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Water hammer model sensitivity study by the FAST method

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Pressure surges occurring in pipeline systems may be caused by fast control actions, start-up and shut-down processes and operation failure, as well as flow rate fluctuation. They lead to water hammer upstream the closing valve and cavitational hammer downstream the valve, which may cause considerable damages to the pipeline and the support structures. Appearance of water hammer in thermal-hydraulic systems was widely studied employing different state-of-the-art thermal-hydraulic codes. Before carrying out the water hammer analysis, it is very important to match the model and to perform the analysis of its sensitivity. The paper presents an analysis of the water hammer experimental test performed at the Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT) using the RELAP5/Mod3.3 thermal hydraulic code. The model sensitivity study was performed by using the Fourier amplitude sensitivity test (FAST) method. The FAST method aims to determine the most important input parameters that are major contributors to the model output uncertainty. Such information can be used further for a more detailed system study and development of improvements or preventive actions.
Key words: water hammer, UMSICHT, RELAP5 model, sensitivity analysis, FAST

1. INTRODUCTION

A rapid closing or opening of a valve causes pressure transients in pipelines. The fast deceleration of the liquid results in high pressure surges upstream the valve, thus the kinetic energy is transformed into the potential energy, which leads to temporary pressure increases [1]. This phenomenon is called a water hammer. The intensity of water hammer effects will depend upon the rate of change in the velocity or momentum. Generally, water or steam hammer can occur in any thermal-hydraulic system, and it is extremely dangerous for the thermal-hydraulic system since it may lead to a failure of the pipeline integrity.

While defining the conditions of a safe operation of pipelines and equipment to avoid water hammer, the modelling of transients is carried out. The phenomena of water hammer in the international engineering practice are modelled using different codes: TREMOLO, TRACE, CATHARE, ATHLET, TRAC, FLOWMASTER and RELAP5. Because the phenomena of water hammer are specific, not all the codes are verified for simulation of water hammer fast transients. Therefore, it is very important to verify a model developed using these codes and to carry out a model sensitivity study.

The paper presents a model sensitivity study by using the Fourier amplitude sensitivity test (FAST) method. The FAST method aims to determine the most important input parameters that are the major contributors to the model output uncertainty. Such information can be used further for a more detailed system study and development of improvements or preventive actions. The FAST is considered to be one of the best sensitivity analysis methods and has attracted many researchers for its further development. In the present study, an extended version of FAST is used [2]. It has enhanced the sampling procedure and allows to compute the first-order and total sensitivity indices by using the same sample.

2. UMSICHT TEST FACILITY EXPERIMENTAL CASE AND RELAP5 MODEL

In this work, as an illustration, RELAP5 analysis of a water hammer test performed at the Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT), Germany is considered [3]. The existing UMSICHT facility in Oberhausen is being modified in order to simulate the piping system and associated supports that are typical of a nuclear power plant (Fig. 1).

This test facility enables various operations and transport of compressible and incompressible liquid due to a modular construction system. Using a modern high-speed measurement (frequency 1–10 kHz), the local phase distribution, the system pressure, the fluid velocity as well as the effective force on the pipe restraints can be measured and calculated. A detailed description of the experimental set-up is presented eslewhere [3, 4].

The experiments were conducted using the dynamic behaviour of closing and opening valves in a steady-state liquid flow. A centrifugal pump produces steady-state flow into the circuit from the pressurized vessel into the test pipe section of 110 mm

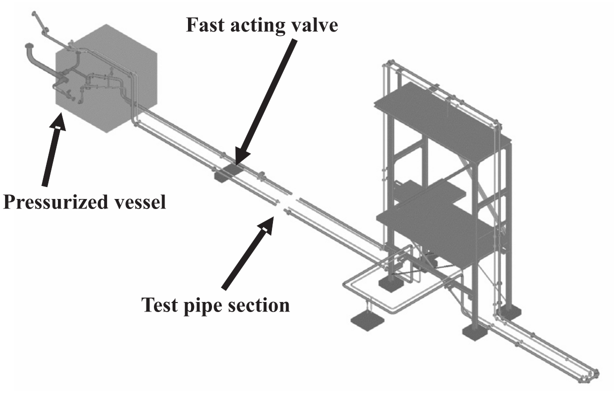

Fig. 1. Perspective view of pilot plant pipework [4]

