precision rotary table and a control/data acquisition computer. The pixel mapping for this setup is 0.113 mm. A Newport 855C precision rotary table with a 0.001° resolution is remotely coupled to a control computer, which automatically synchronizes data collection and rotary table movement.

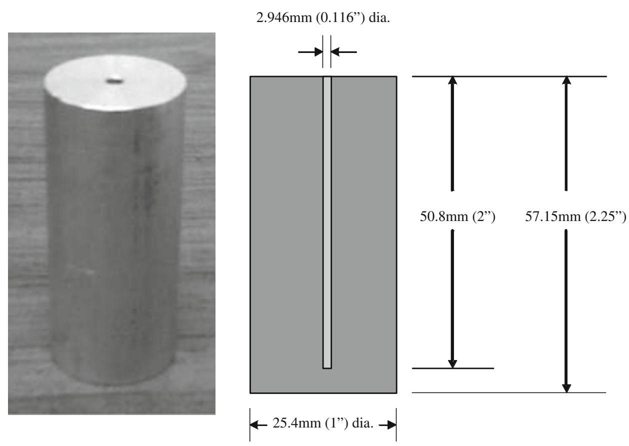

Fig. 1 The aluminum cylinder test sample and its dimensions

Two projection sets were taken, one of the sample empty and one of the sample filled with water. Each projection set contained 601 images acquired at 0.3° intervals. All images were taken with an integration time of 49 s and at a power of 800 kW. Image analysis was performed on a dedicated data processing computer using the neutron and X-ray tomography reconstruction software, Octopus V8.2, the 3-D visualization program, VG Studio Max 1.2, and the radioscopic water quantification program, PSUMagic [9].

Results and discussion

Before reconstruction, a dark current image was subtracted from all projections to remove the G_{offset} term found in Eqs. 1 and 2. Each image in the projection set of the sample filled with water was background normalized using its corresponding image from the projection set of the sample dry. Octopus V8.2 was used to generate cross-sectional slices that were then used to create a 3-D volume in VG Studio Max. The resulting reconstruction produced the sample's column of water alone.

The quantification method outlined in this work was applied to the reconstruction. Voxels of fractional water mass are likely to occur along the outer edge of the water column, but not within the core. The reference gray level G_R was taken to be the average gray level of the water column's interior voxels in the x, y and z directions.

For comparison, the water present in the test sample was quantified using a 2-D radioscopic image and PSUMagic [9]. A theoretical water mass was determined using the test sample void dimensions found in Fig. 1 and assuming a water density of 1 mg/mm^3. These results are presented in Table 1.

In a similar fashion, the quantification technique was applied to ice. The test sample was filled with 300 mg of water measured via syringe, a water mass less than the test sample's theoretical maximum to allow for ice expansion, and then frozen using dry ice. Dry nitrogen gas was blown over the sample to minimize condensation on its surface. After the temperature stabilized, images were collected and then the reconstruction performed. Results of the ice analysis are given in Table 1.

Table 1 Results of liquid and ice phase water mass analysis

Method (phase)	Water mass (mg)	Error (%)
Theoretical (liquid)	346.4	NA
PSUMagic (liquid)	346.0	−0.1
Reference gray level G_R (liquid)	350.8	1.3
Theoretical (ice)	300	NA
Reference gray level G_R (ice)	298.0	−0.7

With the water column having a theoretical value of 346.4 mg, the NCT quantification technique outlined here yields a fairly accurate value of the water column mass, within 2% of the theoretical. PSUMagic provides additional confidence in this result by measuring a water mass value of 346.0 mg: within 0.1% of the theoretical. Table 1 also shows the quantification of ice inside the narrow cavity of the sample to be within 1% of the water mass injected via syringe.

Conclusions and future work

NCT is an important imaging tool in the field of non-destructive testing. It is capable of obtaining important 3-D information about a sample's interior structure and material properties that other traditional methods cannot provide. The comparison of the results found in Table 1 reveals the quantification of liquid and ice phase water mass using a reference gray level is a viable approach with accurate results. For a fuel cell under cold-start conditions, ice becomes a matter of concern; the freeze/thaw experienced during startup can lead to degradation of fuel cell performance. The ability to quantify ice may prove valuable in determining damage caused by ice formation and how it may be mitigated. The NCT quantification approach is very time-consuming, however, requiring the acquisition of two separate projection data sets. Using the insight gained through this method, future NCT work at the Penn State RSEC will explore water mass quantification techniques requiring a single set of projections.

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