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Design of a Compact Neutron Detector with Flat Response in Energy Range from 5-20 MeV

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Abstract

One of the requirements of neutron detection in wide energy range is a detector with flat response. In this work, a compact neutron detector for energy range from 5-20 MeV has been introduced. The detector has two small spherical ^{3}He proportional counters (PC) placed inside a cylindrical polyethylene moderator**.** Flat response (sensitivity) of the detector has been optimized according to the counters positions inside the moderator. Optimization carried out using MCNP4C Monte Carlo code and Artificial Neural Network (ANN). Results show that the flatness of the sensitivity response of the introduced detector has been increased compared to the conventional detectors.

Keywords: Compact Neutron Detector; Optimization;^{3}He Proportional Counter; MCNP4C Code; Artificial Neural Network; Flat Response.

Introduction

The long counter was introduced by Hanson and McKibben in 1947. The main purpose of this design was to construct a counter with uniform detection efficiency (sensitivity) to neutrons in wide range of energies [i]. The long counter has proved invaluable as a simple and reliable instrument for measuring neutron flux [ii].

For an ideal long counter, the most important property is the uniform sensitivity versus energy leading to the name “flat response” [iii]. To achieve the flat response, a bulky neutron moderator is used for slowing the fast neutron; however, it is weigh-wise and cannot be carried easily as its weight is greater than 50 kg [3].

To reduce the size of moderator, a compact neutron detector with two small spherical proportional counters (PC) was introduced [iv]. The counters containing ^{3}He gas sensitive to slow neutrons were placed inside a polyethylene moderator. Positions and the pressures of counters have the great impact on the flatness of neutron detector sensitivity. Thereby, in this study to increase the sensitivity flatness of the introduced detector presented in [4], we optimized counters positions by involving MNCP4C code and an artificial neural network (ANN) model. It is known that ANN is an appropriate method to handle problems of modeling, prediction, classification and optimization [v,vi]. So, this tool accompanied by MCNP4C code is considered as optimization tools.

Design of Detector

Structure

For achieving a flat response for the sensitivity of the compact detector in a wide energy range (similar to long counters), two small counters were embedded at appropriate positions inside a moderator. It is known that low energy neutrons slow down in a shorter path inside the moderator in comparison to both intermediate and fast neutrons. So, they are detected mainly by the small counter placed at the beginning of the moderator (a in Fig. 1) before the leakage or absorption, whereas, fast neutrons travel long paths inside the moderator to slow down then detected mostly by the second detector placed in the far distance from the front surface of the compact detector (b in Fig. 1). Therefore, positions of counters play important roles in achieving a flat response for the total sensitivity of the compact detector.

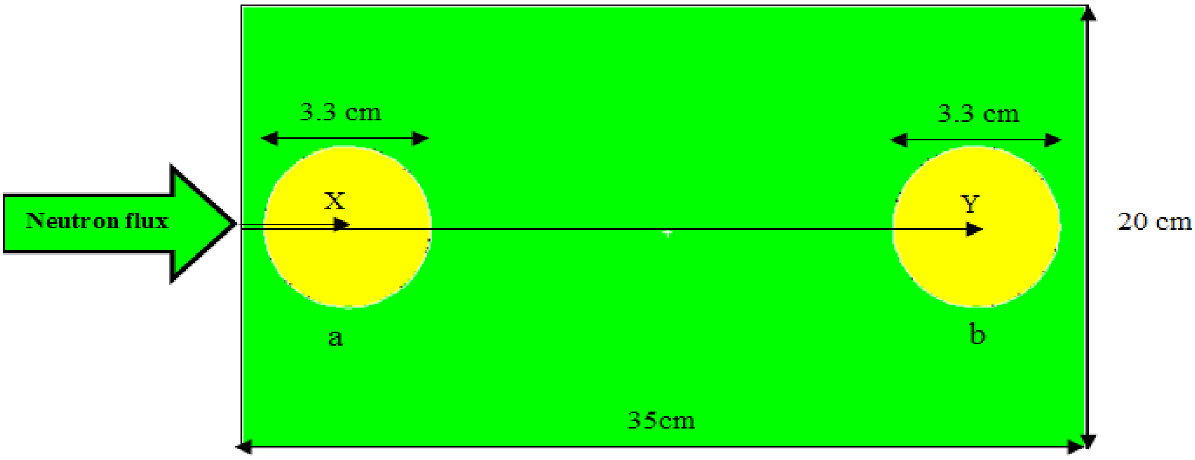


Figure 1.Structure of the compact neutron detector. Two Spherical ^{3}He PCs inside the cylindrical polyethylene moderator

