Evaluation of reliability of a perforated pipe when working in the stream of liquid metal coolant.

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Abstract
The article describes the approach to the assessment of indicators of reliability of products, having in its composition of perforated pipes. The idea of writing this article was born during the practical work on the reliability of the mass transfer performance evaluation system, which is part of the system to maintain the concentration of oxygen in a systems perspective SVBR-100. The article provides an overview of the currently existing, approaches to estimate the reliability of the products containing a perforated structure, as well as theoretical and practical part, to the use of the proposed approach.

1. Introduction
The use of heavy liquid metal coolants in power plants due to several problems. One of them is ensuring corrosion resistance in contact with these fluids structural materials and preventing cases of removing toxins from the circuit or its individual parts[1-4].

Feature of nuclear power plants (NPP) is a large range of different items and often their uniqueness. This determines the requirements for models in parametric estimation of reliability of nuclear power plants and research the nature of all calculations carried out. Studies that are conducted in order to examine the stochastic properties of the performance element of nuclear power plants, allow you to select the model to evaluate the reliability of the parameter.

To remove solids from the coolant often at the points of the technological scheme of the nuclear power unit, where necessary and possible, establish a grid-hole filters. The accumulation of solid particles on the filters last clog and become inoperative, which can lead to the accident of the nuclear power unit. Consequently, the required periodic inspections and replacement of filters that is associated with the need to shut down the reactor and conduct repair works of large scale.

The requirements of reliability and economic efficiency of nuclear power plants lead to the need of optimal inspection and replacement of filters. For this optimization perforated pipe requires the study of the dynamics of clogging.
2. Analytical formulas for determining reliability assessment

2.1 A model of the dynamics of clogging of the mesh and holes in the pipe

Let to some moment of time $t$ on the filter go $n$ particles and flux particles are distributed evenly throughout the filter. Depending on the ratio of the sizes of particles and holes of the filter when particles on the filter can occur, the following two events, leading to clogging of the filter:

1) a particle exceeds the size of the hole of the filter, and the particles on the filter leads to clogging of the openings;

2) the particle does not exceed the size of the hole of the filter, but its getting to the border between the openings of the filter leads to the fact that particles are captured on the filter and block the portion of the passage section of the holes (safety margin).

Suppose that an event $A$ is that when hit by one particle on the filter hole of the filter will be clogged, and the distribution of particle sizes is such that with probability $P_1$ the sizes of the particles exceed the dimensions of the hole and with probability $P_2=1-P_1$ is not exceeded.

Then the probability of event $A$ is $P(A) = P(A/1)P_1 + P(A/2)P_2$, where $P(A/1)$ is the conditional probability that the particle will clog the hole with the larger hole sizes; $P(A/2)$ is the same probability, but assuming that the sizes of the particles smaller than the holes. The probability $P(A/1)$ and $P(A/2)$ are determined by the filter design [5].

Let $N$ filter holes. The probability that any of the holes are not clogged any of the $n$ particles, there are

$$
\Omega = \left(1 - \frac{P(A)}{N}\right)^n
$$

According to the classical definition of probability $\Omega$ is the share of the remaining free holes of the total number $N$. When the equality of the areas of the holes, the probability of $\Omega$ is a fraction of the free flow cross-sections of the filter.

If we denote

$$
\chi = -\ln \left(1 - \frac{P(A)}{N}\right), \quad \chi > 0
$$

then

$$
\Omega = \exp(-\chi n)
$$

Thus, the share of the remaining missed flow area of the perforated pipe decreases exponentially with increasing number of $n$ particles trapped on the filter for some time $t$.

As can be seen, and (1) and (2), the share of the remaining missed flow section $\Omega$ is essentially dependent on the probability $P(A/1)$ and $P(A/2)$. These probabilities are determined by the design of the perforated pipe.

The pipe has openings which perform the filtering function and is called hole filter. At the end of the pipe there is a grid – mesh filter.

2.2 Mesh filter.

Let the filter mesh with the threads of the net that make up the squares with sides $2a$ in figure 1. If we neglect the thickness of the yarn, it is clear that for particles with a largest linear size exceeding $\sqrt{8a}$, $P(A/1) = 1$
It is possible to show that the particles with the largest linear size, not the superior $\sqrt{8a}$ could be kept in the filter probability

$$P(A/2) = 1 - \left(1 - \frac{S}{\pi \cdot a}\right)^2$$

where $S$ is the parameter of the projection of the particles on the plane of the filter.

