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EXPERIMENTAL FACILITY FOR DETERMINATION OF CAVITATIONAL PROCESSES IN THE NPP PIPELINES

В.А. Герлига, В.В. Запорожан, Ю.В. Филонич, М.А. Панченко, А.П. Шолудько. **Проект експериментального стенду для дослідження кавітаційних процесів в трубопроводах АЕС.** Досвід експлуатації теплових і атомних станцій показав, що однією з основних причин появи тріщин в трубопроводах і елементах тепломеханічного обладнання є вібрації. Спрацювання відносно великих перепадів тиску на місцевих опорах, що представляють собою регулюючі органи і дросельні шайби, можуть супроводжуватися нестаціонарними процесами, пов'язаними з пульсаціями статичного і повного тиску. У роботі проводився аналіз міжнародного і вітчизняного досвіду з досліджень кавітаційних процесів, природу їх утворення, а також методи реєстрації. У доповіді представлено проект конструкції експериментального стенду для дослідження кавітаційних процесів в трубопроводах АЕС та опис основних конструктивних особливостей компонентів установки. Стенд розроблено з метою вивчення процесів, які призводять до появи вібрацій в трубопроводах АЕС на місцях встановлення дросельних шайб, та представляє собою замкнутий циркуляційний контур заповнений водою. Слід зауважити, що обрана компоновка обладнання в стенді дозволяє змінювати відстань між дросельними шайбами, а також їх кількість. Для забезпечення в експериментальній установці виникнення процесу розвиненої кавітації заздалегідь була розроблена математична модель стенду, яка дозволила обрати необхідне обладнання за розрахунковими характеристиками. Попередній детальний аналіз нестаціонарних і стаціонарних процесів, які виникають на дросельних шайбах, проводився за допомогою програмного пакету ANSYS. В якості інструмента для моделювання кавітації використовувався модуль CFX, в якому реалізована модель кавітації Релея-Плесета. При цьому, для першого етапу розрахунку була обрана модель турбулентності SST, а для другого LES WALE. Результати експериментальних досліджень, розробленого стенда, мають дозволитирозробити заходи щодо зниження рівня вібрацій у відповідних елементах обладнання АЕС, а також провести валідацію розрахункових комп'ютерних програм з аналізу стаціонарних і нестаціонарних процесів течії двофазних потоків в трубопроводах з шайбовими вузлами.

Ключові слова: кавітація, дросельні шайби, вібрація, експериментальний стенд, АЕС, ANSYS, CFX

V. Gerliga, V. Zaporozhan, Y. Fylonych, M. Panchenko, A. Sholudko. **Experimental facility for determination of cavitational processes in the NPP pipelines.** The obtained experience during operating thermal and nuclear power plants has shown that the vibrations are one of the main causes of the cracks occurrence in the pipelines and elements of thermal-mechanical equipment. The large pressure drops that are accompanied by the appearance of non-stationary processes can occur at the places of throttles and valves installation. These processes are associated with the static and the total pressure pulsations in the system. The paper analyzes the international and domestic experience in the cavitation processes research, the nature of their formation, as well as methods of the registration. The report presents the design of the experimental facility that was developed for the studying of the cavitation processes in the NPP pipelines. Moreover, the paper was augmented by the description of the main design features of the installation components. The experimental stand is designed to study the processes that lead to the appearance of vibrations in the NPP pipelines at the places of the throttle installation. The installation is a closed circulation loop that filled by water. It should be noted that the selected arrangement of the main stand’s equipment allows changing the distance between the throttles, as well as their quantity. In order to ensure the occurring of the continuous cavitation process in the experimental facility, the mathematical model of the experimental stand was developed in advance. The results of the performed simulations have made it possible to select the necessary equipment according to the design's characteristics. The previous detailed analysis of non-stationary and stationary processes occurring at the locations of throttles was carried out using the ANSYS software package. The CFX module was used as the tool for cavitation’s simulation. For this purpose, Rayleigh-Pleset cavitation model was implemented. At the same time, for the first stage of the cavitation’s calculation, the SST model of the turbulence was chosen, and for the second stage - LES WALE. The experimental results will allow us to develop methods to reduce the level of vibrations in the relevant NPP equipment elements and to validate high-performance computational fluid dynamics programs for the stationary and non-stationary processes’ analysis of two-phase flows in the pipelines with throttle nozzles.

