Conceptual design and initial evaluation of a neutron flux gradient detector for partial defect testing of spent nuclear fuel

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Abstract

Identification of the position of a localized neutron source or of local inhomogeneities in a multiplying or scattering medium (such as the presence of small, strong absorbers) is possible by measuring the neutron flux in several spatial points and applying an unfolding procedure. It was suggested earlier, and it was confirmed by both simulations and pilot measurements, that if, in addition to the scalar (angularly integrated) flux, the neutron current vector or the flux gradient vector is measured, the efficiency and accuracy of the unfolding procedure can be significantly enhanced. This idea is used in support of a nuclear safeguards project, whose goal is to develop a non-intrusive methodology to investigate the integrity of spent fuel assemblies and identify possible missing nuclear fuel pins. For the within-assembly neutron measurements, a new dedicated neutron gradient detector is planned. The detector design consists of four small, optical fiber-mounted scintillation detector tips, arranged in a rectangular pattern. Such a detector allows to estimate the flux gradient vector in a 2-dimensional plane. The paper presents a feasibility and sensitivity study of the detector design, through Monte-Carlo simulations.

KEYWORDS: flux gradient detector, scintillation detector, light guiding fiber, Monte-Carlo

1 Introduction

Spent nuclear fuel is particularly important from a safeguards perspective due to its high content of residual fissile material such as Uranium-235 and Plutonium-239. Spent, highly radioactive nuclear fuel that is discharged from a nuclear power plant, is stored in a water pool before it is sent to the final repository. In this period of time it is important to carry out regular inspections and verify that no radioactive material is missing from the water pool.

A novel methodology for a more accurate investigation of the integrity of spent nuclear fuel assemblies is under development, as a collaborative effort by Chalmers University of Technology and the Belgian nuclear research center SCK CEN. The goal of the methodology is to detect whether one or more fuel pins have been removed and replaced by dummy rods, and if so, in which positions. This diversion scenario is known in the safeguards community as detection of partial defects in a fuel assembly. The strategy is to perform neutron flux measurements concurrently in several points of a fuel assembly, to compare the flux shape reconstructed from the measurements with the one calculated for the declared, intact fuel assembly via a machine learning algorithm, and to discover the absence of fuel pins from the possible deviations.

Identifying missing fuel pins from neutron measurements is a so-called “inverse task”, i.e. going from the distribution of the neutron flux to the actual pin arrangement that originated that observable. It was suggested earlier that in such inverse tasks, the efficiency and the accuracy of the localisation of a partial defect can be improved if, in addition to the measured scalar (angularly integrated) neutron flux, the neutron current vector or the gradient of the neutron flux is measured [1]. Both the current and the gradient are vectors, hence they contain more (and independent) information compared to the scalar flux. The feasibility of using the flux gradient in both static and dynamic localisation problems was demonstrated by calculations and simulations in previous works [1, 2, 3].

In this paper, the design of a detector that allows measuring the flux gradient or the neutron current is described. Then a Monte Carlo model is introduced to assess the performance of the detector. Finally, the results of the quantitative analysis are presented and discussed.

2 Detector Design

The measurement of the flux gradient or the neutron current is made possible by the use of small detectors (about 1 mm), developed in Japan [4, 5]. These detectors consist of a volume of a mixture of neutron converter and scintillation material mounted on the tip of a long and thin optical fiber. Then a group of these optical fiber-based scintillators can be arranged in a single dedicated detector that can be used to measure the scalar flux in several positions concurrently and thus provide an estimation of the flux gradient.

The design proposed for the single dedicated detector is shown in Figure 1. It consists of four axial holes in an aluminium cylinder which can serve as holders of four fiber-mounted scintillators, arranged in a rectangular pattern. The size of the aluminium cylinder is limited to 1 cm in diameter since it is planned to be introduced in the instrument/guide tubes of typical Light Water Reactor (LWR) fuel assemblies. Aluminium was chosen as the matrix, holding the scintillators, because of its easy manufacturing properties and its low neutron absorption cross section.

The detector can be inserted into the fuel assembly at a selected axial elevation to estimate the two horizontal components of the flux gradient.

