Annals of Nuclear Energy 36 (2009) 896–900

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Reactor core power measurement using Cherenkov radiation and its application in Tehran Research Reactor

M. Arkani, M. Gharib *

Reactor and Accelerator Research and Development School, Atomic Energy Organization, Nuclear Science and Technology Research Institute (NSTRI), End of Karegar Ave, Tehran 14395-836, Iran

ARTICLE INFO

Article history:
Received 17 November 2008
Received in revised form 4 March 2009
Accepted 16 March 2009
Available online 1 May 2009

ABSTRACT

Cherenkov radiation is a process that could be used as an extra channel for power measurement to enhance redundancy and diversity of a reactor. This is especially easy to establish in a pool type research reactor. A simple photo diode array is used in Tehran Research Reactor to measure and display power in parallel with the existing conventional detectors. Experimental measurements on this channel showed that a good linearity exists above 100 kW range. The system has been in use for more than a year and has shown reliability and precision. Nevertheless, the system is subject to further modifications, in particular for application to lower power ranges.

1. Introduction

Two important criteria for power measurement in nuclear reactors are redundancy and diversity. This holds true both in power and research reactors. Other criteria such as accuracy, reliability and speed in response are also of major concern. Tehran Research Reactor (TRR) is originally equipped with four channels, namely, a fission chamber (FC), a compensated ionization chamber (CIC), and two uncompensated ionization chambers (UIC). In order to improve the power measuring system, two more channels have also been considered for implementation in recent years. One of these channels is based on $O^{16}(n,p)N^{16}$ reaction which is very attractive due to the short half life of N^{16} (about 7 s). The other channel, at the center of our attention in this work, is based on measurement of Cherenkov radiation produced within and around the core. This channel has a fast response to power change and has been in operation since early 2007.

It has been established that the movement of a fast charged particle in a transparent medium results in a characteristic radiation known as Cherenkov radiation (Jelley, 1958). The bulk of radiation seen in and around a nuclear reactor core is mainly due to Beta and Gamma particles either from fission products or directly emanating from the fission process (prompt fission gamma rays) (Kuribara, 1994; Rippon, 1963).

As it will be explained more thoroughly in the following section, Cherenkov radiation is produced through a number of ways when: (a) beta particles emitted by fission products travel with speeds greater than the speed of light in water and (b) indirect ionization by Gamma radiation produces electrons due to photo electric effect, Compton effect and pair production effect. Among these electrons, Compton electrons are the main contributors to Cherenkov radiation.

2. Basic theory of Cherenkov light production

It is established that Cherenkov light is produced by charged particles which pass through a transparent medium faster than the phase velocity of light in that medium. Considering the fact that speed of light in water is 220,000 km/s, the corresponding electron energy that is required to produce Cherenkov light is 0.26 MeV. This is the threshold energy for electrons that are energetic enough to produce Cherenkov light. It is the principal basis of Cherenkov light production in pool type research reactors in which the light is readily visible. For prompt Gamma rays, in general, it makes it possible to assume that Cherenkov light intensity is a linear function of reactor power. Referring to the basics of fission power production, one can write,

$$\text{Power density}: p(r) = E_f \times \overline{\Sigma}_f \times \Phi(r)$$
$$\text{Total power}: P = \int_{\text{core}} p(r) d^3r = \overline{p} \times V_{\text{core}}$$

where E_f is the energy released per fission, $\overline{\Sigma}_f$ the average fission macroscopic cross section, $\Phi(r)$ the neutron flux, and V_{core} is the core volume.

It is clear that neutron intensity, fission rate, power density, and total power itself are all inter-related by a linear relationship. In other words, Cherenkov light intensity is also directly proportional to the fission rate. This leads us to the fact that the measured

* Corresponding author. Tel./fax: +98 21 88221123.
E-mail address: mgharib@aeoi.org.ir (M. Gharib).

