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Statistical testing of temperature fluctuations for estimating thermal power in central subassembly of fast reactor

Paawan Sharma *, N. Murali, T. Jayakumar

Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, India

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ABSTRACT

This paper reports results on the use of various statistical tests for studying the characteristic of temperature fluctuations in central subassembly of the core in a fast breeder test reactor.These tests are useful in establishing a correlation between core thermal power and fluctuations. Tests such as KPSS, Reverse Arrangement Test and runs test are used here to quantify the stochasticity of temperature fluctuations. The use of Approximate Entropy (ApEn) is also highlighted as a measure of complexity. Finally, a model is proposed on the basis of findings of above tests to establish the correlation.

1. Introduction

Systems in Nuclear reactors must follow stringent norms for their operation. One such requirement is that all safety critical systems in Nuclear Power Plants (NPPs) must be validated using diverse methods. Power measurement in fast reactors is carried out by neutronic methods and calibrated by the core temperature readings and thermal balance. This calibration is required to correct the slight difference in reactor power as estimated by neutronics with that of actual core thermal power. Hence, a diverse system is required to validate the power estimation. The core of Fast Breeder Test Reactor (FBTR) consists of 65 fuel subassemblies with 61 pins per subassembly (Srinivasan et al., 2006). The innermost subassembly known as the central subassembly (CSA), exhibits maximum temperature due to the highest value of neutron spectrum at the center.

The present work aims to study the temperature fluctuations in CSA, by performing statistical tests to quantify stochasticity, and to correlate them with actual reactor thermal power. Simple frame statistics is less useful in case of CSA data.The proposed correlation can be utilized as a diverse method to validate the estimated reactor power.

2. Statistical tests

Historically, statistical tests were primarily focused on economic analysis. Recently, they are being used as a tool to analyze real time signals. These tests mainly include KPSS test, Reverse Arrangement Test (RAT) and runs test. Several works such as Brcich and Iskander (2006), Weber et al. (2007), Kay (2008), Bilodeau et al. (1997), and Thexton (1996) have used these tests in signal processing domain. Simple frame statistics as shown in Fig. 1is less useful to derive a direct parameter such as standard deviation, since it varies randomly for different frame lengths at various power levels. These tests are used for determining the stationarity of temperature fluctuations. This is necessary since the variables in a model should be stationary for valid behavioral analysis (asymptotic) and gives confidence in any calculated parameter derived from fluctuations. Additionally, use of such tests indicate their suitability for fluctuation analysis.

2.1. Kwiatkowski–Phillips–Schmidt–Shin (KPSS) Test

The NULL hypothesis (H_o) in this test is: *an observable time series is stationary around a deterministic trend* (Kwiatkowski et al., 1992). Hence, the data is checked for stationarity. GRETL (Baiocchi and Distaso, 2003) tool is used for calculating test statistics. The test statistics are compared against the value at 99% confidence level (0.743). If the value is greater than 0.743, H_o is rejected and data is likely to be non-stationary.

* Corresponding author. Tel.: +91 44 27480500x22258; fax: +91 44 27480228.
E-mail addresses: paawan@igcar.gov.in (P. Sharma), murali@igcar.gov.in (N. Murali), tjk@igcar.gov.in (T. Jayakumar).

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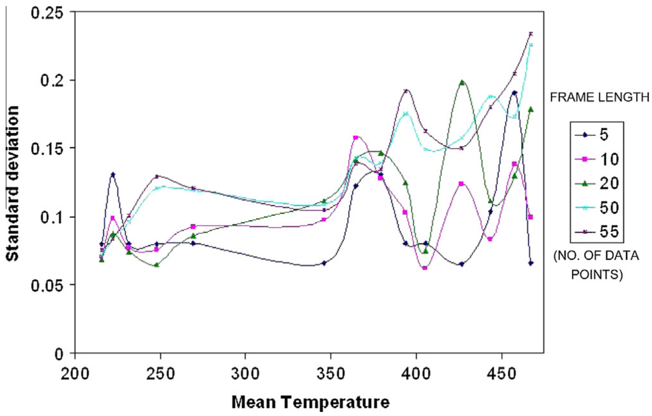

Fig. 1. Mean temperature vs standard deviation for different frame lengths.

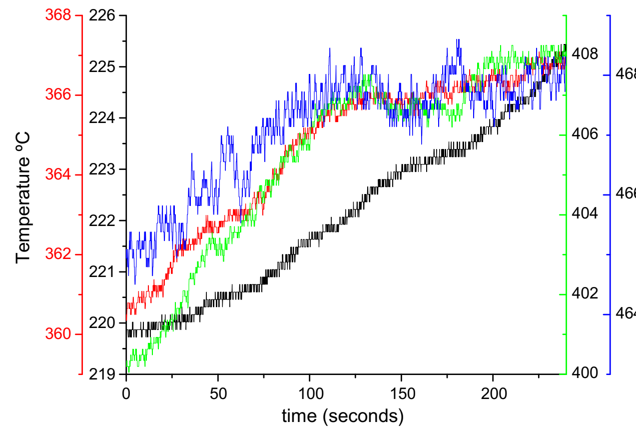

Fig. 2. CSA temperature profile for increasing power levels.

