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RELAP5 code analysis of water hammer wave behavior

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Rapid closing or opening of a valve causes pressure transients in pipelines. 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. 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 hammer can occur in any thermal-hydraulic systems and is extremely dangerous for the thermal-hydraulic system, since, if the pressure induced exceeds the pressure range of a pipe given by the manufacturer, it can lead to the failure of the pipeline integrity.

The paper presents water hammer phenomenon simulations employing the RELAP5 code, a comparison of RELAP5 calculated and measured at CWHTF and AEKI test facilities pressure transient values after a fast opening of the valve and at the appearance of condensation-induced water hammer. An analysis of rarefaction wave travels inside the pipe and the condensation of vapour bubbles in the liquid column for CWHTF experiment is presented. The dependence of the pressure peaks on the evacuation height and the length of the pipeline were investigated. A comparison of RELAP5 code CWHTF experiment simulation by using homogeneous equilibrium options (HEM) and without these options is also presented.

The capability of the RELAP5 computer code to simulate Condensation Induced Water Hammer was investigated. A strong water hammer similar to that observed in AEKI test facility experiment was not obtained in RELAP5 simulation. Results of this analysis showed that the RELAP5 code couldn't capture the condensation-induced water hammer phenomenon, *i. e.* the calculation performed with this code did not predict any pressure peak.

The acquirement of knowledge will allow to develop the RELAP5 code model for the analysis of accidents related to the phenomenon of water hammer for nuclear power plants.

Key words: RELAP5, water hammer, CWHTF, AEKI

1. INTRODUCTION

Water hammer is a pressure or momentum transient in a closed system, caused by a rapid change in fluid velocity. It is classified according to the cause of velocity change. Generally, water hammer can occur in any thermal-hydraulic systems and is extremely dangerous for the thermal-hydraulic system since, if the pressure induced exceeds the pressure range of a pipe given by the manufacturer, it can lead to the failure of the pipeline integrity.

The types of water hammer include the following:

• water hammer due to a fast valve closing or opening or following pipe ruptures with a single-phase or two-phase flow;

• condensation-induced water hammer following an inflow of sub-cooled water into equipment partially filled with steam.

As the first type of water hammer, the experimental investigations performed at Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT) [2] should be mentioned. The UMSICHT facility in Oberhausen was modified in order to simulate a piping system and associated supports that are typical of a nuclear power plant. The main task of experiments conducted at Fraunhofer UMSICHT was to get pressure surges under control and to use results of experiments for developing new methods for the prevention of water and cavitational hammer [3]. Water hammer tests conducted in this facility – depressurization inducing cavitation water hammer initiated by a fast valve closure. After valve closure at $t = 0$, the pressure decreases to a saturation pressure, because the liquid moves on. Thus, big vapour bubbles are created. Since the pressure at the reservoir is constant, the liquid flows backwards; the bubble condenses downstream at the (still closed) valve and causes a pressure peak (cavitational hammer) of approximately 45 bar [2]. A detailed validation of the RELAP5 code model by comparing the numerical water hammer results with the experimental investigation data of the water hammer phenomenon performed in the UMSICHT test facility is presented in the paper [1].

As the second example of the two-phase flow water hammer phenomenon, the Cold Water Hammer experiment performed by Forschungszentrum Rossendorf (CWHTF) [3] should be mentioned. The cold water hammer test facility (CWHTF) of FZR was built in order to perform fluid structural interaction effects at condensational hammers. The cold water hammer experiment performed by Forschungszentrum Rossendorf is initiated by the so-called Water Cannon mechanism: sub-cooled water with condensing steam in a vertical pipe. This experiment is interesting and instructive, because it covers a wide spectrum of particularities. One of them is sub-cooled water interaction with condensing steam at the closed end of the vertical pipe at room temperature and a corresponding saturation pressure. The kind of experiment described in the present paper is a simple facility where overpressure accelerates a column of liquid water into the steam bubble at the closed vertical end of the pipe. A severe water hammer with a high pressure peak occurs when the vapour bubble condenses and the liquid column hits the closed end of the pipe [4].

Water hammer sometimes occurs in steam systems (the second type of water hammer). There are two types of water hammer that can occur in steam systems. One type is usually caused by the accumulation of condensate (water) trapped in a portion of horizontal steam piping. The velocity of the steam flowing over the condensate causes ripples in the water. Turbulence builds up until the water forms a solid mass, or slug, filling the pipe. This slug of condensate can travel at the speed of the steam and will strike the first elbow in its path with a force comparable to a hammer blow. The second type of water hammer is actually cavitation. This is caused by a steam bubble forming or being pushed into a pipe completely filled with water. As the trapped steam bubble looses its latent heat, the bubble implodes, the wall of water comes back together and the force created can be severe. Pressure pulses in the presence of liquid and vapour can lead to rapid condensation of the vapour, leading to the so-called condensation-induced water hammer. This type of transients is still not very well understood and so far no codes are available to accurately simulate this type of pressure pulses. Anyhow, the capability of RELAP5 code to simulate condensation-induced water hammer type transients was verified in this work also. For this purpose, a condensation-induced water hammer experiment performed in the steam line of the integral experimental device PMK-2 of the Hungarian Atomic Energy Research Institute (AEKI) [2] was considered.

The paper presents RELAP5 code analyses of the Cold Water Hammer (two-phase flow) and AEKI (condensation-induced water hammer) experiments.

