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INFLUENCE OF BORON CONCENTRATION, TEMPERATURE, AND PRESSURE ON NEUTRON MIGRATION IN LIGHT WATER

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ABSTRACT

The migration of neutrons from their generation point to the absorption point in light water was analyzed using the Monte Carlo method. Neutron age (NA) of fast neutrons and the diffusion area (DA) of thermal neutrons were calculated as functions of temperature (20 – 100 °C), pressure (2 - 10 MPa), and boron concentration (200 - 1000 ppm), as well as their combined effects. NA and DA at room temperature and pressure have been calculated, and the results are consistent with experimental values. The percentage changes in average NA and DA per unit increase of boron concentration, temperature, and pressure have been estimated. In all cases, the amount of DA change was larger than that of the NA change. The percentage decreases of average NA and DA per fixed amount increment of temperature, pressure, and their combined increment were evaluated with 1000 ppm boron in the medium. Maximum average NA and DA decrements were found to be 2.7% and 64.4%, respectively, at room temperature. This investigation provides critical insights into reactor safety and efficiency by quantifying how boron concentration, temperature, and pressure affect neutron migration in light water systems using MCNP.

Keywords: *Neutron migration, neutron age, diffusion area, thermalization, Monte Carlo method*

1. INTRODUCTION

To design a nuclear reactor, a comprehensive prediction of the balance between neutron generation, absorption, and scattering loss is needed. The key information, such as the rates of neutron production and absorption, is important not only for core design and analysis but also for thermal-hydraulic, heat-mass transfer, accident scenarios, and radioactivity release estimates. Neutrons undergo multiple collisions (absorption and scattering) in the reactor core during migration. Radiative capture and fission are two main absorption processes that may take place in a nuclear reactor. In fission, the target nucleus divides and releases additional neutrons, which contribute to sustaining the chain reaction. However, in radiative capture, the neutron is absorbed and does not contribute to sustaining the chain reaction. In scattering collisions, either elastic or inelastic, neutrons change their energy, spatial position, and direction of motion, and the process is known as moderation. This process represents the transfer of neutrons from higher to lower energies and from one location to another or transported from one location to another and from higher energy to lower energy.

Changes in temperature and pressure within a reactor modify the value of neutron age (NA) and diffusion area (DA). The significant effect is caused by water density changes with variations in temperature and pressure. Increasing the pressure increases moderator density by raising the number

of particles per unit volume. In a thermal nuclear reactor, a more effective neutron moderator increases the likelihood of a sustained chain reaction by thermalizing neutrons, thereby increasing the effective (k-eff) multiplication factor. Since neutron diffusion occurs especially in the reactor's moderator/coolant, the change in the moderator/coolant temperature leads to the change in its density. For example, as the moderator temperature increases, the DA also increases. All macroscopic cross-sections for elastic scattering and neutron absorption significantly decrease, especially due to the thermal expansion of water, which results in the diffusion coefficient (D) increasing. The concentration of boron in the primary moderator (light water) also influences the diffusion length. An increase in boron concentration introduces additional absorbing material into the core, thereby increasing the macroscopic absorption cross-section and reducing DA.

Many researchers have used various methods to calculate neutron age and diffusion area in light water. Yamamura et al. found neutron ages and moderation spectra in light water for a fission source using a stochastic method of calculation [1]. In this study, the obtained neutron age results show good agreement with experimental values from other authors. K. S. Rockey conducted measurements of the thermal neutron diffusion length in water over the temperature range of 25 to 296 °C using the pressure vessel of a high-temperature critical assembly [2]. In this study, the diffusion length was determined by fitting an exponential function to data obtained from manganese foils activated by neutrons from a small Sb–Be source. In another study, the migration area, multiplication factor, and both axial and radial reflector savings of a light water–moderated critical assembly fueled with UO_2 (enriched to 2.596 w/o in ^{235}U) were determined using water height experiments and the one-group diffusion model [3]. In the present study, the world-recognized Monte Carlo method-based code MCNP has been used not only to calculate the neutron age and diffusion area but also to observe their behaviour in various temperatures, pressures, and with the presence of different boron concentrations in light water. The macroscopic cross-section is defined as the probability of a specific interaction per unit distance travelled by a neutron, which is directly relevant when using the Monte Carlo method for neutron transport simulations.

The purpose of this research is to investigate how key reactor parameters—boron concentration, temperature, and pressure—affect neutron migration in light water, using the Monte Carlo method-based code, MCNP. By analyzing these influences, the work aims to provide a deeper understanding of neutron behavior in reactor cores, which is essential for optimizing reactor control, improving fuel utilization, and ensuring operational safety under varying conditions. This research ultimately contributes to the advancement of nuclear reactor physics by offering reliable computational insights into how environmental and chemical factors impact neutron transport in light water reactors.