2.2. Runs Test

H_o in runs test is: *Data is from a random process.* Test statistic z is calculated as follows (Bradley, 1968):

$$z = \frac{R - \overline{R}}{S_R} \tag{1}$$

where R is the observed no. of runs, $\overline{R}$ the expected no. of runs, and S_R is the standard deviation of no. of runs. The absolute value of test statistic $|z|$ is compared with *z-score* for normal distribution at 5% significance level ($z_{1-\alpha/2} = 1.96$). H_o is rejected if $|z| > z_{1-\alpha/2}$ and hence, the data is unlikely to be from a random source.

$\overline{R}$ and S_R are calculated as:

$$\overline{R} = \frac{2n_1n_2}{n_1 + n_2} + 1 \tag{2}$$

$$S_R = \frac{2n_1n_2(2n_1n_2 - n_1 - n_2)}{(n_1 + n_2)^2(n_1 + n_2 - 1)} + 1 \tag{3}$$

where n_1 is the no. of positive values in series (or above mean/median) and n_2 is the no. of negative values in series (or below mean/median).

2.3. Reverse Arrangement Test (RAT)

H_o in RAT is similar to runs test, but is free from any distribution related pre-assumptions. It is helpful in detecting any trends which lead to presence of non-stationarity in time-series. The code for calculating $|z|$ is written in SCILAB (Scilab Enterprises, 2012) with the following relationship (Julius and Bendat, 2010):

$$z = \left| \frac{c - N(N-1)/4}{\sqrt{(2N^3 + 3N^2 - 5N)/72}} \right| \tag{4}$$

where N is the time series length and c is the no. of arrangements in time-series for which,

$$x(i) > x(j+1) \quad \text{where } i = 1 \text{ to } N;\ j = i \text{ to } N - 1$$

2.4. Approximate Entropy (ApEn)

ApEn is a method used to estimate regularity and unpredictability of fluctuations in a time-series data (Pincus et al., 1991). The other methods for measuring regularity such as entropy are not suitable for experimental data. The ApEn code is written in Scilab Enterprises (2012) and is tested using fluctuation data from FBTR. The time-series for which ApEn has lower value (less complex) is more predictable, and vice versa.

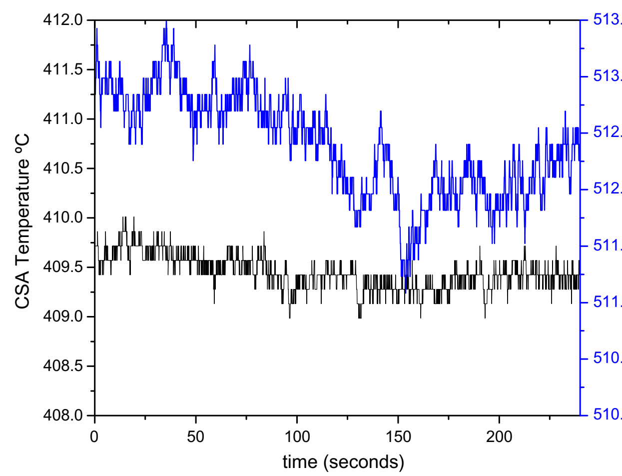

Fig. 3. CSA temperature profile at stable power levels.

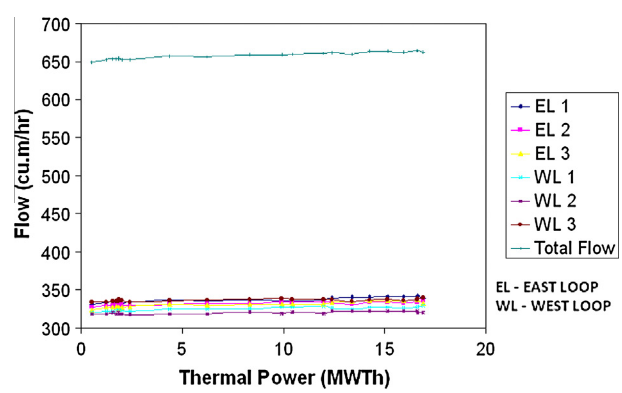

Fig. 4. Primary coolant flow.

3. Experimental data

Performing a number of tests requires vast amount and wide range of data. The thermal power in FBTR ranges from few kilowatts to several megawatts (1 kW Th to 18 MW Th). The full scale is divided in source, intermediate and power range in addition to shutdown state. Central subassembly (CSA) outlet temperature was obtained for full range of operation. The time-series consists of 2400 samples for each power level, with each sample separated by 0.1 s. Also, data was explicitly taken for increasing power cam-