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Advancements in the development of a directional-position sensing fast neutron detector using acoustically tensioned metastable fluids

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ABSTRACT

Advancements in the development of a direction and position sensing fast neutron detector which utilizes the directional acoustic tensioned metastable fluid detector (D-ATMFD) are described. The resulting D-ATMFD sensor is capable of determining the direction of neutron radiation with a single compact detector versus use of arrays of detectors in conventional directional systems. Directional neutron detection and source positioning offer enhanced detection speeds in comparison to traditional proximity searching; including enabling determination of the neutron source shape, size, and strength in near real time. This paper discusses advancements that provide the accuracy and precision of ascertaining directionality and source localization information utilizing enhanced signal processing-cum-signal analysis, refined computational algorithms, and on-demand enlargement capability of the detector sensitive volume. These advancements were accomplished utilizing experimentation and theoretical modeling. Benchmarking and qualifications studies were successfully conducted with random and fission based special nuclear material (SNM) neutron sources (^{239}Pu–Be and ^{252}Cf). These results of assessments have indicated that the D-ATMFD compares well in technical performance with banks of competing directional fast neutron detector technologies under development worldwide, but it does so with a single detector unit, an unlimited field of view, and at a significant reduction in both cost and size while remaining completely blind to common background (e.g., beta-gamma) radiation. Rapid and direct SNM neutron source imaging with two D-ATMFD sensors was experimentally demonstrated, and furthermore, validated via multidimensional nuclear particle transport simulations utilizing MCNP-PoliMi. Characterization of a scaled D-ATMFD based radiation portal monitor (RPM) as a cost-effective and efficient ^{3}He sensor replacement was performed utilizing MCNP-PoliMi simulations, the results of which are discussed and presented.

1. Introduction

The development of directional neutron detectors for SNM is a relatively new field, garnering significant interest over the last decade. Directional fast neutron detectors have a number of potential applications, including locating and monitoring of SNM at nuclear facilities under safeguards regimes and the detection of sources of fast neutrons (including SNMs) in containers and packages. Examples of some of the state-of-the-art directional fast neutron detector systems undergoing development include time projection chambers (TPC) [1,2], neutron scatter cameras [3–5], neutron imaging telescopes (FNIT) [6–8], and coded aperture cameras [9–11]. Development of the directional abilities of the ATMFD system represents a significant advancement to the current state-of-the-art directional neutron detectors. A single D-ATMFD system is capable of the directional detection of neutrons in a single portable detector with an unlimited field of view (4π) [12] and a significant reduction in size while remaining completely blind to non-neutron background [13]. This is accomplished with the potential for a significant cost reduction over comparable systems (e.g. \$500–\$1 K for D-ATMFD vs. \$100 K to > \$300 K for state-of-art directional systems). Advances in the ongoing scientific development and validation of the unique directional-cum-imaging capabilities of the D-ATMFD are the focus of this report.

2. The D-ATMFD sensor system – overview

The D-ATMFD used in this report is similar to the one previously used [14] with the exception that the top acoustic reflector is affixed

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directly to the top of the resonance chamber. Affixing the top reflector increased operational stability by avoiding sloshing of the top reflector and the detector fluid allowing the D-ATMFD system to be utilized in a portable configuration. A schematic of the D-ATMFD utilized is shown in Fig. 1.

When the D-ATMFD fluid is under tension (below vacuum pressure), the state is metastable, whereupon, neutron elastic scattering interactions may be monitored by the formation of transient bubbles [14,15]. Piezoelectric elements that are attached to the outside of the D-ATMFD are used to monitor shock signals generated by the imploding cavitation bubbles which occurs immediately following a neutron induced detection event. The time difference of arrival (TDOA) of the shock signal at each transducer is measured and analyzed with a hyperbolic positioning algorithm to calculate the 3-D location of the neutron detection event in the D-ATMFD. Directional information is ascertainable in the D-ATMFD system due to the increased probability that a neutron induced detection event will occur in the region of the sensitive volume nearest to the neutron source as opposed to the region of the sensitive volume furthest from the neutron source. It has been previously shown that the probability that a neutron induced detection event will occur is a function of the negative pressure in the detector fluid and the energy and magnitude of the neutron flux [14]. Due to the axi-symmetric nature of the D-ATMFD, the probability of a neutron detection event in a given voxel can be simplified by treating it as a function of the neutron flux alone [16]. Uncoupling of the dependence of the probability of a neutron detection event with the negative pressure in the detector fluid allows one to quantify the 2π directional capabilities of the D-ATMFD based solely on the magnitude and energy of the neutron flux [14]. Although the current study is focused on ascertaining directionality in 2π, alternate ATMFD geometries have been developed and proven capable of ascertaining directionality in full 4π fields [12]. Since neutron flux reduces with distance