0306-4549/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.anucene.2009.03.009

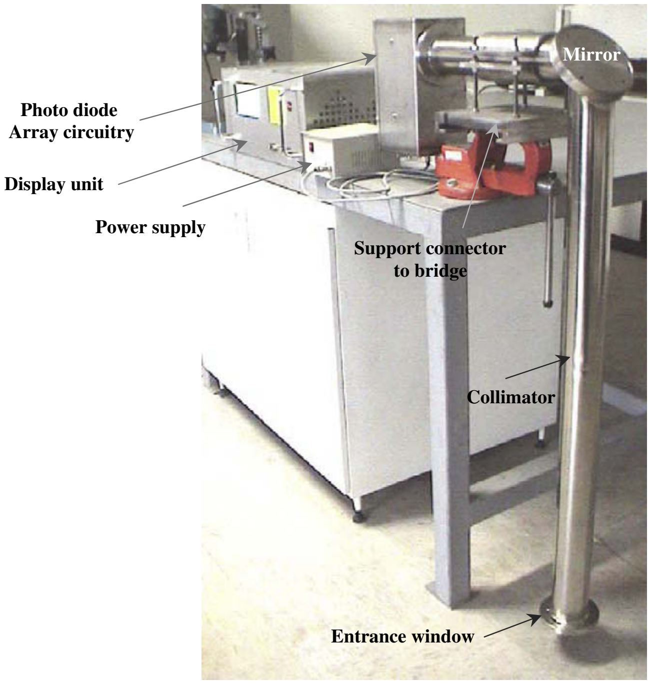

Fig. 1. Major parts of measuring system at workshop.

Cherenkov light intensity at any point in a reactor is linearly proportional to the instantaneous power. As long as the measurement point is fixed, the total power could easily be derived from the light intensity with proper calibration.

It should be noted here that, as mentioned before, Cherenkov light is also emitted by the electrons produced by the indirect ionization of fission products by Gamma rays, which are confined in fuel elements. This light contributes to the total light intensity, irrespective of whether the reactor is ON or OFF. For this reason, a linear relationship between reactor power and Cherenkov light intensity would only hold at the higher power range where fission power is dominant in comparison with residual power.

3. Experimental setup

The measurement system consists mainly of a photo diode array (PDA), electronic circuitry, collimator, and display unit. In this work it was preferred to employ a PDA rather than a photo multiplier tube (PMT) because of the former's simplicity and low cost. Moreover, the PDA is small and does not need high voltage power supply, unlike a PMT. Therefore, it is easier to work with a PDA, which could be operational as an array, as was done in this work. Fig. 1 shows the main items on the laboratory bench in the course of system setup. The heart of this system is the PDA and its associated circuitry. A general block diagram of this section is shown in Fig. 2. The entire system consists mainly of three units: the Cheren-