2. RELAP5 CODE ANALYSIS OF WATER HAMMER WAVE BEHAVIOUR EMPLOYING COLD WATER HAMMER TEST FACILITY EXPERIMENTS DATA

The cold water hammer test facility consists of a pressure vessel (tank), a pipe line with two straight sections (one horizontally and one vertically oriented), two 90° bends (curvature radius 306 mm) and a fast-opening valve. The total length of the pipeline is about 3 meters; the outer pipe diameter is about 219 mm and the wall thickness 6 mm. The vertical pipe region is terminated by a lid flange which acts as a bouncing plate [4].

At the beginning, the valve is open and the pipeline is filled with water at room temperature. The top section of the vertical part of the pipeline contains air ($\alpha = 1.0$). The valve is then set to closed position and holds initial pressure in the vessel and in the first part of the pipeline. The air from the evacuation area is then being evacuated by the vacuum pump. The pressure is reduced close to the saturation pressure at a given fluid temperature. The transient starts when the fast-acting valve is opened again. The pressure difference between the tank and the closed end and the condensation of steam in the evacuation area accelerate water in the pipe, and the water hammer appears when the water column is abruptly stopped by the closed end of the pipe. The process can then repeat but with a weaker intensity of the pressure peak due to the dissipation processes. The height of the pressure peak is proportional to the velocity of water at the moment of reaching the closed end. A higher initial pressure in the tank (p_1) and / or a larger evacuation area L_E increase the acceleration and consequently the velocity of water column and hence the pressure peak. The water level in the vertical pipe and in the vessel (before evacuation) varied between 0.15 m and 0.35 m for the different test series. The valve opening time was about 0.021 s. The free volume beneath the bouncing plate was evacuated to evaporation pressure ($p_2 = 0.029$ bar). Gas pressure in the vessel is $p_1 = 1$ bar. With an evacuation height of 0.3

m the pressure amplitude of some 40 bars was obtained [3].

2.1. Description of RELAP5 cold water hammer facility model

The model employing RELAP5 / Mod3.3 code was developed according to the cold water hammer experimental facility data (Fig. 1).

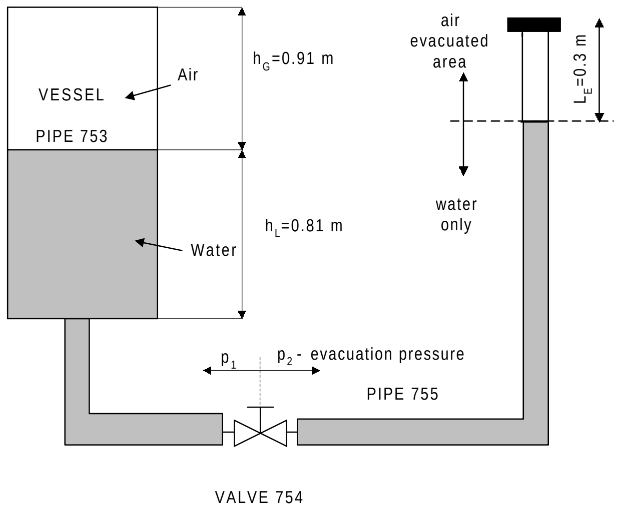

Fig. 1. Geometry of RELAP5/Mod3.3 cold water hammer experimental facility model

In order to obtain the most realistic boundary conditions for wave reflection on the reservoir, it is necessary to represent more precisely gas and liquid volumes in the vessel according to the experiment. In our model, the pressure vessel (tank) is modelled using a RELAP5 pipe component with set initial conditions (pressure, temperature). In experiment No. 290601, the pressure vessel of 800 mm outer diameter and 1.72 m in height contains h_L = 0.81 m of water and h_G = 0.91 m of gas. The volume h_G was modelled using the RELAP5 non-condensable input. Selecting non-condensable input consists of specifying type (Card 110) and mass fraction (Card 115) of species and of selecting options 4, 5, 6 on the volume initial condition cards.

The same pipe component 753, but with the outer diameter 219 mm, is used to simulate the facility pipeline with two straight sections (one vertically and one horizontally oriented) between the vessel and the fast opening valve (component 754). This segment of pipeline 753 in the RELAP5 code is modelled with 16 volumes with the total length of the pipeline 0.8 m, where the length of one computational volume is D_x = 0.05 m. A pipeline downstream the fast opening valve with the same outer diameter 219 mm and two straight sections (one horizontally and one vertically oriented) and with the closed end was simulated using the pipe component 755. The pipeline 755 in the RELAP5 code is modelled with 50 volumes with the total length of the pipeline 2.5 m, where the length of one computational volume D_x = 0.05 m also. The evacuation length L_E = 0.3 m represents the top of the vertical pipe section, which contains a mixture of steam and air. This free volume above this level in real experiment is evacuated through a hole in the bouncing plate by the vacuum pump. This phenomenon was modelled using the RELAP5 non-condensable input also.

2.2. Results of cold water hammer facility test case simulation with RELAP5 / MOD3.3 code

The experiment starts at time t = 0.0 s when the fast opening valve (component 754), which separates two different states in the pipeline, is rapidly opened (valve opening time is 0.021 s). Due to the pressure difference between the tank and the closed end, the liquid column is accelerated into the closed end of the pipe. When liquid water reaches the closed end, a very strong water hammer occurs. After that the velocity in the pipe changes its direction, the pressure is decreased near the closed end, the vapour bubble near the closed end is formed again, and the phenomenon repeats again, but with a lower intensity due to dissipation.

