Pump-stopping water hammer simulation based on RELAP5

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Abstract. RELAP5 was originally designed to analyze complex thermal-hydraulic interactions that occur during either postulated large or small loss-of-coolant accidents in PWRs. However, as development continued, the code was expanded to include many of the transient scenarios that might occur in thermal-hydraulic systems. The fast deceleration of the liquid results in high pressure surges, thus the kinetic energy is transformed into the potential energy, which leads to the temporary pressure increase. This phenomenon is called water hammer. Generally water hammer can occur in any thermal-hydraulic systems and it is extremely dangerous for the system when the pressure surges become considerably high. If this happens and when the pressure exceeds the critical pressure that the pipe or the fittings along the pipeline can burden, it will result in the failure of the whole pipeline integrity. The purpose of this article is to introduce the RELAP5 to the simulation and analysis of water hammer situations. Based on the knowledge of the RELAP5 code manuals and some relative documents, the authors utilize RELAP5 to set up an example of water-supply system via an impeller pump to simulate the phenomena of the pump-stopping water hammer. By the simulation of the sample case and the subsequent analysis of the results that the code has provided, we can have a better understand of the knowledge of water hammer as well as the quality of the RELAP5 code when it’s used in the water-hammer fields. In the meantime, By comparing the results of the RELAP5 based model with that of other fluid-transient analysis software say, PIPENET. The authors make some conclusions about the peculiarity of RELAP5 when transplanted into water-hammer research and offer several modelling tips when use the code to simulate a water-hammer related case.

1. Overview of the RELAP5 code and PIPENET VISION

1.1. Brief introduction of RELAP5 code
The RELAP5 code was developed principally to calculate fluid behavioral characteristics during operational and LOCA transient. The light water reactor (LWR) transient analysis code, RELAP5, was developed at the Idaho National Engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commission (NRC). RELAP5 has been used as the basis for a nuclear plant analyzer. Specific applications have included simulations of transients in LWR systems such as loss of coolant, anticipated transients without scram(ATWS), and operational transients such as loss of feedwater, loss of offsite power, station blackout, and turbine trip. RELAP5 is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of steam, water, noncondensable, and solute.

The hydrodynamics simulation is based on a one-dimensional model of the transient flow for a steam-water noncondensable mixture. The numerical solution scheme used results in a system
representation using control volumes connected by junctions.

1.2. Brief introduction of The PIPENET VISION
The PIPENET VISION suite of programs has been designed to enable the accurate simulation of the flow of fluid through a network of pipes and other components.

PIPENET VISION Transient Module is a powerful tool in the design of piping systems, providing a speedy and cost-effective means of in-house rigorous transient analysis. The Transient Module can be used for predicting pressure surges, calculating hydraulic transient forces or even modelling control systems in flow networks. The Transient Module can model networks with items such as pipes, operating valves, variable-speed pumps, air-release valves, vacuum-breaker valves, accumulators, bursting discs, various caisson models, regulators, pressure envelopes, pressure and flow transmitters, PID controllers and transfer functions (to represent the dynamics of instruments and valves). Changes in a piping system, such as valve closure or pump start-up, can give rise to dangerously high pressure surges in the system. It is important, therefore, that these surges are investigated, and eliminated by careful design.

1.3. Use of RELAP5 in water hammer analysis
Using the code for water and steam hammer analyses is sometimes a controversial topic. Analyst's opinions range from not using the code to using the code with qualifications. At the heart of the various differences in opinion are the finite differencing scheme used in the code and the standard practices exercised by most users. In this paper shows that when carefully chose the time step and the control volume size, the RELAP5 code can well estimate the pressure surge and the pressure variation of the pump and in the pipelines in the pump-stopping water hammer case. And this may the application field of RELAP5 to nonnuclear systems like the water supply system to give valuable references to a certain project.

2. Fluid mechanics control equation in RELAP5
The basic field equations for the two-fluid non-equilibrium model consist of two phasic continuity equations, two phasic momentum equations, and two phasic energy equations. The equations are recorded in differential stream tube form with time and one space dimension as independent variables and in terms of time and volume-average dependent variables.

2.1. Mass Continuity
The phasic continuity equations are:

\[
\begin{align*}
\frac{\partial}{\partial t} \left( \rho g A \right) + \frac{1}{A} \frac{\partial}{\partial x} \left( \rho g v A \right) &= \Gamma_g \\
\frac{\partial}{\partial t} \left( \rho f A \right) + \frac{1}{A} \frac{\partial}{\partial x} \left( \rho f v A \right) &= \Gamma_f
\end{align*}
\]

These equations come from the one-dimensional phasic mass equations. Generally, the flow does not include mass sources or sinks, and overall continuity consideration yields the requirement that the liquid generation term be the negative of the vapor generation, that is, \(\Gamma_f = -\Gamma_g\).