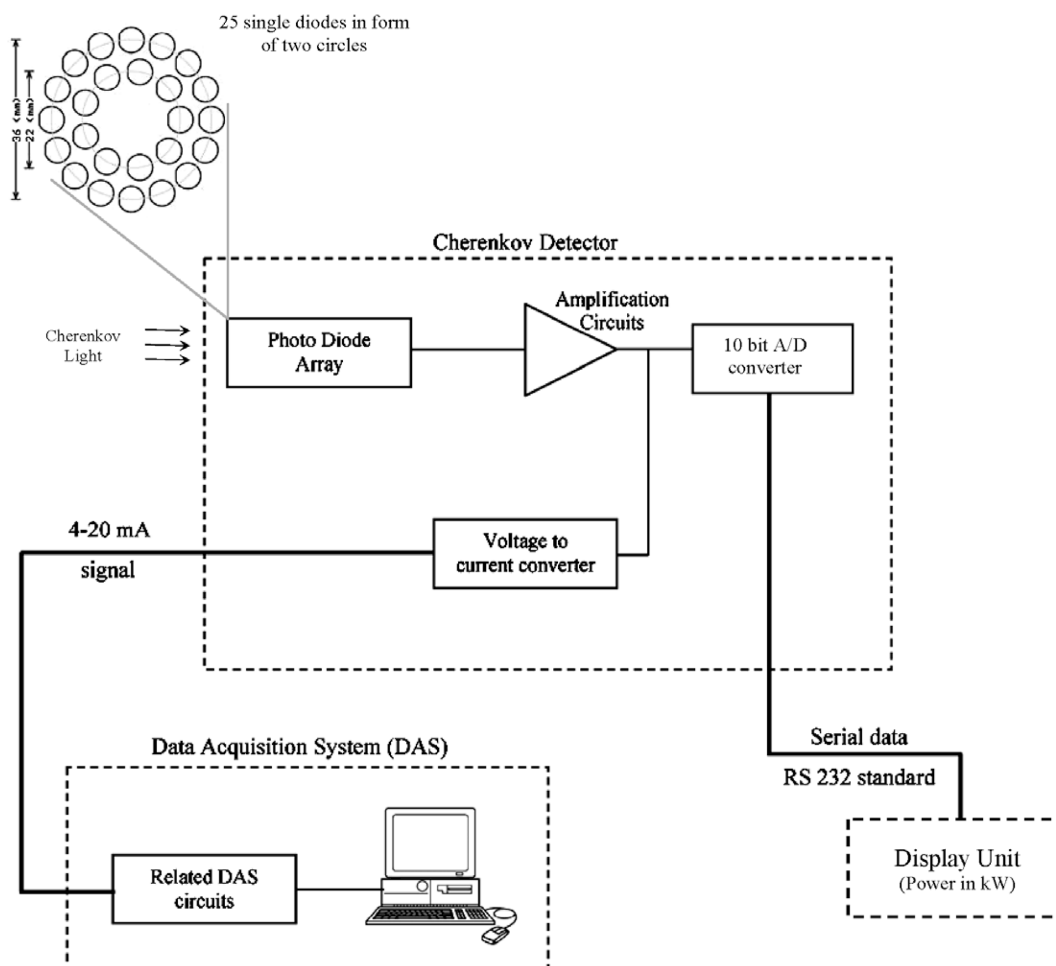

Fig. 2. Simplified diagram of power measuring channel based on Cherenkov light.

kov detection unit, a display unit, and a data acquisition system. Cherenkov light emanating from core is collected by a collimator right above the core and reflected by a mirror onto a sensitive part of the PDA. Fig. 3 shows the integrated system at work, overlooking the core. Fig. 4 shows a schematic diagram of the measurement system with respect to the TRR core and the overall geometries.

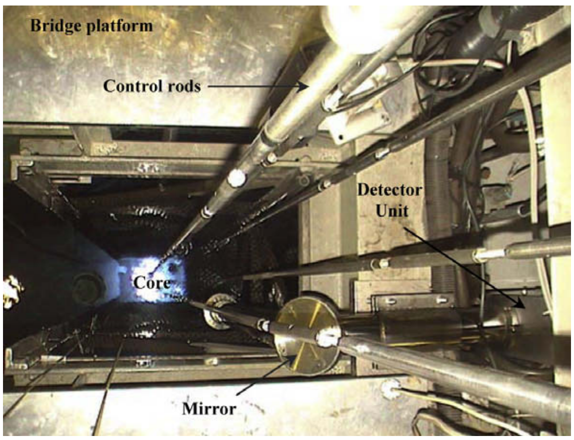

Fig. 3. Power measuring channel at work in TRR while receiving Cherenkov light.

It is important to note that a novel approach is employed in this system in order to have signal amplification in an efficient way. As it is noted in Fig. 5, two operational amplifiers are employed in a special way to maximize photonic current. Relation (1) describes how this idea is fulfilled.

$$V_{out} = V_{os}\left(1+\frac{R_4}{R_3}\right) + R^*\left(1+\frac{R_4}{R_3}\right)(I_B^- - I_B^+) + I_{PDA}\left(\left(1+\frac{R_4}{R_3}\right)2R^*\right) \quad (1)$$

where V_{out} is the output voltage, V_{os} the offset voltage of op-amp A, I_B^- the negative input bias current of op-amp A, I_B^+ the positive input bias current of op-amp A, $R_1 \approx R_2 = R^*$, $\left(1+\frac{R_4}{R_3}\right) \gg R_4$, $I_{PDA} = I_{ph} + I_{dark}$, I_{PDA} the total PDA current, I_{ph} the photonic current of PDA, and I_{dark} is the dark current of PDA.

