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Determination of Two-Dimensional Steady State Conditions in LWR-Loops

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Abstract

The numerical simulation of pressure wave phenomena in primary coolant systems of light water reactors by computer codes demands initial values for all fluiddynamic variables.

A program package "START" has been written to compute the most important initial value distributions.

A selection of the most substantial hydrodynamic features are presented. The modelling of a real PWR-primary coolant system is shown as well as the mathematical model of computations.

1. Introduction

Steady state conditions require specific effort for the numerical solution because of the nonlinearity of the problem. If the real geometry e.g. in the downcomer region of a PWR is modelled, then the mass flow, velocity, and pressure fields have to be determined in an appropriate way. In addition, heat transfer in the core region and in the steam generators have to be considered.

Hydrostatic pressure distribution and hydrodynamic distribution under steady state mass flow satisfy the requirements of compatibility and equilibrium and are therefore well conditioned initial value distributions. Only the letter represents the steady state condition of an operating reactor in reality.

For blowdown computations by the computer codes DAPSY (for rigid structures) and DAISY (for fluid-structure interaction problems) /1/ a new module,START /2/, has been added to solve the realistic boundary value problem and to give accurate initial value distributions.

For consistency, DAPSY/DAISY, the governing equations (Fig.1) for START have been extracted from the time-dependent equations of DAPSY /3/.

START uses the same mathematical models for the different hydrodynamic features, reads the same geometric- and hydrodynamic input data and computes the thermodynamic state by the same algorithm.

2. The method

To determine pressure, enthalpy, velocity and density, five coupled first order partial differential equations (Fig.1) are integrated by Runge-Kutta's method starting at a defined location with given values. The fifth equation is linear dependent on the pressure equation (3). It has been formulated to integrate pressure losses caused by friction and spontaneous changes in momentum separately. This helps in adjusting input data in accordance with experimental data or postulated values.

The main problem is seen in two- and three dimensional subregions, handled in DAPSY by the network technique. The pressure loss in two connected parallel pipes has to be a minimum. For the solution of this problem the sum of the partial mass flows is known. By assigning an estimated value plus a residue for the exact mass flow, and writing the equation for the pressure loss by binomial expansion limited for linear terms, a very simple iteration-formula /4/ is found. The mass flow will be refined continously until a prescribed criterion of convergence for the deviation is reached (Fig.2).
For networks a procedure is established by the superimposing of the residues of adjacent meshes.

To start the procedure, the unknown density distribution is derived from the hydrostatic pressure distribution. This may be done because the density does not depend significantly on the velocity. The integration of the differential equations results in a more accurate density distribution. If an obvious divergence from the hydrostatic density distribution is detected, the mass flow distribution is computed again, but for the most part it is not necessary.

For special hydrodynamic features as valves, pumps and boundaries a number of additional procedures are written. The code is programmed in a manner so that very complex systems can be handled.

3. Example

For a four-loop PWR primary coolant system under operating conditions the complete field of fluiddynamic initial values has been computed. The schematic configuration (Fig.3) shows adjacent loops symmetrically arranged.
All loops are equal in the view of fluiddynamics, but loop 1 has special boundary conditions for the break simulation and loop 2 has the pressurizer in addition. Nevertheless, the isolation of a representative partial circuit from the global system, loop 3 (Fig.4), is possible in order to limit computational effort.

Beginning with the starting point (Fig.6) for which the set of thermodynamic variables is given, the fluid enters the downcomer region through the nozzle of the cold leg at the eccentrically located point K 80. The two dimensional anulus has to be modelled for DAPSY computations by a network consisting of shunted and in-series connected ducts. Leaving the downcomer, the fluid confluences at point K 145 enter the core region and will be heated.

A small portion of fluid bypasses the core unheated and will be mixed with the heated fluid in the upper core region. Then the fluid leaves the pressure vessel at point K 148 and passes through the hot line into the steam generator. Here the heat of the core and of friction is tranferred to the secondary circuit. The cooled fluid flows back to the primary pump where pressure and enthalpy rise, so that the exact same conditions of the starting point exist. Now the remaining loops get their initial values with respect to the equality and inequality which correspond to symmetrical and antisymmetrical situation (Fig.5), respectively. Finally the special subregions such as break location (Fig. 7) and pressurizer (Fig. 8) are added.

4. Results

The quantitative mass flow distribution of the representative downcomer subregion is shown in Fig. 9. The irregular mass flow distribution around the inlet changes quickly in a uniform distribution.
First experiences with DAPSY/DAISY show good and stable results for the complete field of initial values. The capabilities of this START-package are successfully used /5, 6/ for the determination of fluiddynamic loads and structural response of the core internals during a loss-of-coolant accident in a pressurized PWR.