inner diameter back to the vessel (see Fig. 1). When at $t = 0$ sec the valve closes rapidly while the pump is still running, pressure waves are induced in the whole pipe system and measured by fast pressure transducers (P01–P23) [3]. During the first phase of the transient, a rarefaction wave is travelling inside the pipe towards the downstream reservoir. As a consequence, cavitation occurs downstream the valve, and a vapour bubble is formed. The generated pressure wave oscillates between the vessel and the vapour bubble until the cavitation condenses, inducing a cavitational hammer.

A nodalization scheme of the UMSICHT pipe loop model developed by employing the RELAP5 / Mod3.3 code is presented in Fig. 2. Two time-dependent volumes (components 500 and 650) with the specified constant pressures and temperatures to obtain steady-state liquid velocity were simulated in the model. This approach was used to avoid the modelling of the pump which operates in the actual facility. The facility piping from the tank upstream the shut-off valve (component 754) was simulated using the pipe component 753. The segment of actual facility piping with a bridge downstream the valve was modelled using the pipe component 755. The last segment of the piping with the new pipe bridge 2 was modelled by employing the pipe component 758.

Adapting the developed model for water hammer analysis, attention must be given to selection of the cell (control volume) size, valve model, time step of calculation and other parameters. The adoption process of the UMSICHT test facility model is presented in many articles [5–7].

The RELAP5 modelling of water hammer experiment performed in the UMSICHT test facility has shown that the first

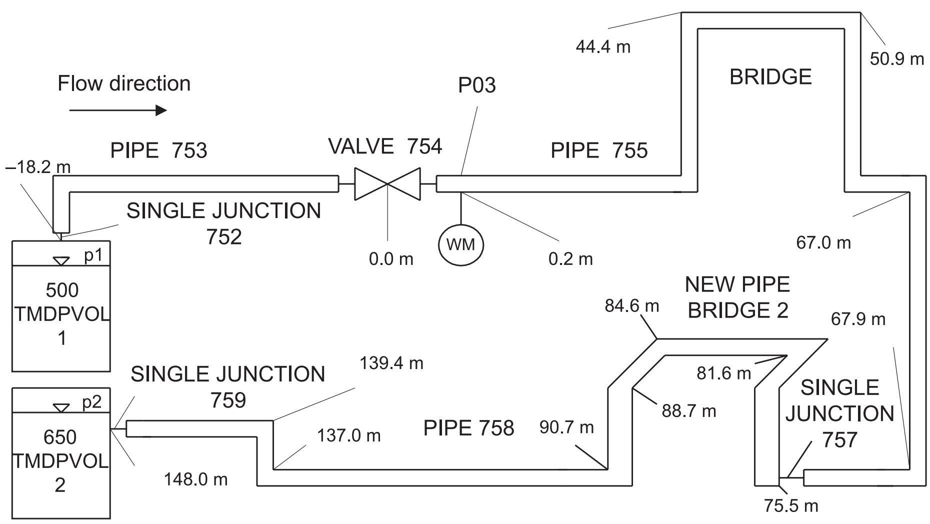

Fig. 2. Pilot plant pipework (UMSICHT) RELAP5 / Mod3.3 code model nodalization scheme

