**HEFAT2012**
**9$^{th}$ International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics**
**16 – 18 July 2012**
**Malta**

# ANALYSIS OF DYNAMIC PROCESSES DURING THE ACCIDENTS IN A DISTRICT HEATING SYSTEM

Kaliatka A., Uspuras E. and Valincius M.*
*Author for correspondence
Laboratory of Nuclear Installation Safety,
Lithuanian Energy Institute,
Breslaujos str. 3, LT-44403 Kaunas,
Lithuania,
E-mail: valinc@mail.lei.lt

## ABSTRACT

The accidents in the District Heating System are inevitable and they occur due to various reasons. Therefore it is necessary to perform the analysis of possible accident in piping system and to evaluate the consequences. After performing such analysis, it is possible to take the necessary measures to ensure safer and more reliable heat supply, so that the consequences of accidents are less severe. This paper demonstrated the capabilities of developed (using RELAP5 code) district heating network model for the analysis of dynamic processes. Three hypothetical accident scenarios in Kaunas city heating network are presented: (1) blackout in the Kaunas central part pump station; (2) break of heat supply pipe to northwestern district of Kaunas city; (3) rapid pump trip in one of Kaunas city pump stations. The discussion regarding dynamic processes (water hammer effect) in pipelines during the accidents is presented. The results of analysis demonstrated that the pressure pulsations as the accident consequences do not lead to the additional failures in pipelines in district heating system.

## NOMENCLATURE

| | | |
|---|---|---|
| $A$ | [m$^2$] | Cross-sectional area |
| $B_x$ | [m/s$^2$] | Body force in x coordinate direction |
| $C$ | [-] | Coefficient of virtual mass |
| $DISS$ | [W/m$^3$] | Energy dissipation function |
| $FIF$ | [s$^{-1}$] | Interface drag coefficient (liquid) |
| $FIG$ | [s$^{-1}$] | Interface drag coefficient (gas) |
| $FWF$ | [s$^{-1}$] | Wall drag coefficient (liquid) |
| $FWG$ | [s$^{-1}$] | Wall drag coefficient (gas) |
| $g$ | [m/s$^2$] | Gravitational constant |
| $h'$ | [J/kg] | Enthalpy, associated with wall interface mass transfer |
| $h^*$ | [J/kg] | Enthalpy, associated with bulk interface mass transfer |
| $P$ | [Pa] | Pressure |
| $Q$ | [W/m$^3$] | Volumetric heat addition rate |
| $t$ | [s] | Time |
| $U$ | [J/kg] | Specific internal energy |
| $v$ | [m/s] | Phasic velocity |
| $x$ | [m] | Spatial coordinate |

Special characters

| | | |
|---|---|---|
| $\alpha$ | [-] | Void fraction |
| $\Gamma$ | [kg/m$^3$s] | volumetric mass exchange rate |
| $\rho$ | [kg/m$^3$] | Density |

Subscripts

| | |
|---|---|
| $g$ | Gas |
| $f$ | Liquid |
| $m$ | Mixture |
| $w$ | Wall |
| $wf$ | "wall to liquid" |
| $wg$ | "wall to gas" |

## INTRODUCTION

District heating (DH), as demonstrated in many Western European countries experience, is the most acceptable way of heat supply for citizens, counting it's existence from the 1877 in USA. In Europe, the first DH systems (DHS) were installed in Germany in the last decade of 19th century - the Hamburg City Hall in 1893 and Technical University of Berlin in 1894. Beginning with the third decade of 20th century, DH became more popular and were installed in other German cities, as well as in other countries (Denmark, Holland, Switzerland, Sweden, Finland). DHS relied on the development and implementation of a purely commercial point of view. For commercial and planned economy purposes, DH is now very widespread in the colder climate countries: Scandinavia, Eastern and Central Europe and Russia [1]-[4]. This may explain the popularity of DHS, because they provide convenient and economically reasonable heat supply for the consumers [5]-[8].

The first power plant in Kaunas city of Lithuania was established in 1898, "Tilsman and Co." nail factory. It was the first industrial power plant in Lithuania. In 1900 in Kaunas a central public power plant was launched with the total power of 2055 kW. The energy demand of the growing city became higher, therefore, in 1930 "Petrašiūnų" 6.4 MW total power

Combined Heat and Power (CHP) plant was launched. In 1958, a department of thermal networks was established at “Petrašiūnų” thermal power plant, which evolved to a Kaunas thermal networks company in 1963. In 1971, a 160 MW total power Kaunas CHP plant was built in the eastern part of the city. It is connected to the “Petrašiūnų” CHP plant via heat supply network.

“Kaunas Energy” is the company in Kaunas, which is currently the operator of the heat supply network. “Kaunas Energy” provides heat supply for 117 thousand citizens and 3.6 thousand companies and organizations in Kaunas city and Kaunas region. The total installed thermal power in Kaunas city is of 534.2 MWth, of which 265.8 MWth power is currently installed in “Petrašiūnų” CHP plant. The total of about 300 km of pipelines is operated by “Kaunas Energy” in Kaunas city and region. To ensure necessary water circulation in the heat supply network, “Petrašiūnų“ CHP plant and a few pump stations (“Jonavos”, “Šilko” and “Pergalės”) are used.

DH system reliability is a very important factor. However, accidents are inevitable, they occur due to various reasons: wear and tear, equipment failures, pipeline breach and so on [9]. It is therefore necessary to perform accident analysis and evaluate causes and consequences of possible accidents. After performing the analysis, it is possible to take the necessary measures to ensure safer and more reliable heat supply, so that the consequences of possible accidents would be minimized. The analysis of other performed works in the field of the reliability assessment of pipeline networks showed that these works present case studies of specific networks and in most cases the investigations are concentrated on the analysis of the specific phenomena important for reliability (such as degradation mechanisms [10], [11]) or available statistical data [12]. There are lot of research woks of pipeline system reliability assessment based on failure data analysis [13], [14], failure data analysis of pipelines integrated with simplified hydraulics [15], and structural integrity analysis [16]. However, the dynamic processes in DH systems are also very important, and in some cases they may generate significant loadings on pipelines. Such analysis of dynamic processes can provide information about the events, the time of their occurrence and their duration.