The proposed compact detector (Fig. 1) contains two small spherical counters (slow neutron detectors) with the radius of 1.65cm placed coaxially inside a cylindrical polyethylene moderator. Counters are filled with ^{3}He gas and designed to contain pressures of 0.275 and 8.8 atm respectively. The dimension of the moderator is 20 cm in diameter and 35cm in length [4]. The weight of this compact detector does not exceeding from 10 kg.

Material and method

The sensitivity, *S*, is defined as the ratio:

$$S = \frac{True\ counting\ rate}{neutron\ flux} = \cdot \qquad (1)$$

With the true count rate *r:*

$$r = \varepsilon_p R = g - \ell \qquad (2)$$

Whereε_p is the counter efficiency, *b* is background counting rate, *g* is gross counting rate, and, *R* is the ^{3}He (n, p) reaction rate [1].

In practice, the sensitivity is defined by the count for unit fluence of neutron [4]. It can be obtained using the ^{3}He (n, p) reaction rate in ^{3}He counters.

As it is shown in Fig. 1, for examining the sensitivity profile of the compact detector, the front surface of the moderator were irradiated by a parallel beam of monoenergetic neutrons with their energies varying form 0.5 eV to 20 MeV.

Training the ANN model

ANN is defined as a numerical method consisting of simple processing elements named neurons running in parallel and generating one or multiple layers [1]. Multi-layer perceptron (MLP) networks are the most commonly used ANNs [1]. In this work, the training of ANN model was performed by MATLAB 7.0.4 and the required dataset was provided using MCNP4C. Training of the proposed MLP networks was performed by Levenberg-Marquardt (LM) algorithm [1]. To find the best ANN architecture with minimum train and test errors, ANNs consisting of different layers and nodes were examined. The proposed MLP model is shown in Fig. 2, where the inputs are *X* and *Y* (positions of counters inside the moderator in cm)and the output is the variance of matrix C , f_r. Table 1 shows the specifications of the proposed ANN model.

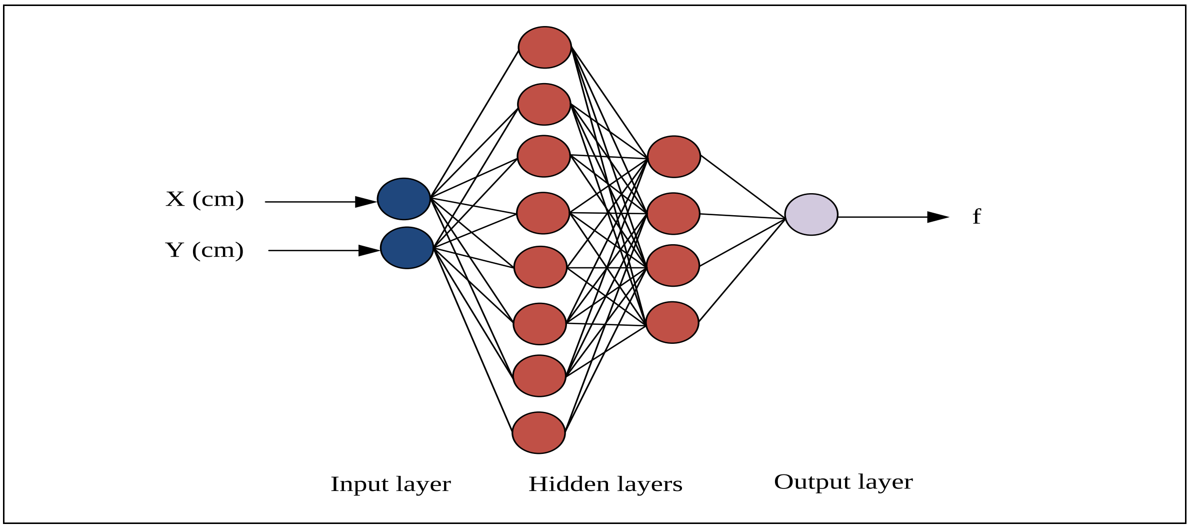


Figure 2.Architecture for the proposed MLP model

Table 1.Specification of proposed ANN model

Neural network	MLP
Number of neurons in the input layer	2
Number of neurons in the first hidden layer	8
Number of neurons in the Second hidden layer	4
Number of neurons in the output layer	1
Number of epochs	1070
Activation function	tansig

