Effect of Temperature Difference and Control Rod Movement on Neutron Flux Distribution in Nigeria Research Reactor-1 Core

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Abstract

We described in this work the effect of coolant temperature difference and control rod movement on neutron flux distribution in Nigerian research reactor-1 (NIRR-1) core, which is a Miniature Neutron Source Reactor (MNSR) in order to verify the theoretical predictions of reactor power. The results show that the reactor neutron flux strongly depends on coolant temperature and control rod movement. These results are in perfect agreement with the constitutive model of the MNSR. A linear dependency predicted power as a function of flux parameter was observed. The rise in control rod position with time was found to compensate for neutron lost due to burn-up and thereby control the reactor flux at the preset flux values.

Keywords: Neutron flux; Temperature; Control rod; Reactor core; MNSR; NIRR-1

Introduction

In a nuclear reactor the neutron in the core of the reactor determines the dynamic behavior of the reactor. In order for the power generated by fission reactions to be maintained at a constant level the fission rate must remain steady over the course of time. In water cooled reactor like Nigeria Research Reactor-1 (NIRR-1), which is a Miniature Neutron Source Reactor (MNSR) the predominantly reactivity changes are brought about by change in the moderator (coolant temperature) and power which result in decrease in reactivity. This property is called Temperature Coefficient of Reactivity [1]. The neutron flux distribution in the core fission reactor determines the power and dynamic behavior of the reactor. The thermal neutron flux reached its peak value at the center of reactor and falls exponentially at the extreme ends of the reactor core which result to the very few thermal neutrons production in the area. Hence the flux distribution is strongest at the middle of the reactor’s core [1]. However, the average flux of a reactor is a variable parameter that depends on the reactor’s moderator and coolant temperature. These parameters are to be monitored for every reactor from time to time to establish the stability of the reactor’s flux. It has been shown that reactor flux stability is a requirement for Neutron Activation Analysis (a major utilization of the reactor) and precious stone irradiation [2-7]. The description of Nigeria Research Reactor-1 (NIRR-1), a tank-in-pool reactor with under-moderation achieved by using a fuel material of highly enriched uranium and light water as moderator and coolant was given in our publications [3, 6, 8]. A major safety concern in operating a nuclear reactor is to prevent the fuel temperatures from reaching levels where they can lead to the release of fission products into the reactor vessel [8]. According to the [1] core region of NIRR-1 is located close to the bottom of reactor vessel under 4.7 m of water. The 1.5 m3 of water contained in the reactor vessel acts as moderator radiation shield and primary cooling medium. Reactor core cooling is achieved when water is drawn into the core through the core inlet orifice by natural convection. The water flows through the channels within the fuel elements to the top of the reactor core and finally exits through the core outlet orifice. The water heated by the fuel elements finds its way to the top of the reactor vessel, while the reactor core draws in colder water from the vessel through its inlet orifice. The heat generated by the fuel elements gives rise to the increase in reactor water temperature. This heat
is extracted through the wall of the of the reactor vessel, into the 30m³ volume of water contained in the reactor pool (SAR, 2005). A temperature coefficient of reactivity is thus a desirable feature since it is an important factor in the reactor stability and operational safety. The single central control rods which perform both regulatory and shim functions in the design of NIRR-1 constitute a single point failure. The rod which is a shim rod and expected to compensate for small reactivity transient caused by change in load demand, core temperature and power level maneuvering, could not stand severe conditions [9]. The control rod cannot shutdown the Reactor when it stuck in full “out” position. Since the reactivity of the reactor is linearly related with flux and power distribution, the position of the control rod in the core at any point in time need to be monitored to establish the density or relative strength of the reactor flux [1]. Since the reactivity of the reactor is linearly related to its flux distribution determination of the control rod behavior will give information on the reactor reactivity and flux distribution. These design consideration were used in order to assess the effect of coolant temperature difference and control rod movement on neutron flux distribution on NIRR-1 core.