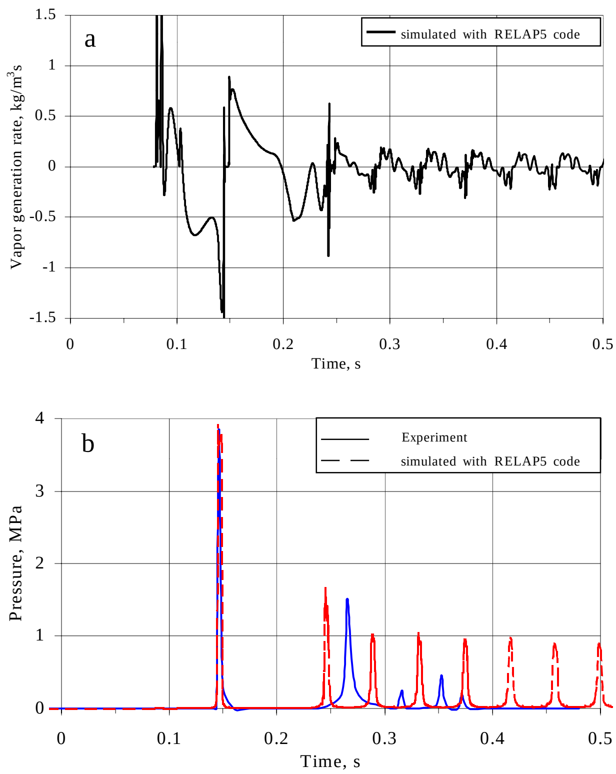

Fig. 2. Pressure time-history and total mass transfer rate per unit volume near the closed end of the pipeline employing the RELAP5 code

The total mass transfer rate per unit volume at the vapour / liquid interface in the bulk fluid for vapour generation / condensation is presented in Fig. 2a. It can be clearly seen from this figure that the pressure peak is formed each time when vapour in the evacuation area is condensed and the water column reaches the closed end. During the pressure peak, the water velocity changes direction, the pressure drops to the saturation level again, and vapour is generated during the flashing process until reflection from the tank. The negative vapour generation rate means condensation and the positive implies evaporation. When the condensation changes into evaporation, the pressure peaks appear.

Graphs in Fig. 2b show calculated pressure time-history in a point just near the closed end of the pipe. The calculated pressure with RELAP5 is compared to the measured pressure. The first pressure peak rises at a time of approximately 0.15 s after the valve closing. This first calculated pressure peak matches very well the measured first pressure peak as well as in UMSICHT facility test case simulation [1], but the following peaks are stronger in calculated results and appear with different frequency (Fig. 2b). However, correct prediction of the first cavitation hammer is the most important while analysing the safe operation of the hydraulic systems.

It can be clearly seen from Fig. 2 that the pressure peak is formed each time when vapour in the evacuation area is condensed and the water column reaches the closed end. During the pressure peak, the water velocity changes direction, the pressure

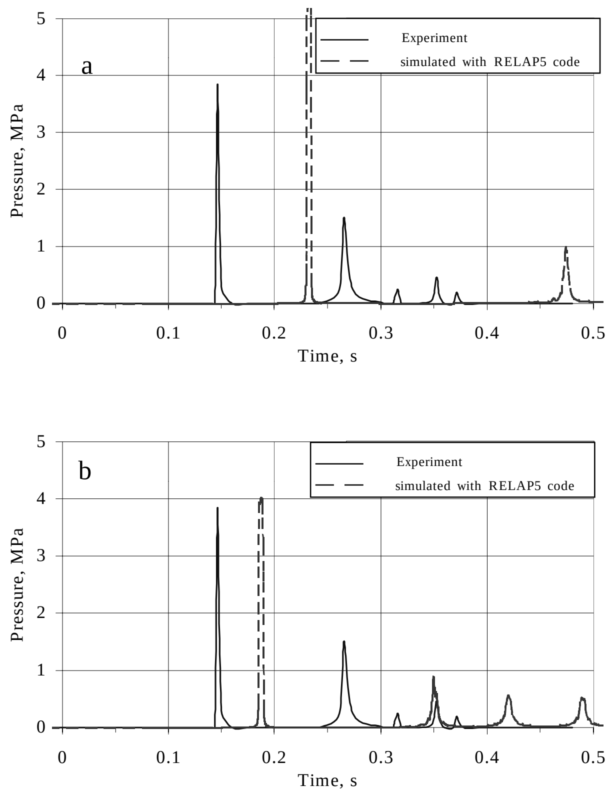

Fig. 3. Pressure time-history near the closed end of the pipeline (component 755) at different evacuation height employing the RELAP5 code:
a – evacuation height (0.3 m); *b* – evacuation height (0.2 m)

drops to the saturation level again, and vapour is generated during the flashing process until reflection from the tank. This is a periodic phenomenon, the number of periods and the frequency of pressure peaks strongly depending on the evacuation height (vapour volume fraction length L_E). To investigate the influence of different initial parameters on the results of calculations, a sensitivity analysis has been performed. The behaviour of the pressure peaks at different evacuation heights (0.3 and 0.2 m) is presented in Fig. 3.