Eq. (1) is applied with the following generic values,

$$R^* \approx 100\,\mathrm{K\Omega},\quad R^* \approx 50\,\Omega,\quad R^* \approx 10\,\mathrm{K\Omega},$$
$$\left(1+\frac{R_4}{R_3}\right) \approx 200,\quad \left(1+\frac{R_4}{R_3}\right)R^* \approx 2\times10^7\,\Omega,\quad \left(1+\frac{R_4}{R_3}\right)2R^* \approx 4\times10^7\,\Omega$$

Since V_{os} is essentially the same as the voltage on PDA and it is always negligible, therefore the voltage on PDA is also small. As a result, the dark current is small and could be neglected. Therefore, according to Eq. (1), the highest contribution is through the third

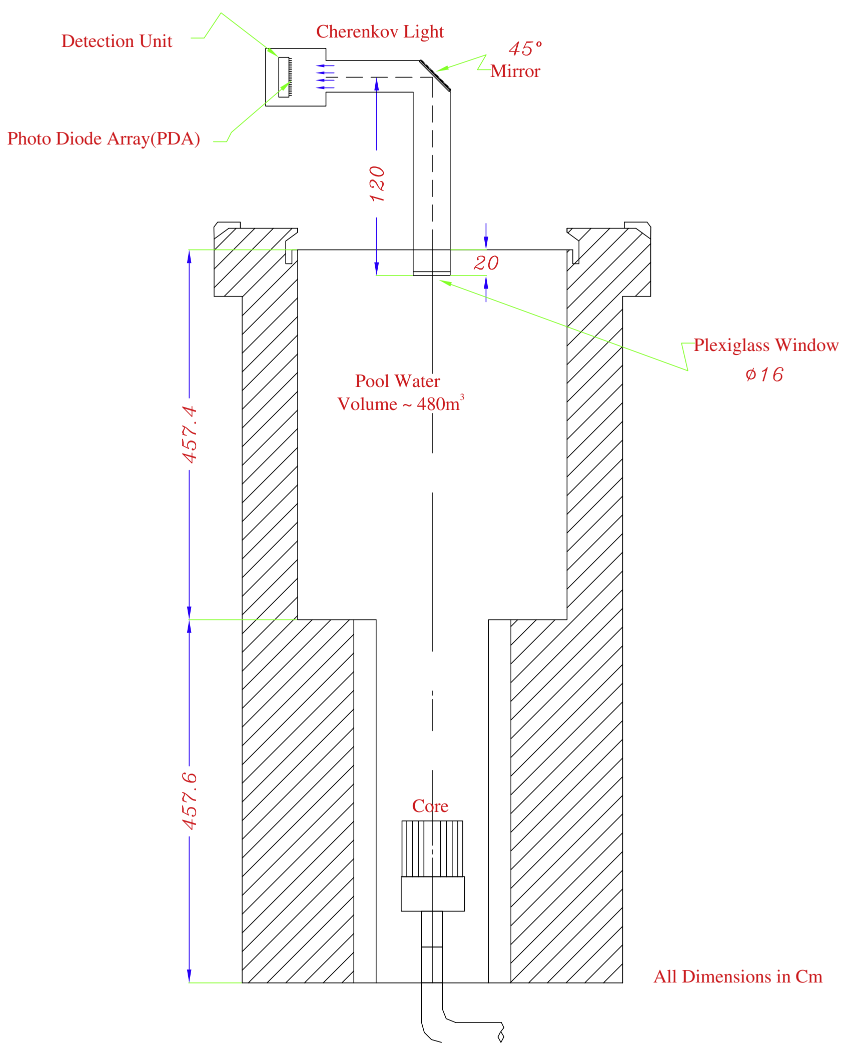

Fig. 4. Experimental setup with respect to reactor vertical profile.

