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TWO-PHASE FLOW AND WATERHAMMER TRANSIENT ASSESSMENTS WITH THE TREMOLO COMPUTER CODE

R. J. Hammersley and G. T. Elicson
Fauske & Associates, Inc.
16W070 West 83rd St., Burr Ridge, IL 60521

R. E. Henry
Fauske & Associates, Inc.
16W070 West 83rd St., Burr Ridge, IL 60521
Henry@Fauske.com

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ABSTRACT

Design and regulatory issues regarding waterhammer and two-phase flow transients occur in nuclear power plants. Check valve closure, MOV differential closing pressure and service water piping systems response during design basis accidents are relevant examples. Analyses in response to these issues have been concerned with heat transfer in containment fan coolers during two-phase flow in the associated service water piping and waterhammer events resulting from steam condensation, water column rejoining and check valve closure. This paper describes a comparison between the TREMOLO computer code and check valve closure experiments and hand calculations for column separation and rejoining in a simulated service water piping network The TREMOLO code has been used to respond to NRC Generic Letter 96-06 to characterize the thermal-hydraulic conditions in the service water piping associated with fan coolers during loss of pumping power and drain-down induced column separation, steam voiding due to continued heat input from the fan cooler and system refill upon the re-establishment of pumping power. The TREMOLO calculated thermal-hydraulic conditions and nodal flow rates were then used by the TREMOLO code to quantify forcing function histories for the relevant piping segments.

1. INTRODUCTION

TREMOLO is a transient thermal hydraulic code developed to analyze single- and two-phase flow conditions in plant piping systems. TREMOLO - **T**hermal hydraulic **RE**sponse of a **M**otor-**O**perated valve **L**ine - was so named since it was originally developed in response to NRC Generic Letter 89-10 (USNRC, 1989) to evaluate pressure oscillations associated with valve closures and openings in piping segments that could be exposed to two-phase flow conditions.

Principally, TREMOLO is a node and junction code that uses a one-dimensional, "one and a half" fluid model which implies separate mass and energy equations for each of the two fluid phases and a single momentum equation to describe the fluid mixture. TREMOLO considers two fluid phases (liquid and vapor), which may exist in a non-equilibrium state. To provide closure to this system of equations, fluid transport between the phases is defined and an equation of state is used.

The TREMOLO code contains additional models of the phenomena relevant to the study of transient two-phase flow and condensation-induced waterhammer events that could occur in process piping systems. These models were selected and developed based on an understanding of the dominant physical processes expected during accident conditions postulated to occur in service water cooling systems of nuclear power plants. Namely, based on in-house scaled experiments and a review of the open literature, the dominant phenomena modeled in TREMOLO include: one-dimensional, non-equilibrium, two-phase fluid flow; presence and influence of residual gas bubbles in the fluid following large scale void collapse; steam condensation on cold pipe walls; steam condensation on the cold liquid phase; non-condensible gas coming out of solution at pressures higher than the saturation pressure corresponding to the liquid temperature; and single and two-phase fan coil heat transfer.

In addition to NRC Generic Letter 89-10 issues, TREMOLO has also been used to prepare responses to the NRC Generic Letter 96-06, i.e., two-phase flow effects and waterhammer loads in containment fan coolers during design basis events. More recently TREMOLO has been used to characterize the dependence of the waterhammer pressure amplitude on check valve closure times. The check valves were being modified for plant operability and maintenance improvements.

This best estimate tool is continually being reviewed for improvements and benchmarked against relevant experiments and plant experience. Several examples of such benchmarks have been presented previously at the NURETH-9 conference (Elicson, 1999). Additional benchmarks are presented in this paper.