3 The Monte Carlo model of the detector and the measurement setup

The gradient detector that is suggested in this study is investigated via detailed simulations performed with the open source code Serpent [6]. This code is a multi-purpose three-dimensional continuous-energy Monte Carlo particle transport code, developed at VTT Technical Research Centre of Finland. It has the advantage that it is very flexible in its geometry and material specifications, and it can be run in parallel on computer clusters and multi-core workstations, which helps to perform tasks that requires high computational resources efficiently and in a timely manner.

For the simulations, a hypothetical test case of a neutron source at the center of an aluminium tank (1 m in diameter and 1 m in height) filled with light water was modelled, see Figure 2. The neutron source is a Californium-252 sphere of diameter of 2 cm. The setup is chosen

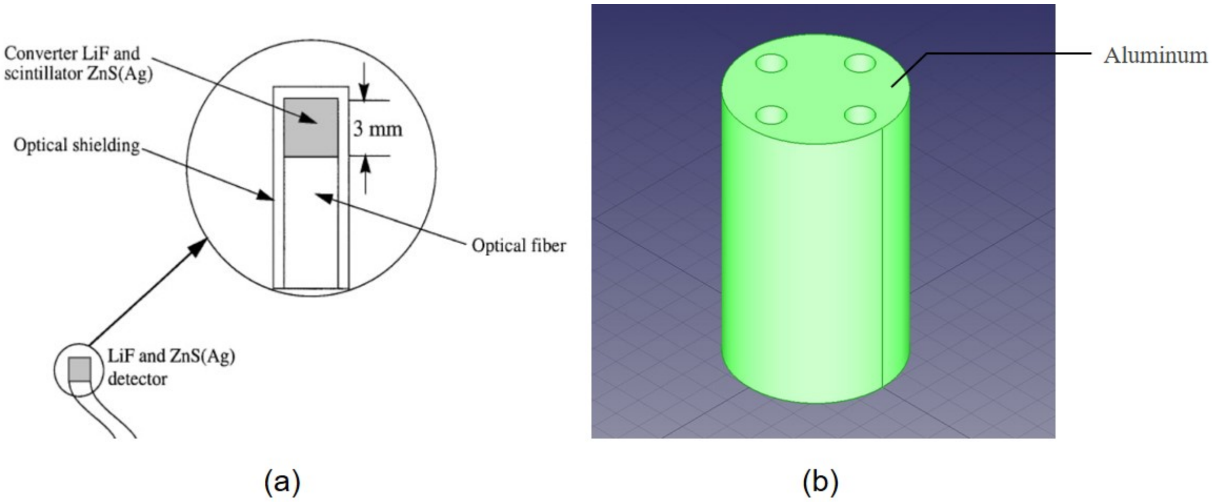

Figure 1: A scheme of the planned gradient detector (a) The optical fibers with the scintillation material at their tips (b) Aluminium cylinder that acts as a holder for the detectors.

because of its simplicity, with an azimuthally symmetric flux distribution in the horizontal plane. In addition, such a scenario was used, and proven to be efficient, in earlier works [2, 3].