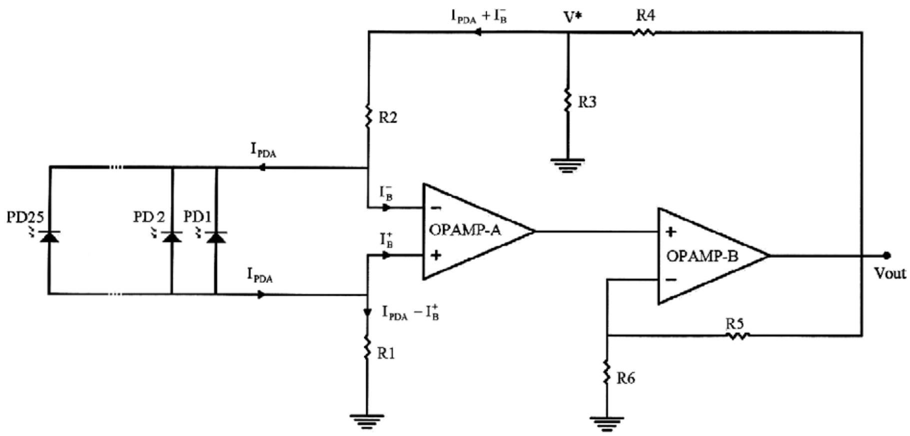

Fig. 5. Schematic diagram of specially designed preamplifier and amplifier circuit to handle optical signal efficiently.

term due to photonic current. In other words, the other two terms are negligible. Noting the orders of magnitude of all these terms in Eq. (1), and neglecting $I_B^- - I_B^+$, it is obvious that only the third term is significant and needs to be retained. It is emphasized that the novelty of this approach is due to the special arrangement of this circuitry in a way to attenuate the thermal fluctuation to almost zero while amplifying the photonic signal as implied in Eq. (1).

Details of each unit with description of all parts are given elsewhere (Arakni and Gharib, 2007). Due to surface water ripples, the optical window at collimator's entrance is covered with a transparent Plexiglas penetrating a few centimeters below the pool water surface. As indicated in Fig. 4, the collimator and detection units are situated out of water overviewing the core. There is about 7 m of water on core top plus 1 m of air to separate the PDA from the light source. Part of Cherenkov light from the core goes through the collimator and reaches the detection unit. The detection unit is comprised of 25 photo diodes, known as photo diode array, arranged in two concentric circles in order to enhance sensitivity. A good feature of the photodiodes is their flexibility to be used in the form of an array. The technical specification of the photo diode used in this system is given in Table 1. The output voltage is amplified and sent through two parallel branches as displayed in Fig. 2. One goes into display unit to show power in kilo watts, and the other is transferred to the data acquisition for proper archiving.

4. Results and discussion

One of the most basic experiments aims at gaining knowledge about the steady state behavior of PDA itself. Prior to any real applications, PDA was tested under no light condition for a period of around 24 h. The output signal was observed for this period, first to make sure of its steadiness and second to have an estimate of

Table 1
Technical specification of a single photodiode used for Cherenkov detector.

Type: silicon NPN epitaxial planar, high sensitivity
Incident light cone: $\theta_{\frac{1}{2}} = 10^\circ$
Dark current ≈ 0.01 μA (at V_{AK} = 30 V)
Current sensitivity ≈ 200 μA at 0.1 mw*/cm^2
Relative sensitivity: 60% (at $\lambda = 500$ nm)
Geometry:
Diameter (mm) = 4.7 ± 0.1
Length (mm) = 6.5 ± 0.5