2. CHECK VALVE CLOSURE BENCHMARK

Check valves are used in many fluid systems found in nuclear power plants. In pipe lines they are used to prevent back flow which could potentially damage equipment or lead to fluid loss in the case of pipe rupture. In particular, piping systems under high pressure which are suddenly depressurized by pipe rupture are known to potentially experience significant waterhammer pressures by check valve closure. Starting in the 1980s, specific attention was given to the development of damped check valves with the goal of reducing the potential waterhammer pressures which could result from check valve closure. Tests were conducted to characterize new types of check valves designed to reduce waterhammer loads (Panet, 1988). As part of this test program classical check valve designs were investigated experimentally to serve for comparison with advanced valve designs. These tests included the use of typical lift check valves which were installed in the test apparatus illustrated in Figure 1. In Figure 1 the check valve is installed in location 3. It is positioned such that flow from the pressurized vessel (position 7) following rupture of the rupture discs (position 4) is in the direction which closes the check valve. The pressure response is measured on either side of the check valve at positions 1 and 2 in the figure. In each test initially the pressure is uniform between the pressurized vessel and the rupture discs. The check valve is completely open, held in the open position by a thin wire. The test is initiated by opening the tap which depressurizes the volume between the two bursting rupture discs which, following their bursting, causes the fluid to accelerate and obtain a high flow velocity. The check valve closes interrupting the flow and initiating a waterhammer pressure pulse which moves between positions 3 and 7.

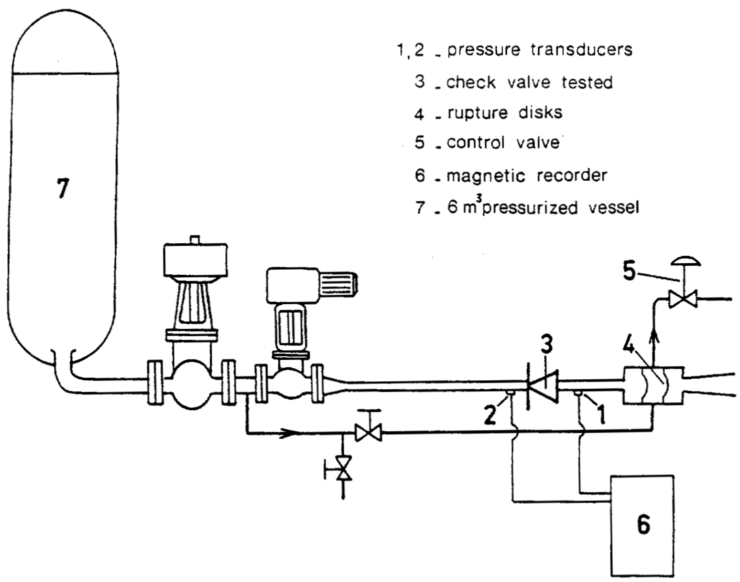

Fig. 1 Check Valve High Pressure Test Loop Arrangement (Panet, 1988)

Test number 5 from this experimental program was simulated using the TREMOLO code to benchmark its behavior. Test number 5 used a standard lift check valve whose diameter was 0.05 meters and whose closing time was 40 ms. In test number 5 the vessel pressure was initially set at 12 MPa. The measured pressure response at position 2 for test number 5 is presented in Figure 2. The peak observed pressure following check valve closure is seen to be 29 MPa. The change in the pressure at that location above the local system pressure is a maximum of 19 MPa. There is some noise in the measured pressure trace such that the differential pressure upon valve closure could be viewed as varying between 13 and 19 MPa.

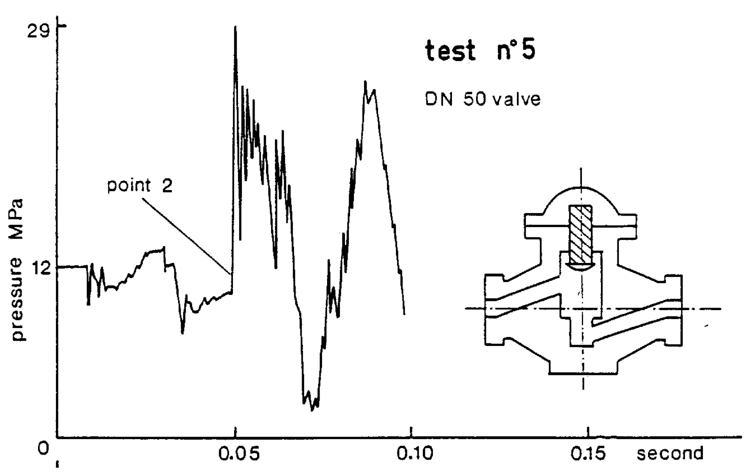

Fig. 2 Check Valve Test Number 5 (Panet, 1988).