2. CALCULATION TOOLS AND TECHNIQUES

Fast neutrons emitted from a neutron source are modified and then diffused in the thermal region and finally absorbed by surrounding media (light water). In the course of the process, neutrons will migrate through space, changing their flight directions every time they collide with the medium. The neutron scattering process in light water is depicted in Fig. 1. Let r_s represent the distance from the source point (A) to the point (B) where neutrons enter the thermal energy region, and r_a represent the distance from point (B), where neutrons enter the thermal region, to the absorption point (C).

From Fermi age theory and neutron diffusion theory, the age and the diffusion area L^2 of a neutron are defined as follows:

$$\tau = \frac{1}{6}\overline{r_s^2} \tag{1}$$

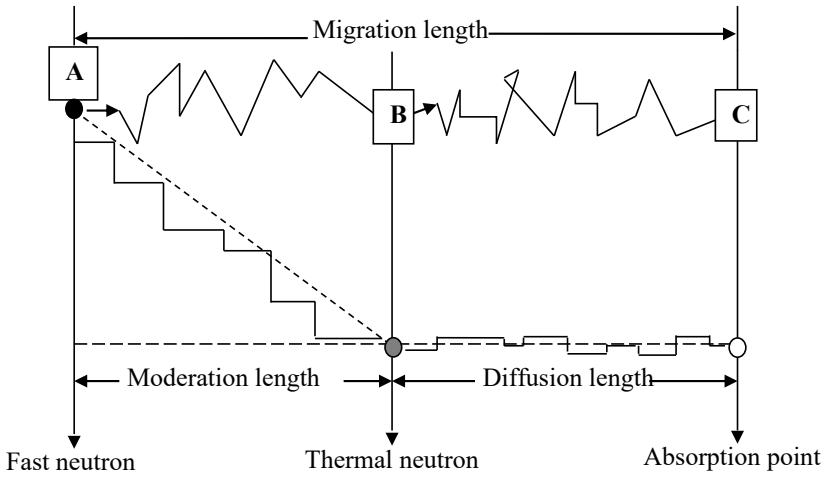

Fig. 1. Schematic diagram of neutron scattering process in light water.

$$L^2 = \frac{1}{6}\overline{r_a^2} \tag{2}$$

Neutron's migration area

$$M^2 = \tau + L^2 = \frac{1}{6}\langle r^2 \rangle \tag{3}$$

In equation (3), migration area (M^2) is equal to one-sixth of the average squared flight distance from the position where a neutron is born (point A) to the position where it is absorbed (point C) [4–7] and this is also the mean squared flight distance a neutron travels from its birth point to the absorption point. The physical quantity $\langle r^2 \rangle$ is also a measurement of particle transport in many other fields and has been widely studied as the mean square displacement (MSD) [8–11].

In the present investigation, Monte Carlo (MC) method-based computer code, the MCNP5 [12] version 1.60 with nuclear cross-section data library based on ENDF/B-VII [13], has been used to calculate neutron migration parameters in light water. Temperature effects were included in the calculation using the 'tmp' card option of MCNP. *S(α,β)* scattering cross section option was used for H_2O. A finite medium of light water with a monoenergetic point neutron source has been defined as emitting fast neutrons of energy in the range between 1 and 20 MeV. The energy range was chosen from 0.2 to 0.253 eV in which the fast neutron was converted into the thermal one and finally absorbed in the medium. Each MC simulation was completed by taking 3.0E+06 neutron histories. Densities of light water at different temperatures and pressures have been incorporated using the reference table [14]. Neutron age counts (C_{na}) and their relative errors were measured at various distances up to 150 cm from the source, at 5 cm intervals from the output file, and the C_{na} weighted average of the square of the distances was calculated for average NA. Finally, using the standard error propagation formula, NA was calculated using equation (1) with the associated uncertainty. Using equation (1), the NA in light water at room temperature was found to be 1.30E+02 ± 0.244 cm². However, the result was significantly different from the experimental result, which was 27.04 cm² [15]. The simulation showed that the rate at which fast neutrons were moderated to thermal

energies decreased significantly with increasing distance from the source, and maximum neutrons were thermalized in the spherical region from the source to 25 cm away, and the remaining neutrons were thermalized gradually with the increase of distances up to 150 cm. Thus, the decision was made to simulate it by dividing the spherical thermal region into a 1 cm interval between the source and 25 cm away from it. Fig. 2 illustrates the MC simulation of NA counts at room temperature and pressure in H_2O. The result for NA was found to be 34.096 ± 0.029 cm², which was higher than the experimental result 27.04 cm^2 [15]. The reason for obtaining a higher neutron age in MCNP is mainly due to idealize assumptions, data library differences, and boundary/leakage modelling, compared to the more complex realities of experiments.