This work presents numerical studies, carried out in Kaunas (Lithuania) DH system. Numerical analysis of three hypothetical scenarios is presented: 1) blackout of the pump station; 2) the pipeline break accident scenario; 3) rapid pump trip accident scenario. The analysis was performed using a developed model of the entire DH system for RELAP5 computer code.

## RELAP5 COMPUTER CODE AND A MODEL OF THE HEAT SUPPLY NETWORK OF KAUNAS CITY

In order to perform accident analysis of a DH system, one needs a thermal-hydraulic model of the network. Such a model enables to simulate the system behavior during the accident and evaluate the consequences of potential failures. Since a DH system usually is complicated and quite a large system, employing a computer code for the analysis is reasonable, especially when transients must be taken into account. RELAP5 computer code [17] was selected to perform thermal-hydraulic analysis of transients and accidents taking place in the Kaunas heat supply network.

The RELAP5 hydrodynamic model is a one-dimensional, transient, two-fluid model for flow of a two-phase steam-water mixture that can contain non-condensable components in the steam phase and/or a soluble component in the water phase. The governing equations of the RELAP5 hydrodynamic model are:

Mass conservation (for gas and liquid phase, respectively):

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g\right)+\frac{1}{A}\frac{\partial}{\partial x}\left(\alpha_g \rho_g v_g A\right)=\Gamma_g ,$$

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f\right)+\frac{1}{A}\frac{\partial}{\partial x}\left(\alpha_f \rho_f v_f A\right)=\Gamma_f ;$$

Momentum conservation (for gas and liquid phase, respectively):

$$\begin{aligned}&\alpha_g \rho_g A\frac{\partial v_g}{\partial t}+\frac{1}{2}\alpha_g \rho_g A\frac{\partial v_g^2}{\partial x}=-\alpha_g A\frac{\partial P}{\partial x}+\alpha_g \rho_g B_x A-\\&-\left(\alpha_g \rho_g A\right)FWG\left(v_g\right)+\Gamma_g A\left(v_{gI}-v_g\right)-\left(\alpha_g \rho_g A\right)FIG\left(v_g-v_f\right)-\\&-C\alpha_g \alpha_f \rho_m A\left[\frac{\partial\left(v_g-v_f\right)}{\partial t}+v_f\frac{\partial v_g}{\partial x}-v_g\frac{\partial v_f}{\partial x}\right] ,\end{aligned}$$

$$\begin{aligned}&\alpha_f \rho_f A\frac{\partial v_f}{\partial t}+\frac{1}{2}\alpha_f \rho_f A\frac{\partial v_f^2}{\partial x}=-\alpha_f A\frac{\partial P}{\partial x}+\alpha_f \rho_f B_x A-\\&-\left(\alpha_f \rho_f A\right)FWF\left(v_f\right)+\Gamma_g A\left(v_{fI}-v_f\right)-\left(\alpha_f \rho_f A\right)FIF\left(v_f-v_g\right)-\\&-C\alpha_f \alpha_g \rho_m A\left[\frac{\partial\left(v_f-v_g\right)}{\partial t}+v_g\frac{\partial v_f}{\partial x}-v_f\frac{\partial v_g}{\partial x}\right] ;\end{aligned}$$

Energy conservation (for gas and liquid phase, respectively):

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\rho_g A_g U_g\right)+\frac{1}{A}\frac{\partial}{\partial x}\left(\rho_g \alpha_g U_g v_g A\right)=-P\frac{\partial \alpha_g}{\partial t}-\frac{P}{A}\frac{\partial}{\partial x}\left(\alpha_g v_g A\right)+\\&+\mathrm{Q_{wg}}+\mathrm{Q_{ig}}+\Gamma_{\mathrm{ig}}\mathrm{h}_{\mathrm{g}}^{*}+\Gamma_{\mathrm{w}}\mathrm{h}_{\mathrm{g}}^{'}+DISS_g ,\end{aligned}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\rho_f A_f U_f\right)+\frac{1}{A}\frac{\partial}{\partial x}\left(\rho_f \alpha_f U_f v_f A\right)=-P\frac{\partial \alpha_f}{\partial t}-\frac{P}{A}\frac{\partial}{\partial x}\left(\alpha_f v_f A\right)+\\&+\mathrm{Q_{wf}}+\mathrm{Q_{if}}-\Gamma_{\mathrm{ig}}\mathrm{h}_{\mathrm{f}}^{*}-\Gamma_{\mathrm{w}}\mathrm{h}_{\mathrm{f}}^{'}+DISS_f ,\end{aligned}$$

The two-fluid model implemented in RELAP5 code is able to model single phase and two phase flows. The benchmark tests for water hammer pressure fluctuations in UMSIHT experimental facility were performed and RELAP5 was justified to be able to predict experimental data [18]. The RELAP5 code is used for modelling processes in nuclear reactors, therefore, a very detailed code verification was performed for a wide area of processes (e.g. pipe break accident, etc.), that can be predicted using this software [19]. Ransom and Mousseau [20] have shown that the RELAP5 implementation of the two-fluid model is consistent, stable, and convergent.