There is no possibility to simulate bends with curvatures using the RELAP5 code, therefore simulations using different lengths of the test facility pipeline have been performed to assess the influence of pipe length on the frequency of pressure peaks and their maximum values. The total length of the actual pipeline is about 3 meters with two 90° bends (curvature radius 306 mm) [4]. Figure 4 shows phenomenon simulation for two cases when the length of the pipeline has been shortened (from 3.3 m to 1.75 m) and when the pipeline has been lengthened (from 3.3 m to 4.85 m).

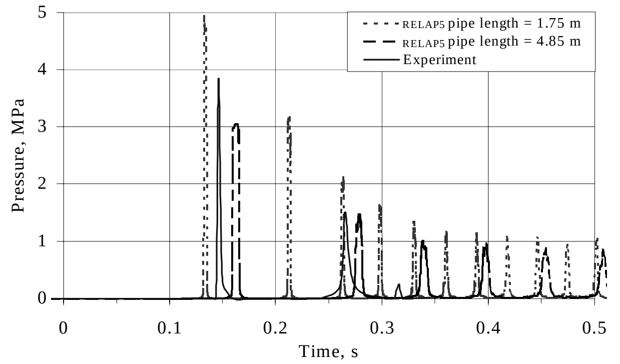

Fig. 4. Pressure time-history near the closed end of the pipeline (component 755) at different length of the facility pipeline employing the RELAP5 code

As is seen from Fig. 4, the length of the pipe as influences not only the pressure peak value, but also the time of pressure peak occurrence. The frequency increases between the two subsequent pressure peaks. The pressure peak decreases and occurs later in the longer pipeline. The peak is reduced in this case because of the pipeline volume increase, and this pressure peak occurs later in the longer pipeline, because the wave of pressure passes longer way up to the closed end of the pipe (component 755) where it is reflected.

Employing the RELAP5 code for water or steam hammer analysis, a very close attention must be paid to the cell (control volume) size (if the pressure wave is expected to have a very rapid rate of increase, then the cell nodalization scheme must be implemented to give a small length dimension) [5]. Detailed investigations for definition of nodalization influence on pressure peaks have been reported in [1].

For modelling the coolant flow rate in the RELAP5 code, non-homogeneous non-equilibrium or homogeneous equilibrium (HEM) options are provided. Comparison of RELAP5 code CWHTF experiment simulation with and without using HEM options is presented in Fig. 5. One can see that experiment simulation without HEM options missed the measured pressure time-history. Therefore, simulation in this experiment was performed using in the RELAP5 code the homogeneous equilibrium options (instantaneous relaxation of heat, mass and momentum transfer) [6].

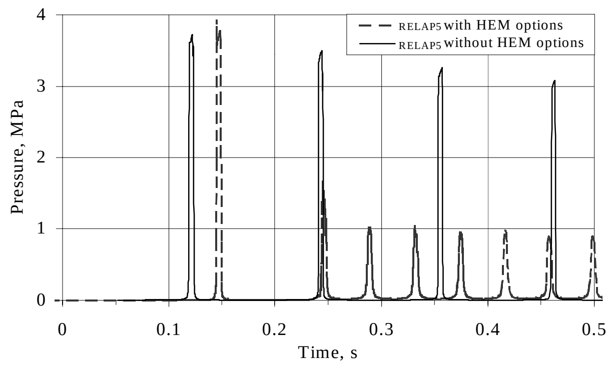

Fig. 5. RELAP5 code simulation of CWHTF experiment with and without employing HEM options

3. RELAP5 CODE ANALYSIS OF CONDENSATION-INDUCED WATER HAMMER EMPLOYING AEKI PMK-2 TEST FACILITY EXPERIMENT DATA

The water hammer test section of the facility consists of a 2.87 m long horizontal pipe with an inner diameter of 73 mm, designed for a maximum pressure of 16 MPa. It is supplied with steam from the dome of the PMK-2 steam generator model. The end of the test section is connected with the condenser unit of this test facility, which substitutes the turbine of the real plant. Both ends of the test section are equipped with inertia blocks with a mass of 200 kg each, serving as 90° bends at the same time. The test section can be isolated by two valves; one is located in the connection with the steam generator head and the other in the connecting line towards the condenser. For cold water supply, a water tank with a volume of 75 l is installed, which is pressurised with nitrogen. The water injection is initiated by opening a valve in the injection line (inner diameter 24 mm).

The experiment performed at the Hungarian Atomic Energy Research Institute (AEKI) is condensation-induced water hammer in the steam-line of the integral experimental device PMK-2 [2]. Horizontal pipe is initially filled with the steam. The transient starts when the sub-cooled water starts to flow into the pipe with a constant mass flow rate. As the flooding of the horizontal section is slow, a stratified flow regime with counter-current flow exists during the first phase of the transient. Vapour is condensing on the liquid–steam interface, and new vapour is entering the pipe from the steam tank. As the flooding continues, the interfacial surface is increasing, the integral vapour condensation rate is increasing, and the vapour velocity is rising until the Kelvin–Helmholtz instability [7] occurs and interrupts the stratification at the head of the liquid wave, and finally a water slug is formed (a steam bubble is entrapped within the sub-cooled liquid). The process becomes very fast after the appearance of the slug: condensation of the entrapped steam bubble accelerates columns of liquid on the both sides of the bubble. A strong water hammer appears when the whole bubble is condensed and two liquid columns collide.

