Selfactuating Valves: Application of Experimentally Supported Numerical Models

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INTRODUCTION

Selfactuating valves are employed as part of overpressure protection systems in various industrial applications, where constructive layout and operating principles may differ according to the requirements of the automatic control circuit involved. Essential features of the dynamical behaviour of these valves are the dependence on the discharging fluid (steam, water or steam-water mixture) (see for instance (1)) and the coupling to the connecting piping and vessel system (2). The first feature is common to all these valve types and simply is due to the fact that mass flow rates in and out the control volumes of a selfactuating valve will change with the fluid conditions upstream the valve orifice. The second feature is mainly observed with very fast operating valves, with operating times in the order of magnitude of the period of the propagating pressure pulses in the feed line. Here geometric design of connecting pipings and vessels have an essential impact on the valve stem motion as it influences fluid transients.

As a consequence a given performance of a selfactuating valve integrated into a certain control circuit may change when integrated into a different system with different fluiddynamic and geometrical boundary conditions.

Hence there is a need for numerical simulation techniques of selfactuating valves as they provide a powerful tool

- in carrying-over of given test facility data to an actual plant safety control system, that is they provide an experimentally supported safety analysis
- in questions of layout such as actual valve performance, including dynamic stability analysis upon changing of valve and system parameters and finally
- estimates of piping loads due to valve performance.

In the following paper we present numerical models for analysis of the dynamic behaviour of valve-piping systems being coupled in the described manner and demonstrate their applications to systems as they are operated in KWU-type Pressurized Water Reactors (PWR). In particular the developed dynamic valve models allow for simulation of

- self-actuating damped check valves
- self-actuating safety and relief valves
- self-actuating spring-loaded safety and pilot valves

as well as hydrodynamically coupled systems of these valve types in various combinations including the connecting pipings and vessel components.

These developments are part of a wider activity at Siemens/KWU that also covers performance and exploitation of appropriate fullscale valve tests in KWU and other Laboratories. The tests in turn provided many experimental data which found input into the numerical models and built a solid basis for the analysis.

COMPUTER CODE

The fluiddynamic code, that has been choosen here, is the Transient Reactor Analysis Code TRAC-PF1 (3) which has essentially the following features:

- one-dimensional two-phase, two-fluid, nonequilibrium hdydrodynamics model (with a noncondensable gas field) including three dimensional simulation of a vessel.

The partial differential equations that describe the two-phase flow are solved by finite differences. The fluid-dynamics equations in the one-dimensional components use a multistep procedure. The three-dimensional vessel option uses semiimplicit differencing. The finite-difference equations for hydrodynamic phenomena form a system of coupled, nonlinear equations that are solved by a Newton-Raphson iteration procedure.

A decided advantage of this computer code is, that the TRAC program is completely modular by component. The components in a calculation are specified through input data; available components allow the user to model virtually any PWR design or experimental configuration. This gives TRAC great versatility in the possible range of applications. It also allows component modules to be improved, modified, or added without disturbing the remainder of the code. TRAC component modules currently include accumulators, pipes, pressurizers, pumps, steam generators, tees, valves, and vessels with associated internals (downcomer, lower plenum, core, upper plenum).

THE VALVE MODEL

The valve component in TRAC as it stands, however, is not sufficiently developed for our purposes as it simulates a valve as a boundary condition only. The valve essentially is given in terms of flow area variations as a function of time where no feedback of the fluid conditions on the valve stem motion is considered.

In a valve model appropriate for the afore mentioned analysis one has to take into account the coupling of the equations of motion of the valve stem and the fluiddynamic equations. This we did in TRAC through extending the code by an additional valve submodule that has implemented the equation of motion of the valve stem and also features the treatment of variable control volumes which are necessary for the description of damped valve types and are not optional in TRAC either.

We choose an additional set of six equations, which have to be solved simultaneously with fluiddynamics equations in TRAC. These equations calculate the pressure in the control volumes, the massflow rates which enter these volumes and the enthalpy in the variable control volume.

