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Original Article

Thermal neutron albedo and flux for different geometries neutron guide

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ABSTRACT

This paper presents a study on thermal neutron reflection properties of neutron guide for cylinder, spindle, elliptic and parabolic geometries using ^{241}Am-Be neutron source (5.2 Ci) and BF_3 detector, whereas neutron guide is important instrument for transportation of neutrons. To this goal, the required inner and outer radii of neutron guide have been calculated to achieve the highest guided thermal neutron flux based on MCNPX Monte Carlo code. The maximum flux of cylinder geometry with a length 50 cm has been obtained at an inner radius 9 cm and an outer radius 21 cm. Also, the maximum value of thermal neutron albedo is 0.46 ± 0.001 at 12 cm thickness of parabolic guide.

1. Introduction

Performance improvement of low-activity neutron source and neutron transportation over long distances are essential subjects in studying neutron scattering. Neutron intensity decreases with increasing distance to a point source. This decrease is inversely proportional with R^2, which R is the source-sample distance. However, neutron scattering and neutron reflection processes can be used to increase the neutron flux and transmit neutron to the desired place. For this purpose, neutron guides are used in the field of neutron physics. Neutron guides are economically affordable by considering the high price of neutron sources. In recent years, there have been studies on neutron guides [1,2]. Neutron guide production has been developed in ESS (European Spallation Source), KAERI (Korea Atomic Energy Research Institute) and FRM-II (Forschungsreaktor Munchen II) [3–5]. In these instruments, the neutron guide increases the available space which has nonzero flux around the neutron source. Also, ultracold neutron guides have been evaluated by prestorage method [6]. In early neutron guides, tubes were used with rectangular cross section [7]. These tubes were coated with nickel or titanium to reflect neutrons [8]. Currently, elliptic and ballistic geometries are investigated for neutron guides [9,10]. Determination of optimum dimension and suitable geometry is important for neutron guide. In this study, we use polyethylene neutron guide and have found the required internal and external radii to achieve the maximum value of thermal neutron flux. Polyethylene is a simple and inexpensive polymer which has a high value of hydrogen. Hydrogen has high scattering cross section and low absorption cross section for thermal neutron. Therefore, polyethylene is a suitable material as thermal neutrons reflector. However, it has been less considered as a neutron guide. The main purpose of this research is to increase the transferred thermal neutron flux due to the thermal neutrons reflection. For this purpose, we investigate the simultaneous change of the inner and outer radii of the neutron guide for different lengths which has been less attended in the previous studies. Past researchers have been showed using the curved geometry has been improved the guide performance. Also, we have designed the cylinder and curved geometries for neutron guide by using MCNPX code. Furthermore, thermal neutrons albedo coefficients have been obtained in order to investigate neutron guides. Albedo coefficient represents the amount of neutrons reflection from a surface. This coefficient has not been considered in the previous studies of the neutron guides, while it is a suitable criterion to evaluate the increment possibility

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of transferred thermal neutron flux. However, the neutron reflection from inner surfaces of guide leads to transfer the neutrons. Measurements of the reflection coefficients of polyethylene neutron guides with a cadmium neutron absorber have been performed using an ^{241}Am-Be neutron source and a BF_3 detector.

2. Methodology

The value of transferred neutrons is the most important criterion to benchmark the neutron guide. The output neutrons flux determined the performance of the neutron guide in a desired distance. The neutron flux depends on the neutrons reflection which is expressed by albedo coefficient. Therefore, transferred thermal neutron flux as the main quantity and albedo coefficient as the confirmed quantity are considered in order to select the best geometry for the neutron guide. Appropriate geometry of the neutron guide should be designed in order to achieve the maximum transferred thermal neutron flux. Firstly, the optimum inner and outer radii of the neutron guide are evaluated for each length. Then, straight and curved geometries of the neutron guide are simulated and output thermal neutron flux and albedo coefficient are achieved using MCNPX code. The obtained results are compared with the available data of other studies. Finally, the optimum dimension and geometry are selected by considering the obtained thermal neutron flux and albedo coefficient.