3.1. Description of RELAP5 AEKI PMK-2 test facility model

A model of PMK-2 test facility employing the RELAP5 / Mod3.3 code was developed according to the experiment No. E33. Its simplified scheme is shown in Fig. 6.

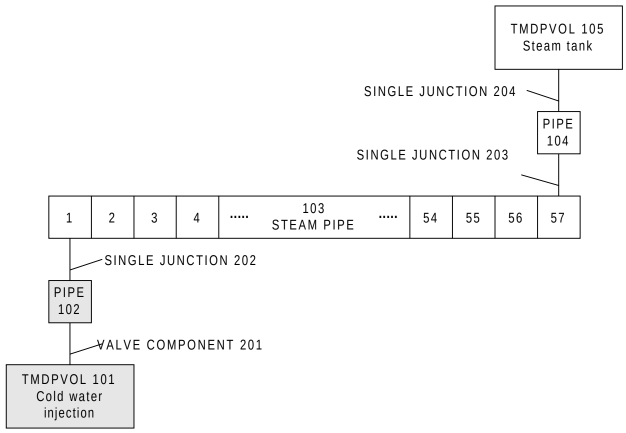

Fig. 6. PMK-2 RELAP5/Mod3.3 code model nodalization scheme

The RELAP5 model includes a horizontal pipe section filled with steam (component 103). Full length of the steam pipe is 2.95 m. The pipe diameter is 77 mm. The main segment of the steam pipe is modelled with 57 volumes with a total length of the pipeline 2.85 m, where the length of one computational volume is D_x = 0.05 m. Two time-dependent volumes (components 101 and 105) with specified constant pressures and temperatures simulate sub-cooled water injection and the steam tank for the entering of new vapour into the steam pipe, respectively. The inlets of the steam pipe for water and steam supply are modelled by the pipe components 102 and 104 respectively with the length of a volume 0.05 m also. The model scheme has been based on investigations presented in [2].

At the beginning of the transient, the pipe (component 103) is the cold water intake with a rather small initial velocity. The water entering the horizontal part of the pipe is horizontally stratified and penetrates into the steam (flood-like). During the flooding, the condensation area increases and therefore increases the condensation rate and steam velocity until the relative velocity between the phases reaches the level where the Kelvin–Helmholtz instability and, eventually, the wave become unstable and grow to block the whole cross-section. When the pipe is blocked with the water slug, the steam bubble is entrapped within the water inlet and water slug, and after condensation of the bubble a very significant water hammer appears [8].

3.2. Results of AEKI PMK-2 experimental facility test case simulation with RELAP5/MOD3.3 code

The initial conditions of the modelled experiment were as follows: pressure inside the pipe p = 14.5 bar, steam and water temperature T_{steam} = 470 K, T_{water} = 297 K and mass flow at the inlet of the pipe G_{water} = 10.11 kg/s (corresponding velocity v = 0.242 m/s).

The transient starts at the time t = 30 s (after the RELAP5 steady-state condition is reached) when the sub-cooled water starts to flow into the pipe with a constant mass flow rate. The horizontal pipe is initially filled with the steam. When the water starts to flow into the horizontal part of the pipe, sub-cooled water and steam are separated and the flow is horizontally stratified during the first phase of the transient. As the flooding continues, the pipe is gradually filled with water (Fig. 7).

At filling with water of the separate segments of the pipe, the fluid temperature drops in them down to the temperature of supplied water (Fig. 8). The pipe is filled with sub-cooled water in approximately 20 s, and this process goes smoothly.

During the flooding of the pipe steam condensation occurs, but the rate of this process is slow (Fig. 9).

The rate of temperature change is the highest in the first segments of the pipe, also steam condensation is fastest here, therefore some oscillations of the pressure are observed at the inlet of the pipe (Fig. 10).

However, it is necessary to note that steam condensation at the liquid–steam interface proceeds

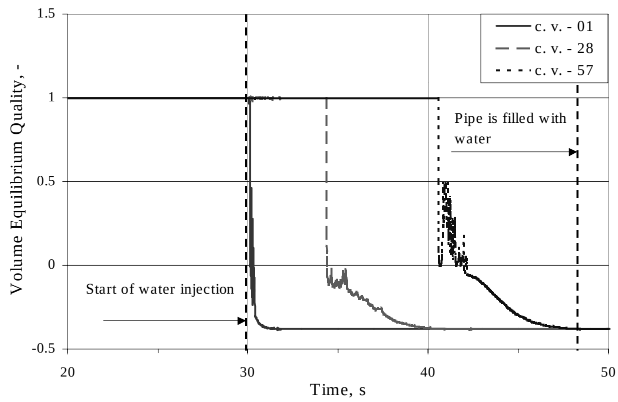

Fig. 7. Simulated volume equilibrium quality in the pipeline (component 103) close to the water injection (c.v. 01), in the middle part of the pipe (c.v. 28) and close to the steam entering (c.v. 57) employing the RELAP5 code