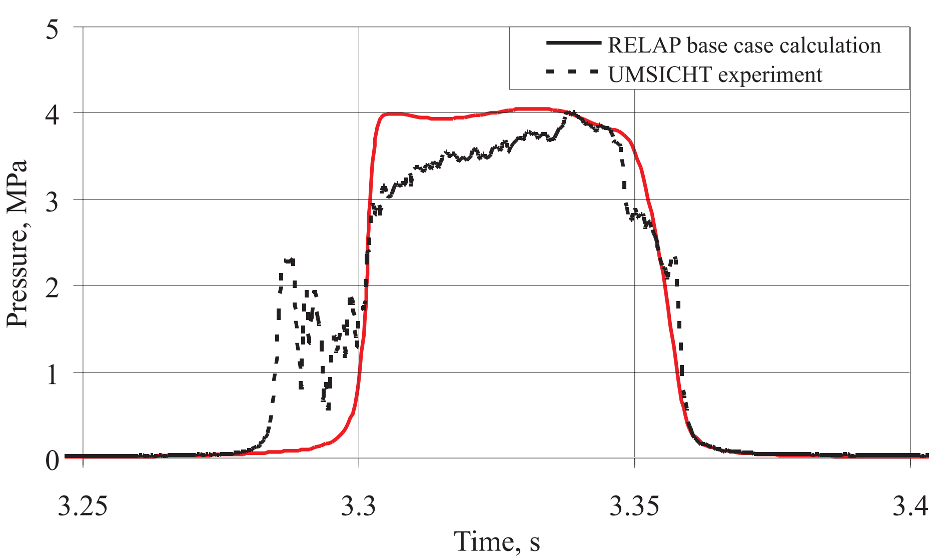

Fig. 3. Comparison of the RELAP5 basic case calculation with UMSICHT experimental data

calculated pressure peak matches very well the measured value of pressure. A comparison of the basic case calculation with experimental data is presented in Fig. 3. The prediction of the first cavitation hammer is most important. The value attained during the first pressure peak is the highest therefore most dangerous in comparison with the successive pressure peaks and can lead to damages of the equipment (valves, pumps, pipe bends) or leakages in the piping. Therefore, the further analysis was carried out only for investigation of the first (peak) pressure increase.

A detailed analysis of UMSICHT test facility experiment, comparison of results obtained using the RELAP5 / Mod3.3 code with calculations of other authors using other best-estimate codes is presented in [5].

3. SENSITIVITY STUDY OF THE RELAP5 MODEL

3.1. Selection and quantification of the most important input parameters

Because the objective of this work was to investigate the possibility to define the influence of modelling parameters on calculation results, first of all we shall discuss the possible sources of uncertainties. Any model is inevitably affected by various types of uncertainties. The major sources of uncertainties are typically the computer code algorithms and the values of model input parameters. The current practice is to apply uncertainty and sensitivity analysis techniques in order to estimate the magnitude of the model output uncertainty and to determine the most influential input parameters. In the present analysis, we mainly focus on the latter objective, i. e. on determining the most influential parameters. Typically, models have many input parameters, and a rigorous quantitative sensitivity analysis is rarely performed on all parameters, mainly due to computational constrains. Instead, an initial screening is performed, and the analysis focuses on a particular selection of these parameters that the modeller evaluates precisely. There are a number of methods for the initial screening, and the Morris method [8] is one of the best known. In some cases, the modeller's expertise and subjective judgment can be used in order to determine an interesting selection of the parameters. The latter approach was used in the present study.

Based on the experience of previous analyses when the GRS methodology [9] was used for such purposes, the following parameters have been selected as the initial condition (1) of the system:

1.1. Water pressure in the pump header.

1.2. Water temperature in the system.

The model parameters (2) contributing significantly to the model output uncertainties:

2.1. Valve closing rate.

2.2. Pipe wall roughness.

2.3. Flow energy loss coefficients in different piping segments.

Table 1 provides the list of the selected input parameters and properties of their distributions for rigorous sensitivity analysis. An assessment of deviations of the selected parameters is presented in [6]. If the mean value is *m* and the deviation value *d*, then the standard deviation *s* and its range are calculated as follows:

the minimum value
of the parameter $\mathrm{Min} = m - m\,(d/100)$;
the maximum value (1)
of the parameter $\mathrm{Max} = m + m\,(d/100)$;
standard deviation (for normal distribution) $s = \frac{\mathrm{Max} - \mathrm{Min}}{4}$.