The basic equation is the motion of the valve stem (1)

$$m\ddot{x} = \Sigma p_k A_k - \Sigma p_i A_{D,i} - c_F x - F_0 \qquad (1)$$

Here x(t) denotes the valve lift, m is the total accelerated mass associated with the valve stem, c_F is a spring constant and F_0 is a constant force that for instance controls the set pressure. The terms $P_k A_k$ are coupling terms that account for a feedback of fluid conditions around the valve stem on the valve stem motion. In Fig. 1 the areas A_k are shown for the example of a damped check valve. The pressures p_k associated with these areas are calculated in TRAC.

The terms $p_i \cdot A_{D,i}$ are pure damping terms and in all cases we are going to consider here, these pressures belong to variable control volumes in the valve.

This valve model is embedded into a TRAC nodalization scheme of the entire system under consideration including the remaining constant valve control volumes as well as the piping and vessel system the valve is connected to. The coupling to TRAC is as follows:

The TRAC cells adjacent to the variable control volumes are closed up by massflow boundary conditions (FILL-components) which are updated at each time step with the actual massflow rate at this boundary. Finally the discharge rate through the valve orifice is controlled by the valve area FA which becomes a function of the valve lift x(t) and is set at each time step according to its actual value calculated from (1).

The equation (1) is integrated for each TRAC time step by a Runge-Kutta integration technique subject to the assumption of thermodynamic and mechanical equilibrium within the variable control volumes V_i $(x(t))$.

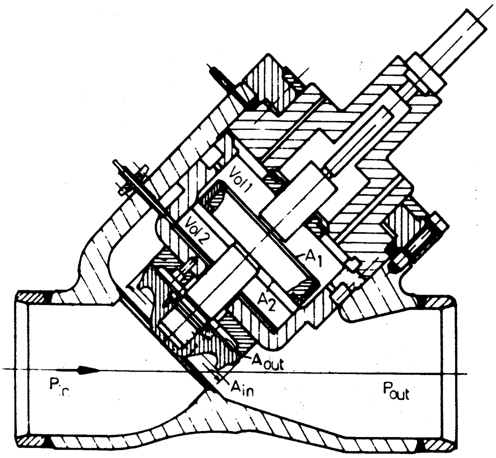

FIG. 1 Damped check valve schematic

APPLICATIONS

In order to demonstrate the applicability of the TRAC valve model to damped check valves, post-test calculations of experiments with a feed water check valve (German standard problem No. 4 (4)) were performed. The objective of the tests was to investigate the closing of a feedwater check valve upon break of the feed water line and to measure the associated backpressure peaks for an estimate of the hydrodynamic loads on this system. Fig. 2 shows the HDR-Test fullscale facility. The Tests are described in (4). Valve closing in the tests was initiated through a simulated pipe rupture at the break nozzle (position 8, Fig. 2) of the blow down pipe, which was loaded with subcooled water. For the numerical simulation of the blowdown an appropriate TRAC nodalization scheme including the valve model was set up (Fig. 3). The obtained test found input into the numerical simulation model of this system with TRAC. The damped check valve operates according to the pressure difference over the valve stem. If the pressure (p_{in}) under the valve stem decreases, the valve closes.

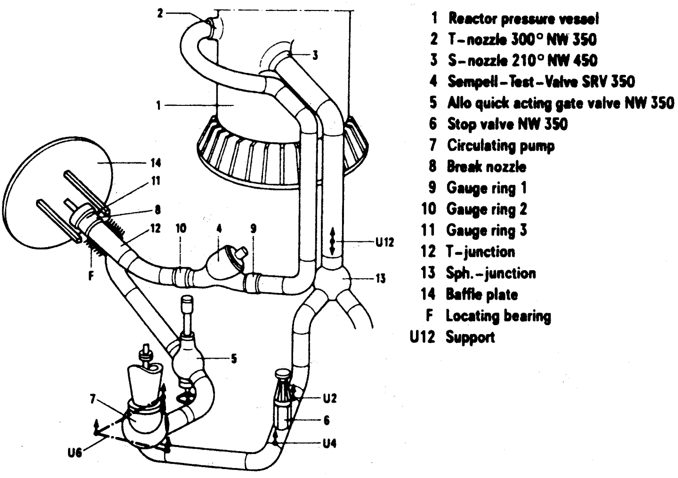

FIG. 2 HDR-test facility for valve experiments with the damped check valve.

