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Calculations of the pressure waves in a water cooled nuclear reactor induced by transients

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ABSTRACT

This paper presents an formulation which treats different aspects of the phenomenum of fluid transients in a common tubular circuit (a cavity connected to a pipeline). The results and predictions given by these models are obtained by the developed code TRANS (Transient Analysis in Nuclear Reactors). Agreement between theoretical and experimental pressure-time, pressure amplitudes and phases profiles diagrams is sufficient to validate a model.

1. INTRODUCTION

Water under pressure circulater through the tubular circuits in a nuclear reactor what may cause dynamic phenomena of a transient nature. A rupture in the piping system; the opening and closing of flow controlling devices; dynamic and vibratory effects on the supports and walls of the piping system; significant pressure variations on main cavities or instability due to flows are examples of generating sources of these transients which may affect the reactor's internal structure as well as elements and components thereofe.

The transient problem in pipelines go back to a lot of years, it appeared at first in hidraulics, and is object of studies since then [1,2,3,4,5].

If the most part of the papers devoted to this matter are found in the hydraulics, petrol industry and gas flow, it was with the nuclear industry that it could have a greater development and sophisticated models.

In all countries where the nuclear eletric sector is developed this phenomenum has been studied a lot, although it still deserves more complex models and some tests and verifications.

Several transient phenomena may cause or be a consequence of those accidents, and they must be very well known before the study of more complex problems, such as the study of the fluid-structure-interaction (FSI) .

The wave propagation phenomenum is considered as uncoupled from the pipeline structural response, but the calculated pressure time evolution can be used to find the imposed in a given test section of the circuit. The main objective of our research, presented in this paper, is to make a preliminary approach to study FSI.

This paper studies the transient waves with basis on the classical plane wave theory. The partial differential equations ruling the problem are solved by the general characteristics' technique using the method of finite differences.

So, in this paper a lot of considerations are done to simplify the problem, however some some models that include most of this effects cited above are already beeing developed, and will be object of future publications.

2. GENERAL FORMULATION

The classic water-hammer theory is adopted for modelling the fluid behaviour [3].

Figure 1(a) shows a nuclear reactor which core and part of its primary circuit may be idealized as a system composed of a great cavity connected to a right tube, Figure 1(b).

Theoretical-numerical approaches of pressure wave propagation have been the object of several of our studies [12,13,14,15,16,17,18,25]. The equations ruling this problem are the equations of continuity, quantity of movement and state, respectively:

$$\frac{\partial p}{\partial t}+\mathrm{div}(\rho\vec{V})=0 \tag{1}$$

$$\rho\left(\frac{\partial\vec{V}}{\partial t}+\nabla\left(\frac{V^2}{2}\right)+\left(\mathrm{rot}\vec{V}\right)\mathrm{x}\vec{V}+\nabla(p+\rho g y)-\mu\nabla^2\vec{V}\right) = 0 \tag{2}$$

$$f(p,\rho) = \mathrm{Cte} \Leftrightarrow \tilde{P} = \tilde{\rho}C^2 \ \text{(linearizada)} \ \therefore \ C^2=\frac{K^*}{\rho} \tag{3}$$

As regards the tension-deformantion relation for a thin elastic tube, longitudinal tensions ($\sigma_l=0$) note being taken into account, there is the following equation:

$$\varepsilon_c = \frac{1}{E}(\sigma_c-\nu\sigma_l) = \frac{\sigma_c}{E} = \frac{pD}{2Ee} \tag{4}$$

And equation (1) may be rewriten as follows:

$$\frac{\partial p}{\partial t}+v\frac{\partial p}{\partial x}+\rho c^2\frac{\partial v}{\partial x} = 0 \quad \text{with,} \quad c^2=\left(K^*/\rho\right)/\left(1+\left(\frac{K^*D}{Ee}\right)\right) \tag{5}$$

c is sound velocity in fluid; E is the Young's modulus of the tube, e is the thickness; σ_c and ε_c are the circumferential tension and deformation.

Supposing an adequate ratio between x and t is chosen, the following characteristic equations may be found:

$$\frac{dv}{dt}\pm\frac{1}{\rho c}\frac{dp}{dt}+\frac{fv|v|}{2D} = 0 \qquad \therefore \quad \frac{du}{dt}=V\pm c \tag{6}$$

The ±c values represent the inclination of the characteristic curve in x-t plane; f is the coefficient of friction, D is the diameter of the duct; K^* is the fluid volumetric modulus of elasticity, p is the pressure, v is the velocity, ρ is the specific mass of the fluid.

