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Justification of RELAP5 code for modeling water hammer phenomenon by employing the umsicht test facility data

Algirdas Kaliatka,
Eugenijus Ušpuras,
Mindaugas Vaišnoras

Lithuanian Energy Institute,
Laboratory of Nuclear Installation Safety,
3 Breslaujos str.,
LT-44403, Kaunas, Lithuania
E-mail: algis@mail.lei.lt

The rapid closing or opening of a valve causes pressure transients in pipelines. The phenomenon is known as a water hammer. The valve closure can result in pressures well over the steady state values, while the valve opening can cause such low pressures that the flowing liquid vaporizes inside the pipe. If the pressure induced exceeds the pressure range of a pipe given by the manufacturer, the pipe may rupture. This unsteady state phenomenon deals with the change between the kinetic and potential energies, which may be positive or negative.

In the paper, the capabilities of the RELAP5 code to correctly represent the water hammer phenomenon are shown. The paper presents a comparison of RELAP5 calculated and measured at UMSICHT test facility water hammer values at various water velocities after a fast closure of a valve. The influence of the calculation time step and control volume sizes in pipe components on the computation results is presented as well. The analysis showed that the RELAP5-calculated first pressure peak matches the measured value of pressure very well, but concerning the following pressure peaks the measured pressures are higher and peaks appear with an accumulating time delay. A comparison of UMSICHT test facility experimental results to RELAP5, MONA and FLOWMASTER calculation results is presented as well.

Key words: UMSICHT, RELAP5, water hammer

1. INTRODUCTION

Pressure surges occurring in pipeline systems may be caused by a fast control interference, start up and shut down processes and operation failure as well as flow rate fluctuations. They lead to the water hammer upstream the closing valve and cavitational hammer downstream the valve, which may cause considerable damages to the pipeline and the support structures. The typical scenarios for the origin of water hammer are the fast closing valves triggered by the breakdown of auxiliary power and fast control interference. 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 the temporary pressure increases [1]. This phenomenon is called 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 systems and it is extremely dangerous for the thermal-hydraulic system since it can lead to the failure of the pipeline integrity. However, water hammer is more frequent in various hydraulic systems, therefore, the objective of this analysis is to validate the RELAP5 code model by comparing the numerical water hammer results with the experimental investigation ones of water hammer phenomenon performed at UMSICHT test facility. Such validation will allow to develop RELAP5 code model for the analysis of accidents with the phenomenon of water hammer for the nuclear power plants.

2. UMSICHT TEST FACILITY EXPERIMENTAL CASE

For the RELAP5 analysis we consider a water hammer test performed at Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT) at Oberhausen, Germany. These water hammer experiments have been initiated under the WAHALoads research project of the 5th Framework Programme of the

European Union. The existing UMSICHT facility in Oberhausen is being modified in order to simulate the piping system and the associated supports typical of a nuclear power plant. The preliminary design is being performed with the support of Framatome ANP, Offenbach in consultation with EDF, Clamart. Fluid dynamic loads, global structural response and the possible fluid-structure interaction were investigated experimentally.

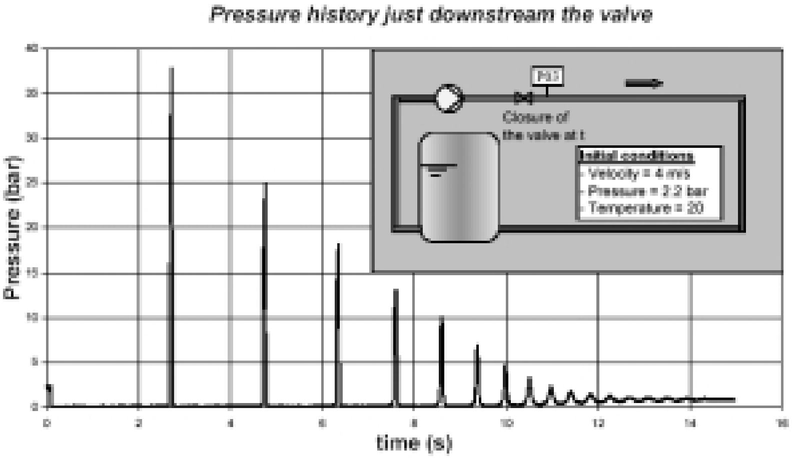

Fig. 2. Example of the result of PPP experiments, cavitation produced by the quick closure of a valve [6]

