ABSTRACT

Enhancing the evaluation of reactor noise diagnostics measurements requires feedback originating from the effect of the circulation of the coolant in the primary circuit loops to be taken into account. Therefore circulation period of the coolant and transfer properties of the steam generator and its effect on the perturbations travelling with the coolant have to be known. Circulation period was determined from the correlation of the noise signals of thermocouples installed in the loops as a part of the standard instrumentation. Circulation time of the perturbations travelling with the coolant was found to be smaller than expected by the raw estimation from total mass and mass flow rate of the coolant. The reason of this is partly coming from stagnating volumes not exactly known in the raw estimation and from the effect of the steam generator. The latter is well demonstrated by the transfer function of the steam generator which was produced by taking its inner structure into account.

1 INTRODUCTION

Noise diagnostics analysis is based on investigations of small fluctuations of reactor parameters around their nominal value (such as coolant temperature or neutron flux fluctuations etc.). In the steady state of the reactor the main sources of these fluctuations are inhomogeneities travelling with the coolant (e.g. inhomogeneities of boron concentration, density or temperature).

For reactor core monitoring with noise diagnostics methods in the low frequency domain (under 1 Hz) the effect of the feedback of the primary circuit loop has to be taken into account. In order to consider it the circulation period of the primary coolant is useful to be determined and the transfer properties of the steam generator to be analysed.

After providing an overview of the primary circuit of a VVER-440 reactor in Section 2, Section 3 introduces a measurement method of the circulation period based on noise measurements, while transfer properties of the steam generator are investigated in Section 4.
2 OVERVIEW OF THE PRIMARY CIRCUIT OF A VVER-440 REACTOR

The primary circuit of a VVER-440 reactor consists of six loops with a horizontally arranged steam generator at each loop (see Fig. 1).

Figure 1: Primary circuit of a VVER-440 reactor
(Courtesy of Paks NPP Simulator Department)

The standard instrumentation of the reactor provides four types of detectors to measure fluctuations in the primary circuit: cold leg temperature signals, neutron flux signals in the core, fuel assembly outlet temperature signals and hot leg temperature signals.

Fluctuating part of the signals is measured by the PAZAR noise diagnostics measurement and evaluation system [1] in operation at Paks NPP. These noise signals are measured with sampling frequency of 100 Hz, and 0.015 Hz high pass, 40 Hz low pass and 50 Hz notch filters are applied.

Difference between the mass flow rates of the coolant in the individual loops is less than 1% in nominal operation conditions. The difference between the largest and the smallest values was less than 0.2% for the measurements investigated in the present paper, so it can be neglected in the calculation of the circulation period. As a consequence, mass flow rates in the individual loops can be considered identical in nominal operation conditions.

The coolant (and also the temperature perturbations travelling with it) flowing from the six primary circuit loops joins together in the lower plenum of the reactor vessel, and after passing the core and exiting from the upper plenum they separate and enter into the six hot legs. Mixing between the loops cannot be neglected. Approximately 50% of the flow entering into a loop comes from the other loops [3], mainly from the two neighbouring loops, of course.

Determinability of the transit time is corrupted by the mixing between the loops because the distance travelled by (and so the transit time of) the perturbations originating from the same source, separated and later joined again is slightly differs from each other, and so the uncertainty of the measured transit time increases.
In order to investigate the global behaviour of the reactor an average loop is constructed. This can be justified as follows: loop flows join in the reactor vessel inducing nearly identical behaviour of perturbations generated in the reactor core, and since perturbations generated in the steam generator are related to the secondary side control, similarity between the loops appears here, as well. Therefore the average fluctuations of the cold and hot leg temperatures are described with the values evolving in the lower and upper plenum. (See Fig. 2.)

\[
\delta T_c(t) = \frac{1}{6} \sum_{j=1}^{6} \delta T_{c,j}(t)
\]

(1)

\[
\delta T_h(t) = \frac{1}{6} \sum_{j=1}^{6} \delta T_{h,j}(t)
\]

(2)

where \( \delta T_{c,j}(t) \) and \( \delta T_{h,j}(t) \) denote the temperature fluctuation in the cold and hot leg of the \( j \)-th loop, respectively. (For more details about averaging, see [4].)

**Figure 2:** Scheme of the effective reactor loop

Perturbations passing through the reactor core change according to the reactor transfer function \( H_r(\tau) \), and also new components are added to it: the temperature noise \( r(t) \) generated by the reactor. \( H_{sg}(\tau) \) stands for the transfer function of the steam generator while \( g(t) \) denotes the noise generated in the steam generator.

Obvious advantages of the averaging compared to the investigation of the individual loops are as follows: perturbations escaping to the neighboring loop do not vanish and averaging increases the weight of correlated signal parts compared to the uncorrelated ones.

### 3 MEASUREMENT OF THE CIRCULATION PERIOD IN THE PRIMARY CIRCUIT

#### 3.1 Simple estimation by using the mass flow rate

A simple estimation of the circulation period can be given by the total mass and mass flow rate of the coolant. The volumes [2] and the coolant parameters (pressure and temperature) taken from the reactor unit overview log were used to calculate the total mass of the circulating part of the coolant and the result was 147,600 kg. At nominal power the mass
flow rate in the reactor vessel is 8830 kg/s by the overview log. Finally the circulation period of the coolant was estimated as 16.7 s.

Note that this calculation provides an upper estimate of the actual value, since smaller stagnating volumes of the coolant are considered with the same weight as the main current of the flow. A typical example is the top of the collector of the horizontally arranged steam generator above the influx of the heat exchanger tubes. The shape of the perturbation is gradually changing with the distance passed and after some period the perturbation disappears. It is caused by the heat spreading, vortexes in the flow and the geometry of the heat exchanger. Since perturbations bypass the dead or stagnating volumes, their circulation period is shorter than the value calculated above. Accordingly the circulation period of the coolant have to be determined principally from measurement.