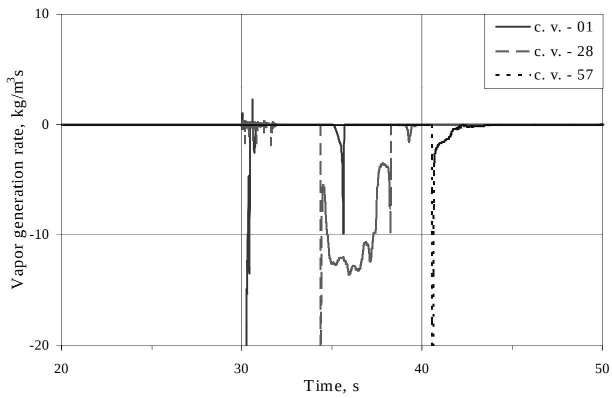

Fig. 9. Simulated vapour generation rate in the pipeline (component 103) close to the water injection (c.v. 01), in the middle part of the pipe (c.v. 28) and close to the steam entering (c.v. 57) employing the RELAP5 code

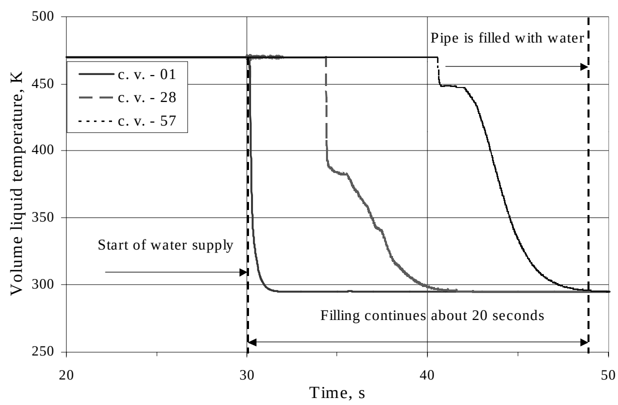

Fig. 8. Simulated volume liquid temperature in the pipeline (component 103) close to the water injection (c.v. 01), in the middle part of the pipe (c.v. 28) and close to the steam entering (c.v. 57) employing the RELAP5 code

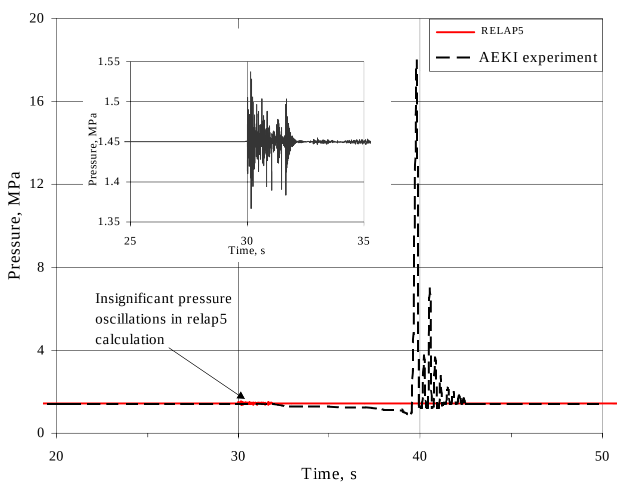

Fig. 10. Pressure history during the most intense water hammer observed close to the water inlet

rather slowly, therefore it does not cause sharp changes of pressure. No water slugs (steam bubbles entrapped within the sub-cooled liquid) were formed at RELAP5 simulation, *i. e.* this code did not predict any pressure peak observed during experiment (Fig. 10).

As has been mentioned in works of specialists from Jozef Stefan Institute, Slovenia, successful simulation of the condensation-induced water hammer requires description of the horizontally stratified and dispersed flow regimes and criteria for transition between both regimes [9]. Such simulations are very sensitive to the interfacial heat and mass transfer correlations and transition correlation between the horizontally stratified and dispersed flow. In RELAP5 simulation, before starting water injection, the horizontal pipe is initially filled with steam. This corresponds to the Mist-pre-CHF flow regime used in the RELAP5 code. When water starts flowing from the vertical volume into the horizontal part of the pipe, sub-cooled water and steam are separated and the flow is horizontally stratified (Fig. 11). Afterwards, when the segment of the pipe is filled with water, a "bubbly" flow regime is established. The horizontally stratified flow regime is characterized by a slow steam condensation, therefore the pressure oscillations are rather small. If only horizontally stratified flow correlations are used, it doesn't form a slug. Because of such flow regimes, no change of the fast condensation of the steam is possible, therefore no pressure peaks typical of water hammer are observed. A pipe is filled with water without any water hammer. If a "slug" flow regime would be generated, the steam condensation would be very fast and we would possibly obtain a strong water hammer similar to the one observed in the PMK-2 test facility experiment.

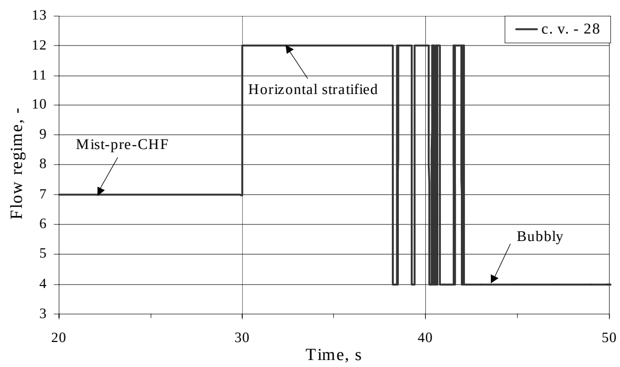

Fig. 11. RELAP5 code flow regime map in the horizontal pipeline (component 103) in the middle part of the pipeline (c.v. 28)

4. CONCLUSIONS

This work aims to analyse the capabilities of the RELAP5 computer code to simulate different water hammer phenomena. For the analysis, experimental investigations of the fast valve closing-induced water hammer test performed at Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT), Cold Water Hammer experiment performed by Forschungszentrum Rossendorf (CWHTF) and the condensation-induced water hammer experiment performed at the Hungarian Atomic Energy Research Institute (AEKI) have been selected. A detailed validation of the RELAP5 code model by comparing the numerical water hammer results with the experimental results on the water hammer phenomenon obtained at UMSICHT is presented in paper [1].