The experiments were conducted using the dynamic behaviour of closing and opening valves in a steady-state liquid flow. The geometry of the test facility is shown in Fig. 1 [2]. The test rig design includes two 240 m pipes with high and low levels (difference in height: 10 m) and the inner diameters 54 mm and 108 mm respectively [3]. A centrifugal pump produces a steady-state flow from the storage tank (B2) through the pipework with the inner diameter 108 mm and approx. 200 m in length back to the tank (see Fig. 1). The tests were carried out with water at room temperature and in the range of the initial velocities v_0 between 1 and 6 m/s. The transient was initiated by a rapid closure of a valve (built in at Pos.1) at an initial time t = 0 s. During the first phase of the transient, a rarefaction wave was travelling inside the pipe towards the downstream reservoir. As a consequence, the cavitation occurred downstream the valve.

Within the test facility, measuring data are transferred via optical fibre transmission and saved in a transient recording station with a professional software. The liquid pressure and the wave velocity are monitored with pressure transducers (P01-P23). Steam/air and fluid distribution in the cross-sectional area of the pipe is measured with wire-mesh sensors [4]. For low steady state liquid velocities (v < 2.5 m/s), the flow profile downstream the valve is monitored with a high speed camera [5]. The liquid flow velocity is measured with an ultrasonic appliance. The time frame resolution of all measurement systems described above varies between 1 and 10 kHz.

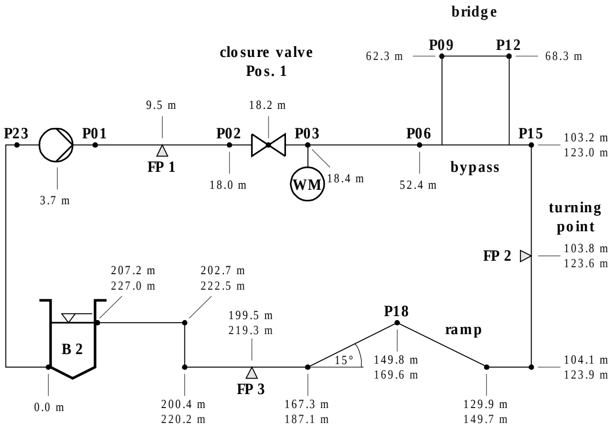

Fig. 1. Pilot plant pipework (UMSICHT) schematic diagram [2]

The objective of the pilot plant pipework (PPP) test is to predict the propagation of the pressure waves. After comparative calculations it will provide information on how flashing is predicted by the code. Experimental data (pressure measurements) with three different steady state water velocities (2 m/s, 3 m/s and 4 m/s) are available for the comparison. An example of pressure history downstream the valve at a steady state water velocity 4 m/s is shown in Fig. 2 [6].

3. SIMULATION WITH RELAP5/MOD3.3 CODE

The model employing the RELAP5/Mod3.3 code was developed according to the experimental facility (Fig. 3). A two time-dependent volumes (components

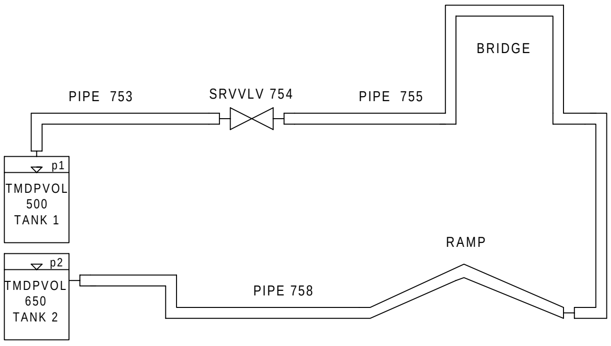

Fig. 3. Pilot plant pipework (UMSICHT) RELAP5/Mod3.3 code model nodalization scheme

"500" and "650") with different specified initial pressures to obtain steady state liquid velocities (2 m/s, 3 m/s and 4 m/s) were simulated in the model. Such an approach has allowed to refuse modelling the pump that operates in the actual piping system of the facility. The 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 the bridge downstream the valve was modelled using the pipe component "755". The last segment of piping with the ramp was modelled employing the pipe component "758".