**Theoretical Considerations**

The thermal neutron flux is the quantity determine by the fission rate (1/cm² s) and thus the power generated in the fuel. Due to the fact that the different at each point of the reactor, its distribution or form is of utmost importance, since it will determine the distribution of power generated in the core. The equation that determined the relation amongst core inlet temperature, coolant temperature and power level as obtained from simulation experiment on MNSR is expressed in the [10].

\[
\Delta T = (5.725 \times 147.6 H^{2.64} T_i^{-0.35} P^{0.5919 T_i} - 0.35) T_i^{0.5919 T_i} (0.59 + 0.0019 T_i) - 1
\]

Where \( \Delta T \) = temperature different between the inlet and outlet orifice

\( H \) = Height of the inlet orifice (mm)

\( T_i \) = inlet temperature oC

The designed of the inlet orifice of NIRR-1 was made to be 6mm for safety and technical reason [11-13]. Therefore substituting the value of \( H \) into equation reduces the equation to:

\[
\Delta T = 7.04 T_i^{-0.35} P^{0.5919 T_i} - 0.35
\]

Thus \( P = \exp [\ln \Delta T / (7.04 T_i^{-0.35})((0.59 + 0.0019 T_i) - 1)] 

Where \( \Delta T \) = coolant temperature given by \( T_0 - T_i \)

\( T_s \) = outlet temperature in oC

\( P \) = predicted power kW

For a fixed height of inlet orifice it is expected from equation 3 that the reactor power varies linearly with temperature. Apart from the above method of determining the power of the reactor via thermal hydraulic parameters, (neutron flux values) could as well be exploited to predict the flux distribution of the reactor, as long as nuclear parameter are accurately known [1] the equation that relate these two parameter obeys the following relation:

\[
P = 3 \times 10^{-10} \sum V_f \phi
\]

Where: \( \phi \) = average thermal neutron flux in the inner irradiation channel (cm² s⁻¹)

\( V_f \) = volume of the core = \( \pi r^2 h \) (cm³)

Core height (h) = 23cm

Core radius (r) = 11.5cm

\( \sum \phi \) = macroscopic fission cross-section of the core fuel = 1.013x10⁻² cm⁻¹

\( P \) = Power of Reactor in kW

A core dimension of 23cm square cylinder and highly enriched uranium was used as fuel for the Nigeria MNSR. The above parameter make it possible to reduce the equation (4) to only flux dependent parameter as shown in equation (5)

\[
P = 3 \times 10^{-8} \phi
\]

Equation (5) reveals a linear relationship between the reactor power and its neutron flux.

**Experiment**

**Table 1:** Coolant temperature difference method.

| Time (Hrs) | Inlet Temperature (OC) | Outlet Temperature (OC) | Coolant Temperature (OC) | Predicted Power (kW) | Predicted Flux (×10¹¹ n Cm⁻² s⁻¹) |
|-----------|------------------------|-------------------------|--------------------------|----------------------|-----------------------------------|
| 9:50      | 26.3                   | 38.4                    | 12.1                     | 13.94                | 4.65                             |
| 10:10     | 27.9                   | 40.4                    | 12.5                     | 14.95                | 4.98                             |
| 10:30     | 29.3                   | 41.7                    | 12.4                     | 14.99                | 5                                |
| 10:50     | 30.1                   | 42.3                    | 12.2                     | 14.74                | 4.91                             |
| 11:10     | 30.2                   | 42.7                    | 12.5                     | 15.32                | 5.11                             |
| 11:30     | 31.6                   | 44                      | 12.4                     | 15.33                | 5.11                             |
| 11:50     | 31.9                   | 43.9                    | 12.1                     | 14.62                | 4.87                             |
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### Table 2: Coolant temperature difference method.