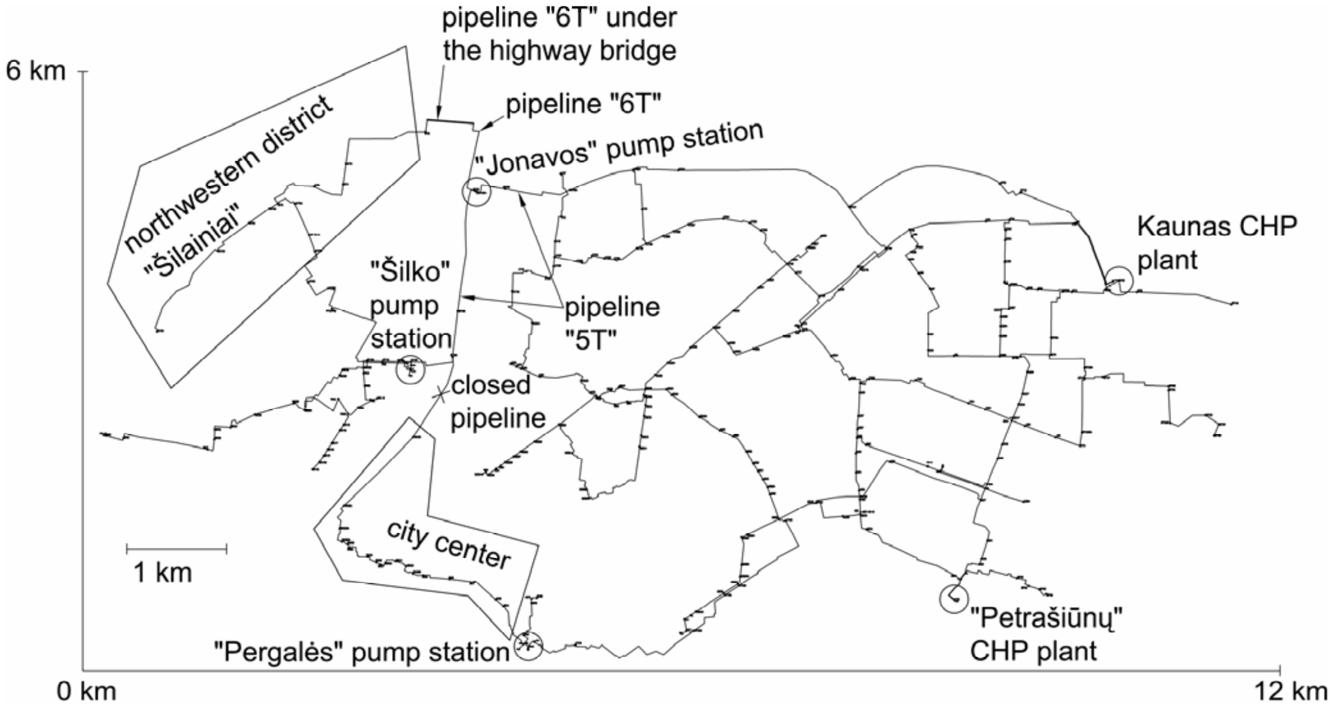

**Figure 1** Layout of Kaunas heat supply network

Table 1. Initial conditions.

| Parameter | Measured value, used for calibration | RELAP5 calculated value |
|---|---|---|
| Pressure at Kaunas CHP plant: | | |
| Supply pressure | 0.78 MPa | 0.78 MPa |
| Return pressure | 0.23 MPa | 0.23 MPa |
| Pressure at "Pergalės" pump station: | | |
| Supply line upstream | | 0.91 MPa |
| Supply line downstream | 0.55 MPa | 0.58 MPa |
| Return line upstream | 0.33 MPa | 0.34 MPa |
| Return line downstream | | 0.8 MPa |
| Pressure at "Šilko" pump station: | | |
| Supply line upstream | | 0.97 MPa |
| Supply line downstream | 0.55 MPa | 0.58 MPa |
| Return line upstream | 0.33 MPa | 0.34 MPa |
| Return line downstream | | 0.71 MPa |
| Pressure at "Petrašiūnų" CHP plant: | | |
| Supply line upstream | | 0.9 MPa |
| Supply line downstream | 0.55 MPa | 0.59 MPa |
| Return line upstream | 0.33 MPa | 0.37 MPa |
| Return line downstream | | 0.72 MPa |
| Flowrate through "Pergalės" pump station | 970 t/h * (269 kg/s) * | 970 t/h (269 kg/s) |
| Flowrate through "Šilko" pump station | 450 t/h * (125 kg/s) *<br>622 t/h (173 kg/s) ** | 622 t/h (173 kg/s) |
| Flowrate through "Petrašiūnų" CHP plant | 250 t/h* (69 kg/s) *<br>198 t/h ** (55 kg/s) ** | 198 t/h (55 kg/s) |
| Supply flowrate from Kaunas CHP plant | 6429 t/h * (1786 kg/s)* | 6429 t/h (1786 kg/s) |

* – measured value at the pump station;

** – value calculated using equation (1).

Basing on Kaunas heat supply network layout shown in Figure 1, a model of the entire network was developed for RELAP5 code. Development of the model was based on the information about the length, diameter, roughness and elevation change of pipe sections in the network as well as the information about heat consumption. Both supply and return lines are modeled using RELAP5 "pipe" elements. A total of 300 "pipe" elements, 250 "valve" elements and 200 "branch" elements were used in the model. At the present stage only the hydraulic phenomena are modeled – the heat loses in the pipelines and heat removal in the consumers heating systems are not modeled. The consumers heating systems are modeled using valve elements, connecting the supply and return lines in the specified places of the heat supply network. The required water flow through the consumers' heating systems was set by tuning the flow energy loss coefficient for the valve, which models the specified consumer heating system. In such way all connected consumer heating systems were modeled. The main hot water source (Kaunas CHP plant) is modeled by two volumes (one for hot water supply and one for water return line). The pressures in these volumes are set constant, depending on the investigated operation regime (in this case it was 0.78 MPa for water supply source, and 0.23 MPa for water return sink). All pressure values in this paper are given as gauge pressure. Kaunas CHP plant is modeled as a constant pressure unlimited water source and sink. The pumps in "Pergalės", "Šilko" and "Petrašiūnų" CHP plant are modeled by special RELAP5 pump models, with specified capacities and pump head data.

Characteristics of the pumps will have an effect on the overall transient characteristics of the district heating system.

The main parameter is the inertia of the pump rotor and pump velocity. For the first case (pump station blackout) the moment of inertia of the pump was $3.7412 \cdot 10^3$ kg·m$^2$ and rated pump velocity was $3.920 \cdot 10^4$ rad/s was used, as it was given in the pump datasheet. The effect of pump inertia is demonstrated in the third (rapid pump trip) accident scenario.