The limited amount of detailed information available in (Panet, 1988) about the test facilities dimensions necessitated several assumptions in establishing the TREMOLO model. However, the initial condition of a uniform system pressure of 12 MPa and the rapid opening of the ruptured discs downstream of the check valve were properly modeled. Furthermore, the check valve closing characteristic, type and size were known and appropriately modeled. The results for test number 16 were first used to confirm the proper behavior of TREMOLO for the assumed facility configuration (pipe lengths, failed rupture disk loss coefficient, water temperature, etc.). Test number 16 also used a standard left check valve. Its diameter was 0.0689 m and its closure time was 37 msec. It was tested with a 3 MPa pressure in the pressurized vessel and produced a 9.5 MPa initial pressure pulse upon check valve closure. The TREMOLO simulation was adjusted such that its results matched the data for test number 16. The same facility characterization and TREMOLO model parameters were then used to simulate test number 5. The TREMOLO simulation resulted in a differential pressure (relative to the system pressure) upon check valve closure of 16 MPa. This is seen to be consistent (Figure 2) with the observed range of pressure change at valve closure.

3. COLD WATER COLUMN SEPARATION BENCHMARK

To investigate the TREMOLO computer code's thermal-hydraulic modeling capabilities when applied to realistic plant piping configurations, the TREMOLO code was used to simulate a cold water fluid transient in the test apparatus depicted in Figure 3. This piping configuration is typical of many nuclear power plant closed service water systems providing supply and return water to containment area coolers. The cooling coils are typically located at higher elevations, represented by the horizontal run of pipe instrumented with thermocouple #4 (TC-4) in Figure 3. The service water pump is typically located at a lower elevation, represented by the water supply vessel in the test apparatus. Under postulated accident conditions a loss of pumping power may occur, leading to drain-down-induced column separation followed by system refill upon the re-establishment of pumping power.