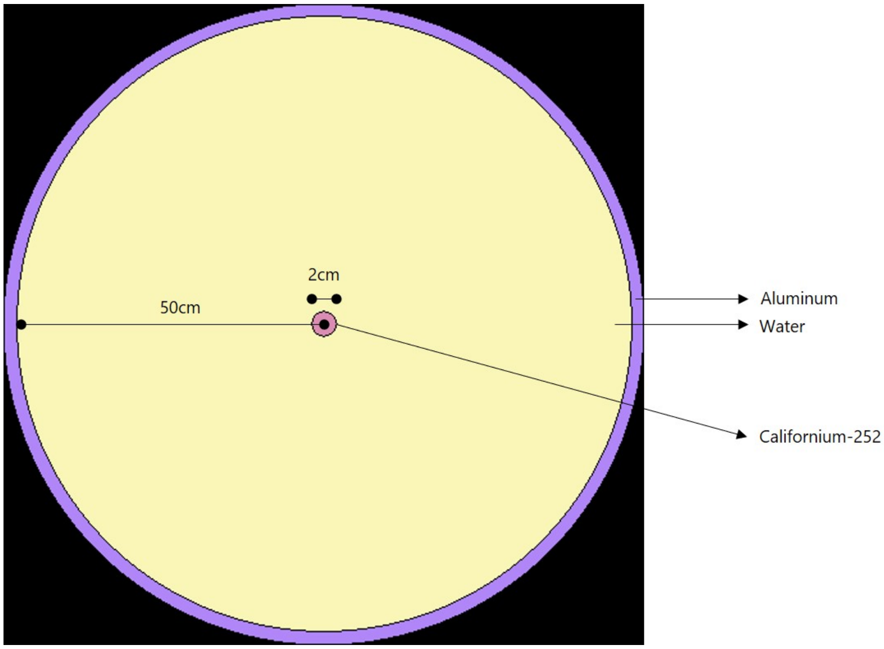

Figure 2: The suggested measurement setup as modelled in Serpent.

A model of the gradient detector described in the previous section was created for the calculations, as shown in Figure 3. Accordingly, it includes an aluminium cylinder with diameter of 1 cm and height of 5 cm, with four axial holes that act as holders for four fiber-mounted scintillators arranged in a rectangular pattern. The optical fibers are 1mm in diameter and their tip (3mm in height) is covered of a LiF/ZnS(Ag) mixture that acts as the converter/scintillation material respectively. The fibers are coated with a thin layer of teflon for protection against external light. Several other converter/scintillation materials could be investigated (LiCaF, boron loaded plastic scintillator etc.). However, in this study the work will be restricted to the type of detectors which we have at hands, namely the LiF/ZnS(Ag). These were recently obtained (courtesy of Kyoto University Institute for Integrated Radiation and Nuclear Science, KURNS).

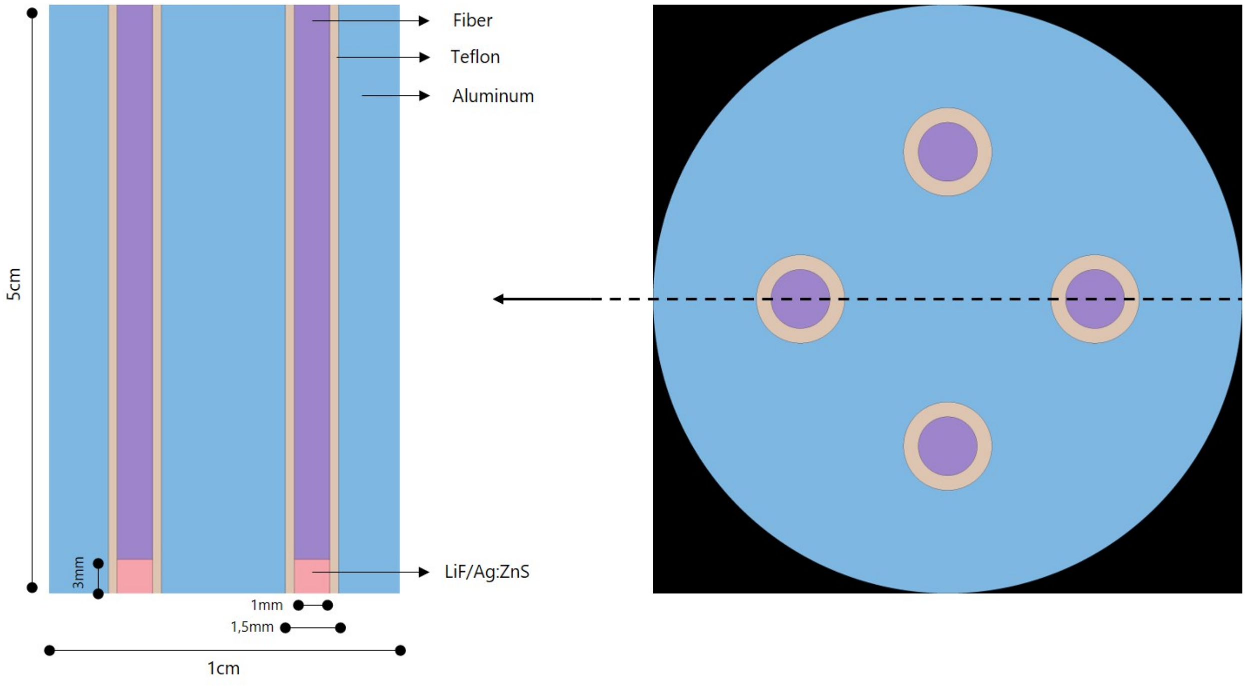

Figure 3: The LiF-based gradient detector as modelled in Serpent.

