CALCULATION OF THE LOADS INDUCED BY PRESSURE WAVE-FLOW IN BRANCHED PIPING IN INTERACTION TO VALVE CLOSING BEHAVIOR

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Rapid changes in flows through a pipe, e. g. as a result of pipe ruptures or quick-closing/quick-opening valves, cause loads in the form of pressure waves which can have an effect throughout the whole piping system. A description of these fluid dynamic processes and knowledge of the resultant, time dependent forces are of great significance for the dynamic computation of the piping structure.

For some time now the EUDRU Program has been available for use in performing such fluid-dynamic analyses. The program is suitable for analyzing piping systems through which liquids, gases or homogenous mixtures flow. Using combination elements such as branches and junctions together with dead ends, even complicated piping systems can be represented. Description of the conditions at the ends of the piping is by means of time-dependent pressure or mass flow functions.

Several subprograms are available which consider the influence of components on the flow medium. In addition to being used to analyze power operated valves and steady state operating pumps, EUDRU allows medium-operated check valves to be represented. In this case, the movement of the valve is considered in conjunction with the flow, i. e., the closing dynamics of the valve and the fluid dynamics in the piping permanently interact. Both non-damped and damped-closing check valves can be simulated mathematically.

EUDRU is a one and a half dimensional, finite difference program which is constructed in accordance with the American STEALTH Program /1/. The main program contains the three fundamental FLOW equations which allow mass, momentum and internal energy to be acquired. The momentum equation was extended by a friction term to take account of the influence of friction. A fourth equation describes the relationship between pressure, density and internal energy. The equations are solved using a finite difference procedure in accordance with the predictor-corrector method of M. Cormack /2/.

The program has already been used on a few occasions for analyses performed within the licensing procedure for nuclear power plants. Experimental proof was necessary for program qualification. In the so-called damping tests /3/ it was demonstrated that the pure damping procedure for a piston check valve was correctly computed. A further proof for program qualification was provided by the subsequent computation of experiments which had been performed on the superheated steam reactor (HDR) in Karlstein with a piston check valve /4/. The result of the computations showed a large degree of coincidence with the results of the tests carried out with un-damped and slightly-damped valves. Further experiments are scheduled for 1979 on the superheated steam reactor in Karlstein. In these tests a piston check valve with damped closing shall be used. The damping properties of this valve were already tested in /3/. The tests are to be simulated mathematically using the EUDRU Program. This should result in final qualification of the EUDRU Program.
1. **INTRODUCTION**

Transient flow conditions in pressure-retaining pipes and/or pipes through which there is a fast flow, such as are caused, for example, by quick-closing and quick-opening valves or by a pipe rupture, exert a load on the entire piping system in the form of pressure waves. Quantitative proof, which is necessary within the framework of a licensing procedure, is usually provided by means of computer programs.

Even though there are many programs for computing pressure waves, there was until now no program directly suitable for simulating the behavior of medium-operated valves. This is the reason why an existing program was developed further. The developers of STEALTH /1/ were commissioned to compile a one-dimensional program alongside the existing Lagrange 1D - version. Based on this fundamental program, the KED Engineering Consultants, commissioned by KWI, developed the EIDRO Program. (Euler Druckstoß - Euler Pressure Surge) /2, 9/.

2. **FUNDAMENTAL EQUATIONS FOR THE FLUID**

To describe the fluid mechanics, the following conservation equations for a one-dimensional pipe are used:

\[
\begin{align*}
\frac{\partial (\rho A)}{\partial t} + \frac{\partial (\rho u A)}{\partial x} &= 0 \\
\frac{\partial (\rho u A)}{\partial t} + \frac{\partial (\rho u^2 A)}{\partial x} + A \frac{\partial p}{\partial x} - \frac{\partial R}{\partial x} &= 0 \\
\frac{\partial}{\partial t} \left[ \rho A \left( \frac{u^2}{2} + e \right) \right] + \frac{\partial}{\partial x} \left[ \rho u A (e + \frac{p}{\rho} + \frac{u^2}{2}) \right] &= 0
\end{align*}
\]

where \( t \) = time coordinate; \( x \) = local coordinate; \( A \) = Cross-sectional area (viewed only as function of \( x \)); \( \rho \) = density; \( u \) = particle velocity; \( e \) = specific internal energy; \( R \) = friction force.