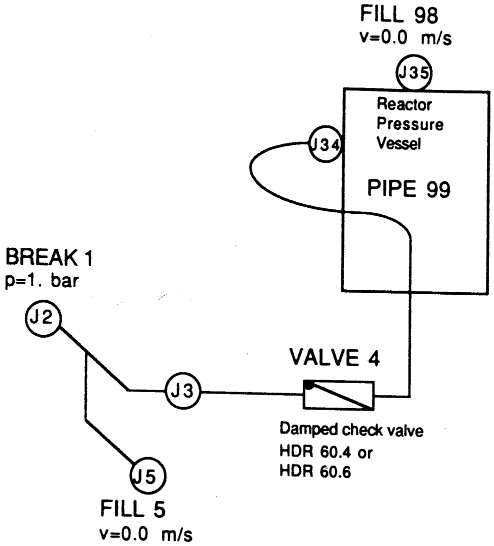

FIG. 3 TRAC nodalization scheme

Fig. 4 shows the results of TRAC post-test calculations against the experimental data of the test.

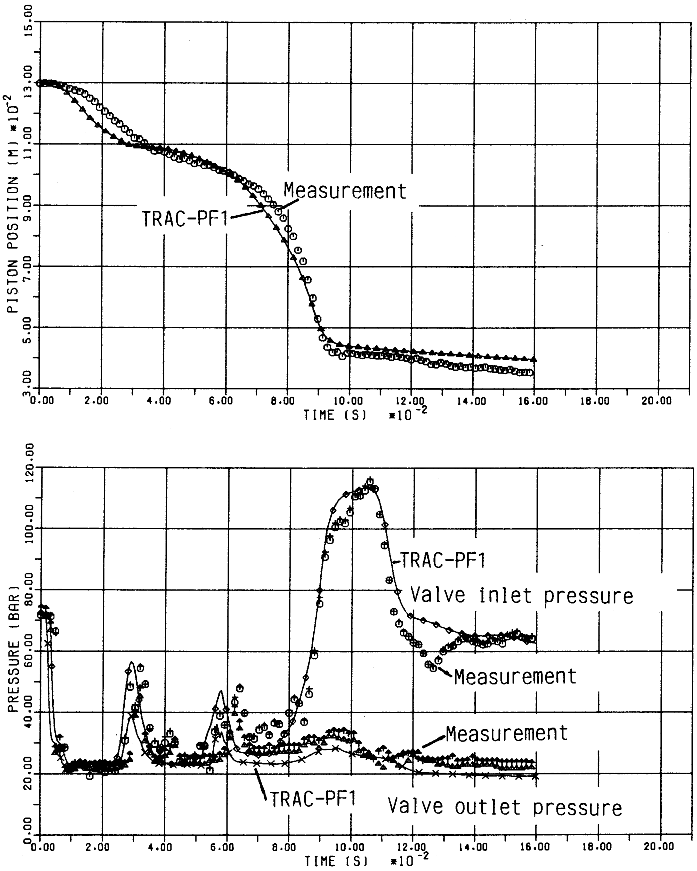

FIG. 4 TRAC post-test calculation of the test PHDR/SRV350 V60.4 with a damped check valve

Experiment and calculation show a good agreement.

In a second step two damped check valves were connected in series, leaving all input parameters unchanged, to investigate this behaviour in a new system environment. This configuration serves the purpose to increase the certainty of closing one of the two damped check valves.

The TRAC nodalization scheme is illustrated in Fig. 5. The transient is initiated by a complete pressure loss to 1 bar at the end of PIPE 20.