2.1. Thermal neutron albedo

The reflection ability of the material is determined by its reflection coefficients, or albedo, and could be defined as the fraction of incoming neutrons leaving the neutron guide in an arbitrary direction [11]. The neutron reflection depends on the element composition of the reflector and the geometry of the measurement [12]. The thermal neutron albedo for a reflector layer can be expressed as [13]:

$$\beta = \frac{J_n^{out}(\theta)}{J_n^{in}} \tag{1}$$

where J_{in} and J_{out} are incoming and scattering neutrons at reflector, respectively, which are determined as:

$$J_n^{in} = 1 + \frac{2D}{L}\coth\frac{a}{L} \tag{2}$$

$$J_n^{out} = 1 - \frac{2D}{L}\coth\frac{a}{L} \tag{3}$$

where a, D and L are reflector thickness, diffusion coefficient and diffusion length, respectively. D and L are calculated by Ref. [14]:

$$L = \sqrt{\frac{D}{\Sigma_a}} \tag{4}$$

$$D = \frac{\Sigma_s}{3\Sigma_t{}^2} \tag{5}$$

where Σ_a, Σ_s and Σ_t are absorption, elastic and total cross section of thermal neutrons. The used materials are defined using ENDF VII.0 library in MCNPX code [15]. Thermal neutron total, scattering and absorption cross sections of polyethylene components which consist of carbon and hydrogen are extracted from this library [16]. According to the obtained cross sections, thermal diffusion length and diffusion coefficient of polyethylene guide are calculated by Eqs. (4) and (5). The properties of used neutron guide are shown in Table 1.

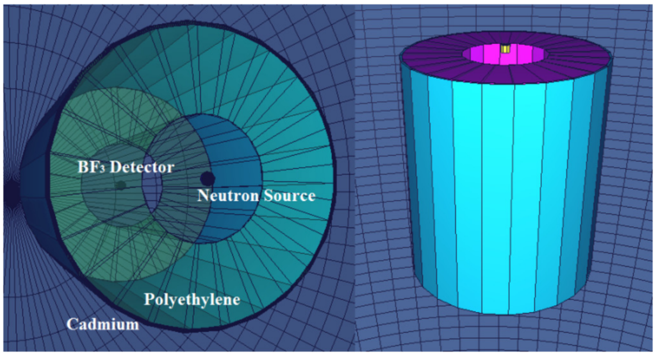

Fig. 1. Geometric measuring system including ^{241}Am-Be source, BF_3 detector, cadmium absorber, and polyethylene guide extracted from MCNPX code.

Table 1
The properties of polyethylene neutron guide used in the MCNPX code.

Absorption Cross Section (cm^{-1})	Scattering Cross Section (cm^{-1})	Diffusion Length (cm)	Diffusion Coefficient
0.0267	6.7836	1.3512	0.0487

2.2. Straight neutron guide

The first configuration considered for a neutron guide is a polyethylene cylinder with a length “L”, an inner radius “a”, and an outer radius “b”. The density of the considered polyethylene is 0.95 g/cm^3. The ^{241}Am-Be neutron source (5.2 Ci) is located at distance of 1 cm from the neutron guide and transmit fast neutrons in range of 0–11 MeV. When the emitted neutrons from the neutron source enter in the polyethylene cylinder, the neutrons are slowed down to thermal energies. These thermal neutrons are guided after several reflections in the neutron guide and are detected by used BF_3 detector, which is located at the distance of 1 cm in the other end of the cylinder. Also, neutron guide is covered with 0.5 cm thickness of cadmium to prevent radiation emission. Because absorption cross section of cadmium for thermal neutrons is very high (2520 barn), we could use it as thermal neutron absorber [17]. Fig. 1 shows the geometry used for measuring the output thermal neutron flux from the neutron guide. Thermal neutron fluxes of neutron guide are obtained for different lengths, inner radii, and outer radii using F4 tally. Thermal neutron flux values of neutron guides are determined by Ref. [18]:

$$\text{Flux} = \text{Tally F4} \times \text{Source Strength}\ (cm^{-2}s^{-1}) \tag{6}$$

In addition, the flow of incoming and scattering neutrons at guide surface is obtained by F1 tally of MCNPX code. Then, thermal neutron albedos of neutron guides are calculated using Eq. (1).