In equations (1) to (3), the following influences are neglected: Viscosity, material diffusion, heat-transfer and the force of gravity.

The four unknowns of equations (1) to (3) can be solved together with a fourth equation, the equation of state

\[
p = p (\rho, e)
\]

where \( p \) = pressure; \( e \) = specific internal energy.

The choice of the equation of state depends on the problem to be solved. For steam and/or ideal gas, the following shall apply:

\[
p = e \cdot \rho (K = 1)
\]

For water and water-steam mixture, it is assumed that the pressure does not depend on the internal energy.

For cold water:

\[
p = p_0 + K \cdot \frac{\Delta \rho}{\rho}
\]

with bulk modulus

\[
K = \rho \cdot c^2
\]

\( p_0 \) = initial pressure; \( c \) = speed of sound
For the equation of state of hot water and water-steam, a table with a maximum of 9 pairs of values (pressure, density), which vary with the problem, are taken from the water-steam table and interpolated.

In the speed of sound calculation, the elasticity of the pipe wall is taken into account:

$$ c = \sqrt{\frac{1}{\tilde{S}} \left( \frac{1}{E_{FL}} + \frac{1}{s} \frac{d}{E_R} \right)} \quad (8) $$

where \( d \) = pipe diameter; \( s \) = pipe wall thickness; \( E_R \) = modulus of pipe wall and \( E_{FL} \) = modulus of elasticity of liquid.

3. NUMERIC SIMULATION OF A PIPING SYSTEM

3.1 Finite difference equation

Equations (1) to (4) are converted into difference equations and solved in accordance with the predictor-corrector method of Mc. Cormack /2/.

The solution procedure leads to stable solutions since the time step is constantly being re-computed by the program. Here the following inequation applies:

$$ \Delta t < \frac{\Delta x}{|u| + c} \cdot S \quad (9) $$

where \( \Delta t \) = time step; \( \Delta x \) = distance between two neighbouring points; \( u \) = flow velocity; \( c \) = speed of sound; \( S \) = time step safety factor \((<1)\).

3.2 Boundary conditions

The predictor-corrector method requires a left and right hand adjacent point for all points when computing the next-time step.

At the model edge, one of these points is missing. Therefore, a further imaginary point is assumed and subjected to boundary conditions.

The variables for such edge points are either specified in the problem which is set or must be based on sensible assumptions. Special attention must be paid to ensure that plausible results are obtained.

3.2.1 Boundary conditions at the closed end

At the closed end the flow velocity must always be zero. This is achieved by making the values for the flow velocity (or mass flow density of energy flow) at the imaginary point equal to the negative values at the last grid point. For the remaining variables - density, pressure and specific internal energy - the values of the imaginary grid point are assumed to be the values of the last point.

3.2.2 Boundary conditions at the open end

Usually the open pipe end opens into a vessel whose pressure is stated as constant or as a function of time. The other variables are only known at the edge at the beginning and must be additionally determined for each step of the computation.

The value for the density is taken from the last point in the piping. The specific internal energy can be computed as a function of the given pressure. When determining the mass flow density linear extrapolation is carried out on the basis of two adjacent points.

In the case of a few problem definitions, the mass flow is known rather than the pressure. In this case the three variables pressure, density and specific internal energy at the imaginary point are given by the values of the last grid point.
3.2.3 Boundary conditions for a branch

Representation of a branch in the model is based on the idea that the main pipe represents a pressure vessel for the branch. Thus, the variables for pressure, density and specific internal energy which are known at the point where the branch joins the main pipe are used as boundary values for the branch. The mass flow is extrapolated linearly from the given values of the two last points of the branch.

3.2.4 Boundary conditions for the junction

A junction consists of three (or four) pipes which merge together at a common point. Thus two (or three) pipes are situated opposite the endpoint of each pipe.