The measurement data of water flows and pressures were used to calibrate the model with the normal operation regime of the actual heat supply network and to reach the correct steady state initial conditions (see Table 1) before modeling accident scenarios.

The calculated values (Table 1) is different than measured in some pump stations. The reason for these differences is the approach, used to calculate consumers demand. In this case, the input data for the model is network geometry, pressures at the Kaunas CHP plant, water flowrate from the plant and the consumers installed power. The flowrate consumption at consumer's connecting point is calculated by the equation (1). The actual flowrate consumption usually is different than calculated using this simple calculation, but there is no possibility to measure all consumptions at once with one specific operational regime.

$$Flow_{consumer} = \frac{Flow_{plant} \cdot Installed\ power_{consumer}}{Total\, Installed\ power\ of\ the\ network}. \quad (1)$$

The objective of this paper is dynamic processes in DH systems, e.g. – water hammer effect. The water hammer is a pressure or momentum transient in a closed system caused by a rapid change in fluid velocity. Such transient can appear due to start-up or trip of pump, fast opening or closure of valve. In the case of sudden closure of valve, the mass of water before the closure point is still moving forward with some velocity, building up a high pressure and shock waves. Also closure of valves means the sharp change of velocity of water flow, thus the kinetic energy of water is transformed to pressure pulse.

The accuracy of water hammer calculation results, based on benchmarking analysis of water hammer effects at UMSICHT facility (Fraunhofer Institute for Environmental, Safety and Energy Technology) was analysed in the paper [21]. In this paper the influences of following parameters to calculation results are investigated using RELAP5 Mod 3.3 model for water hammer event analysis:

- calculation time step;
- control volume size;
- closure time of valve.

The remaining parameters (wall roughness and flow energy loss coefficient [21]) were defined in the stage of model development.

In the system thermal-hydraulic code RELAP5 [17], according the scheme of calculation, the change of pressure inside the single volume affects the adjacent volumes only with the next time step. Therefore, for the water hammer analysis the following condition has to be satisfied:

$$\Delta l \geq a * \Delta t\,, \quad (2)$$

where $\Delta l$ – length of a volume (m); $a$ – sound velocity of the medium (m/s); $\Delta t$ – time step of calculation (s).

The maximum value of the sound velocity for the water is approximately $a$ = 1500 m/s. Thus, to fulfil the requirement of equation (2) the close attention must be paid to the control volume size, where the water hammer is expected to occur and time step of calculation. The time step was assumed 0.01 s, thus length of a volume $\Delta l \geq 15$ m. In the present RELAP5 model the length of volume was assumed $\Delta l \approx 35$ m. The influence of node length on calculation results is demonstrated in the second (pipeline break) accident scenario.

## ANALYSIS OF BLACKOUT IN "PERGALĖS" PUMP STATION

Kaunas city center is located at lower elevation than the heat source (about -40 m), and "Pergalės" pump station (see Figure 1) is used to decrease the pressure at lower elevation. A throttle valve is installed on the supply line and a pump is installed on the return line. A schematic layout of "Pergalės" pump station is presented in Figure 2. As it can be seen from the scheme, the supplied flow is throttled by a throttle valve (2) from 0.9 MPa down to 0.55 MPa and supplied to the city center. The pressure of returning water is increased from 0.33 MPa up to 0.8 MPa by pumps (3).

In case of blackout in "Pergalės" pump station, pumps stop, water is not pumped from the city center, and the pressure starts increasing. To prevent the pressure increase to dangerous limit and to avoid accidents (e.g. damaging consumers' heating systems), the pump station is equipped with a safety system (Figure 2): valve (1) automatically opens and reduces the pressure in the supply line; of the valve (2) automatically closes and terminates the water supply to the city center; check valve (4) prevents the backflow; the safety relief valve (5), which prevents overpressure in circuit (in case of accident the heating water is discharged through this valve to the environment). The activation of these safety systems decreases the pressure at consumers connection points and prevents system from failures.

After the opening of the safety relief valve, the water is discharging to the environment, and the pressure decreases to atmospheric. Since the pump is not operating, the water flow direction reverses.

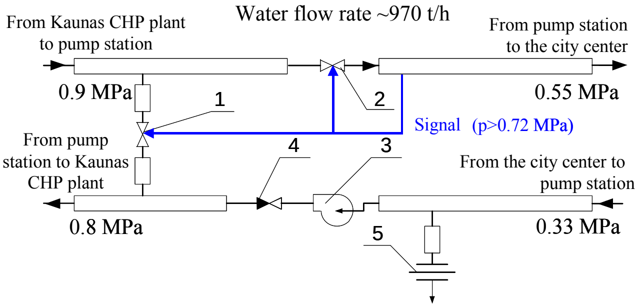

**Figure 2** Simplified layout of Kaunas central part ("Pergalės") pump station. 1 - pump bypass line valve; 2 - throttle valve; 3 – pump; 4 - check valve; 5 - safety relief valve (opens permanently if pressure exceeds 0.71 MPa)

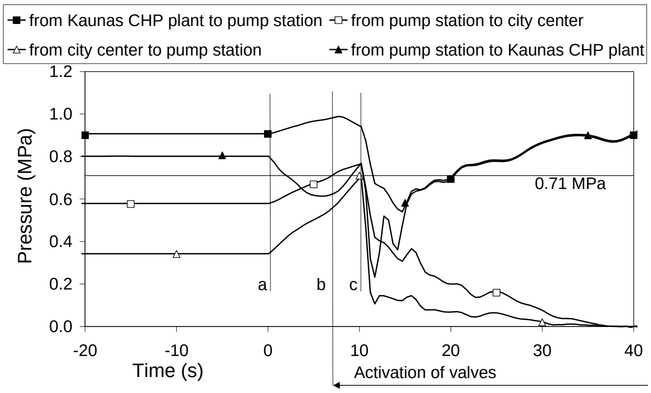

**Figure 3** Pressure in "Pergalės" pump station, when all safety systems operate as designed: a - blackout (t = 0 s), b - pressure in water supply line downstream of the throttle valve reaches 0.71 MPa (t = 7 s), c – pressure in the return line upstream of the pump reaches 0.71 MPa (t = 11 s) – opening of the relief safety valve

Figure 3 shows pressure change in the pump station. After the pump trip (Figure 3, a), the pressure in the city center starts increasing until it reaches 0.71 MPa downstream the throttle valve (Figure 3, b). Then the throttle valve starts closing while the bypass valve starts opening at the same time. These valves open/close quite slowly, therefore, the pressure in the return line from the city center upstream the pump station reaches 0.71 MPa and the relief valve opens (Figure 3, c).