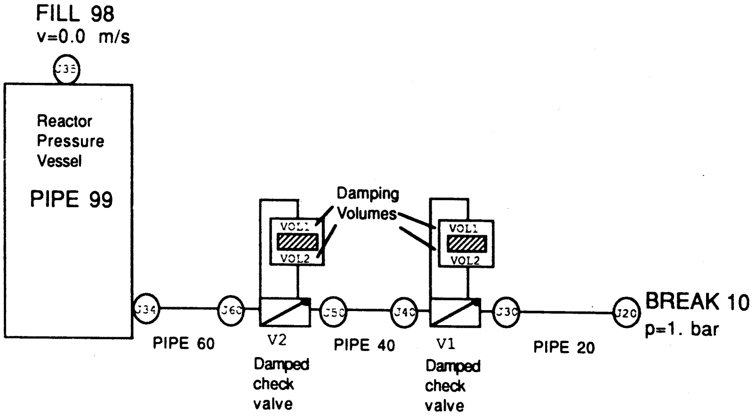

FIG. 5 TRAC nodalization scheme for two in series connected check valves

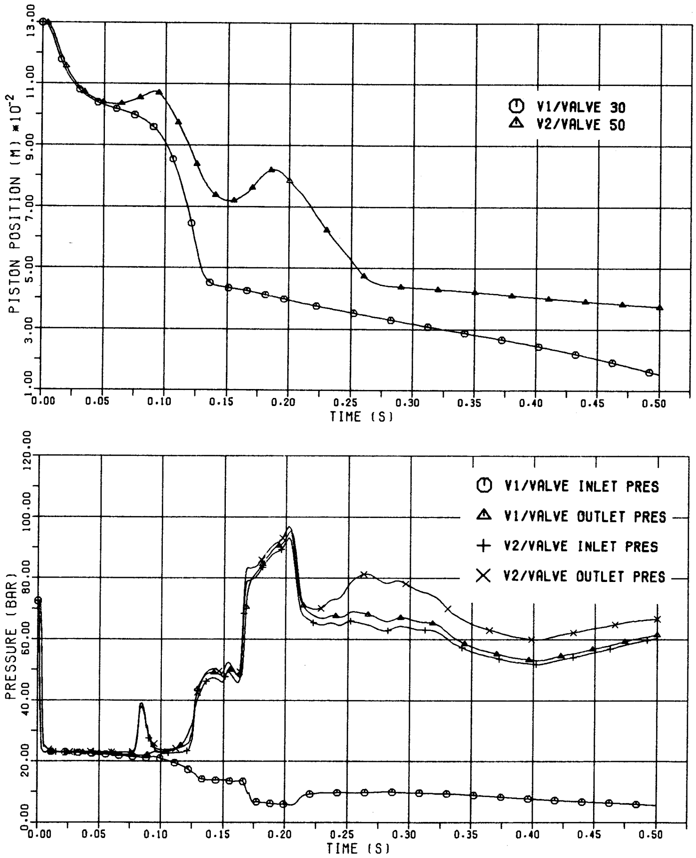

FIG. 6 TRAC calculation of two in series connected damped check valve V60.4

The decompression wave running between the break and the supply tank causes the first damped check valve V1 to close slowly. After a short moment according to the distance between the two valves, the second damped check valve V2 begins to close. After the reflection of the wave at the supply tank, the wave travels with a higher amplitude to the second valve V2, which opens thereupon. For the first valve V1 the pressure difference increases, so this valve closes continuously. Fig. 6 shows the piston position-time-history of the two damped check valves and the corresponding pressure-time-history.

CONCLUSIONS

We have shown that numerical techniques combined with experimental tests on fullscale facilities allow to estimate valve performance and give a better understanding of the valve dynamics under various boundary conditions.

In this context it is remarkable that, although the actual fluiddynamics in the valve region is of course 3-dimensional, the presented 1-dimensional numerical models are sufficient to describe valve performance in very good agreement with experimental test data in all cases considered.

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Authors' Index