Investigation of Coolant Temperature Fluctuations Circulating in the Primary Circuit of VVER-440 Reactors

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ABSTRACT

The neutron noise caused by core inlet temperature fluctuations carries diagnostic information, and it has been investigated since the seventies up to these days. Most of the investigations analyze neutron noise with known temperature fluctuations. In this paper properties of the temperature fluctuations in measurement data are investigated based on noise methods with analyzing auto and cross power spectral density functions as well as transfer functions and coherence of the temperature noise measured in the hot and cold legs of the primary loop. Additionally we have used the transfer properties of the main components of the primary circuit and the circulation time of the coolant (presented at NENE-2013). We have identified the source of the temperature fluctuations furthermore we have analyzed their propagation. There are two main sources of the temperature fluctuations in the primary loop: the reactor and the steam generator. We have separated the main components of these fluctuations. The fluctuations circulating in the primary circuit disappear only after one cycle, and they cannot be neglected in methods investigating low frequency region of the spectra. Ratio of the different components depends on the frequency and the loop position. We have provided the frequency dependences of fluctuation part ratios originated from the different sources both for the hot and the cold leg.

1 INTRODUCTION

In steady state, small fluctuations of the reactor parameters are mainly caused by inhomogeneities of temperature, density, boron concentration, etc. travelling with the primary coolant. Noise diagnostics investigations are based on their statistical analysis. Due to the circulation of the primary coolant, temperature fluctuations arisen in the primary circuit pass through the reactor core and the steam generators several times before totally disappearing. Consequently, perturbations passing through the reactor core are fed back after a significant attenuation with a time delay of the circulation period of the primary coolant. In order to determine the delay and extent of the feedback, it is important to know the propagation process of the temperature perturbations in the primary circuit: the circulation period of the perturbations [1], the effect of the steam generators [2] and of the reactor [3] on the perturbations, the rate of the mixing between the loops [4], the sources of perturbations, their ratio in the loops etc. In this paper measurement data of an operating reactor (a Paks VVER-440 reactor unit) is processed, and so our investigations are limited by the instrumentation installed on the reactor and by the data that can be measured.
2 AVERAGE PRIMARY LOOP

The primary circuit of a VVER-440 reactor consists of six loops. The temperature of the coolant circulating in the loops is measured at two positions in each loop: just before entering into the reactor and just after exiting from it, i.e. in the cold and the hot leg (Fig. 1).

Figure 1: Primary circuit of VVER-440 with the six loops and the cold and hot leg temperature measurement positions

The statistical analysis of the loop temperature fluctuations is highly deteriorated since the coolant coming from the individual loops is mixed in the lower plenum of the reactor. In order to moderate this effect an average loop model is used by averaging the temperature signals of the same loop positions [1]. The properties of the average loop are shown in the left-hand side scheme of Fig. 2, where the distances between different loop positions are characterised by the transit times of the coolant.

Figure 2: Measurement positions characterised by transit times of the primary coolant in the average loop (left) and scheme of the perturbations circulating in the loop (right), for the key to the signs, see Section 3

3 MODEL OF THE PERTURBATIONS CIRCULATING WITH THE PRIMARY COOLANT

The propagation of the temperature fluctuations based on the average loop model is shown in the right-hand side scheme of Fig. 2. In the present section this model is described.
3.1 Model equations of the average primary loop

There are two sources of the temperature fluctuations in the primary circuit: the reactor and the steam generators. Here the temperature noise induced by the main coolant pumps (MCP) is also included, however, its frequency is over our range of interest since the rev of the MCP’s is 1500 rpm, i.e. 25 Hz, whereas the temperature perturbations circulating in the primary circuit virtually disappear in one or two cycles due to the attenuation and mixing in the steam generators.