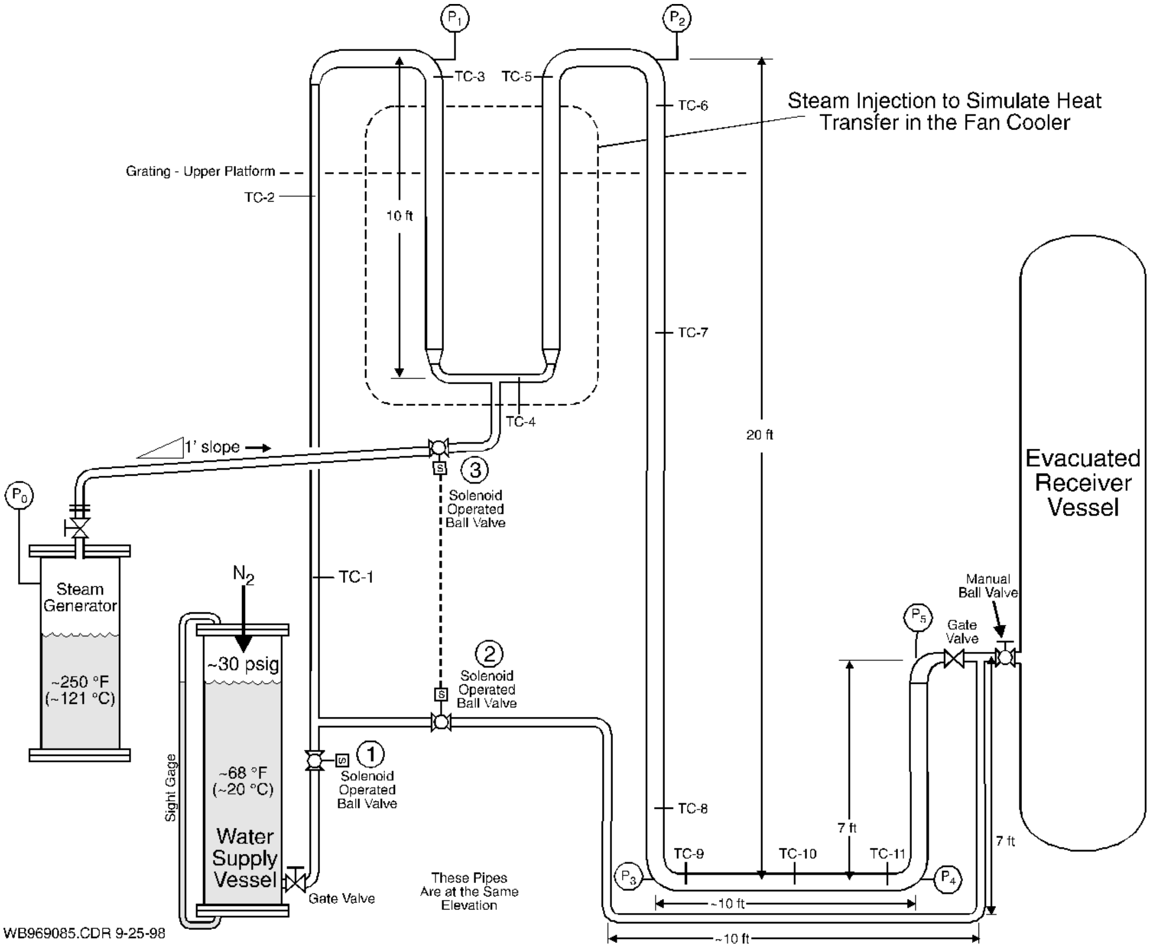

Fig. 3 Waterhammer experimental facility configuration (2" piping in the discharge piping).

In the current simulation, the fluid transient is modeled by initially establishing a prescribed steady state liquid flow through the system and then isolating the water supply by closing the ball valve at position 1 in Figure 3. The ball valve is closed at 1 second and then remains closed for 5 seconds before it is reopened to simulate pump restart. The transient calculation is completed once the pipe system is refilled and the initial steady state flow is recovered. For this case, the ball valve at position 2 remains closed for the duration of the calculation.

The fluid transient initiated as described above is expected to form three distinct regions where column separation could occur. First, due to the sudden valve closure on the supply line, column separation will occur at the face of the ball valve. Second, voiding will occur near the top of the supply riser once the fluid loses momentum and drains back toward the closed ball valve face. The third column separation will occur at the high point of the return piping as gravity facilitates the continued forward motion of the fluid in the return downcomer, while loss of momentum leads to fluid draining back into the simulated fan coil section. When flow is re-established, a series of condensation-induced waterhammer events could be expected as each voided region is refilled.

The TREMOLO simulation will report the location, magnitude, and timing of each column separation as well as the timing and magnitude of waterhammer loads caused by any column rejoining events. The waterhammer loads predicted by TREMOLO will be compared to bounding hand calculations using the Joukowsky equation.

TREMOLO results are presented in Figures 4 through 11. The column separation is characterized by the plots of void fraction near the closed ball valve (Figure 4), the void fraction near the top of the supply riser (Figure 5), and the void fraction near the top of the return piping (Figure 6). Finally, Figure 7 provides axial void profiles immediately before the water supply is re-established. As shown, void formation occurs in three separate regions, as expected, with substantial void collecting at the highest elevations of the supply and return piping (see Figure 7). Figures 8 through 10 show temporal plots of the pressure in the regions where the three column separation events take place. The pressure rises correspond to the times when void collapse (i.e., column rejoining) occurs in the various regions.

