NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 8(1): 37–42
DOI 10.3897/nucet.8.82755

Research Article

Phenomenology of acoustic standing waves as applied to the VVER-1200 reactor plant*

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Academic editor: Yury Korovin ♦ **Received** 22 August 2021 ♦ **Accepted** 29 January 2022 ♦ **Published** 17 March 2022

Citation: Arkadov GV, Pavelko VI, Povarov VP, Slepov MT (2022) Phenomenology of acoustic standing waves as applied to the VVER-1200 reactor plant. Nuclear Energy and Technology 8(1): 37–42. https://doi.org/10.3897/nucet.8.82755

Abstract

The insufficiently studied issues of acoustic standing waves (ASW) in the main circulation circuits of the VVER reactor plants are considered. For a long time no proper attention has been given to this phenomenon both by the researchers and NPP experts. In general, generation of ASWs requires the acoustic inhomogeneities of the medium in the planes perpendicular to the direction of propagation of the longitudinal wave, in which a jump in acoustic resistance occurs, this is shown by the authors based on an example of the wave equation solution (D'Alembert equation) for a certain function of two variables. The ASW classification has been developed based on the obtained experimental material, 6 ASW types have been described, and their key parameters have been specified. The amplitude distributions have been plotted for all major ASW types proceeding from the phase relations of signals from the pressure pulsation detectors and accelerometers installed on the MCC pipelines. The nature of these distributions is general and they are valid for all VVER types. For the first time the globality of all lowest ASW types is identified. Four attribute properties of the ASWs have been formulated. The first attribute is the regular ASW temperature dependences, which is the source of the diagnostic information in the process of heating/cooling of the VVER unit. The linear experimental dependences of the ASW frequencies on coolant temperature have been obtained. The frequencies, at which the MCC resonant excitation due to coincidence of the ASW frequencies with the RCP rotational frequency harmonics, have been found experimentally. The ASW energy, which origin has resulted from the RCP operation, is estimated. The RCP operation can be presented as continuous generation of pressure pulsations, which fall onto the acoustic path inhomogeneities in the form of a traveling wave and generate a standing wave after reflection from them.

Keywords

Acoustic standing wave, VVER-1200, pressure pulsation detector, reactor coolant pump, main circulation circuit, autospectral power density, cross-spectral power density, core, technical diagnostics

Introduction

No proper attention has been given to vibroacoustic studies in reactor engineering. Among many factors of equipment wearing, the vibration is not considered to be the main factor of life expiration in the reactor plant designs and for vibration there are no limiting levels specified by Chief RP Designer, both for frequency and amplitude values. The acoustics of circulation circuits as such is not also taken into account when the reactor plant safety is justified in any Russian or foreign design (Arkadov et al. 2004). At the same time,

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2021, n. 4, pp. 110–121.

the poorly engineered RP designs are known, in which the vibroacoustic effects resulted in the equipment failures or early expiration of the equipment service life (Arkadov et al. 2010). Vibrations are deceptive because when the vibration amplitude is rather small, the contribution of vibrations to life expiration of the equipment is negligible, but they can play a crucial role in resonant vibration phenomena (Arkadov et al. 2001a, 2001b). The resonant excitation of vibrations is considered to be unallowable for any RP design. It is exactly for that reason that Russia would not have been able to enter the international market if it did not offer the different technical diagnostics systems (TDS) included in the NPP design for new generation reactors. The complex science-intensive diagnostic systems are introduced into the operating practice with a great difficulty and skepticism (Arkadov et al. 2002). New NVNPP II units of the VVER-1200 type are equipped with the new generation modern diagnostic systems more than any other VVER units, which has extended greatly the capabilities for analyzing the different abnormal processes in real time. This paper highlights just some of the most weighty issues of the vibroacoustic effects obtained experimentally at VVER-1200 using the different new generation TDSs.

Brief theoretical bases

In general, the wave equation (D'Alembert equation) for the certain function of two variables $U(x, t)$ has the form

$$\frac{\partial^2 U(x,t)}{\partial t^2} = C^2 \cdot \frac{\partial^2 U(x,t)}{\partial x^2} + f(x,t). \quad (1)$$

The equation is presented in an elementary form for a one-dimensional spatial coordinate and time function $U(x, t)$. For a multidimensional and, in particular, three-dimensional space, (x, y, z), the equation is written using the Laplace operator:

$$\frac{\partial^2 U(x,y,z,t)}{\partial t^2} = C^2 \cdot \Delta U(x,y,z,t) + f(x,y,z,t), \quad (2)$$

where $\Delta = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$ is the Laplace operator; $f(x, y, z, t)$ is the external forcing impact; and C is the longitudinal wave propagation speed in the medium.