2.3 Perforation

The perforations may be round, square or oval, offset, oblong or straight rows of holes. It can also be decorative, in the form of a specific pattern of holes of different shape and size. The shape of the holes are manufactured in accordance with specific technical needs of the customer.

In the perforated pipe has holes, they perform the filter function and distribution of the particles. Let the hole radius $r$ arranged on a plane of a regular rectangular lattice with the distance between the centers of the holes is equal to $a$ and $b$ for each of the lattice directions. Let the filter fall of spherical particles of diameter $d$. Using the concept of geometric probability, it is easy to show that in this case

$$P(A/1) = \frac{\pi (2r + d)^2}{4ab} \left[1 + \frac{\pi (\alpha + \beta)}{180} - \sin \alpha - \sin \beta\right]$$

$$P(A/1) = \frac{2 \pi r d}{ab} + \frac{\pi (2r + d)^2}{4ab} \left[\frac{\pi (\alpha + \beta)}{180} - \sin \alpha - \sin \beta\right]$$

where $\alpha, \beta$ is the central angles formed by the intersection of the circles of radius $r+d/2$, the centers of which are located respectively at a distance $a$ and $b$ from each other (figure 2), and
2.4 Stochastic model of the process of clogging of the perforated pipe.

Assume that the flow rate through the pipe is on average constant and the particles are evenly distributed throughout the volume of the coolant. Then the growth in time of the number of particles entering the perforated pipe, occurs on average at constant speed $\nu > 0$, which imposed some random component $\nu(t)$ [5]. This component is determined by random fluctuations in the number of particles per unit volume of coolant and random fluctuations of the flow. Thus, the change in time of the number of particles deposited on the perforated pipe, can be simplified to describe the stochastic differential equation of the form

$$\frac{dn}{dt} = \nu + \nu(t)$$

(4)

Further suggest that $\nu(t)$ is a stationary Gaussian random process, the type of white noise, and for which $M \cdot \nu(t) = 0$ and $\text{cov}(\nu(t), \nu(t')) = \sigma^2 \cdot \delta(t)$

Equation (4) describes a Markov random process $n(t)$ with a constant coefficient of demolition and $\nu$ diffusion $\sigma^2$. For transitional plane $w(n,t/n_0)$ is a Markov process $n(t)$ is the Kolmogorov equation has the form [5]:

$$\frac{\partial w}{\partial t} + \nu \cdot \frac{\partial w}{\partial n} - \sigma^2 \cdot \frac{\partial^2 w}{\partial n^2} = 0$$

(5)

Because in a physical sense $n \geq 0$, the boundary conditions for equation (5) as follows:

$$w(n, 0/n_0) = \sigma \cdot (n - n_0)$$

(6)

$$w(n, t/n_0) - \sigma^2 \cdot \left. \frac{\partial w}{\partial n} \right|_{n=0} = 0$$

(7)

The solution of the boundary value problem (5) – (7) has the following form:

$$w(n, t/n_0) = \frac{1}{2\sigma \cdot \sqrt{\pi \cdot t}} \left[ e^{\frac{(n-n_0-\nu t)^2}{4\sigma^2 \cdot t}} + e^{\frac{-n_0}{\sigma} \cdot \frac{(n-n_0-\nu t)^2}{4\sigma^2 \cdot t}} \right]$$

$$-\frac{\nu}{2 \cdot \sigma^2} \cdot e^{\frac{-\nu t}{\sigma}} \cdot \left[ 1 - \Phi \left( \frac{\nu \cdot \sqrt{t}}{2 \cdot \sigma} + \frac{n + n_0}{2 \cdot \sigma \cdot \sqrt{t}} \right) \right]$$