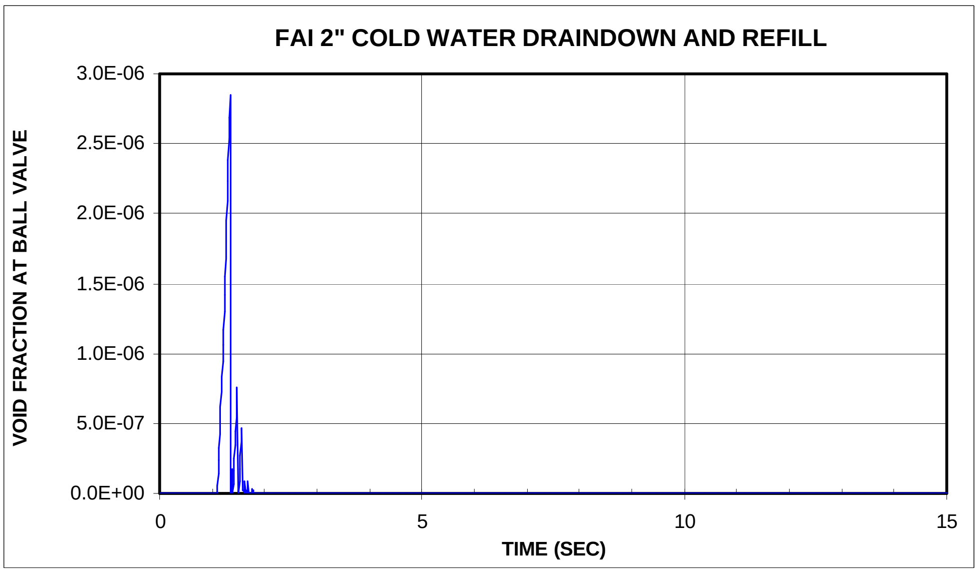

Fig. 4 Void fraction at ball valve.

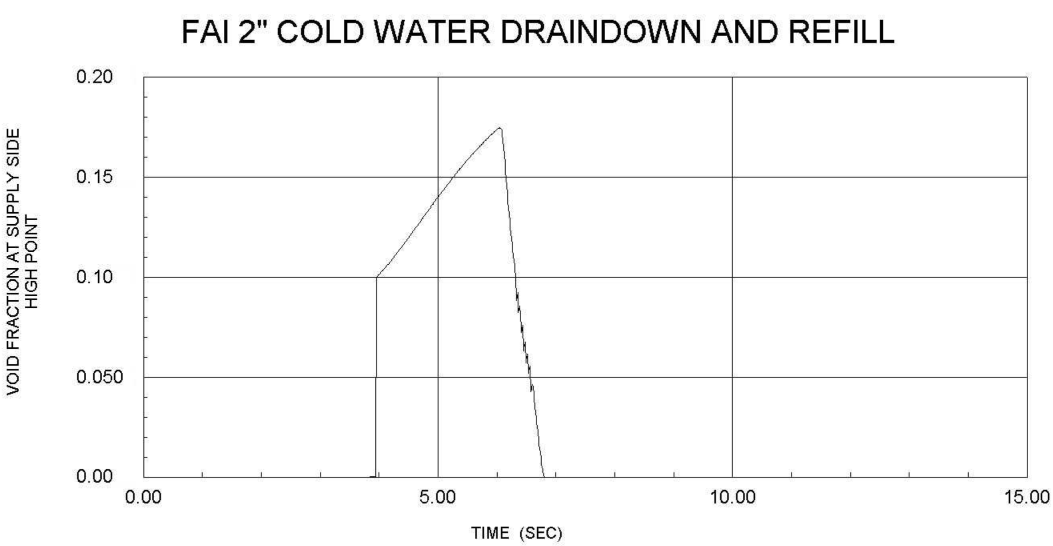

Fig. 5 Void fraction at high point of supply pipe.