A homogeneous (with no external forcing) wave equation can describe acoustic standing waves (ASW) originating from the certain initial stationary action $U_0(x)$. The solution is a complex harmonic function of time, $e^{j\omega t}$, with a spatially dependent amplitude, $U_0(x)$:

$$U(x, t) = U_0(x) \times e^{j\omega t}. \quad (3)$$

With a sinusoidal spatial excitation, a standing wave has the properties of

- spatial sinusoid for each fixed moment of time;
- time sinusoid for each fixed point in space;
- identical amplitudes and identical frequencies of two traveling waves forming the standing wave.

The fundamental properties of the complex harmonic wave presentation and connection of the Helmholtz and D'Alembert equations with the ordinary differential Lagrange equation are described in detail in (Arkadov et al. 2018, Arkadov et al. 2021). In the simplest interpretations, the ASW formation requires acoustic inhomogeneities of the medium in the planes perpendicular to the direction of the longitudinal wave propagation, in which the jump in acoustic resistance occurs (Demazière 2013, Katona 2013). Four key features have been developed to identify the ASW against the background of other physical effects in spectral estimates (Arkadov et al. 2018, Arkadov et al. 2021).

1. The ASW-frequency oscillations in two pressure pulsation detector (PPD) signals will be normally either in-phase (zero phase) or antiphase (180° phase). Rarely, the ASW in-phase or antiphase operation at different points of the main circulation circuit (MCC) can be disrupted. In developed coolant (CL) circulation circuits, this results from the interference of the waves propagating in different ways and having different phase incursions at points where they sum up to form a single ASW. It will be reasonable to illustrate such ASW property by Figs 1–5 which present scans of one VVER-1200 reactor circulation loop with installed pressure pulsation detectors (PPD) where PPD_H is installed on the hot leg, PPD_C is installed on the cold leg, and PPD_U is installed on the U-bend. As can be seen from the figures, the phase value will be 0 or 180° for all ASW types.
2. The mutual spectral power density phases for signals from two PPDs remain frequency-constant in some neighborhood of the ASW central frequency. The ASW resonances are always "fuzzy" or low-quality (Fig. 6: ASW_{L1}; ASW_{V1}; ASW_{L2}; ASW_{V4}) as compared with vibration-originating resonances (Fig. 6: f(RCP) – resonance from the RCP rotational frequency). Other types of resonances, caused, e.g., by forced oscillations on the RCP rotational frequency harmonics, are always high-quality.
3. The ASW central frequency changes also monotonously with the monotonous coolant temperature variation (Fig. 6: ASW_{L1}; ASW_{V1}; ASW_{L2}; ASW_{V4}). This effect is associated with the speed sound variation in the coolant depending on temperature. As shown above, these three features also manifest themselves in full measure in two signals of the accelerometers mounted directly on the loop pipeline.
4. The lowest ASW mode is accompanied by a nearly harmonic ASW train. This feature is hard to use practically for the ASW identification. Some ASW harmonics may be absent, and the amplitude of these does not necessarily coincide with the frequency (Fig. 6: ASW_{L1}; ASW_{V2}; ASW_{L4}).

Experimental determination of the ASW properties for VVER-1200 reactor plant

The new VVER-1200 reactor facility, while differing from the VVER-1000 reactor in terms of weight and dimensions, has other parameters of the structure and coolant natural oscillations. The risk of the natural and induced oscillation frequencies to coincide or the so-called resonant excitation threatens with an increase of the oscillation amplitude which shortens the reactor life. The average coolant temperature in the VVER-1200 core is higher than in the VVER-1000 and the so-called subcooled coolant boiling is expected to shift the ASW frequency harder. Even a minor increase in the coolant's vapor fraction is capable to reduce considerably the ASW frequency. Judging by this factor, one should expect the VVER-1200 ASW frequencies to decrease as compared with the VVER-1000. It is not practically possible to estimate by calculation the resultant effect of the change in the properties of the VVER-1200 ASW, as compared with the VVER-1000 ASW from the above factors. The variation in the parameters of any spectral characteristic peak depends on its origin. Where a natural oscillation resonance is observed, small (in terms of the absolute value) natural frequency variations need to be found. With natural oscillations, the resonance amplitude, frequency and quality are associated with the weight, rigidity and damping of some structural element. The natural frequency, as it changes following a small rigidity variation, may correspond to major changes in the properties of the structural supports. Already a minor natural frequency variation may signal the onset of the defect growth and is, therefore, an important diagnostic sign.