The one-dimensional program, however, only permits a right-hand and a left-hand neighbouring point.

The problem is solved by combining two (or three) pipe endpoints to form an imaginary point. The variables for this point are computed by arithmetically calculating mean values from the known values of the pipe endpoints and weighting them according to the area.

4. SUBPROGRAMS FOR COMPONENTS

When computing whole piping systems a few special subprograms in addition to the boundary conditions are needed for modelling the components which influence the flow or even interact with it.

4.1 Power-operated valves

With this subprogram all valves, for which a definite closing or opening function is known, can be computed. The program simulates the valve by means of a pressure loss coefficient which is contained in the friction term of the momentum equation. The pressure loss coefficient is specified as a time function.

Where such a function is unknown, it is calculated with equation (10).

\[ S = S_0 \left( \frac{A_o}{A(t)} \right)^2 \]  

(10)

where \( S_0 \) = pressure loss coefficient for given area \( A_o \); \( A(t) \) = free area in valve as a function of time.

For this case the area must be known as a function of time, or be computed from the relationships: valve stroke = f (time) and area = F (valve stroke).

Using this subprogram a pipe rupture can also be simulated. The pressure loss coefficient is specified as a time function and runs through values between infinity and one.

Here the values "infinity" and "one" correspond to the closed and completely ruptured pipe respectively. The type of rupturing is determined according to how the pressure loss coefficients are selected.

For steam flows, a controlled valve is contained which takes account of the special requirements of compressible media.

Instead of using the pressure loss coefficient, a discharge coefficient \( \alpha \) is used. This \( \alpha \)-value is defined as the quotient of the steady state mass flow and the maximum possible mass flow, and is stated as a function of time.
4.2 Medium-operated valves

This subprogram is used in the computation of valves which are closed by flow-forces. Here too, the valves are simulated by a pressure loss coefficient. The $\zeta$ value is not prescribed, however, for the program but is computed from the valve stroke by means of a subprogram for each new time step.

The position of the valve can be obtained from the movement equation.

\[ m \ddot{x} = \sum F_i \]  \hspace{1cm} (11)

where $m =$ mass; $F_i =$ forces; $x =$ valve stroke

the valve stroke $x$ is obtained after integrating twice. Using the known relationship - Valve area = $f(x)$ - and equation (10), the pressure loss coefficient is determined.

Equation (11) contains on the right-hand side a varying number of forces depending on the type of valve. Hereinbelow, a valve with damping in the end phase of closing is described as shown in Figure 1. In the case of valves which are undamped, all parts of the program which are necessary for computation of the damping force do not apply.

The following forces act on a damped piston check valve (see Fig. 1) in the direction of the valve axis:

In the closing direction
- the force due to own weight
- flow force
- spring force (if applicable)
- compressive forces (PRH1, A2)

against the closing direction
- friction force
- compressive forces (PRH2, A2, p, ARASFT)
- spring force (if applicable).

4.3 Control rod drive

The control rod drive model consists of a boundary condition for the mass flow and a subprogram for computing this mass flow. The mass flow consists of two parts which are both equal to zero at the beginning.

The leakage flow is determined by the design. The leakage has a constant value during control rod motion. Thereafter, the leakage drops to a very low value but does not reach zero again.

The second part of the mass flow results from movement of the control rod. During movement a volume is created into which the mass flows. The movement equation of the control rod is solved afresh for each time step. The pressure difference across the hollow piston of the control rod drive acts as driving force. The friction force and spring force which slow down the control rod at the end of the stroke act in opposition to the direction of movement.

4.4 Pump

The pump model is still very simple at the moment. An external force is allowed to act on the flowing medium. This driving force acts as the friction term in the momentum equation, only in the opposite direction to the friction force. The friction term in the momentum equation is reduced by the amount of the pressure difference of the discharge head of the pump. This pump model simulates a steady-state operating pump exactly. When the pump operates on the flow curve, an error arises which increases the more the head flow curve deviates from a parabolic shaped curve.
5. RESULTS

Until now the EUDRU computer program has been used to perform pressure wave computations for water and steam piping systems in both boiling water and pressurized water reactors.