2.3. Curved neutron guide

Neutron guides with curved geometry are considered as a mean to increase the transmitted thermal neutron flux. It is expected that the parameters of the transmitted neutrons, including increase of thermal neutron flux, change by changing the curvature which

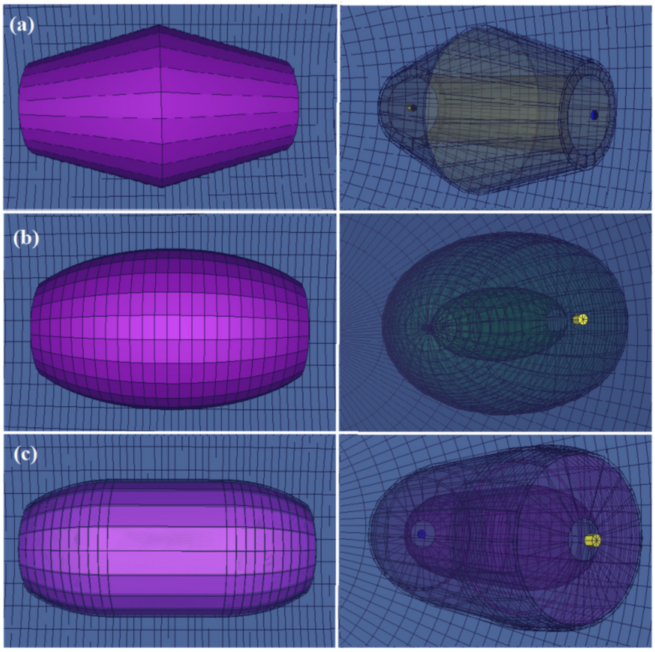

Fig. 2. (a) Spindle, (b) ellipse, and (c) parabolic geometries of thermal neutron guide.

cause to increase the thermal neutron flux. The investigated curved neutron guides are spindle, ellipse, and parabolic geometries. The used curved geometries are shown in Fig. 2. Final length, central inner and outer radii have been considered similar for all geometries, so we can be able to compare the different neutron guide performances. The thermal neutrons fluxes and albedo coefficients of neutron guides are obtained like for a straight neutron guide using F4 and F1 tallies of MCNPX code.

3. Results and discussion

In this part, we present the transmitted thermal neutron fluxes using cylinder tube shown in Fig. 3 for lengths which are 20 cm, 50 cm, 80 cm and 110 cm. These considered lengths have different inner and outer radii. As seen in Fig. 3, thermal neutron flux decrease by increasing length because the number of guided neutrons are reduced. Some neutrons absorbed or escaped, but still the significant values of neutrons are guided by increasing length. Also, the thermal neutron flux increases and saturates when the outer radius is increasing because of increased probability of neutron reflection. In the other words, the guide thickness extends by increasing outer radius. Therefore, the reflected thermal neutrons and albedo coefficient increase up to saturated thickness according to Eqs. (2) and (1). When inner radii are being increased firstly, thermal neutron fluxes are rising because the probability of absorption reduces. Therefore, thermal neutron reflection is increased from two parallel surfaces. At the very small inner radius, neutrons do not have enough space to travel forward. In this case, most of