If the vibration resonance has been caused by external forcing, the change in its parameters may correspond to the change in the properties of both the structure and the external force. Here, the limits for the permissible resonance amplitude, frequency and quality changes are much greater than in the event of natural oscillations. The occurrence nature and specifics of the ASW as the key oscillation excitation source for the internals, the reactor vessel and the RCP had been explored for quite a long time (Arkadov et al. 2001a, 2001b, 2004, 2010), but it relatively recently that information has been systematized, a classification has been developed and the key characteristics have been identified as applied to the VVER-1200 reactor (Arkadov et al. 2018, Arkadov et al. 2021). Information on the ASW resonances is extracted largely from the PPD signals.

The NVNPP experts have developed a methodology of measurements using a portable analyzer as a versatile integrator for interconnecting different measuring systems as a single measuring cluster. A 40-channel instrument, LMS SCADAS Mobile, was used as the analyzer. This is a multipurpose mobile analyzer for measuring and analyzing signals of dynamic processes that is compatible practically with any detector type (accelerometers, bridge detectors, microphone transmitters, speed sensors, thermocouples). It is capable to operate with a PC or a laptop through the Ethernet interface, via a wireless interface or as a standalone recorder. The analyzer is controlled using the LMS Test.Xpress software that includes the accelerator programming, channel calibration, measurement parameter adjustment, measurement control and data analysis functions. More detailed information on measurements is provided in (Pavelko et al. 2016, Fedorov and Slepov 2017).

Thanks to a great deal of experimental work undertaken at different stages of the VVER-1200 commissioning (Pavelko et al. 2016) and regular multichannel synchronized measurements in the course of scheduled operation, the principal ASWs with typical features were described successfully.

ASW_{L1} (loop ASW 1) is the most low-frequency local simple ASW covering the whole of the loop. ASW_{L1} has one node on the pit wall in the reactor vessel's hot nozzle and the second node on the pit wall in the reactor vessel's cold nozzle, and the antinode is on the U-shaped piping, approximately in the loop middle (see Fig. 1). The in-vessel pit, visible if viewed from the cold pipeline, is one of the equivalent pipeline ends. After being reflected from the pit, the wave runs in the opposite direction to the other equivalent end, this being the same pit but visible if viewed from the hot pipeline. Zero phases between the signals of any loop sensors show that the amplitude sign is invariable for ASW_{L1}, that is, there is a single ASW_{L1} half-wave in the loop.

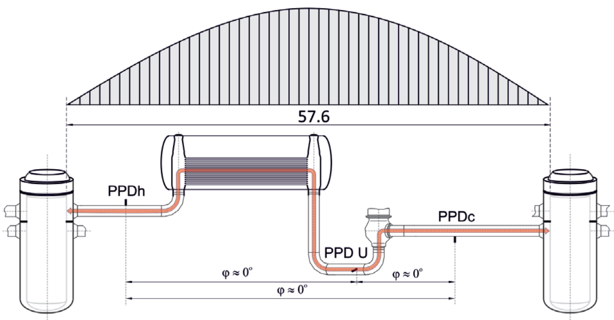

Figure 1. Loop ASW 1 (ASWL1).

The standing wave, following ASW_{L1} in terms of the frequency growth, has zero phases in any pair of signals from four PPDs in four hot pipelines (see Fig. 2). This wave is global and covers the reactor vessel with its half-wave. We shall denote it as ASW_{V1} and shall refer to it further as vessel ASW 1.

According to the known distribution of the ASW_{L1} amplitudes, it is not difficult to proceed to the distribution of the amplitudes of its harmonics (see Fig. 3). We shall denote by ASW_{L2} the second harmonic of loop ASW_{L1} or, simpler, loop ASW 2. Its node fell exactly on the SG's cold header having intensified so its vibration loads. The

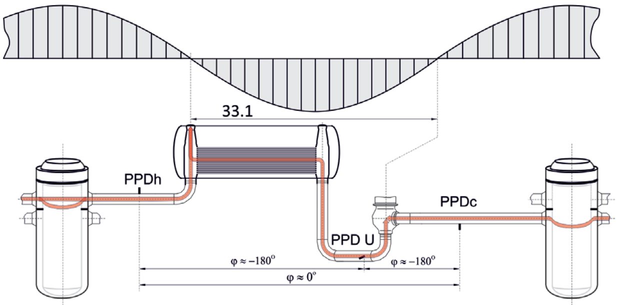

Figure 2. Vessel ASW 1 (ASWV1).