Subsequent computations of the most varied measurements and experiments have been and are being carried out to qualify the program.

In most cases, the degree of coincidence with actual results was high.

Subsequent computations /5/ were performed on measurements /4/ for commissioning of the reactor scram system of the Philippensburg Nuclear Power Station, Unit 1. After the necessary adjustments to the measurements had been made, there was a very high degree of coincidence with the actual results (Figure 2).

In order to prove the functional performance of a piston check valve closing with damping, special damping tests were performed on a test rig /6/. The flow force was replaced by a pneumatic force acting constantly at the valve disc.

In this simplification the substitute force acts from the very beginning with the maximum flow force. These tests were simulated mathematically using EUDRU.

The results from the subsequently computed test are shown in Figure 3 alongside the experiments. The decisive parameters such as closing time and pressures in the valve chambers coincide to within a few per cent.

Final qualification of the program can only be achieved by means of tests in which the valves interact with the flow through the pipe. Particularly suitable for this are experiments in which a complete pipe rupture occurs and in which the valve is closed by the medium flowing out.

The Nuclear Research Center in Karlsruhe is performing, in collaboration with outside companies, such tests on the superheated steam reactor in Karlstein. Experiments with a feedwater piston check valve of DN 200 /7/ have already been concluded. All 5 tests were computed with EUDRU, some in advance and some subsequently.

After the necessary corrections had been performed in the case of the subsequent computations, two of the five tests showed a high degree of coincidence as regards the results /8/ (see Figure 4). The test valve was so adjusted that the closing procedure occurred without or with only very little damping.

In the case of the other tests, the program could not reproduce the experiments exactly. When the medium flowed back, hot water from the reactor pressure vessel got into the test set-up. Thus a thermal condition arises which the program cannot simulate. In these cases the computation supplies conservative results.

By mid 1979 further blowdown experiments will have been performed on the superheated steam reactor with a feedwater piston check valve of DN 350.

The test valve is to a large extent of comparable design to that of the feedwater piston check valves used to be installed in the nuclear power plants equipped with boiling water reactors from Brunsbüttel onwards and in those nuclear power plants equipped with pressurized water reactors from Grafenrheinfeld onwards.

Computations using EUDRU are being performed in advance with respect to the 350 feedwater piston check valves. On the basis of experience gained so far, it is assumed that the computations will be proven valid by the experiments.
6. CONCLUSIONS

In order for computer programs for piping systems to simulate faithfully conditions in actual practice, integrated computation of components which influence the flow in the system is necessary: These components include, above all, valves and flow nozzles but also pumps, pressure-vessels and heat exchangers. With the current version of the program, the following may be computed:

- power-operated valves for water flow
- medium-operated piston check valves (damped and undamped) for water flow
- power-operated valves for steam flow
- control rod for reactor scram system in boiling water reactors.

Under development are:

- medium-operated swinging disk check valves closing without damping
- medium-operated steam valves.

The pump model existing until now takes into account a steady-state operating pump and is being further refined. Problems with heat exchangers cannot as yet be worked on. The fundamental equations contain no provisions for heat transfer.

The program is being constantly further developed so that within the near future other problems may also be dealt with. Even at this state of development, however, it can be stated that EUDRU is capable of successfully coping with most fluid-dynamic piping computations.

7. REFERENCES


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FIG. 1: SKETCH OF A DAMPED CHECK VALVE

FIG. 2: EXPERIMENTAL AND COMPUTED PRESSURE-TIME HISTORY IN CONTROL ROD HOUSING (BWR PHILPSBURG 1)

FIG. 3: EXPERIMENTAL AND COMPUTED VALVE CLOSING HISTORY WITH DAMPED CHECK VALVE

FIG. 4: EXPERIMENTAL AND COMPUTED VALVE CLOSING HISTORY WITH DAMPED CHECK VALVE

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