The maximum and the minimum values constitute a double standard deviation range in case of normal distribution. A double standard deviation range accounts for at least 95% of all parameter values generated by a normal distribution and is considered to be of a rather good approximation. This type of truncation is needed because under the theoretical normal distribution very high or low values are possible (although unlikely), but physically impossible in real systems. Although Table 1 indicates a normal distribution for parameters X1–X7, the sample for sensitivity analysis was generated by using truncated normal distribution.

3.2. Description of FAST

There are numerous references to the FAST method, its modifications and applications. The reader may wish to see the original

Table 1. **Parameters selected for FAST sensitivity analysis**

#	Parameter	Range of values		Mean value (m)	Standard deviation (s) and deviation (p %)	Probability distribution type
		Min	Max			
			Initial conditions			
X1	Pressure at the pump header, Pa	3.871 · 105	4.029 · 105	3.95 · 105	3.95 · 103 (2 %)	Normal
X2	Water temperature, K	292.05	297.95	293.65	1.475 (2 %)	Normal
			Assumptions			
X3	Valve closing rate, s–1	17.52	30.48	24 (according to UMSICHT data)	3.24 (27%)	Normal
X4	Wall roughness, m	2.0 · 10–5	3.0 · 10–5	25.0 · 10–6 (according to UMSICHT data)	2.5 · 10–6 (20 %)	Normal
X5	Flow energy loss coefficient in each node of piping 753	0.04476	0.08313	0.06395	9.59 · 10–3 (30 %)	Normal
X6	Flow energy loss coefficient in each node of piping 755	0.01459	0.02709	0.02084	3.13 · 10–3 (30 %)	Normal
X7	Flow energy loss coefficient in each node of piping 758	6.95 · 10–3	0.0129	9.92 · 10–3	1.49 · 10–3 (30 %)	Normal

paper published by Cukier et al. in 1973 [2] and its later developments in [10–13].

Let us define the model input parameters as x_i, $i = 1 \dots N$, N being the number of the parameters. Then the model output Y could be represented as a function: $Y = F(x_1, x_2, \dots, x_N)$. Typically, the function F is a solution of systems of differential equations. Time is usually an optional parameter of the function F. Let us define the variance of the model output as $Var(Y)$. It is common that complex models have several outputs or time continuous outputs. In case of several outputs, each of them should be investigated separately. In case of time continuous outputs, specific time moments should be selected and investigated separately.

The variance of Y can be decomposed into individual terms:

$$Var(Y) = \sum_i D_i + \sum_i \sum_{j>i} D_{ij} + \sum_i \sum_{j>i} \sum_{k>j} D_{ijk} + \dots + D_{1,2\dots,N}. \quad (2)$$

In equation (2), the term D_i is defined as a variance of conditional expectation of the model output given the fixed input parameter x_i and varying over its range of variability. Thus, $D_i = Var(M(Y \mid x_i))$, where $M(u \mid v)$ is the conditional expectation of u when v is fixed. The higher order terms have similar definitions, and they basically take into account simultaneous interactions among various parameters.

The first-order sensitivity index is introduced as follows:

$$S_1(x_i) = \frac{D_i}{Var(Y)}. \quad (3)$$

The first-order sensitivity index shows which part of the model result variance can be explained by the corresponding variable. This index which could be also expressed as $Var(M(Y \mid x_i) / Var(Y)$, is estimated by the classical FAST, Sobol method [15], correlation ratio or other techniques. The first-order sensitivity indices allow ranking the input parameters according to their contribution to the model output variance. The higher the index, the higher the parameter's influence on the model result uncertainty. Fixing the value of the parameter with the highest sensitivity index would most effectively reduce the model result uncertainty in terms of variance.