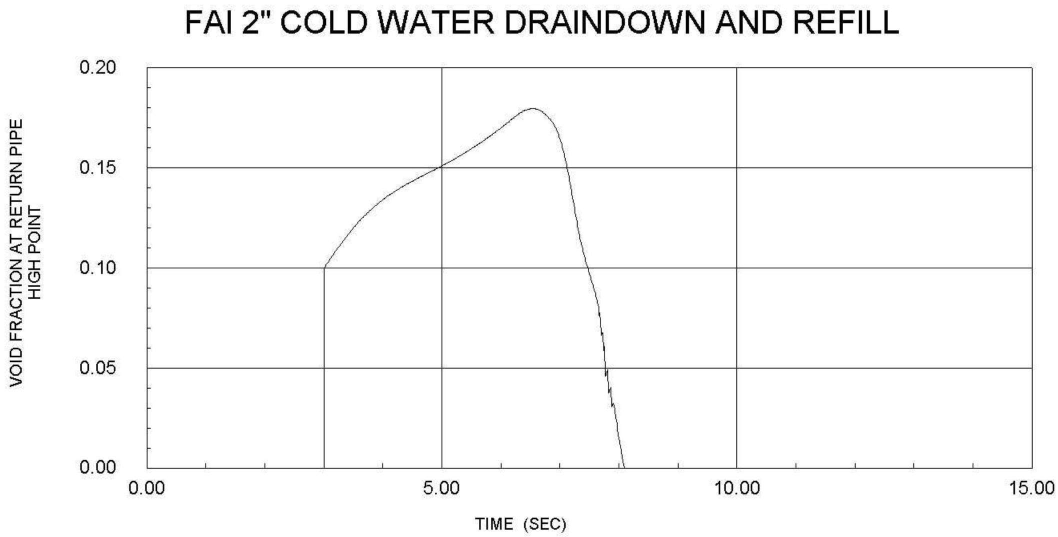

Fig. 6 Void fraction at high point of return pipe.

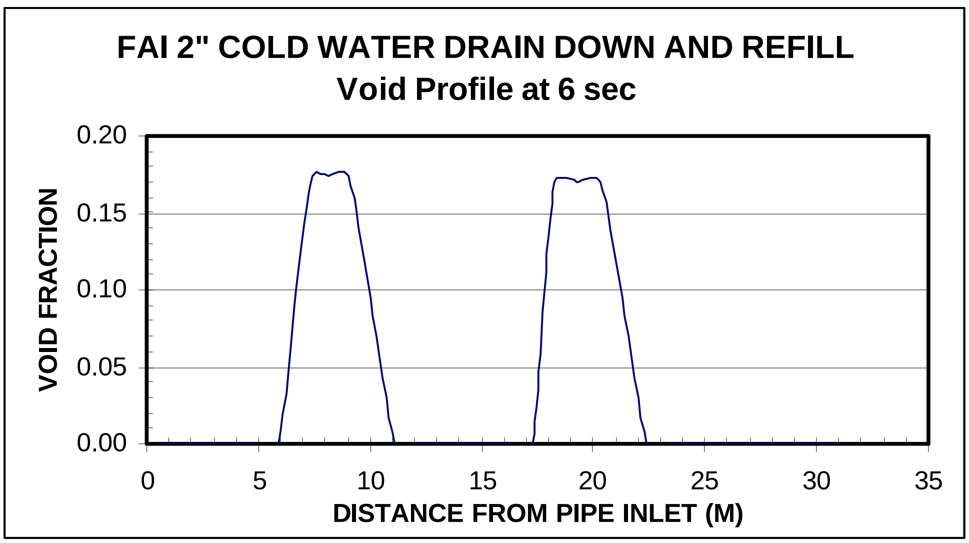

Fig. 7 Void profile along length of pipe at 6 seconds - refill begins at 6.0 seconds (supply pipe high point is 6.3 to 8.6 m from inlet; simulated fan coil section is 11.5 to 13.8 m from inlet; return pipe high point is 16.7 to 19.8 m from inlet).

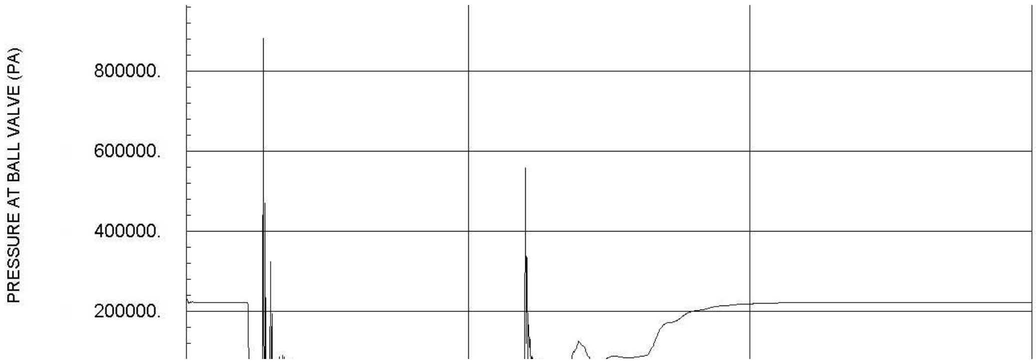

Fig. 8 Pressure at ball valve.