4 Quantitative analysis

4.1 Simulation of the experimental setup

The energy and space dependence of the neutron flux in the suggested setup, namely a water tank with a Cf-252 neutron source, were first investigated without the presence of the detector. These simulations help to make sure that the suggested setup is modelled correctly. Figure 4 shows the energy dependence of the neutron flux both of the Cf-252 neutron source and in the surrounding water as obtained from Serpent. As expected, close to the source, the energy spectrum of the flux is similar to the Cf-252 spectrum, and becomes more thermalised farther away from the source.

Figure 5 shows the space dependence of the thermal neutron flux in the water tank. It is the thermal flux that is of interest since the gradient detector is mainly sensitive to thermal neutrons according to the reaction in Equation 1.

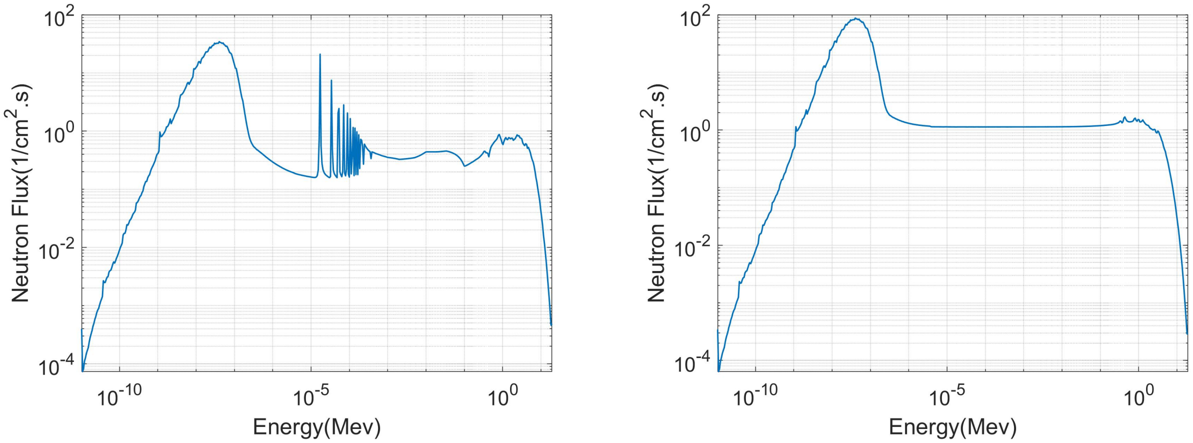

Figure 4: The Flux-Energy spectrum in the Cf-252 source (Left) and the Flux-Energy spectrum in the surrounding water (Right).

$$Li^6 + n_{Thermal} \longrightarrow He^4 + T^3 + 4.8Mev \tag{1}$$

As can be seen in Figure 5, the thermal flux decreases in a non-monotonic way with increasing distance from the source. The dip in the thermal flux in the vicinity of the source is due to the absorption of thermal neutrons in the source itself. This space dependence is suitable for the investigation of the performance of the detector, since there are positions with both small and high flux gradients. For the verification of the Serpent model, the calculations were also performed with the code MCNP [7]. It is seen in Figure 5 that the results from the two codes are in good agreement.

4.2 Investigation of the performance of the detector

4.2.1 Estimation of the magnitude of the gradient

Adding the gradient detector to the setup affects the neutron flux distribution. This flux distortion is usually negligible when taking the scalar flux. However, the effect on the accuracy of the gradient might be stronger because the neutron flux differences between the close locations of the scintillators inside the detector are expected to be small. In addition, scintillators nearer to the neutron source might disturb the neutron flux detected by the other scintillators, so the importance of a possible shielding effect between scintillators leading to over- or under-estimation of the gradient needs to be studied.