Following (3), equation (2) can be transformed into

$$\sum_i S_i + \sum_i \sum_{j>i} S_{ij} + \sum_i \sum_{j>i} \sum_{k>j} S_{ijk} + \dots + S_{1,2\dots,N} = 1. \quad (4)$$

The higher order sensitivity indices estimate the contribution of the interactions of various input parameters into the model output variance. In general, a full sensitivity analysis should compute all sensitivity indices; however, this is rarely done due to computational constraints. The classical FAST was developed to compute only first-order sensitivity indices. The latest developments enable to compute additional sensitivity measures. One of them is the so-called total effect sensitivity index S_{Ti}. It sums up all indices from (4) that contain the contribution from the particular parameter i. For example, in case of $N = 4$ parameters, the total effect sensitivity index for the first parameter is calculated as follows:

$$S_{T1} = S_1 + S_{12} + S_{13} + S_{14} + S_{123} + S_{124} + S_{134} + S_{1234}. \quad (5)$$

The total effect sensitivity index indicates the degree of interaction between the parameter of interest and the rest of the parameters. This index provides important additional information and can be used to determine strong interaction effects among the input parameters or to prove absence of the interactions.

The extended FAST procedure [10] enables an efficient computation of the first-order (3) and the total effect sensitivity indices. It is implemented in the sensitivity analysis software tool SIMLAB [14].

3.3. Results of the FAST application to the UMSICHT model

This section describes the application of the extended FAST method to the UMSICHT model. The generation of the FAST sample and the computation of the sensitivity indices was performed by using the SIMLAB software tool [14]. The total sample size used was 1463, which corresponds to about 20 runs per parameter and is considered to be a good enough sample size for an extended FAST method [10]. The model output was considered to be the maximum pressure during the entire duration of the experiment, but in fact the highest value is attained always during the first pressure peak, and it is considered to be the most dangerous moment for the system integrity. The dynamic pressure evolution sensitivity analysis will be presented in the subsequent papers.

Extended FAST results for the maximum pressure model output are presented in Table 2. The sum of the first-order indices indicates that interactions among the input parameters do not play an important role in this model.

Based on the first-order indices ranking, X6 (flow energy loss coefficient in each node of the pipe component 755, see Table 1) is the most important parameter. It is followed by X4 (wall roughness) and X1 (pressure at the pump header) parameters whose importance is similar, but significantly lower than X6. The rest of the parameters have a negligible direct impact on the variance of the pressure peak. The importance of X6 can be explained from the physical point of view by the fact that the piping segment 755 is just downstream the closing valve, and there the most significant pressure increase is formed. The practical

Table 2. **The first-order and total effect indices for the maximum temperature in three locations**

Parameter	Value
S_1	0.13
S_2	0.01
S_3	0.01
S_4	0.18
S_5	0.02
S_6	0.54
S_7	0.02
Sum of 1st order	0.91
S_{T1}	0.25
S_{T2}	0.11
S_{T3}	0.10
S_{T4}	0.28
S_{T5}	0.11
S_{T6}	0.64
S_{T7}	0.08

Table 3. **The effect of the interactions of input parameters on the maximum temperature in three locations**

Parameter	Value
$S_{T1}–S_1$	0.12
$S_{T2}–S_2$	0.10
$S_{T3}–S_3$	0.10
$S_{T4}–S_4$	0.10
$S_{T5}–S_5$	0.09
$S_{T6}–S_6$	0.11
$S_{T7}–S_7$	0.06

implication of this result is that more precise knowledge of the flow energy loss coefficient in piping 755 would enable to reduce most efficiently the uncertainty of the computed pressure peak value.

The total effect sensitivity indices indicate that all the parameters have an almost equal degree of the interaction effect. One possible way to compare the importance of the interactions is to compare quantities $S_{Ti}–S_i$ for each parameter *Xi*. This is shown in Table 3 which indicates that even if parameters X2, X3 and X5 have an almost zero first-order index, they equally interact with the other parameters as the most important X6. The overall interaction level is rather low, and therefore the FAST method is good enough for this type of model. In case of a high level of interactions among the parameters, particular interactions could be further investigated in detail by the Sobol method [15].