Keywords: cavitation, throttle, nozzle, vibration, experimental facility, NPP, ANSYS, CFX

Introduction

Experience in the operation of thermal and nuclear power plants has shown that vibration is one of the main causes of cracks in pipelines and elements of thermomechanical equipment.

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At the moment, there are problems of vibration damage of the pipelines of important systems for safety at NPPs. They are caused by the generation of dangerous excitatory forces and the presence of destructive dynamic influence of the throttled flow in the pipelines and internal elements of the reinforcement of these systems [1]. In particular, such processes are most common in throttle due to the occurrence of cavitation effects.

A thorough study of the processes with cavitation throttles will allow to determine the mechanism and conditions of cavitation, as well as to develop ways to reduce the intensity or generally eliminate vibrations in different systems of units.

In order to study these issues, a design of an experimental stand was developed, which will explore different approaches to minimize vibration of equipment at the locations of throttles. On the basis of the obtained experimental results, validation of CFD programs will be carried out, which will further allow to investigate the main modes of operation of the NPP throttles and, if negative cavitation effects occur, take appropriate measures.

Analysis of literary data

The current computational and experimental studies are mainly focused either on the development and optimization [2] of mathematical and physical models, or on the prediction of cavitation erosion [3].

It is known that cavitation occurs in a liquid, in places where the pressure is locally reduced to “excessively” low values, which leads to boiling. Formed during cavitation “embryos” may contain both gas and vapor. Further movement of the bubbles in the region with increased pressure is accompanied by condensation of water vapor. Unlike vapors, the gas mixture takes some time to re-dissolve. It is known that the amount of gas that can be dissolved in water is described by Henry's law, and the rate of dissolution by Fick's law. It is obvious that in practical experiments it will be impossible to distinguish between steam and gas cavitation [4], so both types should be considered as one cavitation “cloud” [5].

Cavitation processes have a complex structure and behavior. The results of experimental studies by Kubota et al. showed that the cavitation “cloud” is a vortex and consists of gas bubbles (diameter $\approx 10^{-6}$ m). This structure is periodic and is accompanied by constant pressure fluctuations. In the works of Reisman and Brenn [6], the generated impulses were divided by intensity into local and global.

Pirsol's work shows that small cavitation bubbles generate noise with frequencies up to 3 MHz, whereas Sou [7] found that large bubbles can generate noise up to 10 kHz. The level of cavitation noise increases from the beginning of the formation of the cavitation “cloud” to the moment when the cavitation becomes fully developed (can reach 90 dB), and then decreases.

To date, there are a number of methods for detecting the presence of cavitation, namely:

– determination of changes in pressure, flow rate, noise and oxygen content in the liquid [8];

– vibration measurement – the presence of cavitation in the system causes vibrations with frequencies of about 103 Hz [7];

– take photos using a high-speed recorder. The made images in the device are processed using special mathematical algorithms and the distribution of gas and liquid in the stream is analyzed;

– PIV (VelocimetryImageParticleImage) is an optical flow visualization method. Used to determine the instantaneous velocity distribution in a stream;

– measurement of fluid luminescence, bubble spectrometry, topography and others [9].

Using a simplified Rayleigh-Plesset model [10, 11], it is possible to obtain agreement of the results of numerical simulation with the experimental data at a deviation of 5…15 % [12].

The purpose of the work is to identify ways to increase the resource of equipment by identifying “critical” sites with advanced cavitation. To achieve this it is necessary to study experimentally the mechanism of cavitation process on the nodes of the throttle. According to the purpose, an experimental stand was developed, which allows not only to study the processes of cavitation, but also to develop and experimentally measures to eliminate these negative effects.

Stand description

The stand is a closed circuit (Fig. 1), all the pipelines in it are made of stainless steel.