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References

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/6/ Meier, S. et al., "Kurzzeit-Belastung der RDB-Einbauten und der Primärkreisläufe eines Druckwasser-Reaktors durch einen Blowdown-Störfall. DAISY-Rechnungen für den 2 F - Bruch im kalten Strang" GRS-A- , to be published.

governing equations:

$$\frac{\partial w}{\partial x} = (r_1 - r_3 \varrho w) / (\varrho^2/N - \varrho w^2) \quad \left[\frac{1}{s}\right] \quad (1)$$

$$\frac{\partial h}{\partial x} = 1/w \, (r_2 - \varrho/N \, \frac{\partial w}{\partial x}) \quad \left[\frac{J}{kg\,m}\right] \quad (2)$$

$$\frac{\partial p}{\partial x} = \varrho \, (r_3 - w \frac{\partial w}{\partial x}) \quad \left[\frac{N}{m^3}\right] \quad (3)$$

$$\frac{\partial \varrho}{\partial x} = \frac{\partial \varrho}{\partial p}\frac{\partial p}{\partial x} + \frac{\partial \varrho}{\partial h}\frac{\partial h}{\partial x} \quad \left[\frac{kg}{m^4}\right] \quad (4)$$

$$\frac{\partial p_v}{\partial x} = \varrho \left[r_{31} - w (r_{11} - r_{31} \varrho w) / (\varrho^2/N - \varrho w^2) \right] \quad \left[\frac{N}{m^3}\right] \quad (5)$$

condensations:

$$N = \varrho \frac{\partial \varrho}{\partial p} + \frac{\partial \varrho}{\partial h} \quad \left[\frac{kg\,s^2}{m^5}\right]$$

$$r_1 = -1/N \frac{\partial \varrho}{\partial h} (\Omega + Z A w) \quad \left[\frac{N}{m^3 s}\right]$$

$$r_2 = -r_1 \frac{\partial \varrho}{\partial p} \Big/ \frac{\partial \varrho}{\partial h} \quad \left[\frac{J}{kg\,s}\right]$$

$$r_3 = -Z/\varrho \quad \left[\frac{m}{s^2}\right]$$

$$r_{11} = -1/N \frac{\partial \varrho}{\partial h} R A w \quad \left[\frac{N}{m^3 s}\right]$$

$$r_{31} = -R/\varrho \quad \left[\frac{m}{s^2}\right]$$

$$Z = R + \varrho g \sin\theta \, \delta \quad \left[\frac{N}{m^3}\right]$$

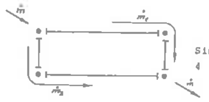
$$R = \sqrt{\pi}/4 \; \lambda/\sqrt{A} \; \varrho w^2 \quad \left[\frac{N}{m^3}\right]$$

$$\Omega = \Phi/l - \varrho g \sin\theta \, \delta A w \quad \left[\frac{N}{s}\right]$$

notations:

w	[m/s]	velocity
h	[J/kg]	enthalpy
p	[N/m²]	pressure
ϱ	[kg/m³]	density
A	[m²]	cross sectional area of pipe
l	[m]	length of pipe
θ	[°]	inclination of pipe axis
Φ	[W]	thermal power
δ	[-]	correction factor
λ	[-]	coefficient of friction
x	[m]	coordinate of pipe

Fig.1 : Governing equations for one phase fluid



$$\dot m = \dot m_1 + \dot m_2 = const. \; ; \quad \Delta P_{v_1} = \Delta P_{v_2} \curvearrowright$$

$$k_1 \dot m_1^2 = k_2 \dot m_2^2$$

using :

$$\dot m_i = \dot m_{i,o} + \Delta \dot m_o \qquad \text{where:} \begin{cases} \dot m_i & : \text{exact} \\ \dot m_{i,o} & : \text{estimated} \\ \Delta \dot m_o & : \text{residue} \end{cases}$$

$$\curvearrowright \; \Delta P_{v_i} = k_i \dot m_i^2 - k_i (\dot m_{i,o}^2 + 2 \dot m_{i,o} \Delta \dot m_o + \Delta \dot m_o^2)$$

for linearisation: $\Delta \dot m \rightarrow 0 \quad \curvearrowright \; \Delta \dot m^2 \approx 0$

applied to the mesh above:

$$\Delta P_{v_1} = \Delta P_{v_2}$$

$$k_1 (\dot m_{1,o}^2 + 2 \dot m_{1,o} \Delta \dot m_o) - k_2 (\dot m_{2,o}^2 + 2 \dot m_{2,o} \Delta \dot m_o)$$

$$\Delta \dot m_o = -\frac{1}{2} \frac{k_1 \dot m_{1,o}^2 - k_2 \dot m_{2,o}^2}{k_1 \dot m_{1,o} - k_2 \dot m_{2,o}}$$