In Fig. 2 the temperature signals measured by the cold leg and the hot leg thermocouples are denoted \( T_{\text{cold}} \) and \( T_{\text{hot}} \), respectively. In the right-hand side scheme of the same figure the Fourier transforms of the fluctuating parts of these signals are shown:

\[
\delta T_c(\omega) = \int_{-\infty}^{\infty} \delta T_c(t) e^{-i\omega t} dt \quad \text{for the cold leg} \quad \text{and} \quad \delta T_h(\omega) = \int_{-\infty}^{\infty} \delta T_h(t) e^{-i\omega t} dt \quad \text{for the hot leg}. 
\]

\( \delta T_h(\omega) \) denotes the temperature noise arising either in the reactor upper plenum where sub-flows coming from fuel assemblies of different temperatures are mixed, or from temperature fluctuations induced by the power fluctuations of the reactor. The latter is in connection with the reactor parameters causing reactivity fluctuations. \( \delta T_{SG}(\omega) \) stands for the temperature noise arising in the steam generators.

In order to keep the nominal power of the reactor at steady state, the temperature of the secondary coolant is controlled, which acts on the reactor power through the moderator temperature coefficient of the reactivity (MTC). Temperature fluctuations entering the reactor cause feedback through the power fluctuations arising through the MTC, however, this effect can be neglected above 0.1 Hz due to the thermo-hydraulic properties of the reactor [3].

Since the time constant of the heat transfer between the coolant and the fuel elements is of several seconds and because of the relatively slow temperature control of the secondary circuit, the coupling between the noise of the steam generator and the reactor can be neglected above 0.1 Hz. With this neglectuon the temperature fluctuations \( \delta T_{SG}(\omega) \) and \( \delta T_{R}(\omega) \) can be considered independent from each other.

Taking these into account, the following equations hold for the process shown in the right-hand side scheme of Fig. 2.

The hot leg temperature fluctuation can be written as

\[
\delta T_h(\omega) = H_c(\omega) \cdot \delta T_c(\omega) + \delta T_R(\omega)
\]

where \( H_c(\omega) \) is the transfer function for the cold leg of the primary circuit (or shortly cold leg transfer function), which consists of the reactor transfer function \( H_R(\omega) \) and the transfer function \( H_L(\tau_{ch}) = e^{-i\omega \tau_{ch}} \) describing the time delay \( \tau_{ch} \) between the cold leg and hot leg thermocouples, i.e. \( H_c(\omega) = H_L(\tau_{ch}) \cdot H_R(\omega) \).

The cold leg temperature noise \( \delta T_c(\omega) \) consists of the hot leg temperature passing through and attenuated in the steam generator and the noise generated in the steam generator:

\[
\delta T_c(\omega) = H_h(\omega) \cdot \delta T_h(\omega) + \delta T_{SG}(\omega)
\]

where \( H_h(\omega) \) stands for the hot leg transfer function and \( \delta T_{SG}(\omega) \) denotes the noise generated in the steam generator. The hot leg transfer function consists of the transfer function \( H_{SG}(\omega) \)
of the steam generator and the transfer function $H_L(\tau_{hc}) = e^{-i\omega \tau_{hc}}$ describing the time delay $\tau_{hc}$ between the hot leg and the cold leg thermocouples. (Note that if the time delay of the coolant as passing through the steam generator is included in $H_{SG}(\omega)$, then its average value has to be subtracted from $\tau_{hc}$.)

With substituting equations (1) and (2) into each other the temperature noises of the hot leg and the cold leg part of the primary circuit can be obtained:

$$\delta T_h(\omega) = \frac{1}{1 - H_c(\omega) \ast H_h(\omega)} [H_c(\omega) \ast \delta T_{SG}(\omega) + \delta T_R(\omega)]$$

$$\delta T_c(\omega) = \frac{1}{1 - H_c(\omega) \ast H_h(\omega)} [\delta T_{SG}(\omega) + H_h(\omega) \ast \delta T_R(\omega)]$$

3.2 Transfer functions

Since the power feedback can be neglected above 0.1 Hz due to the large heat transfer coefficient between the coolant and the reactor core, the reactor transfer function $H_R(\omega)$ is approximated as $H_R(\omega \geq 0.1 \text{ Hz}) \approx 1$.