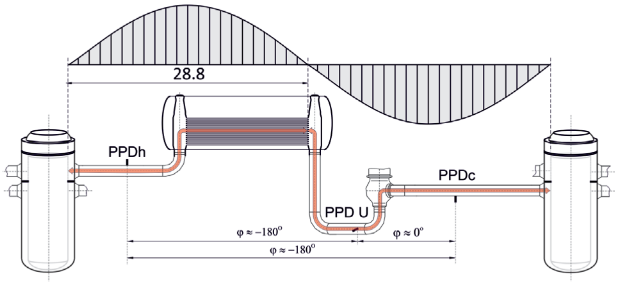

Figure 3. Loop ASW 2 (ASWL2).

second harmonic's amplitude is small as compared with the amplitude of loop ASW 1, so no abnormal vibrations are expected on this frequency. No third harmonic of ASW_{L1} is observed in the experiment and this was predicted by a simple inhomogeneity alteration model when their number is equal to the power of two.

It is not difficult to plot the fourth harmonic for ASW_{L1} as well. We shall denote it by ASW_{L4} and shall refer to it as loop ASW 2 (see Fig. 4). Its node is in the vicinity of the SG's hot header and the amplitude of the fourth harmonic is comparable with the amplitude of ASW_{L1}. An important peculiarity of ASW_{L4}, which requires to be monitored, is its proximity to the RCP's second rotational frequency (33.2 Hz). A variation in the sound speed during the unit heat-up or cooldown leads to the coalescence of these frequencies.

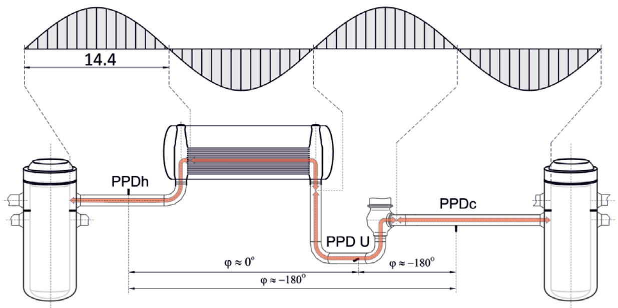

Figure 4. Loop ASW 4 (ASWL4).

Also evident are simple local ASWs which cover the MCC's hot and cold pipelines with their half-wave (see Fig. 5). ASW_{H1} is the simple hot ASW which has one node on the pit wall in the reactor vessel's hot nozzle, and the second on the SG hot header cover.

The ASW data as applied to the VVER-1200 reactor plant is shown in Table 1.

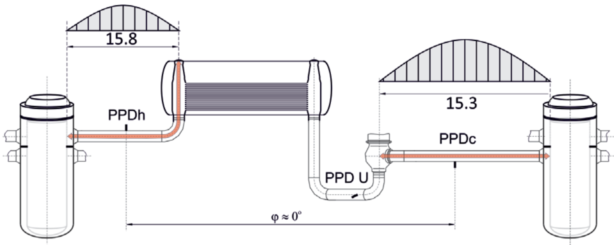

Figure 5. Hot ASW (ASWH1) and cold ASW (ASWC1).

Table 1. Key properties of the VVER-1200 reactor ASW

No.	ASW description	Designation	ASW frequency, Hz with tCL = 40 °C	ASW frequency, Hz with tCL = 290 °C	ASW half-wave length, m
1	Loop ASW 1	ASWL1	11.59	7.09	57.6
2	Vessel ASW 1	ASWV1	15.86	9.96	33.1
3	Loop ASW 2	ASWL2	21.46	13.53	28.8
4	Loop ASW 4	ASWV4	26.10	40.93	14.4
5	Hot ASW	ASWH1	–	–	15.8
	Cold ASW	ASWC1	–	–	15.3

Resonant excitation in case of coincidence of the RCP rotational frequency harmonics with ASW frequencies

The ASW central frequency varies as the coolant temperature varies (during the unit heat-up or cooldown). A monotonous increase in the coolant temperature causes the ASW central frequency to move monotonously towards 0 Hz. Spectra of the pressure pulsations in the hot leg of the VVER-1200 primary loop at temperatures of 121 до 286 °C are presented as an example in Fig. 6.