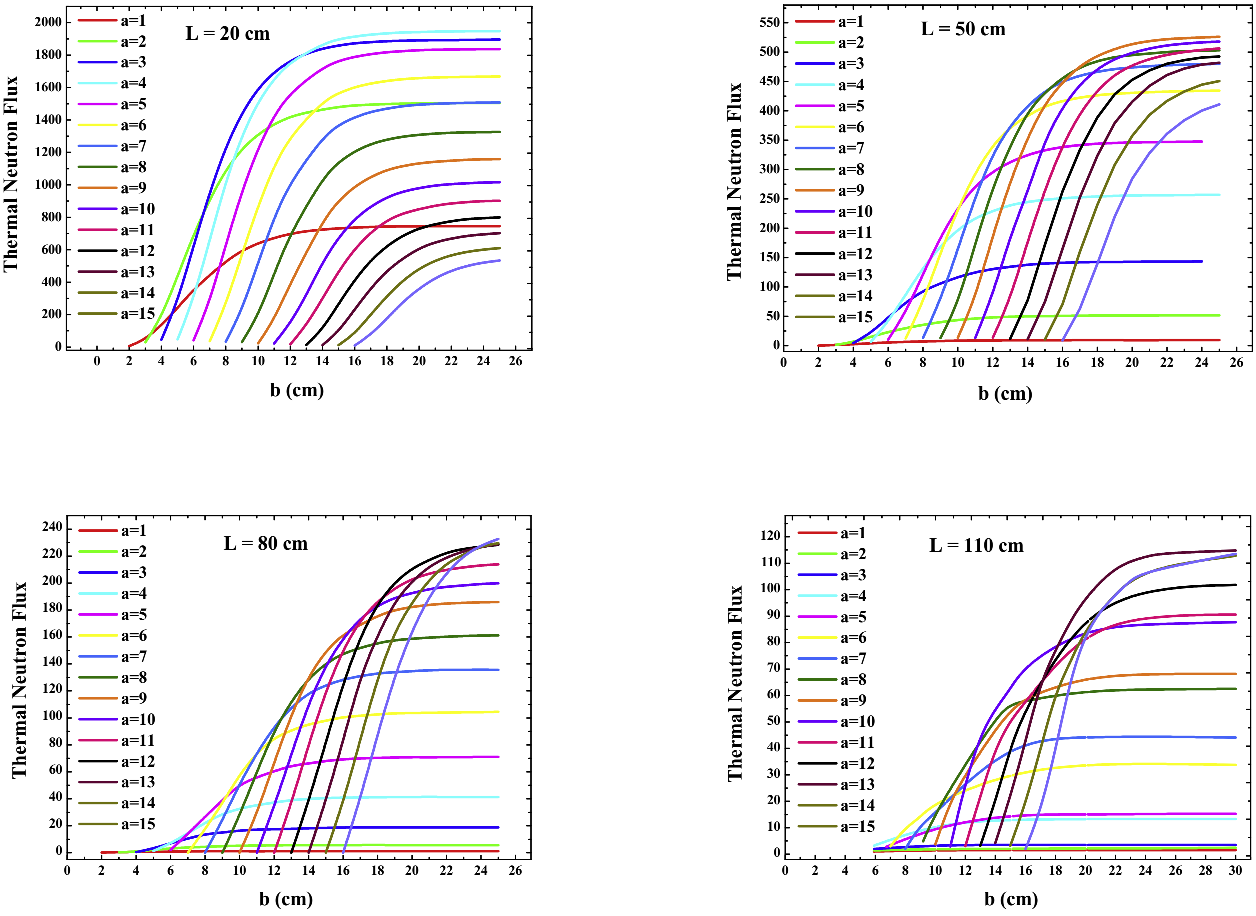

Fig. 3. Thermal neutron fluxes versus outer radius of cylinder guide for different inner radii and lengths.