The paper presents a comparison of RELAP5 calculated pressure transient values and those measured at CWHTF and AEKI test facilities after a fast opening of the valve and at appearing a condensation-induced water hammer. The calculated first pressure peak (*i. e.* the time moment of peak appearance and the maximum value of the peak) matches the measured value of pressure very well in the CWHT simulated case, but the following peaks are stronger in the calculated results and appear with a different frequency. Anyway, a correct prediction of the first cavitation hammer is the most important. The value of the first pressure peak is the most dangerous in comparison with the following pressure peaks and can damage the plant's equipment (valves, pumps, pipe bends) up to a leakage of the pipe system.

Analysis of rarefaction wave travels inside the pipe and the condensation of vapour bubbles in the liquid column for CWHTF experiment is presented. The dependence of pressure peaks on evacuation height and the length of the pipeline was investigated. A comparison of the RELAP5 code CWHTF experiment simulation with and without using homogeneous equilibrium options (HEM) is also presented. The comparison has shown that simulation of this experiment should be performed using the RELAP5 code homogeneous equilibrium options (instantaneous relaxation of heat, mass and momentum transfer), because the simulation of the experiment without HEM options missed the measured pressure time-history.

The capability of the RELAP5 computer code to simulate a condensation-induced water hammer was investigated, as the AEKI experiment is very sensitive to the interfacial heat and mass transfer correlations and a correlation for transition between the horizontally stratified and dispersed flow. In RELAP5 code simulation, the steam condensation process occurs slowly, consequently the flow regimes change from those horizontally stratified to bubbly, without formation of a steam slug. Therefore, no strong water hammer similar to that observed in the PMK-2 test facility experiment was obtained in RELAP5 simulation. Results of this analysis showed that the RELAP5 code couldn't capture the condensation-induced water hammer phenomenon, *i. e.* the calculation performed with this code did not predict any pressure peak.

Abbreviations

AEKI – Hungarian Atomic Energy Research Institute
CHF – critical heat flux
CWHTF – cold water hammer test facility
HEM – homogeneous equilibrium model
LEI – Lithuanian Energy Institute
c. v. – control volume
UMSICHT – Fraunhofer Institute for Environmental Safety and Energy Technology

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HIDRAULINIO SMÛGIO SUKELTOS SLËGIO BANGOS TYRIMAS PANAUDOJANT RELAP5 PROGRAMØ PAKETÀ

S a n t r a u k a
Staigus voþtuvo uþsidarymas arba atsidarymas sukelia pereinamuosius procesus su slëgio pulsacijomis vamzdynuose. Ðis nestabilios bûsenos reiðkinys yra susijæs su pokyèiais tarp kinetinës ir slëgio energijos, kuri slëgio pulsacijø atveju gali bûti teigiama arba neigiama. Tai vadinama hidrauliniu smûgiu. Hidraulinis smûgis gali ávykti bet kurioje termohidraulinëje sistemoje, sukeldamas didelá pavojø ðiai sistemai, kadangi slëgiui pasiekus gamintojo nurodytà ribinæ reikðmæ gali átrûkti vamzdis.

Pateikiamas hidraulinio smûgio reiðkinio modeliavimas panaudojant RELAP5 programø paketà, skaièiavimo rezultatø palyginimas su eksperimentiniø matavimø, atliktø Vokietijos CWHTF eksperimentiniame stende, pereinamojo proceso duomenimis staigaus voþtuvo atsidarymo atveju, bei eksperimentiniø matavimø, atliktø Vengrijos atominës energetikos mokslo tyrimo instituto AEKI eksperimentiniame stende, pereinamojo proceso, kuris ávyksta dël ðalto vandens tiekimo á vamzdynà, uþpildytà garu, duomenimis. Darbe taip pat ávertinta vamzdþio ilgio bei ávairiø RELAP5 programø pakete naudojamø moduliø átaka maksimalioms slëgio reikðmëms. Analizë parodë, jog pirmas slëgio pikas, apskaièiuotas naudojant RELAP5 programø paketà, labai gerai sutampa su CWHTF eksperimentiniame stende iðmatuota slëgio verte.

AEKI eksperimento analizës rezultatai parodë, kad RELAP5 programø paketas negali atspindëti hidraulinio smûgio reiðkinio, kuris ávyksta dël ðalto vandens tiekimo á vamzdynà, uþpildytà garu, t. y. kad atlikti skaièiavimai neparodë jokios rimtesnës slëgio pulsacijos, kuri buvo nustatyta eksperimento metu.

Ði patikros analizë pravers ateityje, kuriant RELAP5 programø paketo modelá, kuriuo bus galima atlikti avarijø analizæ, susijusià su hidraulinio smûgio reiðkiniais atominiø elektriniø cirkuliacijos kontûre.