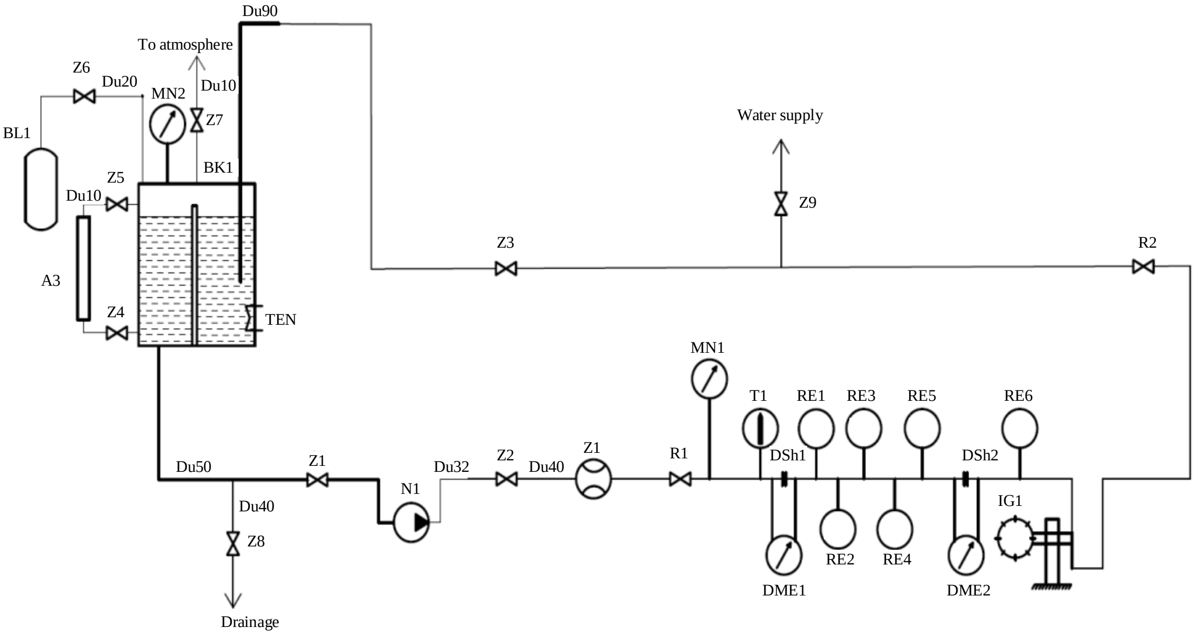

Fig. 1. Stand diagram for the study of processes in pipelines with cavity throttle nozzles

Water in the tank BK1 is heated by an electric heater TEN (2.5 kW) and pumped through the Dy50 pipeline by means of the pump H1 (CNSK-25-200, P=21...26 kg/cm^2, Q=1 l/c, ΔP=20 kg/cm^2). Two intake valves 31 and 32 (HBV-140M) are installed on the suction and discharge lines of the discharge device, respectively. After the pump, the medium moves through the Dy32 pipeline with a length of 400 mm. To achieve the required speed, there is an increase in the throughput diameter of the pipeline to Dy40, by means of a diffuser welded to the Dy32 pipeline. Further along the water is an ultrasonic flowmeter G1 (TUF2000B, Q=1...7 l/c), which is located outside the pipe. To regulate the flow in the pipeline installed control valves P1 and P2 (15c22nj) before and after the throttle unit. The pressure and temperature in front of the control unit are measured using a pressure gauge MN1 (MO 11202) and a thermometer T1, respectively. When certain parameters are reached at the throttle node, cavitation effects occur (in the process of fluid flow through DSh1 and DSh2). Pressure drop on DSh1 and DSh2 is measured with the help of DME1 and DME2 (PD100-DD 2.5-181-0.5) diffmanometers, respectively. The vibration parameters are fixed on the curved section by means of the ІГ1, ІЧ10 displacement sensor and the vibrometer. Up to 30 electrical PE1 sensors (PD100-DI 2.5-181-0.25) are installed between the DSh1 and the knee to measure the cavitation arising from thermoacoustic oscillations. The test section consists of 4 different lengths of pipelines (L1=200 mm, L2=350 m, L3=450 mm, L4=600 mm), which are fixed by means of flange connections. This arrangement will allow you to change the distance of the DSh2 installation relative to the DSh1.

Filling of the contour with water is carried out through the water supply pipe, which is connected to the sewer system. The level in the tank BK1 is fixed by means of a glass tube A3 (on the principle of connected vessels). After raising the water to the required level, the valves Z4, Z5, Z9 are closed and the valve is opened, which increases the pressure in the tank by creating an air cushion over the volume of liquid (the pressure in the tank BK1 is measured using a pressure gauge , which should not exceed the mark at 6 atm, and this pressure corresponds to a saturation temperature of ≈150 °C). For emergency relief of pressure in tank BK1 there is a safety valve 37, which is mounted on the pipe Dy10.