The mean relative error percentage (MRE %), the root mean square error (RMSE) and the mean absolute error percentage (MAE %) of the network were calculated by [8, 9] :

$$MRE\,\% = 100 \times \frac{1}{N} \sum_{j=1}^{N} \left| \frac{X_j(Exp) - X_j(Pred)}{X_j(Exp)} \right| \tag{3}$$

$$RMSE = \left[\frac{\sum_{j=1}^{N} (X_j(Exp) - X_j(Pred))^2}{N} \right]^{0.5} \tag{4}$$

$$MAE\% = 100 \times \frac{1}{N} \sum_{j=1}^{N} \left| X_j(Exp) - X_j(Pred) \right| \tag{5}$$

espectively where N is the number of data, "X (Exp)" is the simulated data (acquired by MCNP4C) and "X (Pred)" is the predicted data (acquired by ANN).

Results and discussion

Total results of ANN in prediction of the two PCs' positions (X and Y values) are shown in one contour graph in Fig. 3. This contour was obtained after testing a large set of PCs' positions using trained ANNmodel.

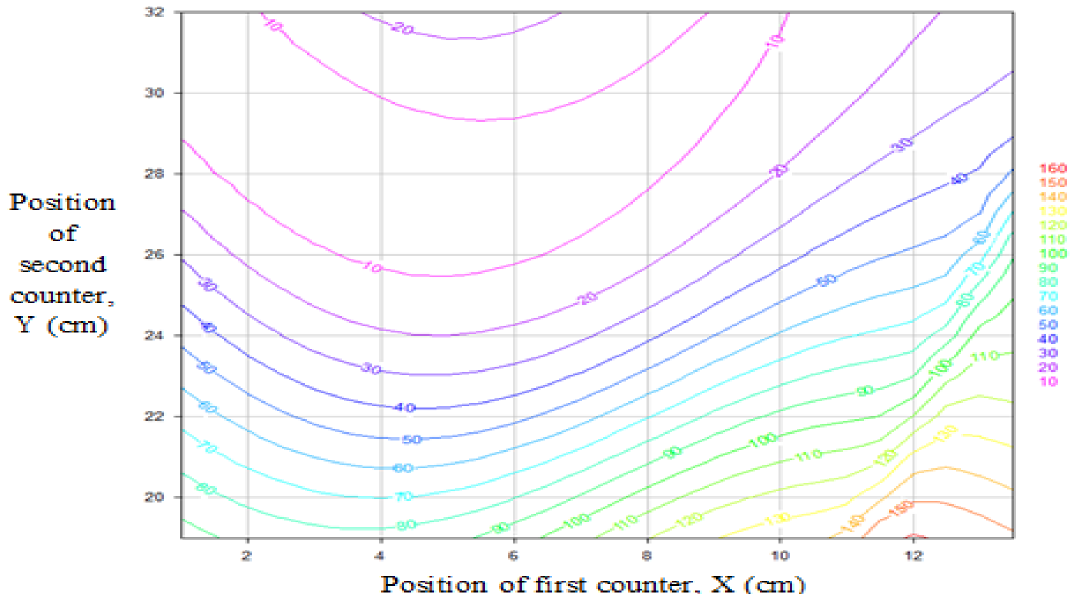
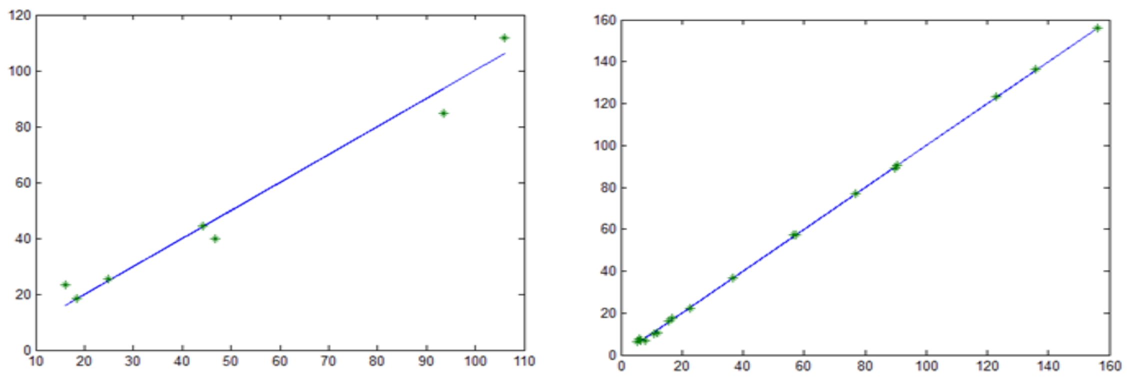