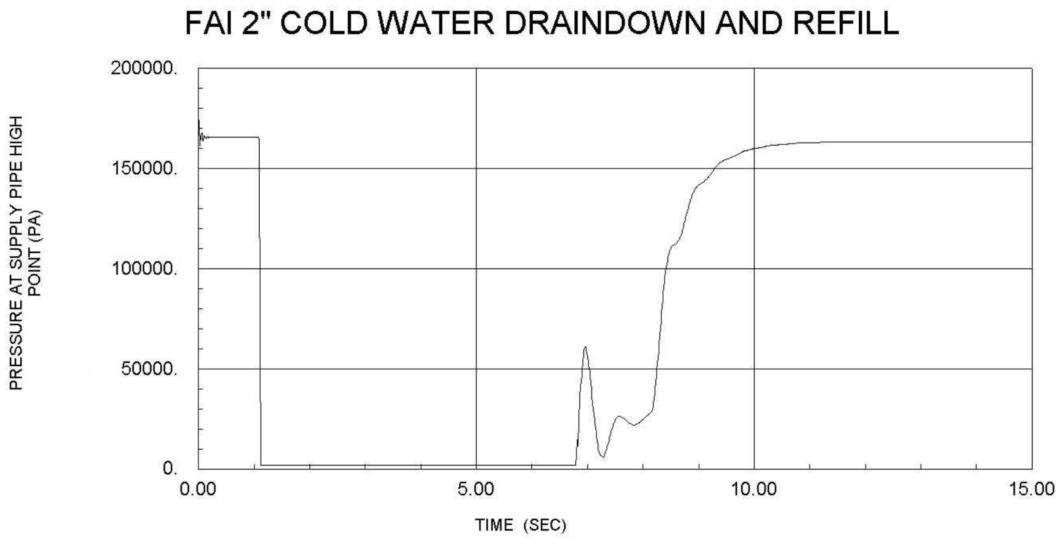

Fig. 9 Pressure at supply pipe high point.

Fig. 10 Pressure at return pipe high point.

Figure 11 shows the mass flow rates of the water columns on either side of the voided region in the high point of the supply pipe. Because the upstream water column is moving at a higher velocity than the downstream column, the two columns will eventually rejoin. The column rejoining event coincides with the collapse, or condensation, of the steam void, which is show to occur in Figure 5 at 6.8 seconds. Thus, the column rejoining causes what is commonly referred to as a condensation-induced water hammer event. The relative velocity of the water columns at the time of void collapse provides the driving force behind the waterhammer pressure rise. As shown in Figure 11, the mass flow rates of the upstream and downstream water columns at 6.8 seconds are 1.8 kg/s and 0.9 kg/s, respectively. Since the upstream water column is moving through 1" pipe while the downstream water column is moving through 2" pipe with a water density of 998 kg/m^3, the relative velocity between the water columns is 3.2 m/s. The maximum pressure rise from a waterhammer event can be calculated from the Joukowsky equation:

$$\Delta P = K r \, u a_w \qquad (1)$$

where ρ is the fluid density, u is the fluid velocity, K=0.5 for column rejoining, and a_w is the sonic velocity in the fluid.