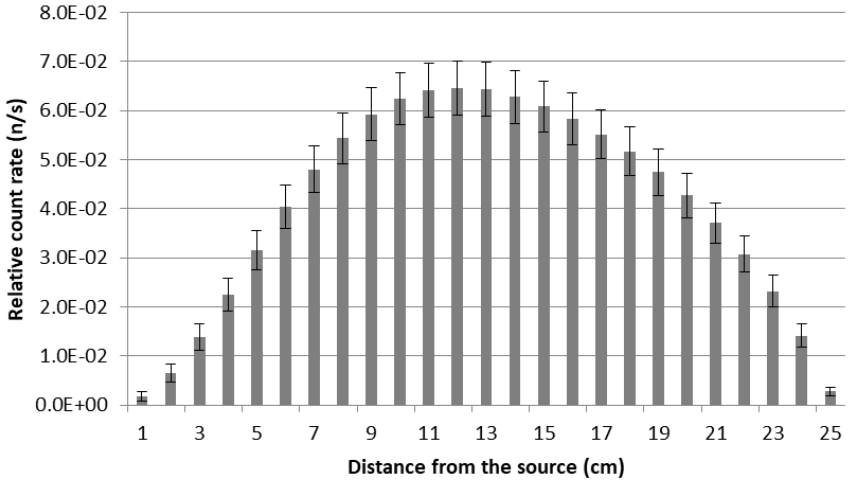

Fig. 2. MC simulation of NA counts at room temperature and pressure in H_2O.

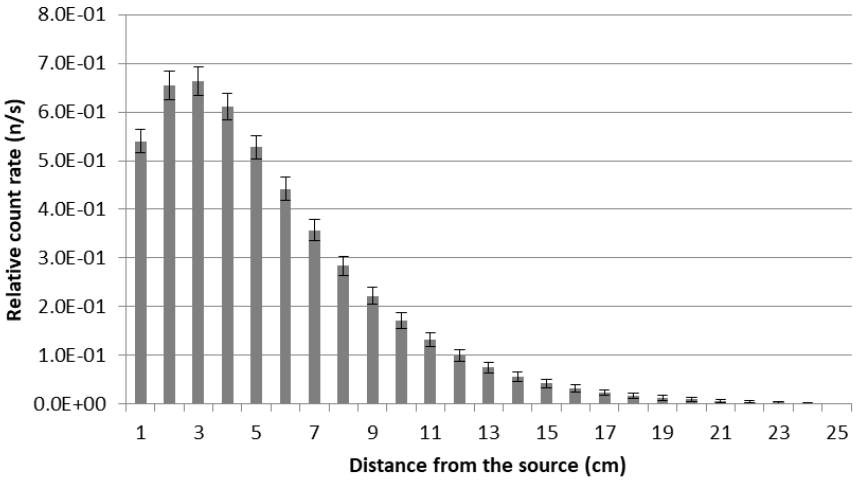

Fig. 3. MC simulation of neutrons DA counts at room temperature and pressure in H_2O.

On the other hand, to find neutron DA, it had to define a finite medium of light water (H_2O) with a point neutron source of energy 0.0253 eV (thermal neutron) in the MCNP input file. An evaluated neutron data file (ENDF) reaction number for radiative capture microscopic cross-section (102) was used for the FM card of the input file. Absorption counts (C_a) and their relative errors at various distances, up to 150 cm (in 5 cm intervals) from the source, were obtained from the output file, and the C_a weighted average of the square of the distances was calculated for average squared diffusion length. Finally, the DA was computed by using equation (2) with the associated uncertainty using the standard error propagation formula. By using equation (2), the calculated neutron DA in light water at room temperature was found to be 1.00E+01 ± 0.04938 cm². However, the result was far away from the experimental result, which was 7.29 cm² [15]. It was observed from the simulation that the neutron diffusion rate decreased significantly as the distances from the source increased; maximum neutrons were diffused in the spherical region from the source to 25 cm away, and the remaining neutrons were diffused frequently with the increase of distances up to 150 cm. Hence, it was decided to simulate it by taking the spherical diffusion region only between the source and 25 cm away from the source with a 1 cm interval. Fig. 3 represents the MC simulation of neutron DA counts at room temperature and pressure in H_2O. The final result was found to be 7.249 ± 0.003 cm², which was almost close to the experimental result 7.29 cm² [15]. Based on the obtained NA and DA results at room temperature and pressure, other calculations have been done.