Using the RELAP5 code for water hammer analysis, a very close attention must be paid to the control volume (c. v.) size and time step. These two factors were considered very carefully in this analysis. The acoustic wave Courant limit is the time required for the wave traveling at the sonic velocity to pass through any given model control volume. Since the sonic velocity can be quite high, the time step usually has to be reduced to a rather small number. For the selection of a suitable RELAP5 calculation time step, the analysis for different ratio of current time step (dt) and current Courant time step (dtcrnt) was assumed.

A number of RELAP5 calculations with different control volume sizes for the pipe elements "755" and "758" was carried out to obtain the pressure peaks without a high rate of change at steady state water velocity 3 m/s (Figs. 4 and 5). In Fig. 4 it is shown that dividing the pipeline component "755" (pipe downstream the valve) into more than 25 control volumes is not necessary, because it does not influence the pressure peaks and the frequencies of cavitational pressure peaks.

The following analysis was performed to estimate the influence of control volume sizes in the pipe component "758" (piping with the ramp). The pipe was divided into 6, 11, 15 and 20 control volumes (Fig. 5). As is shown in the figure, for the pipe division into six control volumes the pressure stops to oscillate considerably earlier in comparison with experiment and with cases when the pipe component "758" is divided into 11, 15 and 20 control volumes. However, dividing the pipeline component "758" into 11 control volumes is enough, because the further reduction of control volume size does not influence the pressure peaks and the frequencies of cavitational pressure peaks.

Thus, the model was employed to simulate three different investigations for different steady state liquid velocities (2 m/s, 3 m/s and 4 m/s). Figures 6, 7 and 8 show the pressure curves from the pilot plant pipework (UMSICHT) experimental data (dot line) in comparison with the calculated RELAP5/Mod3.3 code data (continuous line). The pressure was monitored at position P03 (Fig. 2) downstream the shut-off valve [3].

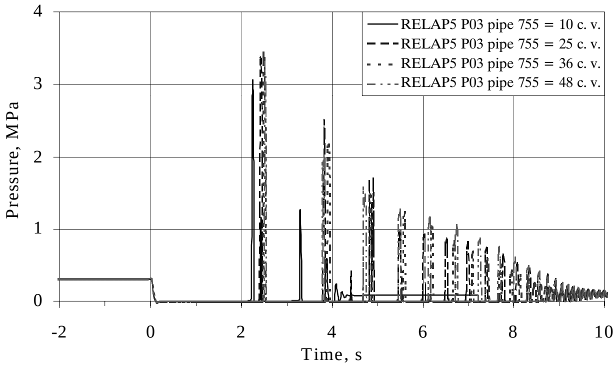

Fig. 4. RELAP5 calculations with different control volume sizes in pipe component "755" to obtain pressure peaks without high rate of change at steady state water velocity v_0 = 3 m/s

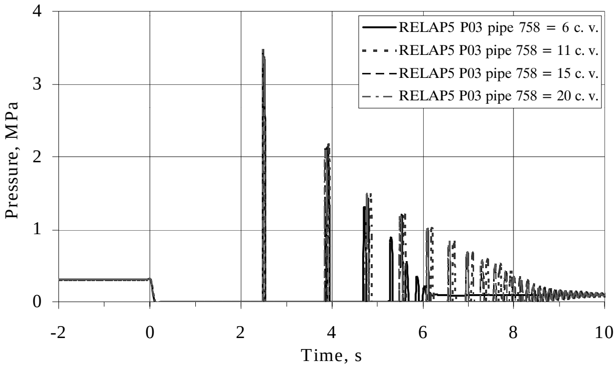

Fig. 5. RELAP5 calculations with different control volume sizes in pipe component "758" to obtain pressure peaks without high rate of change at steady state water velocity v_0 = 3 m/s