2.2. Momentum Conservation
The phasic conservation of momentum equations are used, and recorded here, in an expanded form and in terms of momenta per unit volume using the phasic primitive velocity variables \(v_g\) and \(v_f\). The spatial variation of momentum term is expressed in terms of and. This form has the desirable feature that the momentum equation reduces to Bernoulli’s equations for steady, incompressible, and frictionless flow. The momentum equation for the vapor phase is:

\[
\frac{\partial}{\partial t} \left( \rho g A \right) \frac{\partial v_g}{\partial t} + \frac{1}{2} \frac{\partial}{\partial x} \left( \rho g v_g A \right) + \frac{\partial}{\partial x} \left( \rho g A \right) \frac{\partial v_g}{\partial x} = -\alpha_g \frac{\partial p_g}{\partial x} + \alpha_g \frac{\partial \rho_g}{\partial x} + B_g \frac{\partial}{\partial x} \left( \rho g A \right) \frac{\partial v_f}{\partial x} - \Gamma_g A \left( v_g - v_f \right) - (\alpha_g \rho_g A) \frac{\partial v_f}{\partial x} - \alpha_f \rho_f g \left( \frac{\partial v_g}{\partial t} - \frac{\partial v_f}{\partial t} \right)
\]

\[+ \rho_g \left( \frac{\partial v_g}{\partial t} - \frac{\partial v_f}{\partial t} \right) \frac{\partial v_f}{\partial x} - \alpha_f \rho_f g \left( \frac{\partial v_f}{\partial t} - \frac{\partial v_f}{\partial t} \right) \frac{\partial v_f}{\partial x} \] (1)
and for the liquid phase is:

\[ \alpha_f \rho_f A \frac{\partial \mathbf{v}_f}{\partial t} + \frac{1}{2} \alpha_f \rho_f A \frac{\partial \mathbf{v}_f^2}{\partial x} = -\alpha_f \rho_f A \frac{\partial P}{\partial x} + \alpha_f \rho_f B \mathbf{X} - (\alpha_f \rho_f A)F_WF(\mathbf{v}_f) - \Gamma_g A(\mathbf{v}_g - \mathbf{v}_f) \] (2)

These equations come from the one-dimensional phasic momentum equations with the following simplifications: the Reynolds stresses are neglected, the phasic pressures are assumed equal, the interfacial pressure is assumed equal to the phasic pressures (except for stratified flow), the covariance terms are universally neglected (unity assumed for covariance multipliers), interfacial momentum storage is neglected, phasic viscous stresses are neglected, the interface force terms consist of both pressure and viscous stresses, and the normal wall forces are assumed adequately modeled by the variable area momentum flux formulation.

3. Calculation results and analysis

3.1. Introduction of the model

In the example model, I set up a simple model representing the water supply project via a centrifugal pump. The picture below shows the nodalization of the system.

![Figure 1. Nodalization in RELAP5.](image1)

![Figure 2. Nodalization in PIPENET.](image2)

The system consist of two time-dependent volumes offering the inlet and outlet boundary conditions, a centrifugal water pump providing power needed for the system for water delivery, a valve to control the water flow rate and a straight pipe component as the water passage. The pipe length is 2.0 kilometers with the diameter 300 millimeters, and has a roughness of 0.7 millimeter. The height differences between the inlet and outlet of the pipe equals 106 meters. The pump’s lift is 115m, and the rated mass flow rate is 112.0 kg/s.

The inlet boundary conditions are: water with 20°C and the pressure is 0.1413 Mp. The outlet boundary conditions are: water with 20°C and the pressure is 0.1307 Mp. In the model the pipe component is divided equally into 40 control volumes connected by 39 inner single junctions. I conduct several transient run respectively with the conditions: 1) the pump trips and the valve keeps fully open; 2) the pump trips with the valve linearly closed within 45 seconds; 3) the pump trips and the valve closes in two stages.

3.2. The transient run with the pump trips but the valve keeps wide open

![Figure 3. Flowrate and pump’s speed variation curve in RELAP5 run.](image3)

![Figure 4. Flowrate and pump’s speed variation curve in PIPENET run.](image4)
In this transient run, I set the pump trips at 0 second (at 10th second in PIPENET run), but the valve at the outlet of the pump keeps open during the whole process. The graphs below show the value of the flow rate, the pump rotational speed along with the change of time. As we can from the graphs, the system flow decreases fast to zero at about 3.8 seconds after the pump trips. And both the flow and the pump’s rotational speed drop rapidly from the values of the steady state to zero and continue to fall until they reach the maximum of negative. The result in RELAP5 and PIPENET are quite similar.