3. RESULTS AND DISCUSSION

3.1 Effects of Temperature

Temperature plays a great role in changing the NA and DA in light water at any pressure. An increase in temperature decreases the density of light water, which results in more free movement of neutrons until they become absorbed by the medium. As the temperature of water increases, neutrons can travel longer distances before being absorbed, compared to lower temperatures. Since NA and DA are related to the transport distances of neutrons, their values increase if the temperature of light water increases. Fig. 4 and 5 show the behaviour of NA and DA as a function of temperature. The temperature was increased from room temperature (20 °C) to 100 °C in 10 °C intervals. It is seen that both NA and DA increased at room pressure (1 atm) and 10 MPa with the increase of temperature at each step. At each step, the value of NA was approximately 4.6 times greater than that of DA at all pressures, in the absence of boron in H_2O (Fig. 4). On the other hand, with the presence of 1000 ppm boron in H_2O, NA was observed to vary with pressure at each step (Fig. 5), as pressure directly influences the moderator density and, consequently, the neutron mean free path between collisions. At each step, the value of NA was approximately 12.5 times greater than that of DA at room pressure and about 12.6 times greater at 10 MPa.

Table 1 presents the average NA and DA increments per °C under four conditions. Table 2 shows the average NA and DA decrement due to the presence of 1000 ppm boron in H_2O. It can be observed that the average area decrease is slightly smaller at room pressure compared to 10 MPa.

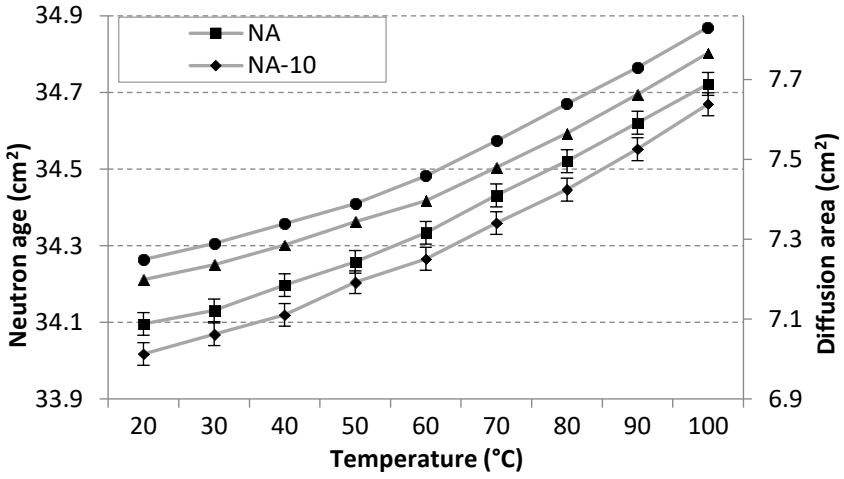

Fig. 4. Effect of temperature on NA and DA with 0 ppm boron in H_2O.

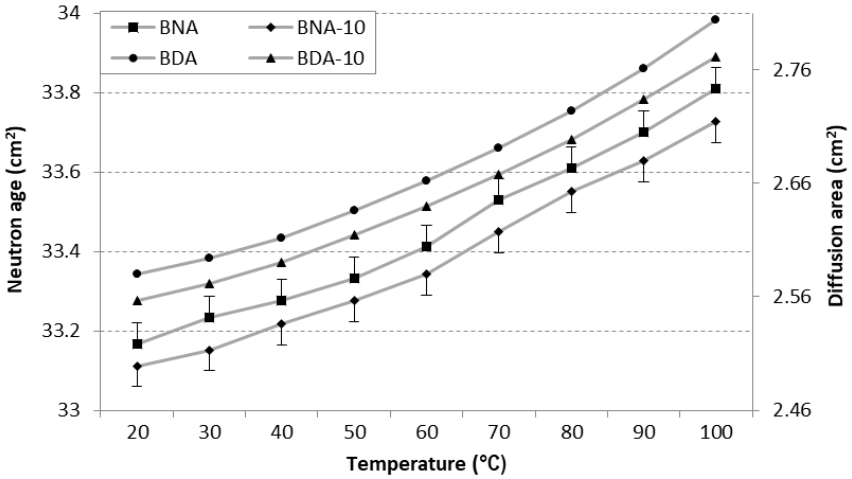

Fig. 5. Effect of temperature on NA and DA with 1000 ppm boron in H_2O.