Rapid closure of a check valve may cause water hammer effect, as demonstrated in [18]. A more detailed study of a check valve in "Pergalės" pump station was carried out, using a fine-mesh nodalization (0.5 m) and appropriate time step as recommended in [21]. The pressure at the check valve is presented in Figure 4.

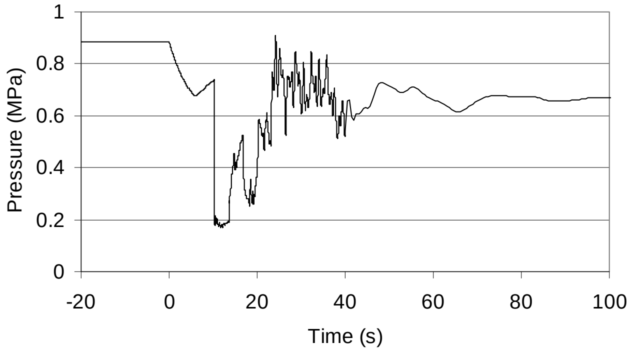

**Figure 4** Pressure downstream (or upstream if reversed flow) of the check valve in "Pergalės" pump station

As we can see there is no water hammer effect (no extreme pressure increase) observed for a given case. This is due to a fact, that a check valve is a wafer type valve (see Figure 5). If the forward flow decreases, it automatically closes due to a flapper weight. Therefore, the back flow cannot accelerate and the closure of a valve does not lead to water hammer effect. There are some pressure fluctuations observed, but they are not extremely large.

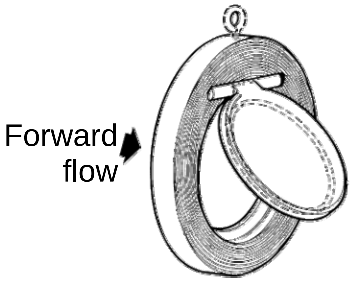

**Figure 5** Wafer type check valve, installed in "Pergalės" pump station

## ANALYSIS OF WATER LOSS IN CASE OF SUPPLY LINE BREAK

In January 2009, there was a bridge accident in Kaunas city bypass highway. The support of this bridge failed and the one of two carriageways fell down by about 20 cm. The bridge dangerously leaned on the heating water pipes, installed under the bridge. Fortunately (it was winter and air temperature was low) that did not lead to the pipe break. Heating water line was closed, the water was discharged from this dangerous section, and the heat to the Kaunas city northwestern district "Šilainiai" was established through roundabout pipelines.

If the bridge accident would have caused a pipeline break (at least one pipe), a huge amount of hot water would be discharged through the break, and this could have unpredictable consequences – it could scour the embankment of the bridge, flood the motorway under the bridge and so on. Therefore, a thermal-hydraulic analysis of this scenario was performed, to determine the loss of heating water from Kaunas heat supply network and to check for possible pressure fluctuations caused by discharged hot water, which could lead to damage of pipelines or equipment in other parts of the network.

A 0.5 m diameter heating water supply pipe guillotine break was assumed in the analysis (the break of supply pipeline was assumed, since supply pressure is higher than return pressure and reaches about 0.76 MPa). After the break of such a large pipe, the pressure would quickly decrease in the entire heat supply network and the main heat source (Kaunas CHP plant) would isolate itself from the network. Only supplementary water would be available from the emergency water supplies after the accident, with the maximum flow of 70 tons per hour. Conservatively it was assumed that the pipe break is a guillotine type – i.e. pipe breaks with full cross section perpendicular to the axis of the tube, the ends of the broken pipe passes each other so that heating water is discharged from both ends to the opposite directions and the streams do not interfere.

Water supply pipe guillotine break nodalization scheme of RELAP5 model is shown in Figure 6. To ensure proper modeling of the transient processes, the pipelines connected to the break location were modeled with similar node lengths of about 25 m.

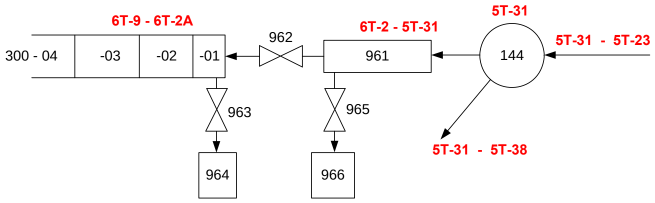

**Figure 6** Water supply pipe guillotine break nodalization scheme

It was assumed in the model that the event (pipe break) starts at t = 0 s. Kaunas CHP plant is disconnected after the break, and 70 t/h of water is supplied into the network. In the analysis it was assumed that no actions are taken to stop the water leak. A water loss during the first 4.5 hours was analyzed and the results of the analysis are presented in Figure 7 – Figure 9. Water discharge through the break is presented in Figure 7. The heating water discharge from Kaunas city northwestern district "Šilainiai" side stops after an hour, but from the other side it lasts for more than 5 hours. About 5,000 tons of heating water is discharged through the break during the first 4.5 hours (Figure 8).