3.3. The transient run with the pump trips and the valve closes linearly

In order to prevent the system from being in the state of backflow and the pump reversing for a long time, we should close the valve right behind the pump to control the flow rate of the backflow and the reverse speed of the pump set. First of all, I try to run another transient case that the pump trips at 0 second and the valve at the outside of the pump begins to close linearly simultaneously. It takes 45 seconds to close the valve from fully open to fully closed. The flow rate of the system, the pump rotational speed and the maximum pressure of the system which is right at the outside of the pump is shown here. In Figure 6 we can clearly see the maximum negative flow is within the value of 1.3 times the steady state flow rate, which conforms to the requirements of the specification. And so it is with the pump’s maximum negative rotational speed. As to the maximum pressure along the system, the first pressure peak arrives at about 43.5 seconds with a pressure of about 2.8Mpa, which is much too large so that it exceeds 2.24 times the steady state pressure. So it is a dangerous scheme to close the valve linearly. By comparing the result in RELAP5 and PIPENET, we see that the first pressure peak (including the time moment of peak appearance and maximum value of the peak) calculated in RELAP5 matches that in PIPENET. Concerning the following pressure peaks, the pressure calculated in PIPENET are higher and the peak appear with an accumulating time delay. On the other hand, the pressure peaks following the first one calculated in RELAP5 code are lower than in the PIPENET calculation result, that’s say the pressure results offered by RELAP5 damped greater than that in practice. See Figure 7 and 8.

Figure 5. Flowrate and pump’s speed variation curve in RELAP5 run.

Figure 6. Flowrate and pump’s speed variation curve in PIPENET run.

Figure 7. Pressure variation curve of the pump discharge valve in RELAP5 run.

Figure 8. Pressure variation curve of the pump discharge valve in PIPENET run.
3.4. The transient run with the pump trips and the valve closes in two stages
From the previous trial, we see that it’s not practicable to close the valve linearly. So this time I try to close the valve in two stages. In the first stage which can also called quick closing stage, the valve close to only 20% area of fully open in only 3.8s. In the second stage which can be called slow closing phase in the similar way, the valve continue to close down in 41.2s. So it takes a total time of 45s to fully close the valve, which is the same time with that used in closing the valve linearly. The flow rate of the system, the pump rotational speed and the maximum pressure of the system is shown here. We can clearly see the maximum negative flow and the pump’s speed are both within the value of 1.3 times the steady state values, which conform to the requirements of the specification. In the meantime, the maximum pressure caused by closing the valve is no more than 1.5Mp, which is less than 1.2 times the steady state pressure. So this scheme of closing the valve in two stage is an acceptable solution. In comparison with Figure 11 and Figure 12, we see that the calculated first pressure peak matches well with the actual value, and the pressure peaks calculated employing the RELAP5 code stop to oscillate earlier in comparison with that in the PIPENET water-hammer simulation.

Figure 9. Flowrate and pump’s speed variation curve in RELAP5 run.

Figure 10. Flowrate and pump’s speed variation curve in PIPENET run.

Figure 11. Pressure variation curve of the pump discharge valve in RELAP5 run.

Figure 12. Pressure variation curve of the pump discharge valve in PIPENET run.

4. Conclusion
Via setting up and calculating the sample pump-stopping water hammer scheme, the conclusions include that: (1) While PIPENET Transient Module is one of a most authoritative and credible software in fluid transient calculation. The use of RELAP5 code in pump-stopping water simulation is quite suitable, for the results provided by it are quite similar as that in PIPENET VISION. (2)By using the RELAP5 code, the calculated first pressure peak matches well with the that shown in the
PIPENET result. (3) In RELAP5 run, the pressure peaks following the first one are lower than the actual value, that’s say the pressure results offered by RELAP5 damped greater than that in practice as well as in the PIPENET result. (4)the pressure peaks calculated employing the RELAP5 code stop to oscillate earlier in comparison with that in the PIPENET water-hammer simulation.

The case may be one of the pioneering trial in engaging RELAP5 code into water hammer estimation or assessment. And it may give some valuable references in water hammer calculations. As it has been known to many, PIPENET is one of the effective software to calculate water-hammer, since it cannot calculate the transients with heat transfer, its uses hence are more or less limited. As the RELAP5 code contains abundant heat transfer model and component, the limits of PIPENET in water hammer analysis with heat transfer may find way out in RELAP5 code. The acquirement of knowledge will allow to develop RELAP5 code model for the analysis of accidents with the phenomenon of water hammer for the nuclear power plants.

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