3.2 Effects of Pressure

NA and DA slightly vary by a pressure change in light water. An increase in pressure raises the density of light water, which results in less free movement of neutrons until it becomes absorbed by the medium. As a result, neutrons travel a short distance at a higher pressure compared to that at a lower pressure. Since NA and DA are related to the transport distances of neutrons, their values decrease if the pressure of light water increases. Fig. 6 and 7 show the behaviour of NA and DA as a function of pressure. Here, the system pressure increases from 2 MPa to 10 MPa with a 1 MPa interval. It is seen that NA and DA decreased both at room temperature and 100 °C with the increase

of pressure at each step. At each step, NA was almost 4.72 and 4.45 times higher than DA at room temperature and 100 °C, respectively, in boron-free light water (Fig. 6). On the other hand, with the presence of 1000 ppm boron in H_2O, NA was almost 12.91 and 12.13 times higher than DA at room temperature and 100 °C, respectively (Fig. 7). Average NA and DA change in light water for per unit change of boron concentration, temperature, and pressure at four different conditions are represented in Table 1. It is seen that NA shows the highest decrement at room temperature without boron while DA at 100 °C with boron. Table 2 represents the average NA and DA decrement in light water for the presence of 1000 ppm boron. It is observed that the percentage area decrement is slightly higher for room temperature compared to that of 100 °C.

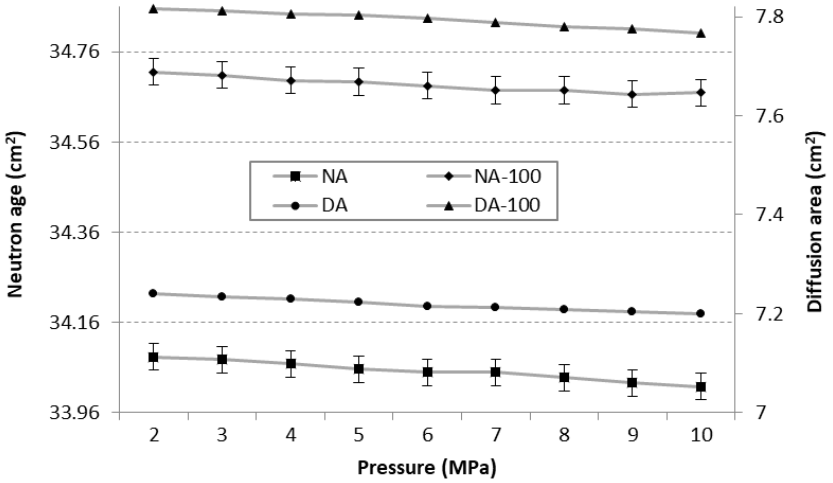

Fig. 6. Effect of pressure on NA and DA with 0 ppm boron in H_2O.

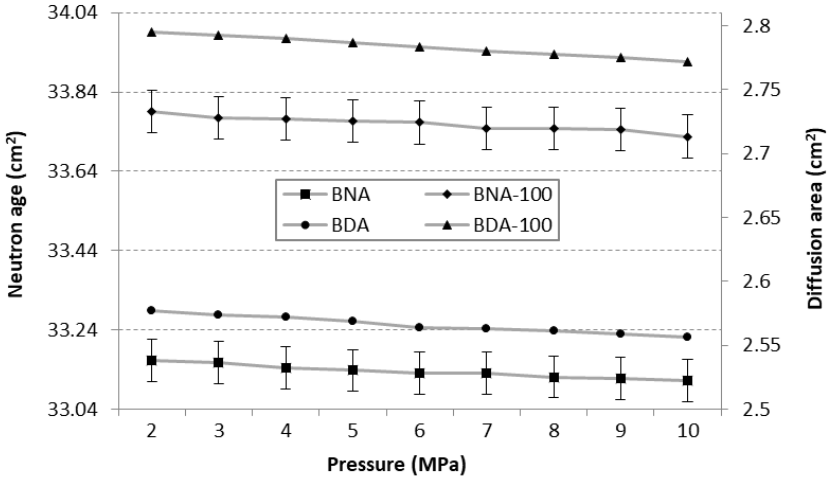

Fig. 7. Effect of pressure on NA and DA with 1000 ppm boron in H_2O.

Table. 1. Average NA and DA change in H2O for per unit change of boron concentration, temperature, and pressure.

Condition	Constant parameter	Unit change	Average NA change (%)	Average DA change (%)	Effect
1	Room T & P	ppm	0.00200	0.08676	Decrement
2	Room T & 10 MPa		0.00194	0.08687	Decrement
3	100 ° C & Room P		0.00194	0.08669	Decrement
4	100 ° C & 10 MPa		0.00200	0.08679	Decrement
1	Room P	°C	0.02278	0.09709	Increment
2	Room P & 1000 ppm B		0.02400	0.10470	Increment
3	10 MPa		0.02377	0.09530	Increment
4	10 MPa & 1000 ppm B		0.02306	0.10160	Increment
1	Room T	MPa	0.02415	0.07178	Decrement
2	Room T & 1000 ppm B		0.01886	0.09837	Decrement
3	100 ° C		0.01660	0.08040	Decrement
4	100 ° C & 1000 ppm B		0.02324	0.10584	Decrement

Table. 2. Average NA and DA decrement in H_2O for the presence of 1000 ppm boron.

