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Modelling of valve induced water hammer phenomena in a district heating system

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ABSTRACT

Water hammer is one of the most dangerous phenomena in liquid or liquid/gas systems, because it can cause failure of the system integrity. A water hammer in a district heating system is investigated in this article. The reasons of the water hammer phenomenon are investigated quite well in the scientific literature. However, the conditions when the water hammer may occur depend on the specific system and the thermal–hydraulic specifics of the system. In this paper an accident scenario of blackout in a pump station is investigated and the analysis of fast check valve closure due to a pump station blackout is presented in the paper. A computer code RELAP5 was employed to perform accident analysis. The analysis showed that under some hypothetical conditions, pressure peak could exceed the value used during the hydraulic tests of the pipelines.

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 the velocity change. Generally water hammer can occur in any thermal–hydraulic systems and it 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. Water hammer features are described in excellent textbooks, such as Wylie and Streeter (1985), Moody [7] and Chaudhry and Hanif [1].

There are three basic types of severe water hammer occurring at piping systems that can result in significant system damage [12]:

- valve-induced water hammer;
- void-induced water hammer;
- condensation-induced water hammer.

The cases, when the water hammers occurred in the pipeline systems as the consequences of standard actions such as start-up or shut-down of systems and components, opening or closure of valves, switch-over from one component (e.g. pump, heat exchanger) to another, belong to the first type of water hammer. The most severe water hammers may be caused due to rapid isolation valve closure.

The interaction of sub-cooled water with condensing steam in a pipeline may be the cause of a void-induced (second type) water hammer. In this case, the pressure difference between the part of pipeline filled by water and part where the condensation of steam appears accelerates water in the pipe, and the water hammer appears when the water column is abruptly stopped by the closed end of the pipe.

The third type of water hammer usually is related to steam systems. Pressure pulses in the presence of liquid and vapour (for example due to accumulation of condensate (water) trapped in a portion of horizontal steam piping) can lead to rapid condensation of the vapour, leading to the so-called condensation-induced water hammer.

In this paper, a water hammer phenomenon in a district heating network was analysed. Generally, the sub-cooled single phase water is used as a coolant in district heating systems (DHS), therefore, we concentrating only on the first type – water hammer due to a fast valve operation.

2. Modelling of valve-induced water hammer phenomena in pipeline systems

To understand the processes in pipeline system in the case of first type of water hammer (valve-induced water hammer), the experimental investigations performed at Fraunhofer Institute for

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Nomenclature

CHP	combined heat and power (plant)
DHS	district heating system
FSI	Fluid–Structure Interaction
D_x	length of computational volume (m)
δt	time step (s)
δt_{crnt}	courant time step (s)
t	time (s)

Environmental, Safety and Energy Technology, UMSICHT (Fig. 1) should be mentioned [2]. Water hammer tests conducted in this facility – depressurization inducing cavitation water hammer initiated by a fast valve closure. After valve closure at time $t = 0$ s, the pressure decreases to 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).

To understand and be able to model this phenomenon, the experimental data [8] obtained in the UMSICHT experimental facility was employed. In Lithuanian Energy Institute, the water hammer has been numerically investigated since the year of 2000 [9]. For the numerical modelling the system thermalhydraulic code RELAP5 was used taking into account that there is wide experience in use of this program tool in the institute.