Scope of the stand

The triggering of relatively large pressure drops at local supports, which are regulators and throttles, can be accompanied by non-stationary processes associated with static and full pressure ripples. These processes have not been studied with the necessary completeness and can create dangerous excitations of forces that lead to resonant oscillations of pipelines. Excitations can occur in areas of local flow separation at the DP due to the non-stationarity of the jet at the DP and due to the “cortical” nature of the flow at the DU.

At the second unit of Zaporizhzhya NPP during testing of efficiency of pump TQ21D01 the leak was detected in the welding connection. The cause of cracks is the vibration that occurs during cavitation processes. Also, during testing, the vibration of the sprinkler pump recirculation line was recorded in the area of the DP diaphragm, which is a standard throttles. Accordingly, the pressure drop on the throttle, when implemented during the modes of fluid flow, was the source of the formation of negative excitatory forces.

SUNPP also confirms the presence of vibration in pipelines related to safety systems.

According to the above is the need for experimental study of cavitation processes in pipelines with throttle nozzles. In the future, the results of the experiments will allow the validation of heat-hydraulic CFD programs using them to predict the occurrence of cavitation processes in other NPP systems.

Description of model ANSYS CFX

To study the occurrence of cavitation in the system, a preliminary detailed analysis of the non-stationary and stationary processes occurring on the throttles using the ANSYS software package was carried out.

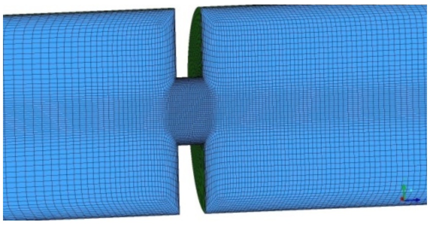

Fig. 2. Calculation grid for channel with throttle

ICEM CFD was selected as the grid generator. It was used to build a structured grid, which consists entirely of hexagonal elements, which in turn made it possible to shorten the estimated time and reduce the CPU load. Presented in Fig. 2 calculation grid has been adapted (“smoothed”) by flow. This method minimizes approximation errors during the calculation process.

The calculated CFD model includes the following assumptions:

– the design model contains one plane of symmetry;

– no heat losses in the work area (q=0);

– isothermal flow (t=140 °C);

– steam and liquid have the same velocities.

It is important to note that the latter assumption is typical of a homogeneous medium with two-phase flow mode.

ANSYS CFX was used as a cavitation simulation tool, which implemented the above-mentioned Rayleigh-Pletset cavitation model. This model calculates the volumetric content of vapor and liquid in the cell. Therefore, the model takes into account two important factors - the rate of bubble growth and the statistical nature of the distribution of bubbles in the cavitation flow.

The rate of increase of the bubble is calculated by the simplified Rayleigh equation:

$$\frac{dR}{dt}=\sqrt{\frac{2}{3}\frac{p_h-p}{\rho}},$$

where R – cavitation bubble radius; p_h – pressure inside the bubble (saturated vapor pressure in the model); p – local fluid pressure (absolute CFD pressure).

The modeling process was divided into two stages:

– finding the convergence of the solution with the excluded cavitation model under the conditions of stationary flow. As a result, the initial distribution of parameters in the calculation zone was obtained;

– initialization of the cavitation model (initial conditions, the so-called “first approximation”.

For the first stage, the SST turbulence model was selected [13]. Combining the best sides of both the k-e and k-w models of turbulence and with high precision, the appearance of turbulent vortices behind a throttle.

For the second stage of the calculation, a model was selected that allows to take into account large eddies in the non-stationary formulation of the LES WALE problem. This model is not as costly as the SST, however, requiring grinding of the mesh in the wall layers [14].

An absolute pressure equal to $P_{abs,\ inner}$=1 721 826.4 Pa, was selected as the input boundary conditions. Output – mass flow rate was equal to G_{outer}=2.2 kg/s. This flow provides the necessary pressure drop, which is triggered on the throttle and, therefore, the emergence of advanced cavitation. As can be seen from Fig. 3, with the pressure drop on the throttle, cavitation occurs, which is followed by further separation of steam bubbles further down the stream. The accumulation of the vapor phase behind the throttle is related, first of all, to the formation of low pressure at the section 0.13 m behind the throttle, as well as to the occurrence of turbulent backflows behind the throttle.