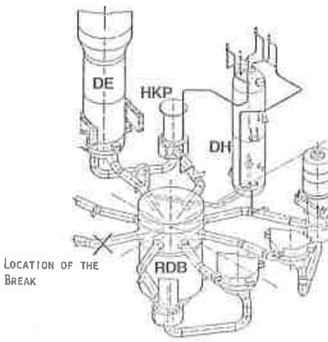
iterative formula: $\boxed{\Delta \dot m_j = -\frac{1}{2} \frac{\sum_{i=1}^{n} \Delta P_{v_{i,j-1}}}{\sum_{i=1}^{n} (\Delta P_{v_{i,j-1}} / \dot m_{i,j-1})}}$

particular mass flow after refinement j :

$$\boxed{\dot m_{i,j} = \dot m_{i,j-1} + \Delta \dot m_j}$$

$$j = 1 \dots \qquad 0 < \Delta \dot m_j < E$$

Fig.2: Iterative refinement of the estimated particular mass flows of a single mesh



DE = Steam Generator
DH = Pressurizer
HKP = Primary Pump
RDB = Pressure Vessel

Fig. 3 : Schematic configuration of a 4-loop PWR primary system

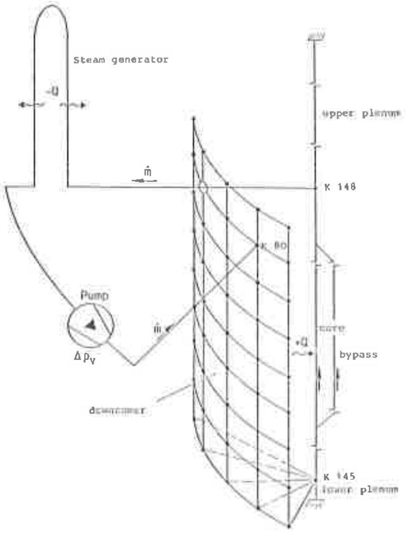


Fig. 4 : Representative partial primary coolant circuit

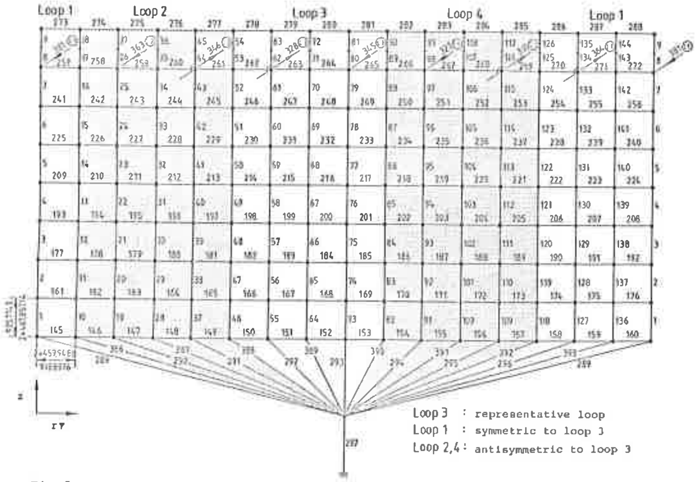


Fig.5 : Idealzation of the unwinded downcomer region

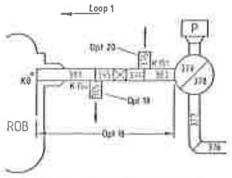


Fig.8 : idealization of a 2A-break region

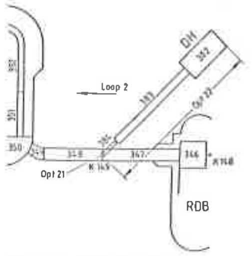


Fig.9 : Idealization of pressurizer

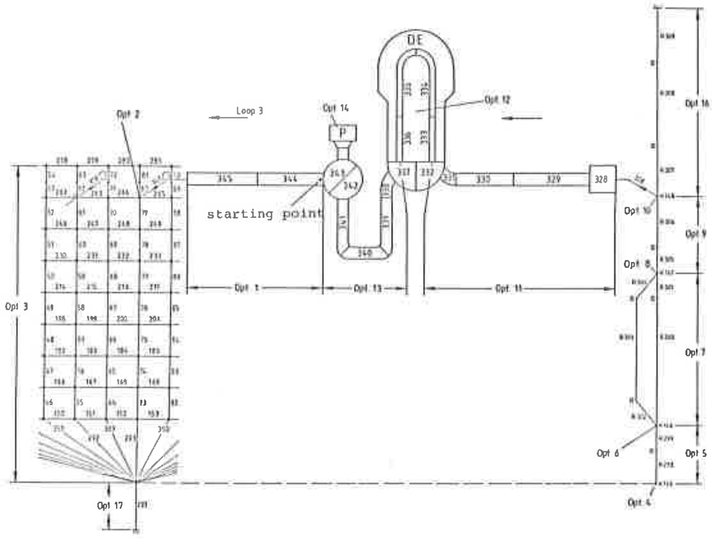


Fig.6 : Idealization of the representative circuit

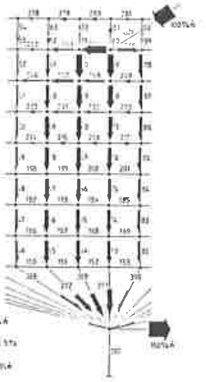


Fig.9 :Mass flow distribution of the downcomer subregion