The calculation results for the first two pressure pulses match the measured values of pressure reasonably well in the case with the steady state velocity 2 m/s (Fig. 6). Concerning the following pressure pulses, the measured pressures are higher and the peaks appear with an accumulating time delay while the pressure in calculation employing the RELAP5 code stops to oscillate in approximately 5–6 seconds.

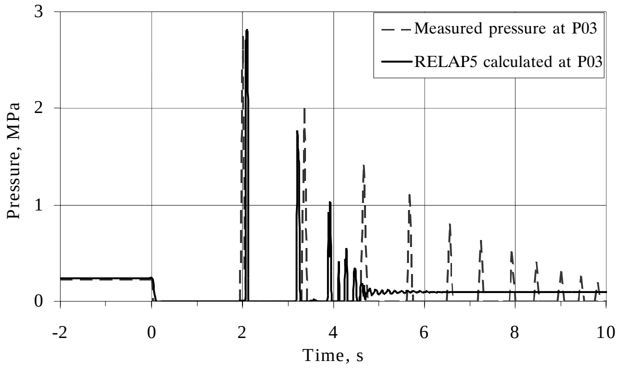

Fig. 6. Pressure history for a quick shut-off of the valve at steady state fluid velocity v_0 = 2 m/s

Figures 7 and 8 show that the calculated first pressure peak (*i. e.* time moment of peak appearance and maximum value of the peak) very well matches the measured value of pressure in case with the steady state velocities 3 m/s and 4 m/s. The first cavitation hammer is most dangerous and can lead to damages of the plant equipment (valves, pumps, pipe bends) up to leakage of the pipe system. These damages have an impact on the plant availability and plant safety, therefore, water hammer effects investigation is important to ensure the safety of NPPs. Concerning the following pressure peaks, the measured pressures are higher and the differences in the frequency of oscillations are observed also.

Figure 9 shows the simulation of the process for the initial liquid velocity $v_0 = 4$ m/s. After the valve has been closed, the pressure decreases to the saturation pressure, which is close to vacuum. The steam fraction increases and reaches a value of about 0.8, *i.e.* the tube is almost completely empty within the time span of 0–3 seconds. The water flows back in the slug, the steam fraction decreases rapidly, and then the steam is completely condensed. Therefore, a pressure peak at the measuring position (P03) downstream the check valve is observed, it is caused by the collapse of the void in this place. The pressure wave travels through the pipeline. It is reflected at the entrance into the storage tank and returns as the wave of pressure decrease. When this wave reaches the closed valve, a new cavitation bubble is generated. This process repeats several times and a series of water hammers with decreasing amplitudes is observed. The pressures of the following cavitational processes decrease with time due to the friction between the liquid and the structure.