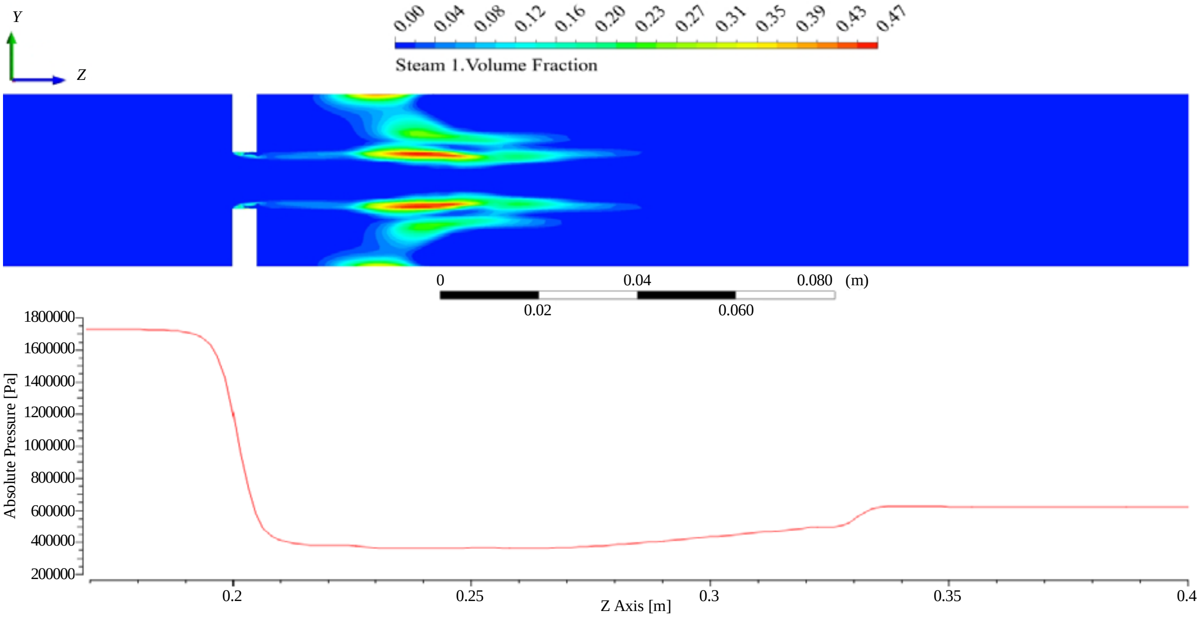

Fig. 3. Flow picture of cavitation in flow and graph of pressure distribution in axial direction of calculation zone

A mathematical model, previously developed for the experimental stand, showed the possibility of developed cavitation and allowed to select the necessary equipment of the stand according to the calculated parameters: pump, manometers, regulators, thermocouples, etc.

Conclusions

Existing empirical mathematical models allow us to determine the presence of cavitation in the system, as well as its character with an error that can reach 15 %. In addition, these models do not fully reflect the distribution of the main characteristics, namely pressure, velocity, etc., on local equipment. In addition, the results of the calculations of sequentially installed multiple throttles have certain uncertainties related to the variation of local resistance coefficients depending on the distance between the throttles and the change of local resistance coefficients when the axes of the holes in the throttles are displaced.

For detailed modeling of cavitation processes on the real equipment of NPPs (safety systems), it is first necessary to carry out the validation of thermal-hydraulic CFD programs through experiments, i.e. to determine the correcting coefficients, to correctly select the initial conditions and to use such mathematical models (initialize), in which the error of results will be minimal. In particular, in order to reduce or prevent cavitation processes, it is necessary to study in detail the possibility of installing on the pipeline two or more throttles, a throttle with a perforated cellular hole, additional resistance over the throttle opening.

Accordingly, the validated models, based on the results obtained from the experimental stand, will allow develop measures to reduce the level of vibration in the relevant elements of the NPP equipment. In turn, the stand will test the developed measures and confirm their effectiveness, as the design features of the stand include a wide range of possible combinations of elements and boundary conditions for the study of cavitation processes.

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