3.2 Evaluation applying noise measurement

In order to determine the circulation period, cross covariance function will be calculated from the signals of detectors with identical transfer properties and placed at the opposite sides of the average primary circuit:

$$R_{c,h}(\tau) = \langle \delta T^\text{average}_c(t), \delta T^\text{average}_h(t-\tau) \rangle = \int_{-\infty}^{\infty} \delta T^\text{average}_c(t) \cdot \delta T^\text{average}_h(t-\tau) \, dt$$

The cross covariance function contains two peaks since it is a circulation in a closed loop: a transit time from the cold leg detector to the hot leg detector and a transit time in the other leg of the loop between the same detectors in reverse order (see Fig. 3).

Figure 3: Cross covariance function between the cold and hot leg temperature signals of the average loop

It can be clearly seen that the transit time from the measurement position in the cold leg to the position in the hot leg is 6.0±0.5 s, and in the opposite direction it is 7.3 s. The peaks according to the transit time can clearly be identified and the time between the peaks was found 13.3 s. However, the peaks are broadened adding some uncertainty when reading the value. Accordingly, the circulation period of the perturbation determined from the measurements is 13.3±0.5 s which is at least 2.9 s smaller than the value of 16.7 s provided by the simple estimation (see Fig. 4) [4].
Dead or stagnating volumes of the primary coolant (such as the top third of the steam generator collectors’ volume) are responsible for only a part of this difference; another main contribution is from the structure of the steam generator.

4 TRANSFER PROPERTIES OF THE STEAM GENERATOR

A perturbation exiting from the reactor core reaches the steam generator through the hot legs of the primary circuit. Passing through the steam generator it is significantly attenuated and then reaches the reactor again through the cold leg. In this way a feedback is formed which depends on circulation period, phase and time history of the perturbation. The degree of smoothing of the perturbations before returning to the core (and so the magnitude of the feedback) is fundamentally controlled by the transfer properties of the steam generator which is determined mainly by its structure (see Fig. 5).
4.1 Transit times of the coolant

The primary circuit side of the steam generator consists of two large collectors interconnected with thousands (originally 5536) of heat exchanger tubes having different lengths (7.5÷12.5 m) [5]. Based on the engineering drawings tube lengths were determined and their distribution was created (see Fig. 6.).

![Distribution of the heat exchanger tube lengths](image)

Figure 6: Distribution of the heat exchanger tube lengths

After a perturbation traveling with the coolant enters into the hot leg collector it is divided into myriad small parts, and after passing different distances in the exchanger tubes the parts are joined again in the cold leg collector with time delays proportional to the passed tube lengths. During the time spent in the heat exchanger tubes, the size of the perturbations decreases to the fifth in average (due to the heat loss), and they also broaden, since the coolant parts go through tubes with different length under different time intervals and cool down in different degrees.

In order to obtain the transit time of the perturbations spent in the steam generator, the transit time spent in the collectors has to be added to the transit time in the heat exchanger tubes (see Fig. 7).
Figure 7: Mixing process of the coolant going through a steam generator

The two collectors are identical, but the transit times spent in them are different because of the different temperatures and so the different velocities. However, the sum of the transit times measurable in the two collectors equals to the sum of the two transit times calculated with average temperature. Along an approximately 2 m long part of the nearly 4 m high collectors the coolant velocity is continuously changing, since coolant gradually exits to the heat exchanger tubes (in the hot leg; while in the cold leg the coolant gradually enters from the tubes). Volume of the collectors above the influx of the heat exchanger tubes is a dead (stagnating) volume. For the calculations the flowing coolant is divided to partial mass flows: one is assigned to each heat exchanger tube.

Based on the distribution of the tube lengths and the construction of the collectors all of the transit times were calculated and their distribution is shown in Fig. 8.

Figure 8: Distribution of the mass flow rates as a function of the transit time
Fig. 8 shows the distribution of the mass flow rates as a function of the transit times calculated with nominal parameters of the steam generator. Thick red arrows show the average transit time calculated from nominal operation data. It can be seen that the maximum of the distribution is located at approximately 1 s smaller transit times than the average.

4.2 Transfer function of the steam generator in the frequency domain

Additionally to the above detailed distribution of the transit times, dynamical behaviour of the steam generator was also taken into account based on a point model of the heat exchange which was fitted to a temperature drop response calculation with the CATHARE thermal-hydraulic code [6]. The resultant (total) frequency response function is shown in Fig. 9.

![Figure 9: Transfer function of the steam generator](image)

Fig. 9 also shows the transfer function based on the point model only. It can be seen, how strong is the effect of the steam generator’s structure on the transfer properties compared to the “pure” dynamical behaviour; the resultant transfer function is definitely more steeply decreases and virtually vanishes above 1 Hz.

5 CONCLUSIONS

Circulation period of the primary circuit loop can be measured through average cold and hot leg temperature noise signals of the standard instrumentation. The measured value (13.3 s) is significantly lower (2.9 s difference) than the result of a simple estimation based on the total mass and mass flow rate of the primary coolant. This difference is mainly caused by the dead and stagnating volumes of the primary circuit, but an important contribution can be attributed to the structure of the steam generator, as well.

By the investigation of the transfer properties of the steam generator (SG) it was found that the magnitudes of the noise signals are damped to their fifth in the SG, the maximum of the fluctuations passing through the SG is shifted to a smaller value than the average, and the frequency response of the SG has a strongly cut-off above 1 Hz.
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REFERENCES