The frequencies of all standing waves start moving and, importantly, each ASW central frequency has its own rate [Hz/deg.] of movement along the frequency axis. The process of the coolant heat-up by ~ 300 °C leads to the coalescence of some reactor coolant pump (RCP) rotational frequency harmonic with the central frequency of some ASW (or its harmonic). Such calescence cannot be allowed in the nominal mode of operation with a 100% level of the reactor power but is inevitable in dynamic modes (Pavelko et al. 2016, Fedorov and Slepov 2017). As estimated by the authors, the whole of the MCC undergoes, sequentially, eight resonant excitation modes during the unit heat-up (Fig. 7) when there is a coalescence of the ASW central frequencies with the RCP rotational frequency (f_{rot} = 16.6 Hz) or its harmonics ($n \times f_{rot}$).

It was proved experimentally in the course of the studies that there is resonant excitation as the coolant temperature reaches ~ 170 °C (mode 2; ASW_{L2}) and ~ 190 °C (mode 3; ASW_{L4}). These resonant excitation modes have not been taken into account by the chief designer in estimating the endurance and are not described in operating documentation as critical modes requiring the minimum time for these to be over. This adds importance to vibration measurements in the process of commissioning when VVER units are put

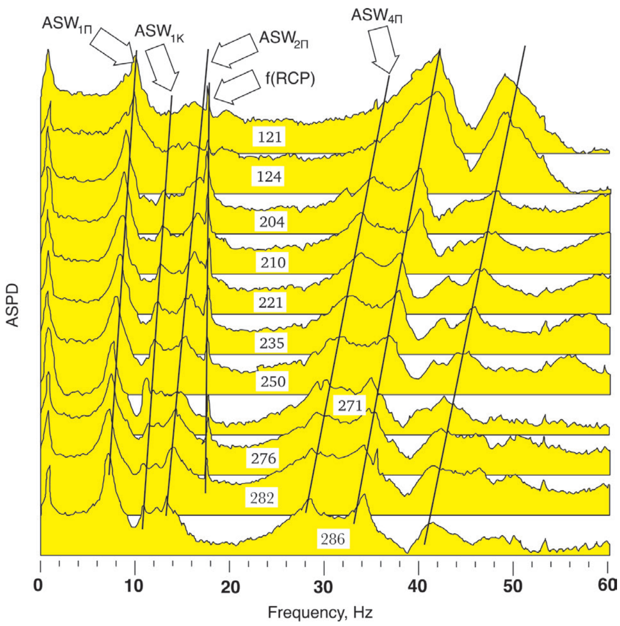

Figure 6. Pressure pulsation spectra in the hot leg of the VVER-1200 primary loop for a temperature range of 122 to 286 °C. ASW coalescence with the second harmonic of the RCP rotational frequency at 276 °C. Coalescences for lower- and higher-mode ASW at low temperatures.

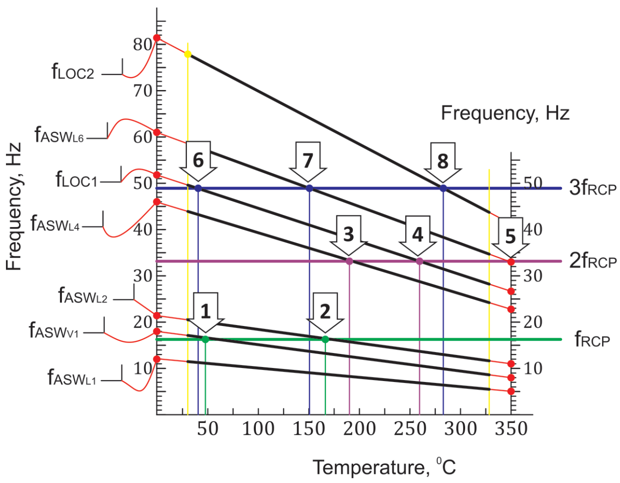

Figure 7. Dependence of the ASW central frequencies on the primary coolant temperature (digits 1 through 8 are the mode numbers).

into operation. Practically valuable is the approach in accordance with which the vibration state of a new VVER-1200 reactor is the same as for VVER-1000 in the sense that the above frequencies vary just slightly (Arkadov et al. 2019). This argument is based on the fact that the weight and dimensions of a structure and the thermal-hydraulic performance of coolant in further VVER generations will change insignificantly as compared with the VVER-1000 proceeding from the principle of structural conservatism. However, this does not exclude a triple coincidence effect from induced frequencies, natural oscillations and the RCP harmonics given that there is no such effect in the VVER-1000 reactors in rated modes of operation (Arkadov et al. 2019, IEC 61502:1999).