| Time (Hrs) | Inlet Temperature (°C) | Outlet Temperature (°C) | Coolant Temperature (°C) | Predicted Power (kW) | Predicted Flux (×10^{11} n Cm^{-2} s^{-1}) |
|------------|-------------------------|--------------------------|--------------------------|-----------------------|---------------------------------------------|
| 10:15      | 25                      | 37.6                     | 11.6                     | 12.81                 | 4.27                                        |
| 10:40      | 27.6                    | 39.9                     | 12.3                     | 14.52                 | 4.84                                        |
| 11:00      | 28.8                    | 40.9                     | 12.1                     | 14.35                 | 4.79                                        |
| 11:20      | 29.8                    | 41.8                     | 12                       | 14.33                 | 4.78                                        |
| 11:40      | 31.1                    | 42.6                     | 12.5                     | 15.45                 | 5                                            |
| 12:00      | 30                      | 42.9                     | 12.9                     | 16.05                 | 5.35                                        |
| 12:20      | 31.4                    | 43.3                     | 11.9                     | 14.37                 | 4.79                                        |
| 12:40      | 31.4                    | 43.4                     | 12                       | 14.55                 | 4.85                                        |
| 13:00      | 31.3                    | 43.9                     | 12.6                     | 15.67                 | 4.22                                        |
| 13:20      | 31.1                    | 43.6                     | 12.1                     | 14.7                  | 4                                           |
| 13:40      | 31.3                    | 43.6                     | 12.1                     | 14.73                 | 4.91                                        |
| 14:00      | 32.4                    | 43.4                     | 12.2                     | 15.06                 | 5.02                                        |
| 14:20      | 33.7                    | 44.6                     | 11.7                     | 14.28                 | 4.72                                        |
| 14:40      | 32.2                    | 44.4                     | 12.3                     | 15.23                 | 5.08                                        |
| 15:00      | 32.5                    | 44.5                     | 11.7                     | 14.14                 | 4.71                                        |
| 15:20      | 32.6                    | 44.4                     | 11.6                     | 13.97                 | 4.66                                        |
| 15:40      | 33                      | 44.8                     | 11.8                     | 14.39                 | 4.8                                          |
| 16:00      | 32.8                    | 45.5                     | 12.2                     | 15.11                 | 5.04                                        |
| 16:20      | 32.8                    | 44.7                     | 11.9                     | 14.54                 | 4.85                                        |
| Average    | 32.7                    | 43.1                     | 12.1                     | 14.91                 | 4.88                                        |

### Table 3: Control Movement method.

| Time (Hrs) | Rod Position (Mm) | Predicted Power (kW) | Predicted Flux (×10^{11} n Cm^{-2} s^{-1}) |
|------------|-------------------|----------------------|---------------------------------------------|
| 9:50       | 122               | 15.18                | 5.06                                        |
| 10:10      | 125               | 15.18                | 5.06                                        |
| 10:30      | 127               | 15.3                 | 5.1                                         |
| 10:50      | 132               | 15.41                | 5.14                                        |
| 11:10      | 134               | 15.24                | 5.08                                        |
| 11:30      | 135               | 15.27                | 5.09                                        |
| 11:50      | 137               | 15.21                | 5.07                                        |
| 12:10      | 139               | 15.33                | 5.11                                        |
Investigation on the effect of temperature and control rod movement on neutron flux distribution on NIRR-1 core was used as part of the ongoing research in the NIRR-1 laboratory to monitor the stability of the reactor flux required for sample activation analysis. The reactor was operated at automatic mode, in order to operate the reactor in the automatic mode, the power and the control rod limiting position of the NIRR-1 were preset to its half-power value of 15kW (flux of $5 \times 10^{11}$ n cm$^{-2}$ s$^{-1}$) and 220mm respectively. This makes the reactor to operate at a power of half of its expected installed capacity. Readings were taken after every twenty minute for the two experiment for six hours and were tabulated in (Table 1-4).

### Results and Discussion

The measurements were carried out at a preset flux value of $5 \times 10^{11}$ cm$^{-2}$ s$^{-1}$ for the whole duration of our experimental work. The result obtained shows that there is a fairly constant reactor power (15kW) and flux distribution with coolant temperature. The temperature difference recorded during the operation has also been steady at approximately 12.1 oC for the whole period of operation (Table 5). As can be seen in Tables 1-5 there is steady rise in the inlet and outlet temperature with time. This is due to the compact nature of the core, which was designed to cause insufficient thermal circulation of coolant in the core which implies that no any significant effect cause