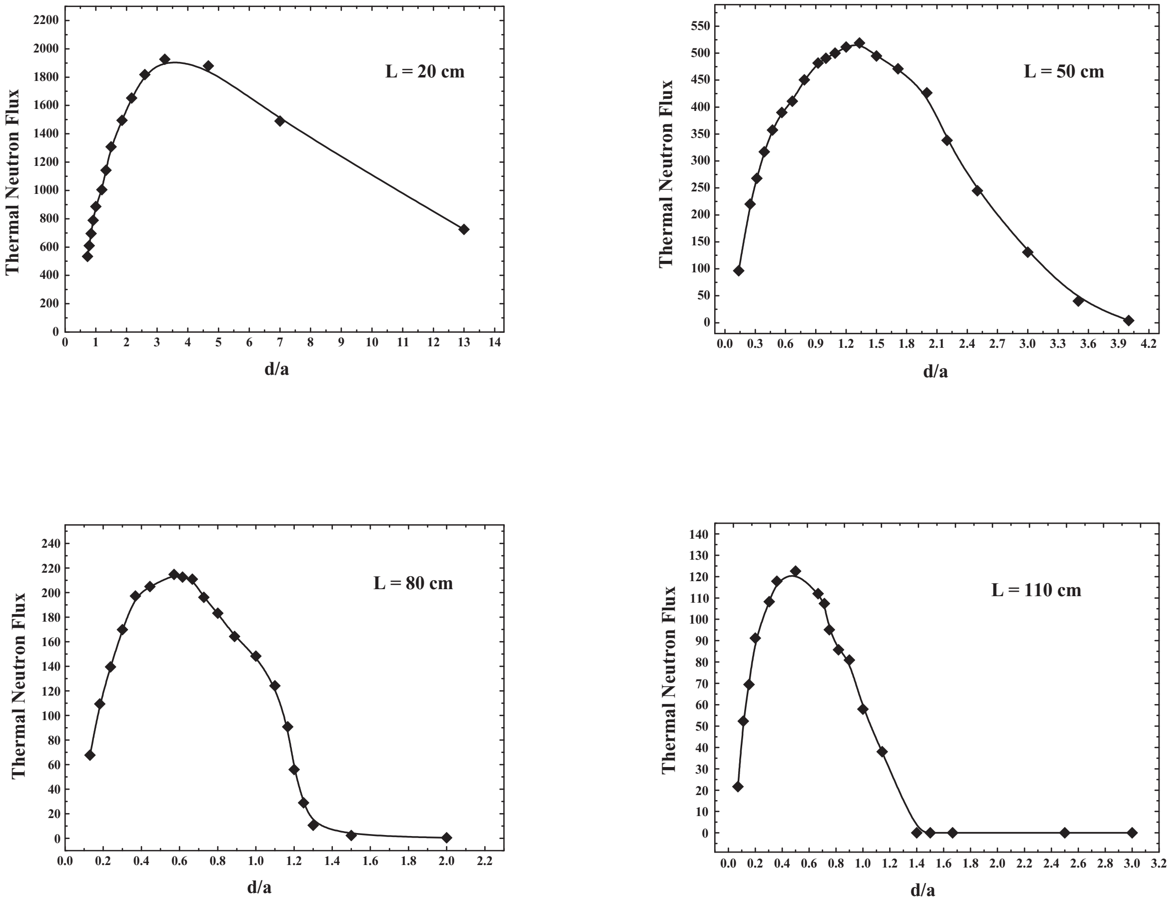

Fig. 4. Thermal neutron fluxes at saturation thicknesses as a function of d/a for the lengths of 20 cm, 50 cm, 80 cm, and 110 cm.