The low level of parameter interactions implies also another important practical result: the corresponding change in the value of the flow energy loss coefficient in piping 755 (the most important parameter) would enable to reduce the pressure peak value in the most efficient way. The latter implication is very important from the practical point of view as it can be used for safety improvements in case of need. The FAST analysis does not provide information about the parameters' importance, i. e. it is not possible to judge whether increase of the parameter value would cause an increase or a decrease of the model output value. In the case of complex non-linear models with strong interactions, this information is not straightforwardly obtainable and usable. However, in many practical situations, and also for this model, the simplest methods like scatter plots using the same FAST sample, could be useful to determine the directional behaviour of the model output. As is clear from Fig. 4, an increase of the X6 value would cause the most effective decrease in the calculated pressure peak value. This result is possible to obtain also from the physical reasoning about the system.

Calculations of the sensitivity indices were also done for the time moment of the maximum pressure, but because for this model output the sum of the first-order indices was rather low (about ~0.25), the results are not presented here.

4. CONCLUSIONS

Water hammer phenomena are specific, not all the codes are verified for simulation of water hammer fast transients. Therefore, it is very important to verify a model developed using these codes and to perform a sensitivity analysis of the model (to investigate the impact of the parameters on the results of calculations). The UMSICHT test facility model developed by employing the RELAP5 / Mod3.3 code is presented in this work. A water hammer induced by a fast valve closing was investigated using this model. The sensitivity study of the model parameters was performed using the FAST method.

The FAST sensitivity study was carried out, and the most important parameters affecting the pressure peak value were determined. The sensitivity analysis results indicate that the flow energy loss coefficient in a pipe component downstream the fast-acting valve is the most important parameter with the highest contribution to the variance of the estimated pressure peak. It is followed by the wall roughness and the pressure at the pump header parameters whose importance is similar, but significantly lower than that of the junction loss coefficient in the pipe component downstream the fast-acting valve. The importance of this parameter can be explained from the physical point of view because this piping segment is just downstream

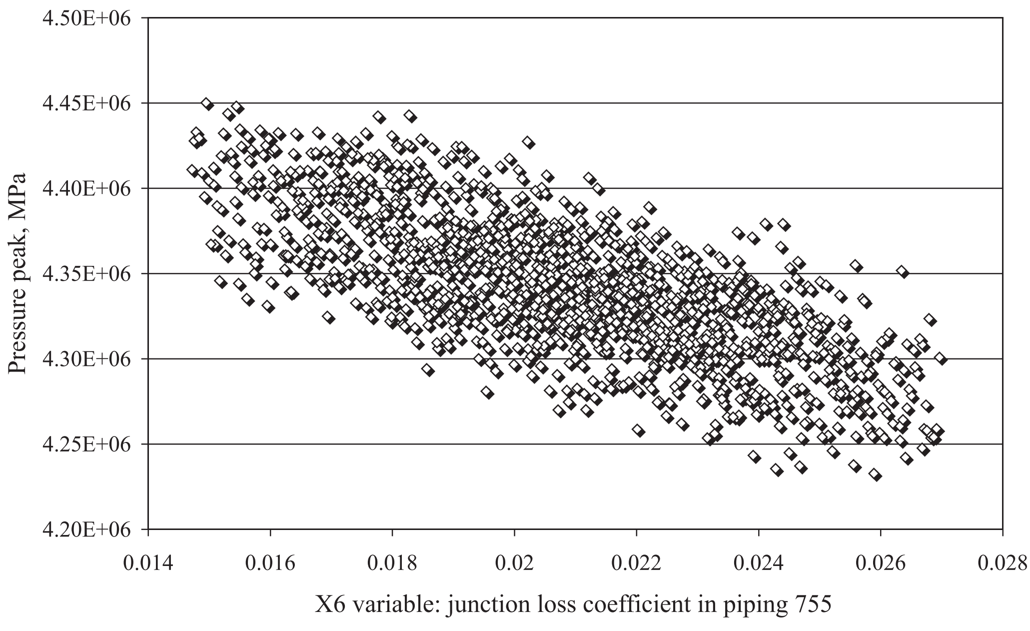

Fig. 4. Scatter plot of X6 against the model output (pressure peak)

the closing valve, and there the most significant pressure increase is formed. The practical implication of this result is that more precise knowledge of the flow energy loss coefficient in the pipe component downstream the fast-acting valve would enable to reduce most efficiently the uncertainty of the computed pressure peak value.