| Time (Hrs) | Rod Position (Mm) | Predicted Power (kW) | Predicted Flux ($\times 10^{11}$ Cm-2s$^{-1}$) |
|------------|-------------------|----------------------|------------------------------------------|
| 10:15      | 119               | 15.12                | 5.04                                     |
| 10:40      | 125               | 15.18                | 5.06                                     |
| 11:00      | 127               | 15.27                | 5.09                                     |
| 11:20      | 130               | 15.3                 | 5.1                                      |
| 11:40      | 132               | 15.27                | 5.09                                     |
| 12:00      | 134               | 15.39                | 5.13                                     |
| 12:20      | 136               | 15.18                | 5.06                                     |
| 12:40      | 137               | 15.33                | 5.11                                     |
| 13:00      | 138               | 15.24                | 5.08                                     |
| 13:20      | 140               | 15.36                | 5.12                                     |
| 13:40      | 141               | 15.24                | 5.08                                     |
| 14:00      | 141               | 15.3                 | 5.1                                      |
| 14:20      | 142               | 15.18                | 5.06                                     |
| 14:40      | 144               | 15.21                | 5.07                                     |
| 15:00      | 143               | 15.24                | 5.08                                     |
| 15:20      | 143               | 15.33                | 5.11                                     |
| 15:40      | 144               | 15.33                | 5.11                                     |
| 16:00      | 145               | 15.24                | 5.08                                     |
| 16:20      | 149               | 16.92                | 5.64                                     |
| Average    | 138.9             | 15.29                | 5.1                                      |

Table 4: Control Movement method.
by heat in the flux of NIRR-1 (Figure 1 & 2). The readings in all the Tables 1-4 were collected for 6hr at a different date and time. It was observed that the averages of inlet temperatures as well as the outlet temperature were all above the room temperature which has approximate values of 32.7 oC and 43.1 oC respectively. This is in agreement with the fact that the reactor was operated not quite long to obtain the readings in (Tables 1-4) and coolant not completely cooled during the few days period of the shutdown. These values gave an average temperature difference of 12.1 oC. These temperature values did not give rise to a sharp increase in predicted flux but rather fluctuate due to the inherent features of the reactor and according to the rules governing insertion of excess reactivity into the reactor by the withdrawal of the control rod during the startup [7]. As the inlet and outlet temperature values increase, the effect of coolant temperature and control rod withdrawal on the predicted flux which shows an oscillatory behavior have an approximate values of 4.92×10^{-11} n cm^{-2} s^{-1} and 5.11×10^{-11} n cm^{-2} s^{-1} respectively [14,15]. This indicated that there was no rise in the different between average values of the predicted flux and preset values. The Figure 3 show that the reactor was not completely cooled during the period of non-operation and that have no significant effect on average predicted flux of the operation which also shows the oscillation of the predicted flux around 5.00×10^{-11} cm^{-2} s^{-1} at shutdown. Furthermore the temperature difference recorded and control rod position for the two different experiment were found to be fluctuating in both cases which was constant with time due to the time delay nature shown by the flux as in Figure 4. However, the control rod position rises gradually with time to compensate for high negative temperature coefficient of reactivity in order to keep the reactor at preset power level (Table 5). This finding satisfies one of the safety requirement of the reactor which does not permit unnecessary power excursion and occurance of boiling. (Tables 1-4) reveals that NIRR-1 could be operated at half power (flux of 5×10^{11} cm^{-2} s^{-1} for about seven to eight continuous hours before the control rod attains it maximum value of 232mm which by implication will trigger the reactor to automatically shut down [1]. This, in combination with the limited MNSR excess reactivity that is less than 0.5$ is another safety feature guaranteed by in-build negative temperature coefficient of reactivity, [7] just in case the reactor is left unattended to for so long [16,17].

Table 5: Average values for temperature and control rod measurement.

| Preset Values       | Temperature Difference Method | Control Rod Method |
|---------------------|-------------------------------|-------------------|
|                     | Power (kW)                    | Flux(×10^{-11} cm^{-2} s^{-1}) |
| Exp1                | Exp2                          | Average            |
| 15                  | 5.00×10^{-11}                 | 14.85              |
| average             |                               | 14.74              |
|                     | Exp1                          | Exp2              | Average |
| 15.29               | 15.35                         | 5.11              |
| average             |                               | 5.11              |
| Deviation from preset Values & %Deviation from preset | Power | Flux | Power | flux |
| Exp1                | -0.03                        | -0.01             | 0.20%   |
| Exp2                |                              |                   |         |

Figure 1: Variation of predicted flux with coolant temperature.