neutrons are absorbed and few of them are reflected from two parallel surfaces. By increasing the radius, neutrons have adequate space to travel forward after every reflection from surfaces. Therefore, the neutron reflection is increased and the probability of neutron capture is decreased. This process is repeated at successive reflections from two parallel surfaces. When the inner radii reach certain values, thermal neutron fluxes decrease because few number of neutrons can reach to opposite surface of neutron guide. Actually, at the very big inner radius, the hole radius of the neutron guide is enlarged and the neutrons must travel a long distance to reach the opposite surface. Therefore, most of neutrons are absorbed and the value of reflected and transferred neutrons decrease after the special inner radius. This procedure is observing at all lengths of neutron guide. At small lengths, the possibility of neutrons transfer is high, so lower inner radius is required compare to long lengths, so the neutrons are transferred without high absorption. As seen in Fig. 3, the maximum transferred thermal neutron flux of 20 cm length is obtained for 4 cm inner radius. By increasing the neutron guide length, the possibility of neutron removal is increased and more inner radius is required, therefore the maximum transferred thermal neutron flux of 110 cm length is obtained for 13 cm inner radius. For better understanding, the maximum thermal neutron flux of every inner radius and saturated thickness related to its outer radius are extracted from Fig. 3 for each length. The maximum thermal neutron flux versus $\frac{d}{a}$ is plotted in Fig. 4, d is the guide thickness which is equal to the difference between the outer radius (b) and the inner radius (a). This ratio shows the guide thickness to the radius of guide aperture. According to Fig. 4, the ratio of $\frac{d}{a}$ can be determined to obtain the maximum flux for any fixed length. The increment procedure of the thermal neutron flux to a certain proportion of $\frac{d}{a}$ and after that its reduction procedure are clearly observed in each length. At the maximum flux, the inner radius values are 4 cm, 9 cm, 15 cm, and 20 cm and the outer radius values are 17 cm, 21 cm, 23 cm, and 30 cm for the mentioned lengths, i.e. of 20 cm, 50 cm, 80 cm, and 110 cm, respectively. The ratio $\frac{d}{a}$ for the maximum flux versus length are shown in Fig. 5. After fitting the curve of Fig. 5, the obtained equation of $\frac{d}{a}$ is $5.5*\exp\left(-\frac{L}{43.80}\right)-0.21$. According to this equation, the needed inner and outer radii which thermal neutron fluxes are maximum can be obtained for any length. The cylinder geometry can be used as base geometry to determine the inner and outer radii of all neutron guide geometries. Several inner and outer radii are considered for different geometries, and their transferred neutron fluxes are obtained. The output thermal neutron fluxes for these radii are shown in Fig. 6. As seen in Fig. 6, the values of thermal neutron flux are different for the various geometries, but the optimum inner and outer radii are approximately identical for all neutron guide geometries. There is only a low shift that it can be discarded. However, the main difference of all used geometries is in the end region of these guides and the central region is approximately identical. Therefore, the cylinder geometry is used in order to determine the inner and outer radii of the neutron guide. These radii are generalized to other geometries of neutron guide. Also, we investigate the effect of the curved geometries based on the output thermal neutrons in neutron guide. Output thermal neutron fluxes

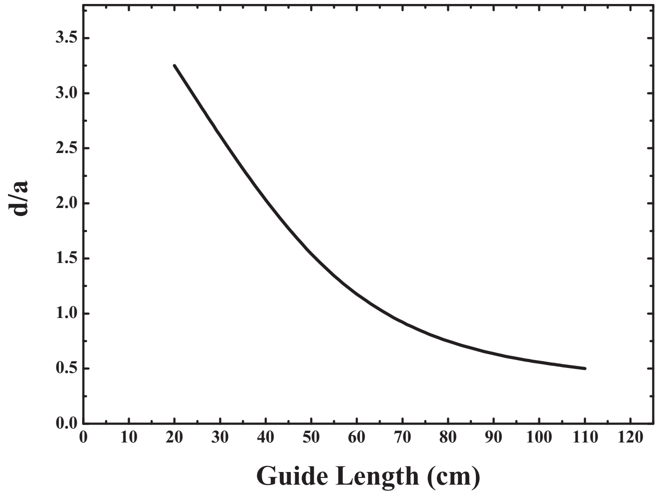

Fig. 5. Ratio of guide thickness to inner radius as a function of guide length at the maximum flux.