(8)

where $\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-z^2} \, dz$ is the error integral.
One-to-one relationship (2) between $\Omega$ and $n$ at the same time allows you to record that $\Omega$ is also a Markov process described by the stochastic differential equation

\[ \frac{\partial \Omega}{\partial t} = \alpha \cdot \Omega + \Omega \cdot \nu(t) \]

where $\alpha = \chi \cdot \sigma$; $\nu(t)$ is a Gaussian stationary process (white noise). For a Markov process $\Omega(t)$ from (2) we can obtain the expression for the transition density $w(\Omega, t/\Omega_0)$, which has an entry similar to (8), if we introduce the variable $\omega = \ln \Omega$:

\[ w(\omega, t/\omega_0) = \frac{1}{2\sigma \sqrt{\pi t}} \left[ e^{-\frac{(\omega - 0)^2}{4s^2}} + e^{-\frac{\alpha \omega_0 - (\omega - 0)^2}{4s^2}} \right] \]

\[ - \frac{\alpha}{2s^2} e^{-\frac{\alpha \omega_0}{s^2}} \left[ 1 - \Phi \left( \frac{\alpha \sqrt{f} + \omega + \omega_0}{2s \sqrt{f}} \right) \right] \]

where $s = \chi \cdot \sigma$.

The expression (9) allows to investigate the dynamics of clogging of the perforated pipe, which in the model is completely determined by the values of $\alpha$ and $s$. These values can be estimated from the results of the inspection pipe.

However, the complexity of the expression (9) for the transition density $w(\omega, t/\omega_0)$ complicate its use for the estimation of the model parameters $\alpha$ and $s$. In these circumstances you can do this by using an approximate expression for $w(\omega, t/\omega_0)$, which is taken as the fundamental solution of the Kolmogorov equation (5) for the process $\omega(t)$, i.e.

\[ f(\omega, t/\omega_0) = \frac{1}{\sqrt{2\pi t}} \exp \left\{ -\frac{(\omega - \omega_0 - \alpha t)^2}{2s^2 t} \right\} \]

To determine the coefficients of $\alpha$ and demolition diffusion $s$ using the maximum likelihood method

\[ \frac{\partial \ln \prod_{i=1}^{M_0} f(\omega_i, t/0)}{\partial \alpha} \bigg|_{\omega=\omega_i} = 0; \]

\[ \frac{\partial \ln \prod_{i=1}^{M_0} f(\omega_i, t/0)}{\partial s} \bigg|_{\omega=\omega_i} = 0; \]

here $f(\omega, t/0)$ is determined by the expression (10); $\omega_i$ - operational data pipe inspection at time $t_i$. It is assumed that after inspection and cleaning, the pipe is clean.

The solution of the systems (11) estimates of $\alpha$ and $s$ are determined from the expressions

\[ \hat{\alpha} = \sum_{i=1}^{M_0} \frac{\omega_i}{t_i} \]

\[ \hat{s}^2 = \frac{1}{2M_0} \left[ \sum_{i=1}^{M_0} \frac{\omega_i^2}{t_i} - \left( \sum_{i=1}^{M_0} \frac{\omega_i}{t_i} \right)^2 / \sum_{i=1}^{M_0} t_i \right] \]

where $M_0$ is the number of inspections of the filter.

Next, using the static data on the results of inspections of the pipe, estimate the coefficients of drift and diffusion and solve the problem of the definition of reliability.
3. Evaluation of reliability of the perforated pipe.
As an example, reliability assessment, take any existing pipe, the service life of which is 9 years. As a rule, during the period of operation is checked for defects ($\omega$), then there is cleaning or replacement. Assume that operating according to the regulations, the inspection of the perforated pipe 1 times in 1.5 years. For 9 years, during which time carried out 6 inspections, there have been 3 defect. We use the formulas (12) and (13) to determine the reliability assessment. Substituting our data, we see that:

$\alpha = 0.33$ [1/year] (the failure rate of a perforated pipe)

$S = 0.29$ (probability of failure)

Then find the uptime, using the formula:

$S(t) = e^{-\alpha t}$

substituting our values, we obtain that

$0.288 = e^{-0.33t}$

$t = 3.75$ [year] (uptime)

4. Conclusion
Developed computational model of a perforated pipe, which allows to analyze the reliability characteristics of a perforated pipe when pumping through it of the liquid coolant. According to the result obtained by the example, it can be concluded that the perforated pipe is not high quality, with experience in the operation. Completed work confirms the possibility of estimating the reliability characteristics of a perforated pipe with the aim of selecting the optimal design and parameters of its work.

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