Variable	Constant parameter	Initial Migration Area (cm^2)	Final Migration Area (cm^2)	Average NA Decrement (%)	Average DA Decrement (%)
T	Room P	41.34515±0.02958	42.55378±0.03020	2.66313	64.33791
	Room P & B	35.74773±0.05274	36.61397±0.05376		
P	Room T	41.32401±0.02947	41.21673±0.02948	2.69263	64.45311
	Room T & B	35.73884±0.05281	35.66862±0.05286		
T	10 MPa	41.21673±0.02958	42.43617±0.03014	2.67121	64.37832
	10 MPa & B	35.66862±0.05281	36.49965±0.05359		
P	100° C	42.53238±0.03019	42.43617±0.03014	2.67509	64.28449
	100° C & B	36.58602±0.05372	36.49965±0.05359		
T & P	-	41.32401±0.02957	42.43617±0.03014	2.67856	64.36262
	B	35.73884±0.05276	36.49965±0.05359		

3.3 Effects of Boron Concentration

Boron acts as a neutron absorber through the (n,α) reaction involving the isotope ^{10}B. It is used in a moderator (light water) to compensate for the initial excess reactivity of the core. It can play a vital role in reducing the number of neutrons in the medium. Fig. 8 and 9 depict the behaviour of NA and DA as a function of boron concentration. Boron concentration in ppm increased from 200 ppm to 1000 ppm with a 100 ppm interval. It is seen that both NA and DA decreased with the increase of boron concentration at each step. At a constant temperature (100 °C) and varying pressures (room pressure and 10 MPa), DA values remained approximately constant as boron concentration increased, while NA values decreased at 10 MPa. (Fig. 8). On the other hand, values of both NA and DA at constant pressure (10 MPa) and different temperatures (room temperature and 100 °C) were found to decrease, keeping a larger difference with the increase of boron concentration (Fig. 9). Average NA and DA decrements per ppm boron at four conditions are represented in Table 1. It is observed that the NA had the highest average decrements both at condition 1 (room temperature and pressure) and 4 (100 °C and 10 MPa) per ppm increment of boron in H_2O, while they had the lowest average decrements at condition 2 (room temperature and 10 MPa) and 3 (100 °C and room pressure). Besides, the DA had the highest and lowest average decrement at conditions 2 and 3, respectively.

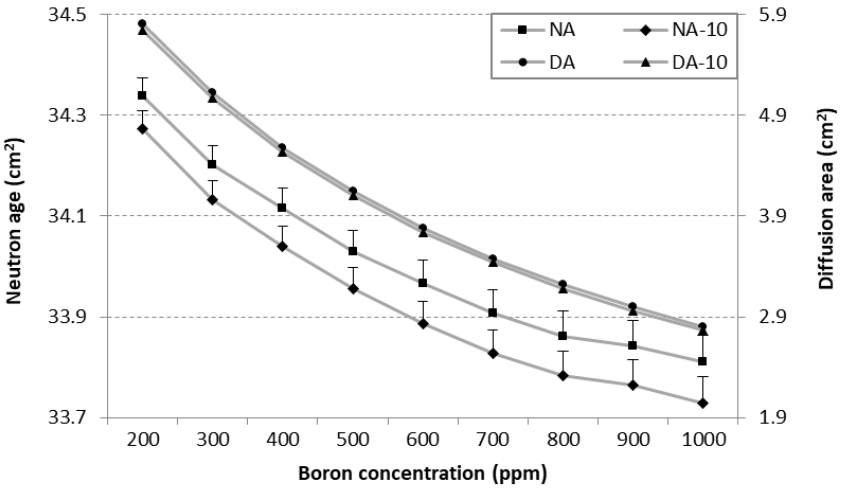

Fig. 8. Effect of boron on NA and DA with constant temperature (100 °C).

3.4 Combined Effects

NA and DA can be influenced by the combined effects of boron concentration, temperature, and pressure. Hence, it is important to know the behaviour of NA and DA when more than one of them is applied in light water. It is also important to determine which factor is predominant in the combined effect. Fig. 10 shows the behaviour of NA and DA as a function of temperature and pressure. It is seen that both NA and DA increased gradually with rising temperature and pressure, with temperature playing a dominant role. With 1000 ppm boron in H_2O, the average decrements in

NA and DA per ppm boron are 2.68% and 64.36%, respectively. The behaviour of NA and DA as a function of temperature and boron concentration is depicted in Fig. 11. It is observed that the DA gradually decreases with the increase of temperature and boron concentration. However, initially, NA was found to decrease up to 50 °C and 500 ppm boron, and after that, it raised dramatically up to the last point. The performance of NA and DA as a function of pressure and boron concentration is depicted in Fig. 12.