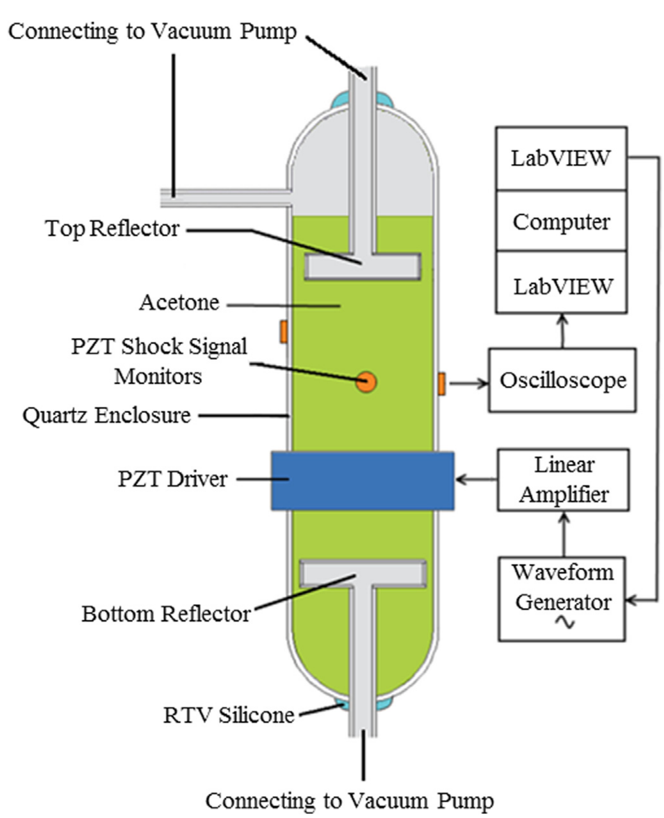

Fig. 1. Schematic of cylindrical ATMFD system used for direction-position sensing studies.

and with the amount of down scattering and absorption in the detector fluid, the side of the sensitive volume nearest to the source naturally has the highest probability of neutron interaction locations, and therefore, for the formation of neutron induced detection events. Detecting the position of these events inside the detector now allows the user to ascertain information on the direction of the neutron source. This is accomplished via the stochastic directionality model developed previously [14] which utilizes the neutron attenuation law to estimate the probability, P, that a detected neutron had traversed a distance, d, in the detector fluid without interacting and then interacting within the distance δd from the following expression:

$$P(d,\delta d) = P_{non-reaction}(d)\cdot P_{reaction}(\delta d). \quad (1)$$

The distance, d, from any position in the detector to the wall of the detector in the direction, θ, is derived as,

$$d = r\cos(\theta+\pi-\theta_0) + \sqrt{r^2\cos^2(\theta+\pi-\theta_0) - r^2 + R^2} \quad (2)$$

where (r, θ_0) is the detection location (as defined in a 2-D polar coordinate system) and R is the radius of the detector. Therefore, the probability associated with the neutron originating from the direction, θ, and then interacting at the detection location is given by

$$P(\theta) = e^{-\Sigma d}\left(1 - e^{-\Sigma\delta d}\right) \quad (3)$$

where δd is the spatial resolution of the detector (found to be ~0.1 mm) [14]. Every detected neutron induced nucleation event's source direction probability distribution is then normalized, and the total source direction probability distribution of n detection events is calculated as

$$P_{total}(\theta) = \prod_{j=1}^{n} P_j(\theta). \quad (4)$$

Thereafter, the neutron source direction is determined to be located at the most probable angle, and confidence values are evaluated by numerical integration of the total angular probability distribution.

3. Refinement of the stochastic neutron directionality model for enhanced accuracy

The stochastic directionality model as developed previously makes two basic assumptions: the effects of solid angle on the neutron flux are negligible (i.e. neutrons are traveling uni-directionally) and that the detected neutron traveled directly from the neutron source to the detection location (i.e. no interactions with the detector fluid occurred between the neutron detection location and the source origination). MCNP-PoliMi assessments were performed to test the validity of these assumptions. Firstly, assessments were performed with a ^{252}Cf fission neutron source at a direction of 0°, a distance of 50 cm from the center-line of the ATMFD and a sensitive volume size of $r = 1.25$ cm and $h = 4.0$ cm (modeled as a right circular cylinder). The locations of simulated neutron detection events in the sensitive volume of the detector were then analyzed with the stochastic directionality model. The predicted source direction and angular resolution at the 68% confidence level (C.L.) and 95% C.L. were calculated for a sample size of 2000 simulated detection events. The accuracy of the stochastic directionality model was calculated by testing whether the true source direction (i.e. 0°) was within $\pm 1\sigma$ and $\pm 2\sigma$ of the predicted direction at the 68% C.L. and 95% C.L., respectively. Analysis of the simulated data sets revealed that the stochastic directionality model was 57.7% accurate at the 68% C.L. and 90.4% accurate at the 95% C.L. In order to test whether the deficient accuracy is the result of solid angle effects, MCNP-PoliMi assessments were performed utilizing a planar source geometry consisting of a uni-