The calculation method of the steam generator transfer function $H_{SG}(\omega)$ taking its structure into account, was described in our previous paper [2]. The numerically calculated frequency response of the steam generator is shown in Fig. 3.

![Figure 3: Transfer function of a VVER-440 steam generator in the frequency domain](image)

Transit times in the primary loop are given in Fig. 2; their determination is described in more detail in [1].

3.3 Attenuation of the primary circuit

The first factor of equations (3) and (4) stands for the feedback of the loop and it can be written as the sum of a geometrical series:

$$\frac{1}{1 - H_c(\omega) \ast H_h(\omega)} = 1 + H_c(\omega) \ast H_h(\omega) + H^2_c(\omega) \ast H^2_h(\omega) + \ldots = \sum_{i=1}^{\infty} H_c(\omega)^{i-1} \ast H_h(\omega)^{i-1}$$

(5)
Terms of this series describe the remaining noise after each circulation cycle. Let us see how strongly attenuated the system is, how quickly it reaches its steady state, so let us compare the noise remaining after the $n$-th cycle to the effective noise.

$$
\zeta_n(\omega) = \frac{\delta T_c^{(n)}(\omega)}{\delta T_c^{(0)}(\omega)} = \frac{\delta T_h^{(n)}(\omega)}{\delta T_h^{(0)}(\omega)} = \frac{\sum_{i=1}^{n} H_{c}^{i-1}(\omega) \cdot H_{h}^{i-1}(\omega)}{1 - H_{c}(\omega) \cdot H_{h}(\omega)} = 1 - H_{c}^{n}(\omega) \cdot H_{h}^{n}(\omega)
$$

(6)

Above 0.1 Hz

$$
H_{c}(\omega) = H_{L}(\tau_{ch}) \cdot H_{R}(\omega) \leq |H_{L}(\tau_{ch})| \cdot |H_{R}(\omega)| \approx 1
$$

(7)

and

$$
H_{h}(\omega) = H_{L}(\tau_{hc}) \cdot H_{SG}(\omega) \leq |H_{L}(\tau_{hc})| \cdot |H_{SG}(\omega)| < 0.08
$$

(8)

hence

$$
\zeta_{1}(\omega) = 1 - H_{c}(\omega) \cdot H_{h}(\omega) \geq 1 - |H_{L}(\omega)| \cdot |H_{SG}(\omega)| \geq 0.92
$$

(9)

$$
\zeta_{2}(\omega) = 1 - H_{c}^{2}(\omega) \cdot H_{h}^{2}(\omega) \geq 1 - |H_{L}(\omega)| \cdot |H_{SG}(\omega)| \geq 0.9936
$$

(10)

The resulting values of equations (9) and (10) show that the fluctuations approach their steady state to 95% already after 1 cycle above 0.1 Hz, and then they virtually reach it after the second cycle. This means that it is enough to follow 1 cycle to investigate the feedback.

4 RATIO OF THE NOISE COMPONENTS IN THE PRIMARY CIRCUIT

In order to estimate the ratio of the noise components $\delta T_{SG}(\omega)$ and $\delta T_{R}(\omega)$ circulating in the primary circuit, their power spectral density functions need to be calculated:

$$
APSD_{\tau_{SG}}(\omega) = \{ \delta T_{SG}(\omega), \delta T_{SG}^{*}(\omega) \}
$$

$$
APSD_{\tau_{R}}(\omega) = \{ \delta T_{R}(\omega), \delta T_{R}^{*}(\omega) \}
$$

Substituting equations (1) and (2), the above spectra can be estimated with the spectra of the temperature signals measured in the loops.

$$
APSD_{\tau_{SG}}(\omega) = APSD_{\tau_{SG}}(\omega) + |H_{h}(\omega)|^2 \cdot APSD_{\tau_{h}}(\omega) - H_{h}(\omega) \cdot CPSD_{\tau_{h},\tau_{h}}(\omega) - H_{h}(\omega) \cdot CPSD_{\tau_{h},\tau_{h}}(\omega)
$$