* *Note*: color temperature = 2870 K, standard tungsten lamp

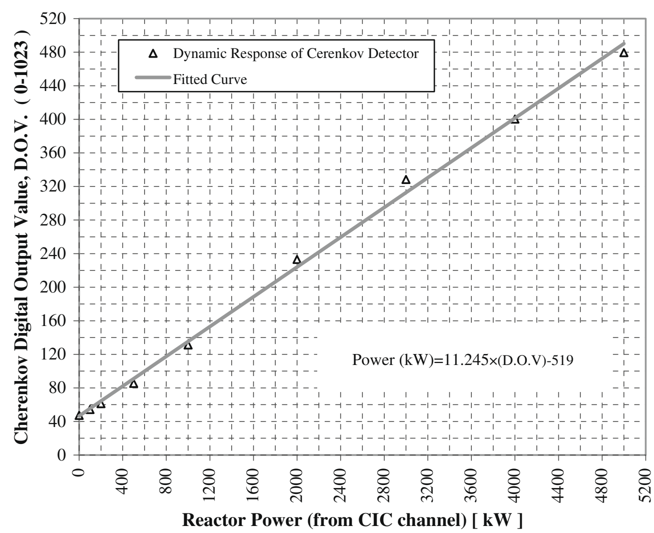

Fig. 6. Correlation between TRR power and digital output value of Cherenkov detector.

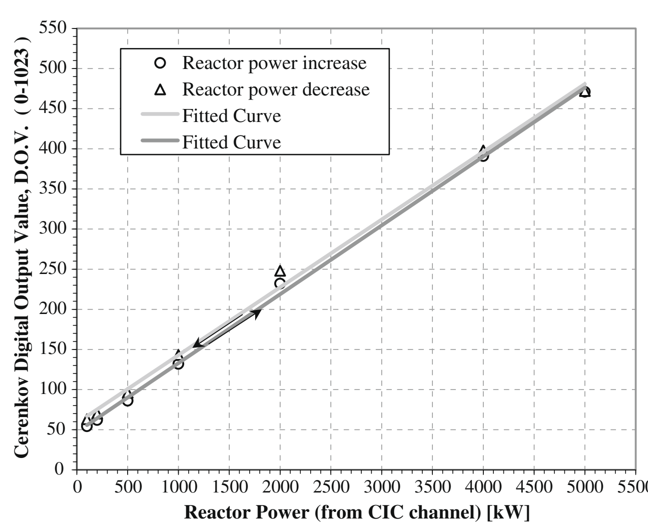

Fig. 7. Fidelity check of detector in response to consecutive power increase and decrease.

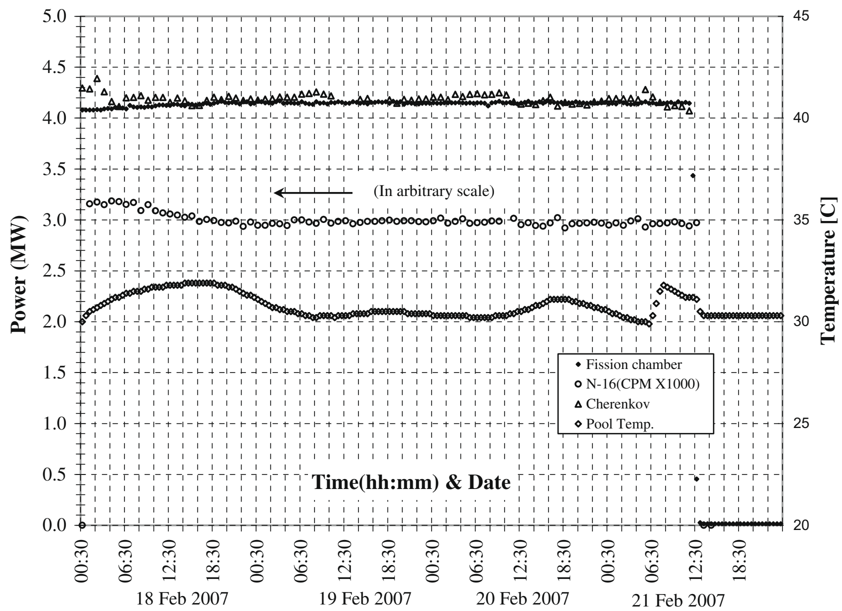

Fig. 8. Comparison of Cherenkov detector output with other regular channels within a typical operation shift of TRR.

the dark current (in fact, this is the output voltage due to dark condition). It was observed that the output signal due to dark condition is as low as 47.4 ± 0.1, which is obviously due to the intrinsic structure of the electronic circuitry (Arakni and Gharib, 2007).