Figure 2: Variation of predicted flux with coolant temperature.
Conclusion

The temperature differences recorded for all the experiment conducted in this work were found to be oscillating at a constant range with time. The average predicted flux obtained for temperature and control rod methods were approximately $4.92 \times 10^{11} n cm^{-2} s^{-1}$ and $5.11 \times 10^{11} n cm^{-2} s^{-1}$ respectively. This shows that the flux in the core of NIRR-1 is stable. The control rod position shows a gradual rise with time. This is an in-built future to compensate for high negative temperature coefficient of reactivity in order to keep the reactor at the preset power level [7]. This result is in agreement with the safety requirement of the reactor, which does not permit power excursion and occurrence of boiling. The result obtained here also shows that mathematical relationship based on thermal hydraulics data and neurotics parameters could be used to predict the reactor’s operating power level can be estimated from the preset thermal neutron flux values and vice versa.

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References

1. Ahmed YA, Balogun GI, Jonah SA, Funtua II (2008) The behavior of reactor power and flux resulting from changes in corecoolant temperature for a miniature neutron source reactor. Annals of Nuclear Energy 35(12): 2417-2419.
2. Jonah SA, Balogun GI, Umar IM, Mayaki MC (2005) Neutron spectrum parameters in irradiation channel of the Nigerian research reactor-1 (NIRR-1) for the k0 NAA standardization. Journal of Radio analytical and Nuclear Chemistry 266(1): 83-88.
3. Jonah SA, Umar IM, Oladipo MOA, Balogun GI, Adeyemu DJ, et al. (2006) Standardization of NIRR-1 irradiation and counting facilities for instrumental neutron activation analysis. App Radiat Isot 64(7): 818-822.
4. Kapsimalis R, Landsberger S, Ahmed YA (2009) The determination of uranium in food samples by Compton suppression epithermal neutron activation analysis. App Radiat Isot 67(12): 2097-2099.
5. Ahmed YA, Landsberger S, O’Kelly DJ, Braisted J, Gabdo H, et al. (2010) Compton suppression method and epithermal NAA in the determination of nutrients and heavy metals in Nigerian food and beverages. App Radiat Isot 68(10): 1909-1914.
6. Ahmed YA, Mansir IB, Dewu BBM (2013) Installation of permanent cadmium-lined channel as a means for increasing epithermal NAA capabilities of miniature neutron source reactors. Nuclear Engineering and Design 263: 70-76.
7. Ahmed YA, Mansir IB, Yusuf JA, Balogun GI, Jonah SA, et al. (2011) Effects of core excess reactivity and coolant average temperature on maximum operable time of NIRR-1 miniature neutron source reactor. Nuclear Engineering and Design 241(5): 1559-1564.
8. Anas MS, Ahmed YA, Yusuf JA, Yahaya B (2016) Implication of removal of cadmium poison on neutron flux and related parameters in Nigeria research reactor-1. J Nucl Ene Sci Power Generat Technol 5: 4.
9. Anas MS, Ahmed YA, Rabiu N, Agbo SA, Balarabe B, et al. (2015) In-core power prediction and effects of average core temperature on miniature neutron source reactor’s core performance. Int J Nuclear Energy Science and Technology 9(4): 279-292.
10. Shi S (1990) Low power research reactor thermal hydraulics; IAEA workshop on low power research reactors. CIAE, Beijing.
11. Yang YW (1992) MNSR reactor complex manual, CIAE, Beijing, China.
12. Yang Y (1992) Reactor complex manual. CIAE Technical Report, Code MNSR DC-3.
13. Khamis I, Alhalabi W (2007) Assessment of cooling effects on extending the maximum operating time for the Syrian miniature neutron source reactor. Progress in Nuclear Energy 49(3): 253-261.
14. Abrefah RG, Nyarko BJ, Akaho EHK, Anim Sampong S, Sogbadji BBM, et al. (2010) Axial and radial distribution of thermal and epithermal neutron fluxes in irradiation channels of the Ghana Research Reactor-1 using foil activation analysis. Annals of nuclear energy 37(8): 1027-1035.
15. (2005) Final safety analysis report of Nigeria research reactor-1. CERT Technical Report-CERT/NIRR-1/FSAR-01.
16. Zhang Y (1984) Simulated heat transfer test for MNSR, CIAE Technical Report.
17. Zhu G (1990) Neutron physics experiments on low power research reactor; IAEA Workshop on Low Power Research reactors. CIAE, Beijing.