Estimation of the RCP power losses for ASW generation

The standing wave energy owes its origin to the RCP operation (Rohde et al. 2016). The RCP operation can be presented as continuous generation of the pressure pulsations which fall onto the acoustic path inhomogeneity and form a standing wave after they are reflected. The coolant pressure pulsations form as a result of the RCP shaft rotation independent of whether there are the RCP vibrations or not (Kozmenkov et al. 2015, Rohde et al. 2016). The RCP vibrations give rise to an additional source of the coolant pressure pulsations. The diagnostic sign will be exactly the mutual response, e.g., such as coefficient of regression between the parameters under consideration (the amplitude and the dispersion or the RMS in different frequency sub-bands of one autospectral power density) obtained from long-term vibration measurements of one and the same PPD signal (Andersson et al. 2003, Demazière and Pázsit 2004).

We shall estimate the energy spent by the RCP to generate and maintain the ASW in the MCC. The ASW specific energy in a volume unit is

$$E(x, t) = I(x, t)/c, \text{ J/m}^3, \quad (4)$$

where $I(x, t)$ is the ASW power flux density, and H/(m×s), s is the speed of sound.

By solving wave equations for the longitudinal wave pressure, $P(x, t)$, and speed, $V(x, t)$

$$\partial^2 P(x, t)/\partial x^2 = c^{-2}\times\partial^2 P(x, t)/\partial t^2, \quad (5)$$
$$\partial^2 V(x, t)/\partial x^2 = c^{-2}\times\partial^2 V(x, t)/\partial t^2, \quad (6)$$

we shall get the following complex expressions

$$P(x, t) = A\times e^{-j(kx - \omega t)},\ V(x, t) = A\times e^{-j(kx - \omega t)}, /(\rho\times c), \quad (7)$$

where A is the pressure wave amplitude; and ρ is the coolant density.

The ASW power flux density modulus is then

$$|I(x, t)| = |\langle \text{Re}P\times\text{Re}V\rangle| = A^2/(2\times\rho\times c^2), \quad (8)$$

where ⟨ ⟩ is the averaging for the period; and Re is the real part.

The ASW power for the whole of the RCP is estimated by the expression

$$N(x, t) = V_k\times|E(x, t)|\times\omega_{ASW}, \quad (9)$$

where V_k is the RCP volume; and ω_{ASW} is the ASW frequency.

The ASW power in terms of one circulation loop is

$$N_1(x, t) = 0.25V_k\times|E(x, t)|\times 2\pi\times f_{ASW} =$$
$$0.25(M_{CL}\ \rho)\times 0.5A^2/(\rho\times c^2)\times 2\pi\times f_{ASW} =$$

$$= 0.25\pi \times f_{ASW} \times M_{CL} \times [A/(\rho \times c)]^2, \quad (10)$$

where M_{CL} is the coolant mass in the MCC.

We shall define that the pressure pulsation value, A, is in a broad range of 1×10^5 to 1×10^6 Pa, according to (Katona 2013), then $N_1(x, t) \in [0.036, 0.36]$ MW.

Let us note that the RCP (Pavelko et al. 2016, Fedorov and Slepov 2017) is an asynchronous ac machine which, just like any pump set, has an efficiency equal to 0.7 in operating modes. Electricity needs to be therefore consumed to generate and maintain the ASW in the MCC with efficiency taken into account which leads to a new interval estimate of the power loss per one RCP of [0.048, 0.48] MW, this being ~ 0.2 to ~ 2.0 MW for the entire unit.

The above estimate is rough but it gives an idea that the existing RCP configuration and the field of different ASWs may lead to up to 9% of the RCP power lost.

Conclusion

The use of vibroacoustics in reactor engineering advances extremely slowly, possibly, due to the departmental barriers, due to the complexity of mathematical tools, science intensity of diagnostic systems, and absence of normative requirements regulating the acoustic and vibration effects in the MCC and their continuous monitoring (Andersson et al. 2003). The RP equipment features are specific that requires an individual approach. The large weight and dimensions of the vibrating structural elements, unique hydrodynamics of flow paths, and huge values of the forces inducing the vibrations identify the vibration factor in justification of reliability and service life of the RP equipment into a special problem that requires the individual and strictly regulated approach (Pavelko et al. 2016).

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