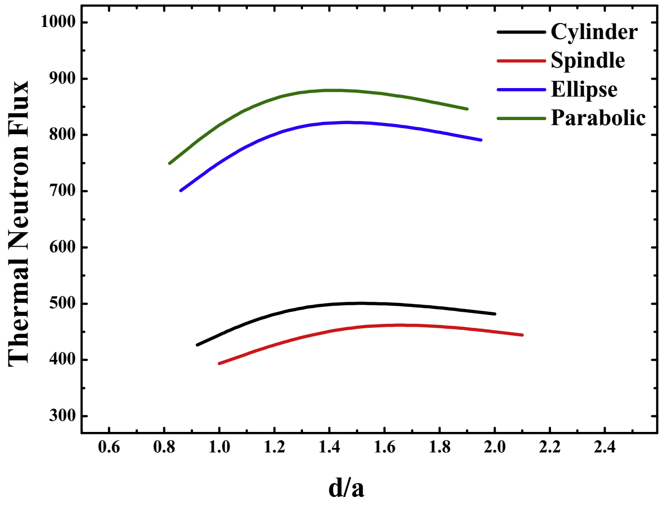

Fig. 6. The thermal neutron flux of neutron guide as a function of d/a for different geometries with 50 cm length.

for neutron guides with cylinder, spindle, ellipse and parabolic geometries are obtained and are shown in Fig. 7. In these geometries, the lengths, central inner, and outer radii are considered similar in all of them. Also, our results are compared with the data of other study and are shown in Fig. 7. In that study, brilliance transfer was investigated and it was shown that the curved geometries had better performance than straight geometry. In comparison between different geometries, ellipse and parabolic geometries were obtained more yield of the guided thermal neutrons. We converted the brilliance transfer (neutrons/s/cm^2/sr) into the flux (neutrons/s/cm^2), so we can accomplish the comparison of the obtained values. The achieved results show that neutrons in elliptic and parabolic geometries can be guided in longer distance than in straight geometry. In spindle geometry, outer radius is curved and it has not any effect on increasing flux and as seen in Fig. 7, the minimum value of thermal neutrons is transferred. In elliptic geometry, inner and outer radii are curved whereby more thermal neutrons can be guided by reflection, resulting in increased thermal neutron flux. In parabolic geometry, whereas the first and end areas are curved, the maximum flux is obtained for this geometry. In parabolic geometry is obtained the maximum thermal neutron flux because of the great focus of neutrons and the increment of sequential reflections from the surfaces. Thermal neutron albedo coefficients of neutron guides for used geometries are shown in Fig. 8. Also, our results are compared with the data of other study and are shown in Fig. 8. According to the values of the converted brilliance transfer into the thermal neutron flux, albedo coefficients of the other work are calculated. The results of albedo coefficients are similar to the results of flux values, so these results confirm that output flux is increased by increasing the neutron reflection. The obtained results for cylinder path show that some of the neutrons have removed after one or more reflections, due to large reflection angle. Some neutrons are incident on the guide under an angle larger than the critical angle for total reflection, so they do not arrive to opposite surface and are eliminated from the reflection path. On the other hand, the results of elliptic path show that these neutrons again trap in the same surface and are affected by the consecutive reflections. The obtained results for parabolic geometry show that the first and final surfaces act as focusing surfaces, and cause the reflections to increase in comparison with the elliptic geometry, as seen in Fig. 8. In addition, inner surface of