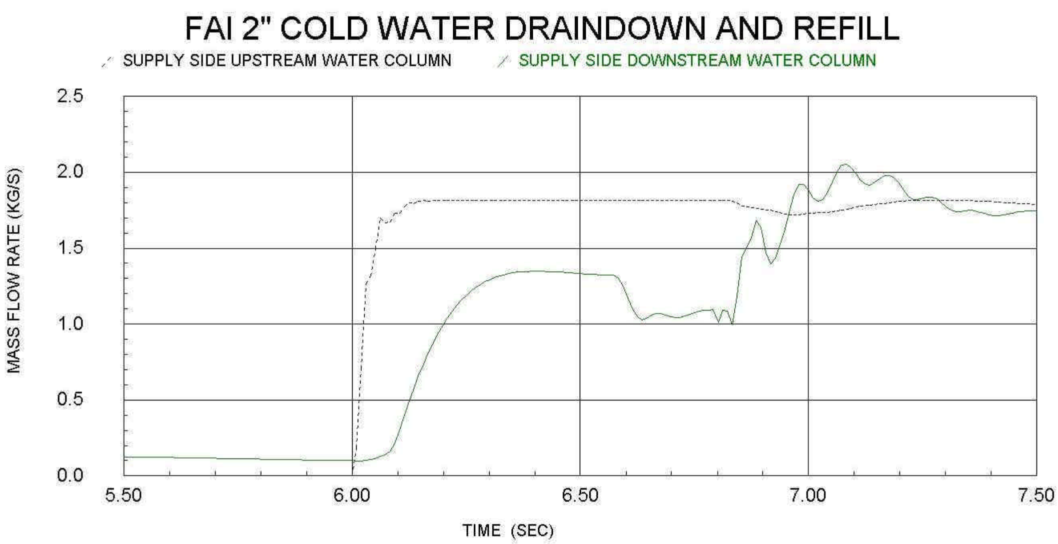

Fig. 11 Mass flow rates of water column on upstream and downstream side of voided region at the supply pipe high point.

Given a sonic velocity of 1440 m/sec based on water density and bulk modulus at 302 K and a water column relative velocity of 3.2 m/s at a density of 998 kg/m^3, the Joukowsky equation yields a pressure rise of 2.3 MPa. The TREMOLO-predicted pressure rise shown in Figure 9, however, is only 0.06 MPa, which is significantly lower than the all-liquid waterhammer calculation. The lower pressure is a result of the residual void present in the system at the location of the column rejoining – a phenomenon considered in the TREMOLO calculation. For example, even if the residual void were only .05% of the total volume (compared to the peak void in this region of 18%, as shown in Figure 5), then the sonic velocity in the fluid would decrease to about 100 m/s. Given this reduced sonic velocity, the Joukowsky equation yields a pressure rise of 0.15 MPa. If the residual void is doubled, to .1%, then the sonic velocity decreases by a factor of five to 20 m/s. The calculated peak pressure then becomes .03 MPa, which is in line with the more detailed TREMOLO calculation. Clearly, the waterhammer pressure rise is sensitive to the presence of very small quantities steam and non-condensible gas. Comparisons of TREMOLO calculations against experimental data (Elicson, et al.) support the assumption of residual void in the range of .05% to 0.1%. Also, when residual void in the range of .05% to 0.1% is used in the Joukowsky equation, the calculated results bound the TREMOLO calculations.

4. CONCLUSIONS FROM TREMOLO BENCHMARK EXERCISES

The TREMOLO benchmarking effort has demonstrated the code's ability to analyze check valve closure induced waterhammer as well as column separation and condensation-induced waterhammer events that could occur in the cooling water piping systems of nuclear power plants. This extends the benchmarking effort previously reported in the literature (Elicson, 1999). In particular, the benchmarking activities demonstrated the code capability to adequately model key phenomena encountered in transient waterhammer and two-phase flow analyses, such as,

- Sonic velocity in single and two-phase mixtures
- Column separation and rejoining
- Pressure wave transmission in combined single and two-phase fluids
- Independent movement of multiple water columns
- Void collapse in multiple voided regions
- Fluid flow reversal
- Check valve closure

Furthermore, the benchmarking exercises validate the TREMOLO approach of using a one-dimensional, five equation fluid model with assumptions of residual void to analyze the types of transient thermal hydraulic events postulated to occur in the service water piping systems of nuclear power plants.

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