Next, to check the system in real operation, one has to examine its linearity with respect to the reactor power. Fig. 6 shows a comparison between Cherenkov digital output value and the reactor power. It is important to note that output signals of all existing power channels are calibrated from time to time against real thermal throughput to make sure that their readings are reliable and accurate. This means that any of these channels is an independent indicator of true reactor power. Note, however, that in most cases the CIC output is formally taken as the true reactor power indicator for its accuracy and extended range of operation. A good linear correlation is observed between these two parameters especially for the power ranging above 100 kW. The correlation factor, a measure of goodness of fit, is around 0.9988 with maximum relative error not exceeding 5%. At lower power levels, the Gamma particles originating from the fission products are comparable with those from prompt fission and therefore linearity is not valid. According to Fig. 6, considering the fact that the PDA detector saturates at digital value of 1023, the maximum power level correctly recordable in this system is around 10 MW. Another important factor to be checked is the system fidelity. This means that the response of the system must be the same when the reactor power is raised or lowered. Fig. 7 shows that there is a good fidelity within the linearity range. Moreover, there has been no drift observed in the system in the long run as the system functioned properly for almost 2 years since it was installed. Finally, it is necessary to examine whether the reading from the Cherenkov detector is consistent with other channels. Fig. 8 shows its good consistency with other conventional channels (only the fission chamber is shown for the sake of simplicity) within a typical shift operation. It is observed that the steadiness and stability of the Cherenkov detector is as good as other existing channels. The N-16 counts and pool average temperature are also included as further confirmation of the general behavior of the reactor during the operation. Reasonable stability is observed in the hourly readings of all the channels. Based on statistics, the output value of the present PDA system is valid within ±1% at its nominal power.

5. Conclusion

It is concluded that, at least for the case of research reactors, one can simply increase redundancy and diversity of medium-range reactors by employing the Cherenkov detector as an auxiliary tool for monitoring purposes. It is seen that such a system can provide a stable and reliable tool for the major part of power range, and it can assist in the reactor operation with additional safety interlocks to issue appropriate signals. The advantage of the present detector system over conventional ones is that it is far from the radiation source and thus easily accessible for maintenance and fine tuning. It contains no consumable materials to degrade in long term, and it is relatively inexpensive and simple.

Finally, it is worthwhile to mention that a salient feature of the present work is that it employs a PDA system rather than a conventional photo multiplier tube (PMT). The advantage of PDA over PMT is its simplicity and ease of usage in all experimental conditions. Therefore it is a low cost device while being reliable and accurate. The PMT, on the other hand, is good for conditions where the light intensity is very low, which would be unsuitable for the present application because the linear relationship breaks down in such conditions. Nevertheless, a drawback of the Cherenkov system, which is also true about uncompensated ionization chambers, is its lack of linearity in the low power range.

Acknowledgement

The authors wish to thank the operating personnel of TRR, especially Mr. Ashkan Hossnirokh and Mr. Majid Haerizadeh Nabavi, for their invaluable contribution and cooperation.

References

Arakni, M., Gharib, M., 2007. Design and Construction of an Independent Channel for Tehran Research Reactor Power Measurement Using Cherenkov Detector, M. S. Thesis, Azad University, Research and Science Department, Tehran.

Jelley, J.V., 1958. Cherenkov Radiation and its Application. Atomic Energy Authority, United Kingdom.

Kuribara, M., 1994. Spent fuel burn-up estimation by Cherenkov glow intensity measurement. IEEE Trans. Nucl Sci. 41, 1736–1739.

Rippon, S.E., 1963. Cherenkov detectors for the measurement of reactor power. Nucl. Ins. Methods 21, 192–196.