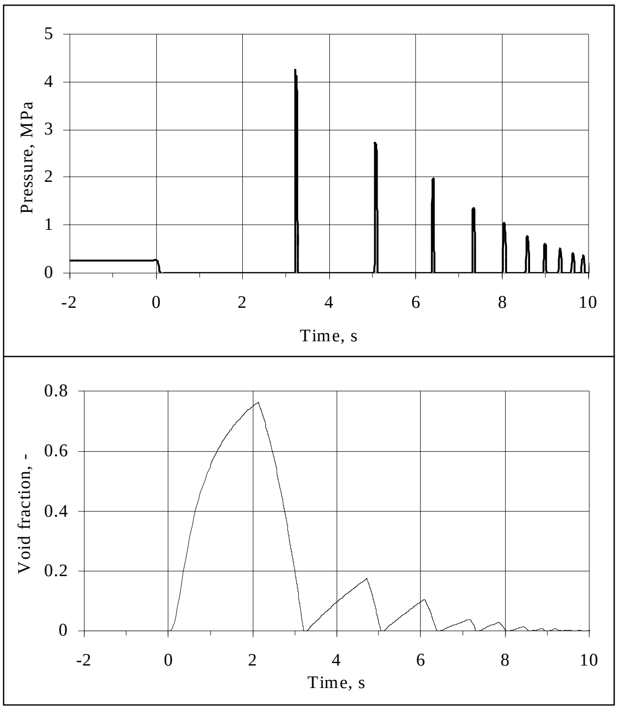

Fig. 9. Simulated pressure and average void fraction downstream the closed valve (p03) for an initial liquid velocity of $v_0 = 4$ m/s

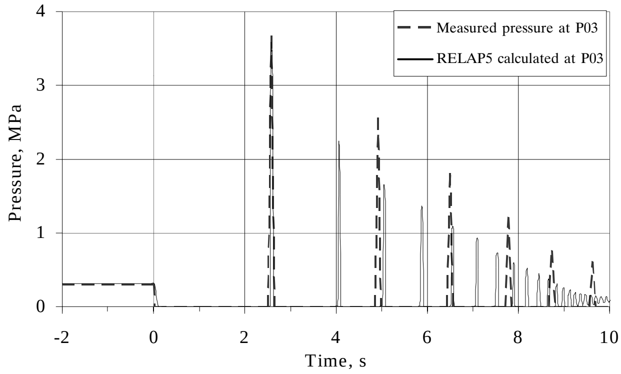

Fig. 7. Pressure history for a quick shut-off of the valve at steady state fluid velocity $v_0 = 3$ m/s

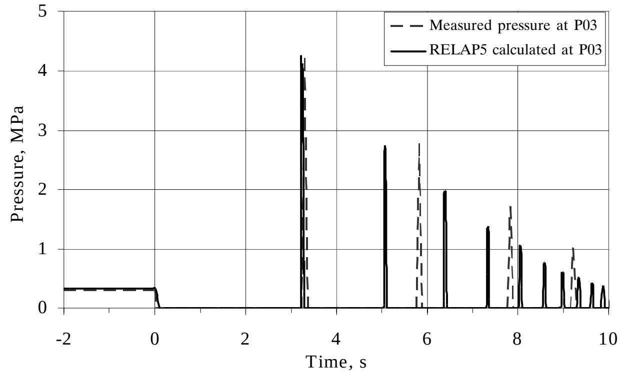

Fig. 8. Pressure history for a quick shut-off of the valve at steady state fluid velocity $v_0 = 4$ m/s

4. COMPARISON OF EXPERIMENTAL INVESTIGATIONS WITH CALCULATION RESULTS OF DIFFERENT SOFTWARE CODES

The appearance of water hammer in thermal-hydraulic systems was widely studied employing different state-of-the-art thermal-hydraulic codes in many organizations. A comparison of UMSICHT test facility experiment calculations employing the RELAP5 code performed in LEI with the MONA and FLOWMASTER calculation results [7] are presented in this section.

Lithuanian Energy Institute employs the RELAP5 code to ensure the Ignalina Nuclear Power Plant safety since 1992. RELAP5 is a general-purpose computer code for analyzing the thermal hydraulics of a liquid/vapor/noncondensible gas mixture. It is based on the two-fluid model in the two-phase flow.

Each phase is governed by its conservation equations (*i.e.* mass, momentum and energy). This code, being highly generic, has also found use in a variety of fluid transient problems, including water hammer analysis in piping systems.

The software tool FLOWMASTER originally developed by The Flowmaster Group (UK) [7] is used for water hammer calculations in liquid transporting pipes using the method of characteristics that is valid for the one-phase flow. Additionally to the one-phase calculations it is possible to calculate the cavitation due to the pressure decrease behind (downstream) the acting valves using the Discrete-Vapor-Cavity model [1].