Raktaþodþiai: RELAP5, hidraulinis smûgis, CWHTF, AEKI

Àëüãèðäàñ Êàëÿòêà, Åâãåíèé Óøïóðàñ, Ìèíäàóãàñ Âàéøíîðàñ

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Ð å ç þ ì å
Áûñòðîå çàêðûòèå èëè îòêðûòèå êëàïàíà âûçûâàþò ïåðåõîäíûå ïðîöåññû ñ ïóëüñàöèÿìè äàâëåíèÿ â òðóáîïðîâîäàõ. Ýòî ÿâëåíèå íåóñòîé÷èâîãî ñîñòîÿíèÿ ñâÿçàíî ñ èçìåíåíèÿìè ìåæäó êèíåòè÷åñêîé ýíåðãèåé è ýíåðãèåé äàâëåíèÿ, êîòîðàÿ ìîæåò áûòü ïîëîæèòåëüíîé èëè îòðèöàòåëüíîé âî âðåìÿ ïóëüñàöèé äàâëåíèÿ. Îíî íàçûâàåòñÿ ãèäðàâëè÷åñêèì óäàðîì. Ãèäðàâëè÷åñêèé óäàð ìîæåò ïðîèçîéòè â ëþáûõ òåïëîãèäðàâëè÷åñêèõ ñèñòåìàõ, è ýòî ÷ðåçâû÷àéíî îïàñíîå ÿâëåíèå: åñëè äàâëåíèå ïðåâûøàåò ïðåäåëüíîå çíà÷åíèå äàâëåíèÿ, êîòîðîå óêàçûâàåòñÿ èçãîòîâèòåëåì òðóáû, ìîæåò ïðîèçîéòè ðàçðûâ òðóáû.

Â ñòàòüå ïðåäñòàâëåíû ðàñ÷åòû ÿâëåíèÿ ãèäðàâëè÷åñêîãî óäàðà ñ èñïîëüçîâàíèåì

ïðîãðàììíîãî ïàêåòà RELAP5, ñðàâíåíèå ðàñ÷åòíûõ ðåçóëüòàòîâ ñ ðåçóëüòàòàìè ýêñïåðèìåíòàëüíûõ èçìåðåíèé, âûïîëíåííûõ íà ýêñïåðèìåíòàëüíûõ ó÷àñòêàõ CWHTF (Ãåðìàíèÿ) äëÿ ïåðåõîäíîãî ïðîöåññà ïîñëå áûñòðîãî îòêðûòèÿ êëàïàíà, è Íàó÷íî-èññëåäîâàòåëüñêîãî èíñòèòóòà àòîìíîé ýíåðãèè AEKI (Âåíãðèÿ) äëÿ èçó÷åíèÿ ãèäðàâëè÷åñêîãî óäàðà, ïðîèñõîäÿùåãî èç-çà ïîäà÷è õîëîäíîé âîäû â òðóáîïðîâîäû, çàïîëíåííûå ïàðîì. Òàêæå ïðåäñòàâëåíî âëèÿíèå äëèíû òðóáîïðîâîäà, èñïîëüçîâàíèÿ ðàçíûõ ìîäóëåé ïðîãðàììíîãî ïàêåòà RELAP5 ê ìàêñèìàëüíûì ïèêàì äàâëåíèÿ. Àíàëèç ïîêàçàë, ÷òî ïåðâûé ïèê äàâëåíèÿ, ðàññ÷èòàííûé ñ ïîìîùüþ êîäà RELAP5, ïî ñðàâíåíèþ ñ ýêñïåðèìåíòàëüíûìè äàííûìè ó÷àñòêà CWHTF î÷åíü õîðîøî ñîîòâåòñòâóåò èçìåðåííîìó çíà÷åíèþ äàâëåíèÿ.

Ïîêàçàíà âîçìîæíîñòü ìîäåëèðîâàíèÿ ãèäðàâëè÷åñêîãî óäàðà, ïðîèñõîäÿùåãî èç-çà ïîäà÷è õîëîäíîé âîäû â òðóáîïðîâîäû, çàïîëíåííûå ïàðîì, èñïîëüçóÿ ïðîãðàììíûé ïàêåò RELAP5. Ðåçóëüòàòû àíàëèçà ýêñïåðèìåíòà AEKI ïîêàçàëè, ÷òî ïðîãðàììíûé ïàêåò RELAP5 íå ìîæåò îòðàçèòü ÿâëåíèå ãèäðàâëè÷åñêîãî óäàðà, âûçâàííîå ïîäà÷åé õîëîäíîé âîäû â òðóáîïðîâîäû, çàïîëíåííûå ïàðîì, ò. å. ðàñ÷åòû, âûïîëíåííûå ýòèì ïðîãðàììíûì ïàêåòîì, íå ïðåäñêàçûâàþò íèêàêîãî ïèêà äàâëåíèÿ.

Ïðèîáðåòåííûå çíàíèÿ ïîçâîëÿò ðàçâèòü ìîäåëè ïðîãðàììíîãî ïàêåòà RELAP5 äëÿ àíàëèçà àâàðèé ñ ÿâëåíèåì ãèäðàâëè÷åñêîãî óäàðà, ïðîèñõîäÿùèõ íà àòîìíûõ ýëåêòðîñòàíöèÿõ.

Êëþ÷åâûå ñëîâà: RELAP5, ãèäðàâëè÷åñêèé óäàð, CWHTF, AEKI