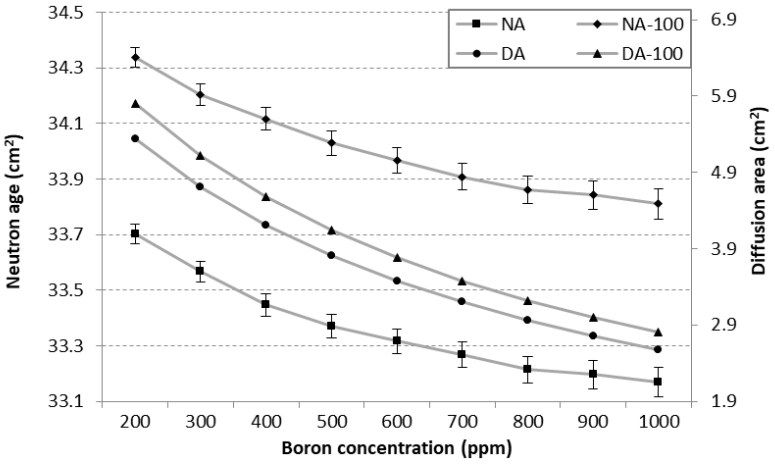

Fig. 9. Effect of boron on NA and DA with constant pressure (10 MPa).

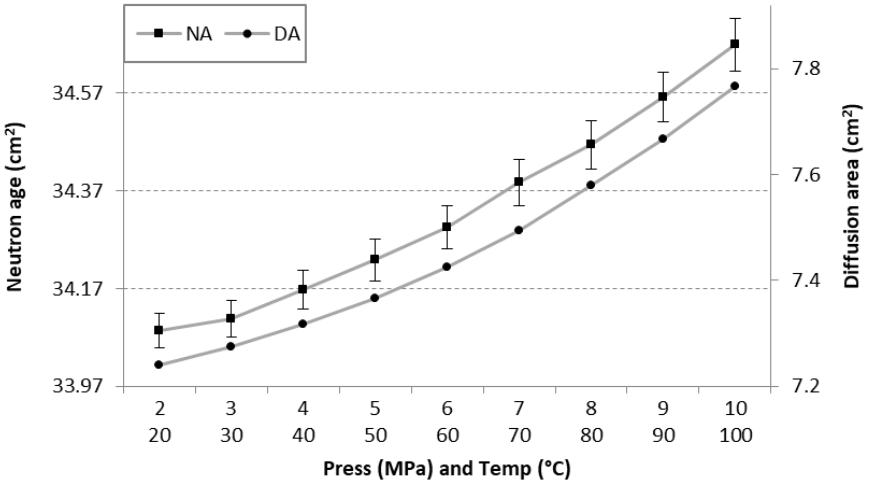

Fig. 10. Effects of temperature and pressure on NA and DA in H_2O.

It is observed that both NA and DA decreased gradually with increasing pressure and boron concentration, and boron played a vital role. Finally, the combined effects of boron concentration, temperature, and pressure are shown in Fig. 13. It is observed that the DA gradually decreased with

the increase of boron concentration, temperature, and pressure. On the other hand, NA was found to fall sharply from the initial point (room temperature, pressure, and 200 ppm boron) to the next point (30 °C, 3 MPa, and 300 ppm boron) initially. Then it decreased slowly up to 50 °C, 5 MPa, and 500 ppm boron. After that, the NA was found to increase gradually up to the final point. This non-monotonic behavior (initial decrease then rise) is caused by the competition between absorption and density-driven scattering effects. At lower temperatures and lower boron concentrations, the increase in ^{10}B atoms significantly raises the macroscopic absorption cross-section. High absorption cross-section removes neutrons before they travel long distances which results in a decrease in NA. As temperature continues to rise toward 100 °C, physical changes in the moderator begin to outweigh the absorption effects. Lower moderator density increases the distance between collisions, leading to a higher NA value.