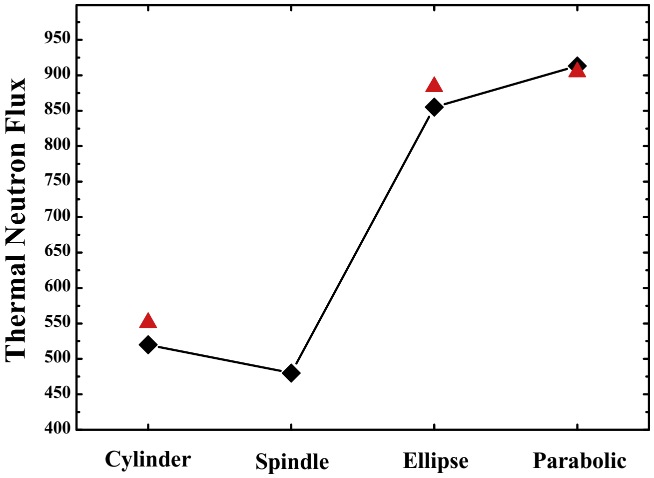

Fig. 7. The thermal neutron flux of neutron guide for different geometries with 50 cm length. The scatter curve (red solid triangles) has been taken from Ref. [4].

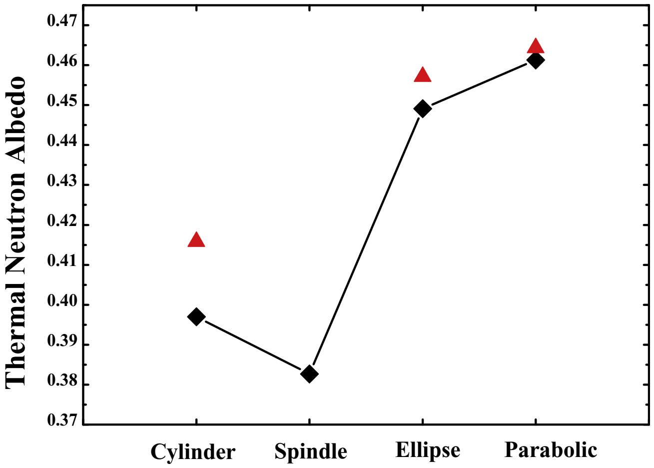

Fig. 8. The thermal neutron albedo coefficient of neutron guide for different geometries with 50 cm length. The scatter curve (red solid triangles) has been taken from Ref. [4].

spindle geometry is similar to cylinder geometry. On the other hand, the thickness of the spindle is less than cylinder thickness, therefore albedo coefficient has obtained a minimum value.

4. Conclusions

We have shown that the reflection coefficients depend on the inner and outer thicknesses and length of neutron guide. The thermal neutrons can be transferred by neutron guide over long distances. This transportation is performed using reflection technique inside the neutron guide. By increasing thermal neutron reflection, the guided neutron flux increases. The values of optimum inner and outer radii of the neutron guide are obtained according to the required length to transmit the neutrons using the proposed equation in this study. The obtained results show that more neutrons in elliptic and parabolic geometries can be transmitted, so more flux can be obtained in comparison with the spindle and straight geometry. Albedo coefficient is important quantity to determine the reflected and transferred thermal neutrons in the neutron guide. The measured value of the thermal neutron albedo for a parabolic guide is 0.46 ± 0.001 in comparison with three others guides. Also, the maximum flux of guided neutrons is obtained for parabolic geometry. Therefore, parabolic geometry is the best geometry for the thermal neutron guide according to the output thermal neutrons flux and albedo coefficient. Our results have reasonable agreement with the results of the other studies. This investigation is confirmed that the curved geometry has good effectiveness on performance of the thermal neutron guide. The cost of using neutron sources is greatly reduced by transferring neutrons to the desired distance and place. The maximum albedo coefficient and transferred neutron flux are obtained by selecting the appropriate dimension and geometry for neutron guide. Neutron guides not only increase the neutron flux, but can also be used as a neutron shield. Investigating cold neutrons in neutron guide could be considered, because neutrons can be transmitted over longer length by increasing wave length and decreasing energy. Also, for studying fast neutrons, other materials like lead are suggested.

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