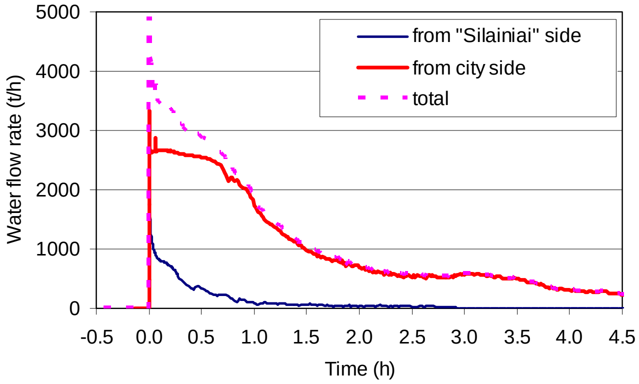

**Figure 7** Water discharge through the broken heating water supply pipe under the bridge

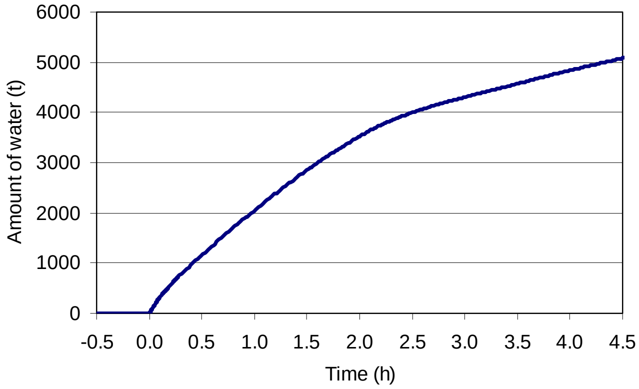

**Figure 8** Integral quantity of water discharged through the break

Pressure change in the supply pipeline at "Jonavos" pump station is shown in Figure 9. The supply pipe pressure suddenly decreases to 0.4 MPa, and then decreases slowly.

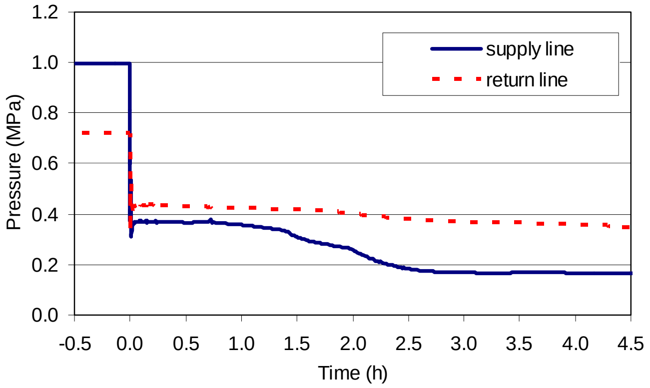

**Figure 9** Pressure change in the supply and return pipelines in "Jonavos" pump station

The results of calculations are sensitive to the nodalization (node size) assumed in the modelling. The influence of node size (length) on the behaviour of pressure in water return line is presented in Figure 10. There is a time period from 0.7 h to 2.7 h when pressure oscillations occur if too long nodes are used for the calculations. As it is seen from presented figure, the use of long nodes leads to numerical oscillations in pressure behaviour. The calculations were performed using different lengths of nodes and trial showed, that the node length of 32.5 m is optimal for the developed Kaunas district heating pipelines model.

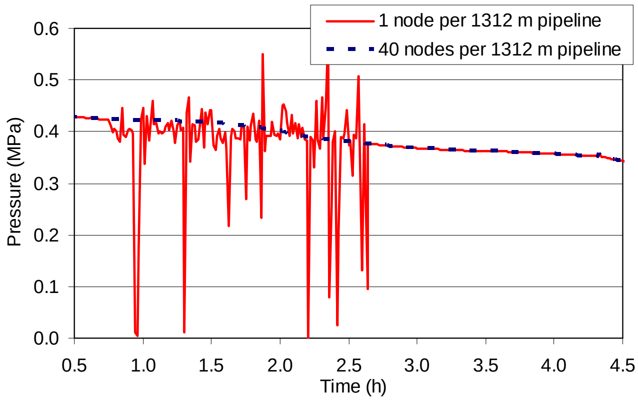

**Figure 10** Numerical pressure fluctuations in the return line at "Jonavos" pump station using two different nodalizations

## ANALYSIS OF RAPID PUMP TRIP IN A PUMP STATION

The heating water to the northwestern and western districts of Kaunas is supplied via pipelines "6T" and "5T" (see Figure 1). In the case of hypothetical bridge failure described in the previous section, the pipeline "6T" had to be closed. The lack of heat supply could be compensated by activating the backup boiler-house. However, the cost of produced heat in the backup boiler-house is higher than in the CHP plant. Therefore, activating the "Jonavos" pump station would be reasonable, which could pump the water through return pipe back into CHP plant and maintain sufficient heating water flows.

"Jonavos" pump station, is a category III power consumer, therefore uninterruptible power supply is not guaranteed. Sudden stop of water pumps would cause pressure pulsations in the heat supply network. The amplitude of these pressure pulsations and possible damage to the heat supply network and the equipment were analyzed in this work.

It was assumed during the modelling, that pipeline from "Jonavos" pump station to the pipeline under the bridge "6T" is closed. The pressure in Kaunas CHP plant supply line is 0.78 MPa, and in the return line – 0.23 MPa. The pressure in water supply line in "Jonavos" pump station is 1.03 MPa. The pumps in the pumps stations increase the pressure in water return line. The pressure upstream of the pumps is 0.678 MPa, downstream – 0.746 MPa. Water flow through the "Jonavos" pump station is assumed 1550 tons per hour and the total flow of water from Kaunas CHP plant is 7300 tons per hour. With this flow from CHP plant, the return heating water temperature of 55 $^{o}$C and supply water temperature of 98 $^{o}$C, the thermal power is 366 MW, which is normal heat consumption during moderately cold winter weather.

Nodalization scheme of modeled "Jonavos" pump station is presented in Figure 11. There are two pumps in the operation in the "Jonavos" pump station: one operates at its nominal power, and the other maintains the target pressure. These pumps are modeled as element "951" in the RELAP5 model, a pressure regulator valve is modeled as element "953". As it can be seen from the scheme, that if the pumps "951" stop, water flows through the check valve (element "954"). This valve is closed while pumps are operating.