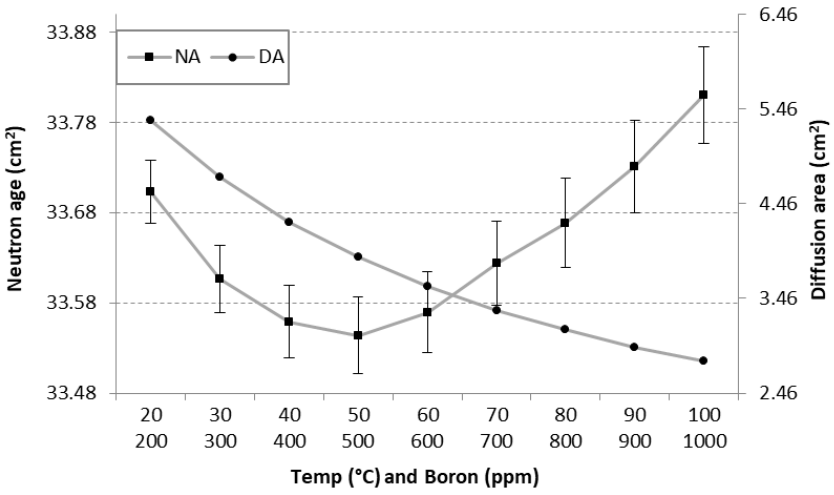

Fig. 11. Effects of boron and temperature on NA and DA in H_2O.

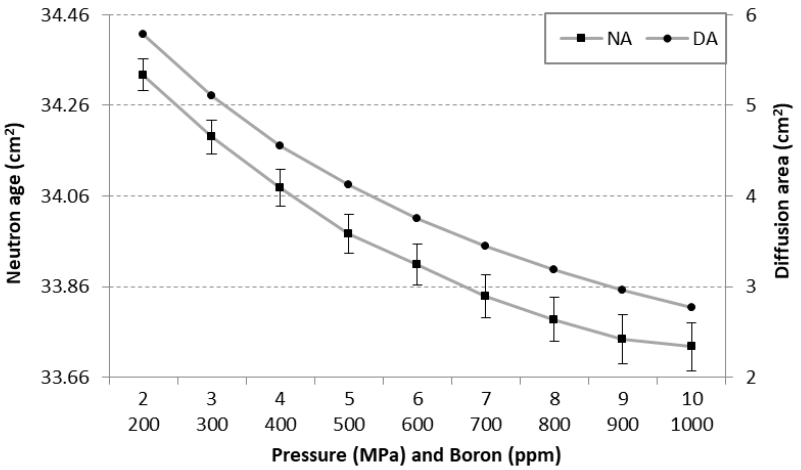

Fig. 12. Effects of boron, and pressure on NA and DA in H_2O.

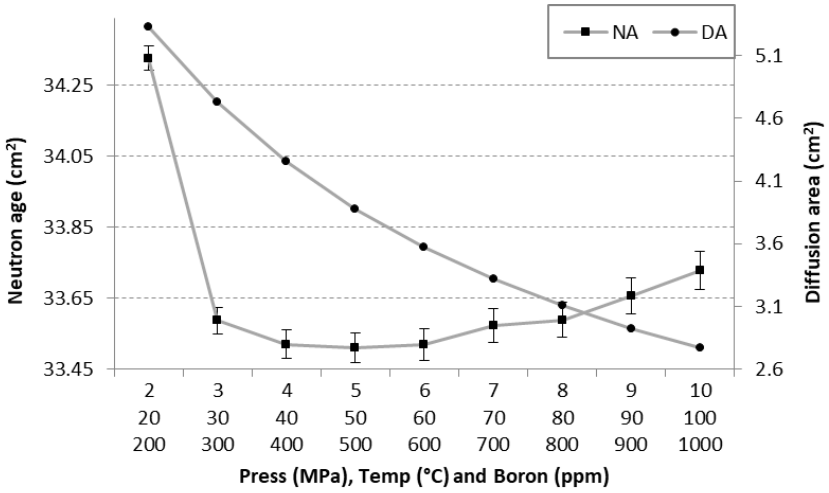

Fig. 13. Effects of boron, temperature, and pressure on NA and DA in H_2O.

4 CONCLUSIONS

The effects of boron concentration, temperature, and pressure on neutron migration in light water were investigated using the Monte Carlo code MCNP. Neutron age (NA) and diffusion area (DA) were evaluated under a wide range of conditions relevant to light water reactor operation. The calculated values at room temperature and pressure showed good agreement with available experimental data, validating the modeling approach.

The results indicate that temperature has the strongest influence on neutron migration, as increased temperature reduces moderator density and allows neutrons to travel longer distances, leading to higher NA and DA. Increasing pressure slightly decreases both parameters due to enhanced moderation from higher water density. Boron concentration significantly reduces neutron migration by increasing neutron absorption, with DA showing much higher sensitivity to boron than NA. For 1000 ppm boron, maximum average reductions of approximately 2.7% in NA and 64.4% in DA were observed.

Overall, this study provides quantitative insight into how operational and chemical parameters affect neutron migration in light water. The findings are relevant for reactor physics analysis, reactivity control, and safety assessment of light water reactors.

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