(11)

$$
APSD_{\tau_{R}}(\omega) = APSD_{\tau_{R}}(\omega) + |H_{c}(\omega)|^2 \cdot APSD_{\tau_{c}}(\omega) - H_{c}(\omega) \cdot CPSD_{\tau_{c},\tau_{c}}(\omega) - H_{c}(\omega) \cdot CPSD_{\tau_{c},\tau_{c}}(\omega)
$$

(12)

Amplitude spectra can be calculated from these power spectra

$$
|\delta T_{SG}(\omega)| = \sqrt{APSD_{\tau_{SG}}(\omega)}
$$

$$
|\delta T_{R}(\omega)| = \sqrt{APSD_{\tau_{R}}(\omega)}
$$

$$
|\delta T_{R}(\omega)| = \sqrt{APSD_{\tau_{c}}(\omega)}
$$

$$
|\delta T_{h}(\omega)| = \sqrt{APSD_{\tau_{h}}(\omega)}
$$

$$
|\delta T_{h}(\omega)| = \sqrt{APSD_{\tau_{h}}(\omega)}
$$
The estimates of $\zeta_n$ in equations (9) and (10) can be used to provide an estimation of the extent of the different noise components after $n$ cycles of circulation.

$$\delta T_{R,1st}(\omega) = \zeta_1 \cdot \delta T_R(\omega), \quad \delta T_{R,2nd}(\omega) = \zeta_2 \cdot \delta T_R(\omega)$$

$$\delta T_{SG,1st}(\omega) = \zeta_1 \cdot \delta T_{SG}(\omega), \quad \delta T_{SG,2nd}(\omega) = \zeta_2 \cdot \delta T_{SG}(\omega)$$

Measurements were performed with the PAZAR noise diagnostics measurement system with its standard sampling frequency of 100 Hz, low pass filter of 40 Hz and high pass filter of 0.03 Hz. In order to reach the frequency resolution of 0.06 Hz, an FFT window width of 16384 was applied. The 24-hour long measurements provided more than 500 averages and so the statistical error was kept under 4.5%. Finally the noise components are shown in the frequency domain in Fig. 4 (the spectra were corrected assuming a time constant of 2.8 s of the thermocouples).

![Figure 4](image-url)

**Figure 4:** Relative magnitudes of the temperature fluctuations arisen and circulating in the primary circuit

It can be seen in Fig. 4 that the feedback of the rounding coolant is less or equal to the stripes between the red ($\delta T_R(\omega)$) and plum ($\delta T_{SG}(\omega)$) areas. It can be seen from the figure that the ratio of the fluctuation in the cold leg signal coming from the reactor (and passing through the steam generator) is only 10%. The steep decrease of the curve below 0.05 Hz is caused by the high pass filter of the noise measurement system. The peak at 0.5 Hz comes from the data acquisition system of the core monitoring system. Stripes denote the frequency region out of our model.

It is more expressive when the ratios of the components are shown along the loop at a specific frequency like in Fig. 5 at 0.1 Hz. The colour coding in Fig. 5 is equivalent to Fig. 4. The horizontal distances of the graph correspond to the distances of the underlying scheme.
5 CONCLUSIONS

In order to investigate temperature fluctuations measured in the primary circuit of a VVER-440 reactor, an average loop model was applied. The average loop model removes the effect of mixing between the individual loops and improves the statistics of the results. Based on our investigations the following statements can be made.

- Feedback of the perturbations through the circulation is important, however it is enough to describe one cycle because of the strong attenuation of the steam generator.
- The two main sources of the temperature fluctuations are the steam generator and the reactor. Their ratio depends on the measurement position in the loop.
- The dominant frequency range of the fluctuations arising in the steam generator is below 0.25 Hz, while this range extends up to 1 Hz in the reactor.

Our model is valid above 0.1 Hz. Investigations below 0.1 Hz become more complicated for three main reasons:

- The measurement system has to be distortion free in the low frequency region, and longer measurements are needed in order to keep statistical errors at the same level. This can be problematic due to the requirement of steady state.
- The effect of the control systems has to be taken into account.
- The reactor transfer function cannot be considered as constant.

REFERENCES