As shown in Figure 6, the detector was placed so that two scintillators were lined up on the x-axis, i.e. the line connecting two of the scintillators points to source (towards the centre of the water tank). In such configuration the absolute value of the gradient will be equivalent to the radial component of the gradient (calculated from the two scintillators along the x-axis). On the other hand, the azimuthal component (from the two scintillators along the y-axis) will be zero due to the symmetry of the setup.

The flux gradient was calculated from the reaction rate in the scintillators and compared with

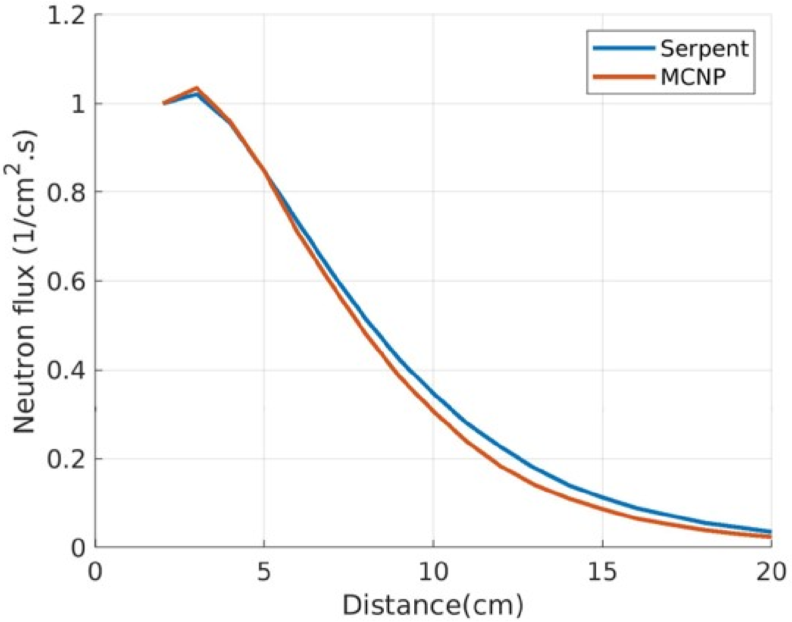

Figure 5: The space dependence of thermal neutrons in the measurement setup.

the gradient estimated from the neutron flux calculated in the system without the detector and integrated over the volume corresponding to the sensitive volume of the scintillators. The assessment of the capability of the detector to measure the gradient can be judged from the fact whether the ratio of the two gradients is the same in all space points. In other words, the space dependence of the gradient calculated from the unperturbed flux and the one taken from the reaction rates should be proportional to each other to a constant factor.

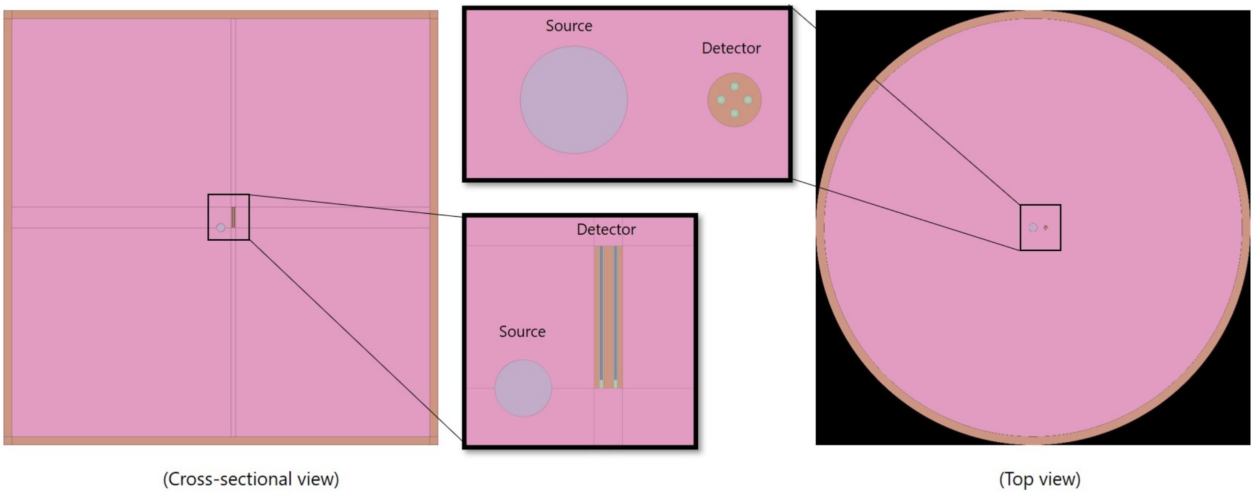

Figure 6: The Serpent model of the measurement of the radial component of the gradient.