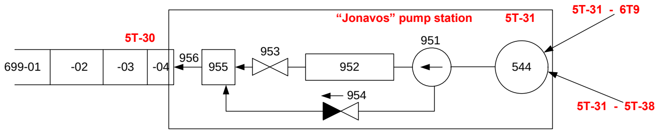

**Figure 11** Nodalization scheme of "Jonavos" pump station

The real moment of inertia of the pumps was unknown, therefore, the analysis was performed for two cases: (a) slow pumps trip (pumps stop within 70 s) and (b) rapid pumps trip (pumps stop within 4 seconds).

It was assumed that the event (pumps stop) occurs at t = 0 s in the modeling. Two cases were analyzed to determine how much pump characteristics (inertia) may affect the pressure fluctuations. It can be seen, that after pumps stop, a check valve opens, and the water flows through the opened valve. A small portion of water flows through the stopped pumps (Figure 12).

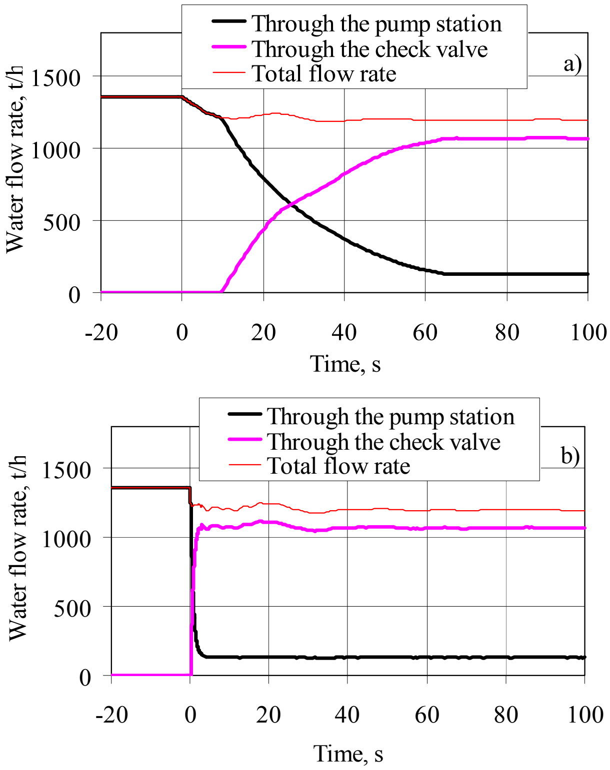

**Figure 12** Water flows in "Jonavos" pump station: a) slow pumps trip and b) rapid pumps trip

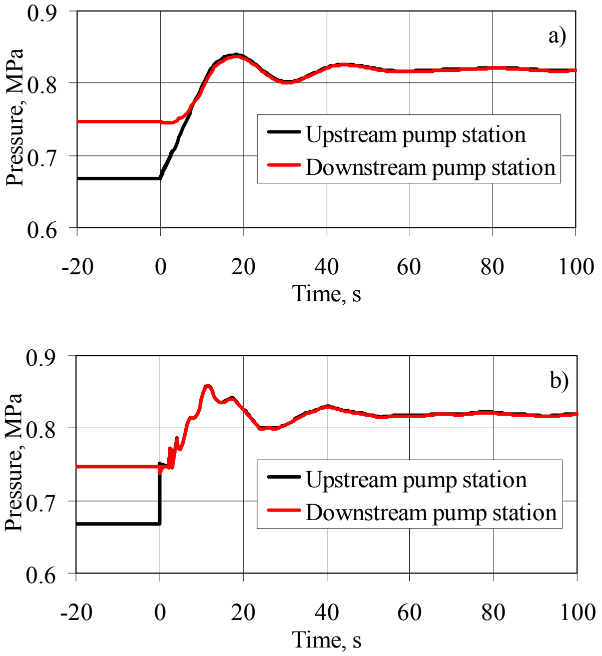

**Figure 13** Pressure gauge in the return pipeline upstream and downstream the "Jonavos" pump station: a) slow pumps trip and b) rapid pumps trip

A total water flow rate decreases by only about 8%. Pressure downstream the pump station increases a little because of pumps stop, and the pressure upstream the pump station increases by about 0.1 MPa (Figure 13). Pump inertia practically does not increase the pressure pulsations in pipelines. Pressure difference between supply and return line decreases (Figure 14) due to stop of "Jonavos" pump station - it would worsen the heat supply for consumers at the upstream of the "Jonavos" pump station.

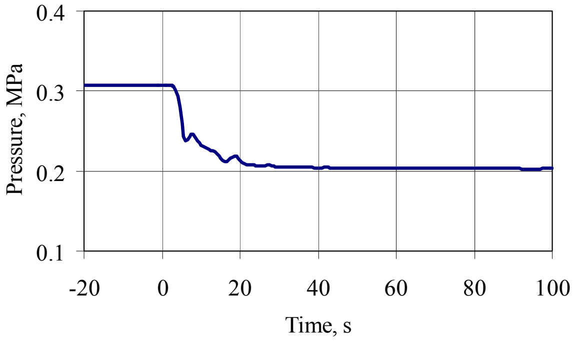

**Figure 14** The pressure difference in the pipelines at the end of northwestern district of Kaunas (pipeline "6T-13" .. "6T-18")

The performed analysis shows that during a transitional regime due to rapid pumps trip in "Jonavos" pump station, pressure pulsations may occur. However, they are insignificant and should not cause additional damages in the heat supply network.

The fast close or opening of valve in the pipeline can lead to strong pressure pulsations in this pipeline (water hammer phenomena). This phenomenon was analysed performing benchmarking of test, performed in UMSICHT facility [18]. In the case of valve closure in Kaunas city DHS pipeline, pressure pulsations after the trip of pump and opening of check valve are low. This is because quit big diameter of pipelines and significantly low water velocity in pipelines.