Figure 3.Plot of Variance of the total response, *f*, as a function of PCs' positions (predicted by ANN)

According to Fig. 3, the best predicted positions of ^{3}He PCs are 1.65cm and 30.25 cm, which are the X and Y values at the minimum value of f.

Fig. 4 shows the comparison between the simulation results from MCNP4C and the predicted results obtained from the proposed ANN model for training and the testing data. Testing set is used to verify the network. For a precise network the simulated results (real values) should be close to the predicted results (ANN output).As shown in Fig. 4, the predicted f values by the proposed ANN are close to the simulated results generated by MCNP4C. This agreement verifies the

capability of ANN as a precise and trustworthy model for the PCs positions prediction. Table 2 depicts the obtained errors for the presented ANN model.



a) b)

Figure 4.Comparison of simulated results from MCNP4C and predicted results (regression diagram) for a) testing data b) training data.

Table 2.Obtained errors for training and testing results of the presented ANN model

Error	Train	Test
MRE%	0.0214	0.6198
MAE%	0.5885	1.2520
RMSE	0.0027	0.0063

Ultimately, Fig. 5 shows the sensitivity curves of each PC placed at the given positions and the total sensitivity of the compact detector.The average of total sensitivity is calculated 0.79cm2for the neutron energy range from 0.5eV to 20 MeV. While, it’s maximum deviation from the mean value is 46% in the whole energy range which is not satisfactory. However, according to Fig. 5, the average of total sensitivity in energy range of 5-20 MeV is 0.90 cm2where the maximum deviation from this average value is only 16%. This result is better (at least 4%) than the similar case reported in literatures [1,1].

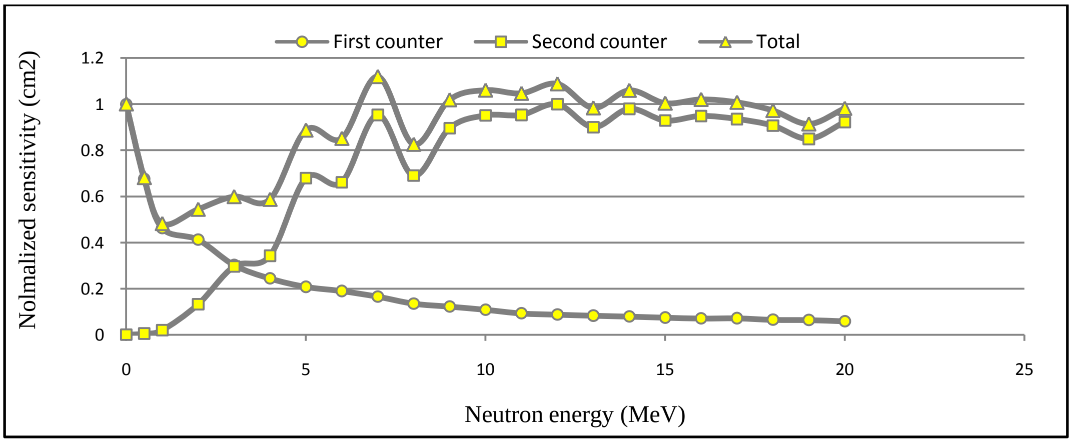


Figure 5.Sensitivity curves of the two PCs and total sensitivity curve of the optimized compact neutron detector

Conclusion

In this study, a compact neutron detector (with the weight of about 10 kg) was designed using MCNP4C code and ANN. The detector contains two spherical ^{3}He PC’s inside a cylindrical polyethylene moderator. For improving the sensitivity flatness of the detector, the optimum positions of PCs inside the moderator were obtained. Results show that the sensitivity flatness of the compact neutron detector in the energy range of 5-20 MeV is efficient. At the completion of our study, it seems that better sensitivity flatness is obtainable by optimizing the PCs’ pressures inside the moderator.

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