MONA is a general flow simulator for steam-water/inert gas systems and has been developed with the objective of updating the hydraulic modelling. MONA contains a set of 7 conservation equations based on the modelling of three flow fields: the bulk liquid or the liquid film at the wall, the liquid droplet field and the gas or steam phase. Thus, 3 mass conservation equations, 2 momentum and 2 energy equations are solved [8]. The main difference of the two cavitation models used in the FLOWMASTER software code in comparison to the 3-phase-model used in MONA is that using the Discrete-Vapor-Cavity model sudden changes of gas content in the liquid (*e. g.* in case of pressure decrease) cannot be calculated. Therefore, the prediction of cavitational hammer in liquids that contain gas may lead to pressure peaks and frequencies deviant from experimental data.

Figure 10 shows pressure curves from experimental data in comparison with simulated ones employing the RELAP5 and FLOWMASTER codes. The pressure was monitored at the position P03 downstream the closed valve. The first cavitation hammer (at t = 2.7 s) matches the measured value of pressure very well in the RELAP5 calculation and reasonably well in the FLOWMASTER calculation. Concerning the following condensation hammers, the pressures calculated with the FLOWMASTER code are too high and the peaks appear with an accumulating time delay.

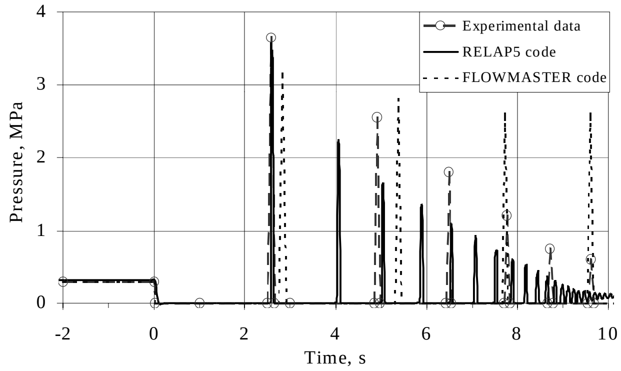

Fig. 10. Comparison of experimental results and RELAP5, FLOWMASTER [7] codes calculation results (pressure for a quick shut-off of the valve at steady state fluid velocity v_0 = 3 m/s)

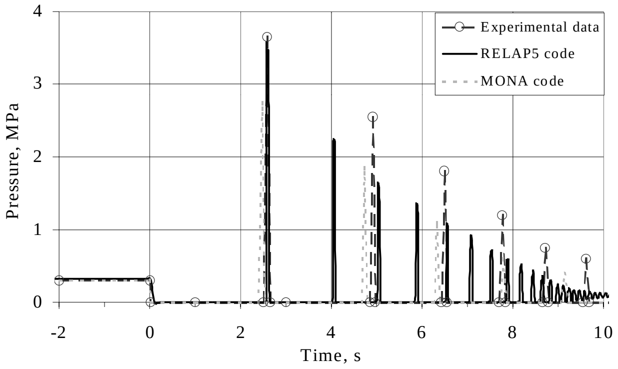

Fig. 11. Comparison of experimental results and RELAP5, MONA [7] codes calculation results (pressure for a quick shut-off of the valve at steady state fluid velocity v_0 = 3 m/s)

Simulating with the MONA code, the first cavitational hammer is too low in comparison with the measured data and the RELAP5 calculation, but the frequency agrees quite well with the experimental data (Fig. 11).

5. SUMMARY

In order to validate calculation software for water supply cases, the pressure surge experiments were conducted using the dynamic behavior of closing and opening valves. In this paper, the RELAP5 code is discussed in comparison with the UMSICHT test facility as well as the other software tools (MONA and FLOWMASTER) [7].

The RELAP5 code has not been designed to simulate water hammer. Therefore, to assess the RELAP5 code capabilities for a rapid valve closure applications, it has been benchmarked against the water hammer test performed at Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT) at Oberhausen, Germany.

The paper presents a comparison of the calculated and measured water hammer values of various tap water velocities after a fast closure of a valve. The influence of the calculation time step and control volume sizes in pipe components on the maximum pressure peaks is discussed.