The comparison of the space dependence of the "true" flux gradient and the "measured" gradient by the detector is shown in Figure 7. The reaction rate in the detector is the total (n,t) reaction rate calculated with Serpent, inside the sensitive part of the scintillators (again, according to the reaction described in Equation 1). The flux was calculated from neutrons with an energy range up to 1 ev in order to include the whole range of thermal/slow neutrons. From Figure 7, the two curves are in very good agreement which means that the flux distortion that may result from the presence of the detector did not have a major effect on the accuracy of the determination of the gradient. Also, no major consequence of a self-shielding effect was recognised in the results.

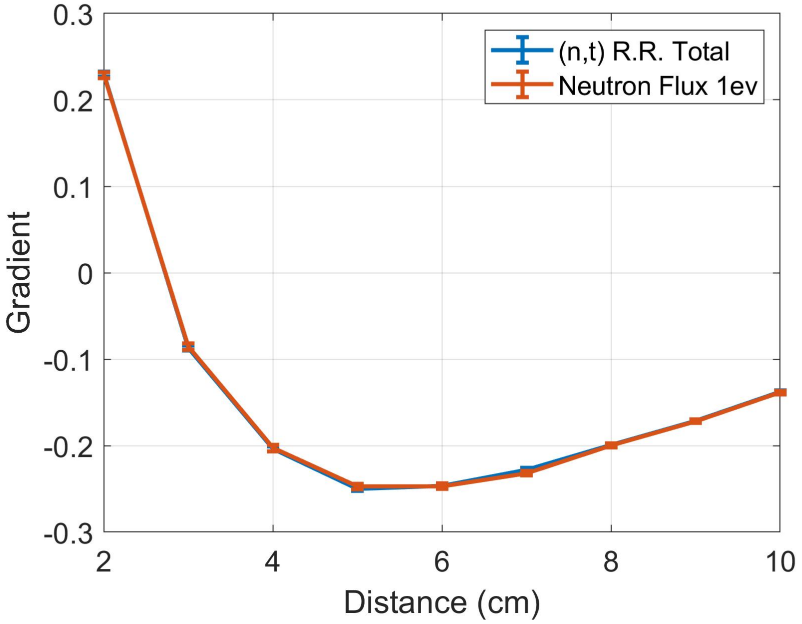

Figure 7: The spatial dependence of the magnitude of the gradient with and without the presence of the detector.

4.2.2 Estimation of the direction of the gradient vector

As mentioned earlier, the measurements obtained from the gradient detector can help to identify possible missing fuel pins in a spent nuclear fuel assembly via an inverse/unfolding procedure. In such unfolding problems, the space dependence of both the magnitude of the gradient and its direction will be used. The absolute value and the direction of the gradient vector are physical concepts with more intuitive content than the two components of the gradient. Therefore it is useful to investigate the suitability of the detector to estimate the direction of the gradient vector.
The best way of estimating the direction of the gradient vector is when both components of the gradient are non-zero. This means that the detector needs to be positioned in a way that none of the two scintillator pairs lie on the same radial line with respect to the location of the neutron source. For this purpose, the orientation of the detector was changed as shown in Figure 8. The detector was then rotated by a 30° angle from its original placement given in Figures 3 and 6.