The analysis has indicated that the interactions among the parameters are not very strong; however, in quantitative terms, they are of almost equal magnitude for all the parameters. As a consequence, none of the parameters can be excluded as having an-insignificant effect on the model output, even if some first-order indices suggest so. The investigation of the interaction effect and its quantitative magnitude is the unique feature of the extended FAST method, and it cannot be obtained by the conventional random sample-based sensitivity methods. The low level of parameter interactions also implies another important practical result: a corresponding change in the value of the flow energy loss coefficient in the pipe component downstream the fast-acting valve would enable to reduce the pressure peak value in the most efficient way. Scatter plots were used to determine the directional behaviour of this parameter, and they showed that an increase of this flow energy loss coefficient value would decrease the calculated pressure peak value.

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HIDRAULINIO SMŪGIO MODELIO JAUTRUMO TYRIMAS FAST METODU

Santrauka

Slėgio bangos vamzdynų sistemose dažniausiai atsiranda dėl eksploatacijos klaidų, sistemų paleidimo arba stabdymo, staigaus vožtuvų atsidarymo arba užsidarymo vamzdyne ir panašiai. Tai sukelia hidraulinį smūgį prieš užsidariusį vožtuvą ir kavitacinį smūgį už užsidariusio vožtuvo, todėl gali sugęsti vamzdynai ir jų atraminės struktūros. Hidraulinio smūgio termohidraulinėse sistemose atvejai yra plačiai nagrinėjami naudojant įvairius šiuolaikinius termohidraulinius programų paketus. Prieš analizuojant hidraulinį smūgį, labai svarbu tinkamai suderinti skaičiavimo modelį ir išanalizuoti jo jautrumą. Šiame straipsnyje pateikiama hidraulinio smūgio eksperimento, atlikto Vokietijos Fraunhoferio instituto UMSICHT eksperimentiniame stende, analizė panaudojant termohidraulinį RELAP5 / Mod 3.3 programų paketą. Modelio jautrumo analizė atlikta panaudojus Furje amplitudžių jautrumo testą (FAST). FAST metodas leidžia patikimai nustatyti svarbiausius modelio parametrus, turinčius didžiausią įtaką skaičiavimo rezultatų neapibrėžtumui. Ši informacija gali būti svarbi tobulinant sistemą arba kuriant sistemos apsaugos nuo slėgio padidėjimo priemones.

Raktažodžiai: hidraulinis smūgis, UMSICHT eksperimentinis stendas, RELAP5 modelis, jautrumo analizė, FAST metodas

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ИССЛЕДОВАНИЕ ЧУВСТВИТЕЛЬНОСТИ МОДЕЛИ ГИДРАВЛИЧЕСКОГО УДАРА МЕТОДОМ FAST

Резюме

Волны давления в системах трубопроводов в основном возникают из-за эксплуатационных ошибок, во время пуска или останова систем, из-за резкого открытия или закрытия клапанов в трубопроводе и др. Это вызывает гидравлический удар до обратного клапана и кавитационный удар после закрытого клапана, в результате чего могут произойти повреждения трубопроводов и их опорных структур. Случаи гидравлического удара в теплогидравлических системах широко исследуются с использованием разных современных программных пакетов. До проведения анализа гидравлического удара очень важно должным образом согласовать модель и выполнить анализ ее чувствительности.

В статье представлен анализ эксперимента гидравлического удара, выполненного на экспериментальном участке UMSICHT (Германия), с использованием теплогидравлического кода RELAP5 / Mod 3.3. Анализ чувствительности модели выполнен с помощью теста чувствительности амплитуд Фурье (FAST). Метод FAST позволяет достоверно определить самые важные параметры модели, которые в наибольшей степени влияют на неопределенность результатов расчета. Эта информация может оказаться очень важной при усовершенствовании системы или при создании мер по защите системы от превышения давления.

Ключевые слова: гидравлический удар, экспериментальный участок UMSICHT, модель RELAP5, анализ чувствительности, метод FAST