Test calculations were performed varying the steady state velocity between 2 m/s, 3 m/s and 4 m/s. The pressure increases on proportion to the steady state flow velocity, *i. e.* a higher tap water velocity leads to higher pressure peaks.

The comparison of experimental results and RELAP5 calculations results showed that:

- the calculated first pressure peak (*i. e.* the time moment of peak appearance and the maximum value of the peak) matches very well with the measured value of pressure;
- concerning the following pressure peaks, the measured pressures are higher and the peaks appear with an accumulating time delay;
- the pressure peaks calculated employing the RELAP5 code stop to oscillate earlier in comparison with the measured pressures in the UMSICHT water hammer test. The rate of pressure pulse decay depends on the liquid steady state velocity. For lower initial liquid velocity the pressure pulses stop to oscillate faster.

Analysis of the RELAP5 code model validation by comparing the numerical water hammer results with the UMSICHT test facility experimental investigation data on water hammer phenomena was performed. Such validation allowed to develop the RELAP5 code model for analysis of accidents related to the phenomenon of water hammer at nuclear power plants.

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**Algirdas Kaliatka, Eugenijus Ušpuras,
Mindaugas Vaišnoras**

RELAP5 PROGRAMŲ PAKETO PATIKRINIMAS MODELIUOTI HIDRAULINIO SMŪGIO REIŠKINĮ PANAUDOJANT UMSICHT EKSPERIMENTINIO STENDO MATAVIMŲ DUOMENIS

Santrauka

Šiame straipsnyje pateikiamas hidraulinio smūgio reiškinio modeliavimas panaudojant RELAP5 programų paketą, skaičiavimo rezultatų palyginimas su eksperimentinių matavimų, atliktų Vokietijos UMSICHT eksperimentiniame stende, duomenimis esant įvairiems pradiniams fluido tekėjimo greičiams. Darbe įvertinta skaičiavimo laiko žingsnio bei kontrolinių tūrių dydžio vamzdžio elemente įtaka maksimalioms slėgio reikšmėms. Analizė parodė, jog pirmas slėgio pikas, apskaičiuotas naudojant RELAP5 programų paketą, labai gerai sutampa su išmatuota slėgio verte, bet vėliau atsirandančios slėgio pulsacijos matavimų rezultatuose turi didesnę amplitudę bei skiriasi pasikartojimų dažniu. Taip pat straipsnyje pateikiamas gautų rezultatų palyginimas su skaičiavimais, atliktais kitų autorių, naudojantis MONA ir FLOWMASTER paketais.

Raktažodžiai: UMSICHT, RELAP5, hidraulinis smūgis

**Альгирдас Калятка, Евгений Ушпурас,
Миндаугас Вайшнорас**

ПРОВЕРКА ПРОГРАММНОГО ПАКЕТА RELAP5 МОДЕЛИРОВАТЬ ЯВЛЕНИЕ ГИДРАВЛИЧЕСКОГО УДАРА, ИСПОЛЬЗУЯ ИЗМЕРИТЕЛЬНЫЕ ДАННЫЕ ЭКСПЕРИМЕНТАЛЬНОГО УЧАСТКА UMSICHT

Резюме

В статье представлены расчеты явления гидравлического удара с использованием кода RELAP5, сравнение расчетных результатов с результатами экспериментальных измерений, выполненных на экспериментальном участке UMSICHT (Германия) для различных начальных расходов воды после быстрого закрытия клапана. Также представлено влияние шага времени вычисления и размеров ячейки в компонентах трубы к максимальным пикам давления. Анализ показал, что первый пик давления, рассчитанный с помощью кода RELAP5, очень хорошо соответствует измеренному значению давления, но что касается последующих пиков давления, они по амплитуде повыше, и пики появляются с задержкой во времени. В статье представлено также сравнение результатов расчетов с результатами расчетов, выполненных другими авторами, используя коды MONA и FLOWMASTER.

Ключевые слова: UMSICHT, RELAP5, гидравлический удар