The computer code RELAP5 [4] was developed by Idaho (U.S.) National Laboratory for the analysis of nuclear reactors cooling circuit failures. Fluid flow is described by one-dimensional, non-homogeneous and non-equilibrium two-fluid model, using six equations: energy, mass and momentum conservation equations for both liquid and vapour phases. It uses flow regime dependent approach, semi-empirical closure equations of interfacial energy, mass and momentum transfer are used in the conservation equations. Also, specific modules to model critical flow, heat release, pumps, valves, branches, etc., are implemented into the code. The RELAP5 code, being highly generic, has found use in a variety of fluid transient problems, including water hammer analysis in piping systems [10]. Unfortunately, the RELAP5 code has a significant limitation in prediction of complex water hammer phenomena. The standard water hammer and the Fluid–Structure Interaction (FSI) theory consider the correction of the speed of sound in a fluid as a consequence of the pipe elasticity. Obviously the elasticity of tubes also influences the speed of sound and one of the features not covered by RELAP5 code is elasticity of the pipe wall, which affects the propagation of the pressure waves in the pipe. Pressure waves are weaker if pipe elasticity is taken into account. Unfortunately, but FSI models are not integrated into RELAP5 code. Despite the fact that RELAP5 is not the most appropriate or user-friendly code for solving water hammer problems, but it is well documented, easy to access and able to produce reliable results, and therefore is commonly used for such purposes in many countries. For instance, the RELAP5 code has been applied to study the water hammer event due to clearing of a water slug downstream of a safety relief valve [3], to investigate water cannon phenomenon [10] and the dynamic of a liquid slug driven by a non-condensable gas [11]. In all these studies, it has been demonstrated that the code reasonably predicts the physical behaviour of the transient event.

The benchmarking analysis of experimental measurements and calculation results was performed by LEI specialists [5]. Sufficiently close agreement between the calculation results using RELAP5 code and the measured values of peak pressure in test case performed at UMSICHT test facility was found (Fig. 2).

During simulation of UMSICHT experiment it has been noticed that initial values of input parameters (both from initial and boundary conditions, and RELAP5 code models, assumptions and correlations) have a significant impact on the water hammer modelling results. The investigations of benchmarking have shown two groups of parameters [5]:

(1) parameters of thermal–hydraulic system conditions
  - initial fluid velocity;
  - pressure;
  - water temperature;
  - flow energy loss coefficient in the piping;
  - valve closure time;

(2) parameters of modelling
  - calculation time step;
  - scheme nodalization.

It has been determined from the benchmarking analysis that the most contributing factors with respect to the maximum pressure values are [5]:

- the ratio of current time step (δt) and current Courant time step (δt_{crnt}) should not exceed 0.1 at modelling of water hammer transients using RELAP5;

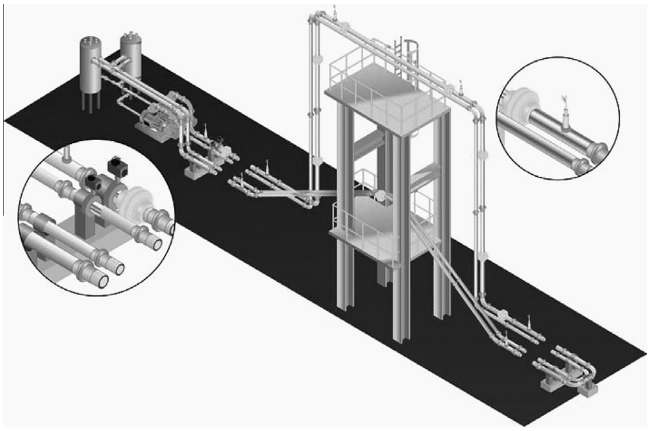

Fig. 1. Perspective view of pilot plant pipework [2].

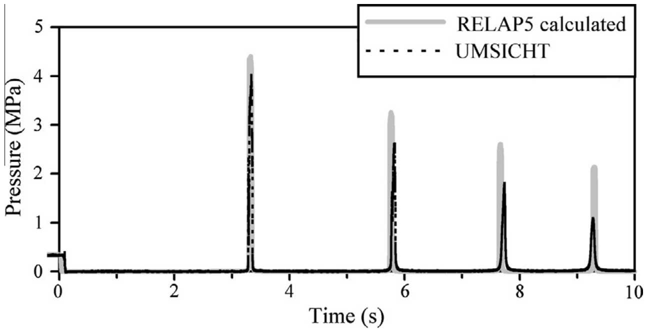

Fig. 2. Pressure history downstream the closed valve [5].