Simulations were performed at different distances from the neutron source along the x

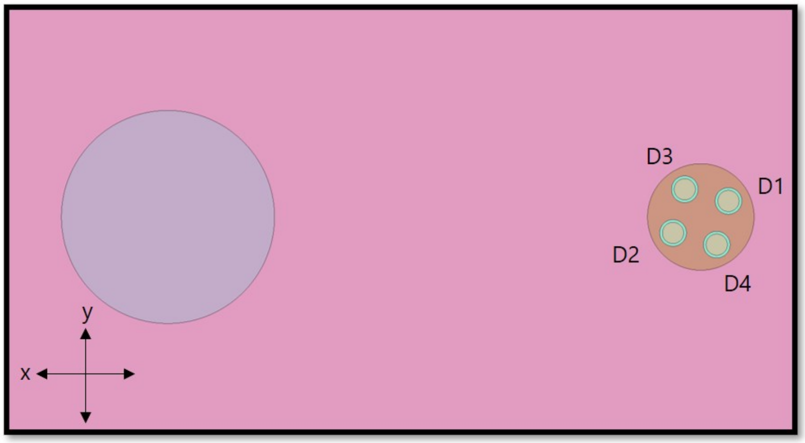

Figure 8: The Serpent model of the measurement of the direction of the gradient showing the detector shifted in a 30° angle.

axis. The results of the direction of the measured gradient vector are shown in Figure 9. As expected from the space dependence of the magnitude of the gradient (Figure 7), the direction of the gradient vector always points towards the source at points that are farther than about 3 cm from the source. The direction of the gradient vector is opposite in the vicinity of the source, i.e., for distances less than 3cm.

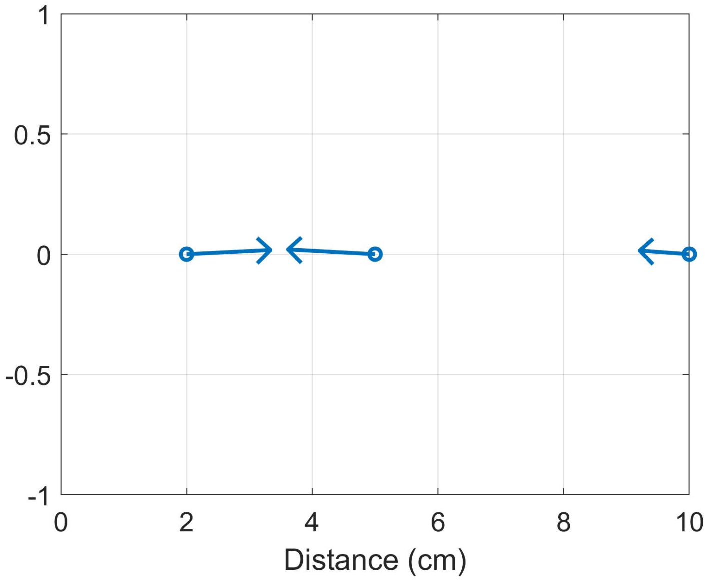

Figure 9: The direction of the gradient vector at different placements of the detector along the x-axis.

5 Conclusion

In this paper the design of a new neutron detector has been introduced and evaluated using Monte Carlo simulations. The detector allows measuring the magnitude and direction of the neutron gradient vector within a multiplying or scattering neutron system. The detector is based on four thin LiF/ZnS(Ag) optical fiber-based neutron scintillators placed together in a rectangular pattern in an aluminium matrix. The detector can be used to estimate the two components of the gradient of the scalar neutron flux, from the difference between the measurements provided by the diagonally-opposite pair of scintillators.

The detector was modelled and tested in a hypothetical setup with a Cf-252 neutron source in a water tank using the Monte Carlo code Serpent. First, the space dependence of the magnitude of the gradient calculated for the detector was compared with the "true" gradient estimated in the system without the presence of the detector. This showed that the detector can properly evaluate the gradient without any severe distortion of the neutron flux distribution.

The possibility of measuring the direction of the gradient vector along with its magnitude was also investigated. The absolute value and the direction of the gradient vector has more intuitive value in unfolding tasks compared to the two components of the gradient. The results showed that the detector can provide a reasonable estimation of the direction of the gradient vector.

Future work is necessary to evaluate the effect of different efficiencies of the four scintillators, to study the behavior of the detector in a full fuel assembly (instead of the simple case of a neutron source in a water tank), and to investigate the performances of the detector to identify possible local inhomogeneities in the assembly (e.g., a missing fuel pin). Manufacturing and testing of the proposed detector has already started.

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