## CONCLUSIONS

The computer code RELAP5, developed for the modeling of accidents in nuclear reactors, was adapted to model processes in a district heating network. Three hypothetical accident scenarios in Kaunas city heating network were analysed: (1) blackout in the Kaunas central part pump station; (2) break of heat supply pipe to northwestern district of Kaunas city; (3) rapid pump trip in one of Kaunas city pump stations.

Analysis of blackout of "Pergalės" pump station showed, that the if safety systems are operating as designed, the activation of these safety systems decreases the pressure at consumers connection points and prevents system from failures. The water hammer phenomenon would not occur in case of this scenario. This is mainly due to check valve wafer type design, which prevents reversing and accelerating the water flow before the closure of the valve.

Analysis of loss of water due to guillotine break of 0.5 m diameter supply line break showed, that assuming no actions being taken to stop the leak, about 5,000 tons of heating water will be discharged through the break within 4.5 hours. The fast change of water flow in pipelines after pipeline break leads to pressure change in the supply pipeline. The supply pipe pressure suddenly decreases to 0.4 MPa, and then decreases slowly.

The pressure pulsations in the DHS pipelines may occur due to rapid trip of pump in pump station. The performed analysis of pump trip in "Jonavos" pump station showed, that the pressure pulsations, even assuming very rapid pump trip (when the pump rotor has low moment of inertia and stops rotating within a few seconds), are insignificant and should not cause additional damages in the heat supply network.

The performed analyses allowed to investigate the dynamic processes in DHS pipeline in case of various accidents. This allows foreseeing the mitigation measures in order to minimise the consequences of failures and to increase the reliability of heat supply for the consumers.

## ACKNOWLEDGMENT

This research was funded by a grant (No. ATE-10/2010) from the Research Council of Lithuania. This research was performed in cooperation with the SC "Kaunas Energy".

## REFERENCES

[1] Verbruggen A., van Speybroeck P.. District heating for the city of Ghent: Results of a project appraisal study, *Energy Economics* 1982, Vol. 2, No. 4., 1982,pp. 111-120.

[2] Iacobescu F., Badescu V.. Metamorphoses of cogeneration-based district heating in Romania: A case study, *Energy Policy*, Vol. 39, 2011, pp. 269-280.

[3] Difs K., Danestig M., Trygg L., Increased use of district heating in industrial processes – Impacts on heat load duration, *Applied Energy*, Vol. 86, 2009, pp. 2327-2334.

[4] Gabrielaitiene I., Bøhm B., Sunden B., Modelling temperature dynamics of a district heating system in Naestved, Denmark—A case study, *Energy Conversion and Management*, Vol. 48, 2007, pp. 78-86.

[5] Persson U., Werner S., Heat distribution and the future competitiveness of district heating, *Applied Energy*, Vol. 88, 2011, pp. 568-576.

[6] Lund H., Möller B., Mathiesen B.V., Dyrelund A., The role of district heating in future renewable energy systems, *Energy*, Vol. 35, 2010, pp. 1381-1390.

[7] Torchio M.F., Genon G., Poggio A., Poggio M., Merging of energy and environmental analyses for district heating systems, *Energy*, Vol 34, 2009, pp. 220-227.

[8] Möller B., Lund H., Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. *Applied Energy*, Vol. 87, 2010, pp. 1846-1857.

[9] Chang Y.S., Jung S.W., Lee S.M., Choi J.B., Kim Y.J., Fatigue data acquisition, evaluation and optimization of district heating pipes. *Applied Thermal Engineering*, Vol. 27, 2007, pp. 2524-35.

[10] Efimenko LA, Konovalova OV, Efimenko AM. Evaluating pipeline causes from metal structural mechanics states. Chem Pet Eng 1999;35:56–8.

[11] Baker TN, Rochfort GG, Parkins RN. Pipeline rupture – conclusion. Stresscorrosion cracking studies prompt changes in pipeline operating conditions. Oil Gas J 1987;2:37–8.

[12] Seventh Report of the European Gas Pipeline Incident Data Group. 1970–2007 [Doc. Number EGIG 08. TV-B.0502, 2008].

[13] Suna Y, Ma L, Morris J. A practical approach for reliability prediction of pipeline systems. Eur J Oper Res 2009;198(1):210–4.

[14] Crawley FK, Lines IG, Mather J. Oil and gas pipeline failure modelling. Process Saf Environ Prot 2003;81(1):3–11.

[15] Han ZY, Weng WG. An integrated quantitative risk analysis method for natural gas pipeline network. J Loss Prev Process Ind 2010;23:428–36.

[16] Amirat A, Chateauneuf A, Chaoui K. Reliability assessment of underground pipelines under the combined effect of active corrosion and residual stress. Int. J Pressure Vessels Piping 2006;83(2):107–17.

[17] The RELAP5 Code Development Team, RELAP5/MOD3.3 Code Manual, *NUREG/CR-5535, INEL-95/0174*, 1995.

[18] Kaliatka A., Ušpuras E., Vaišnoras M., Justification of RELAP5 code for modeling water hammer phenomenon by employing the Umsicht test facility data. *Power Engineering*, Vol. 3, 2004, pp. 1-6.

[19] Moore R.L., Sloan S.M., Schultz R.R., Wilson G.E. RELAP5/MOD3 code manual volume VII: summaries and reviews of independent code assessment reports. *NUREG/CR-5535; INEL-95/0174*. 1996.

[20] Ransom V.H., Mousseau V.A., Convergence and Accuracy Expectations for Two-Phase Flow Simulations. *Proceedings of Canadian Nuclear Society International Conference on Simulation Methods in Nuclear Engineering*, Montreal, Canada. 1990.

[21] Kaliatka A., Uspuras E., Vaisnoras M., Benchmarking analysis of water hammer effects using RELAP5 code and development of RBMK-1500 reactor main circulation circuit model, *Annals of Nuclear Energy*, Vol. 34, 2007, pp. 1-12.