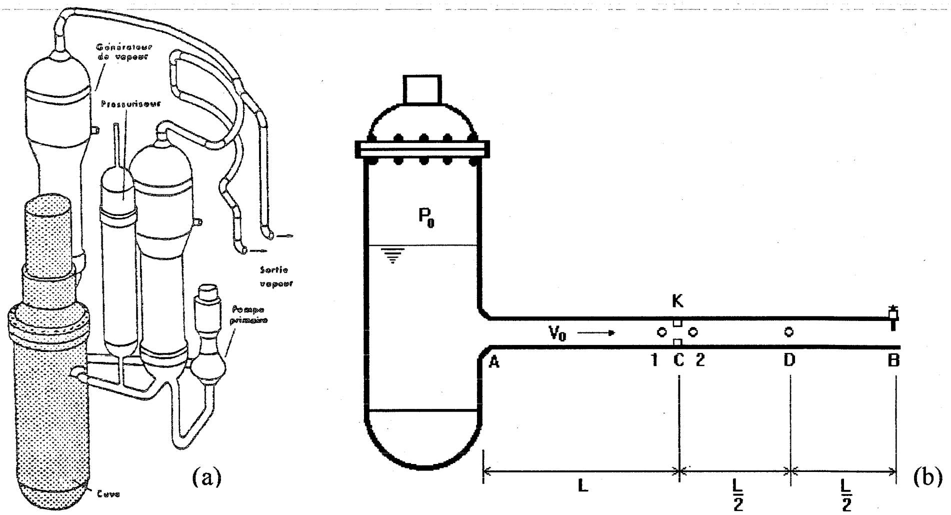

Figure 1 - Real scheme (a); and the simplified model - reactor's core (cavity) +pressurized circuit (piping system) (b).

Equations (6) define a first-order quasi-linear hyperbolic system of partial differential equations with p an v as dependent variables. When this system is transformed into ordinary differential equations (called compatibility equations) by the method of characteristics (MOC), two families of propagating characteristic lines are found.

3. RESULTS

3.1 Wave Propagation, Reflections and Damping

Some theoretical-numerical studies about these effects have been object of other papers [12,13,14,19,20,25]. When this pressure wave is generated, for example by a sudden obstruction of flow, such wave propagates itself through the tube until finding a singularity (orifice) of the duct.

The presented simulations refer to Figure (1)b where there is a pressurized cavity, at normal temperature, having a permanent flow at (V_o) velocity created by (P_o-P_v) gradient.

Data of the problem : P_0 = 34bar; V_0 = 2m/s; P_v = 15bar; K = 1000; L = 50 m; D = 0,10m; t_0 = 120ms; c = 2000m/s; f = 0,02.

In the Fig.(2)a, P(t) is the response at D point for the valve closing; in a typical case (Fig.(2)b).

It must be noted that at AB step height, (B) point refers to the first reflected wave (P_r). At the height of the second step, (C) point corresponds to the return of the first reflected wave, totally reflected in the valve.

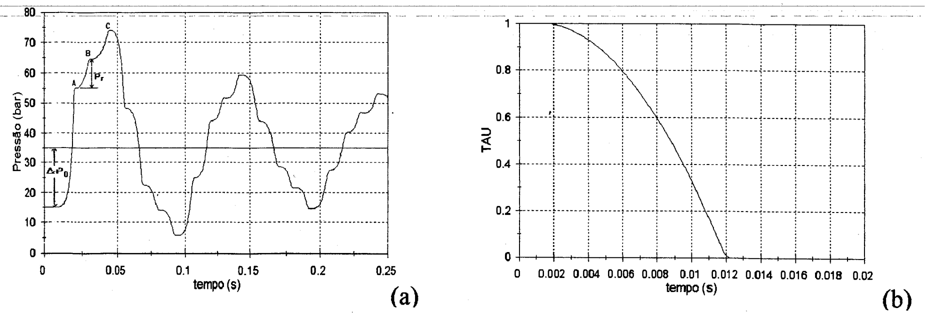

Figure 2 - Pressures on D point - Study of the reflections in the first cycle of the transient (a); Valve closing curves - real and ideal (b).

Figure 3 shows a graph of the pressures and velocities of two points neighbouring the singularity, one before (P_1) and one after it (P_2).

The values indicated by letters A_1 and B_1 represent the difference of pressure between the faces of the singularity along several stages of propagation (ΔP transient), which characterizing the effects of the significant losses in the orifice. These transient losses are not constant during each cycle or passage of the wave by the singularity.

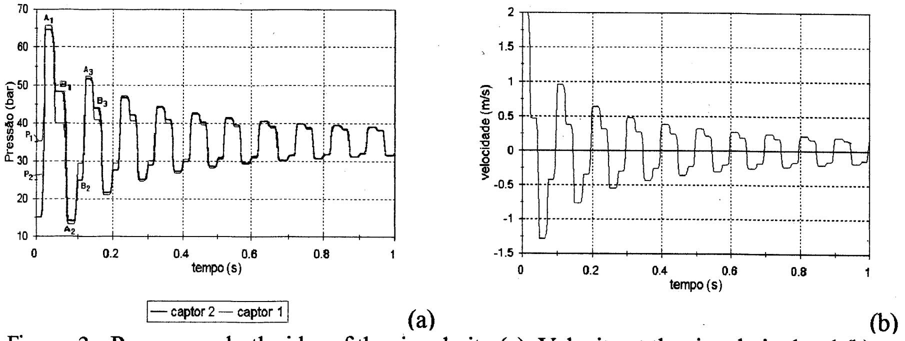

Figure 3 - Pressure on both sides of the singularity (a); Velocity at the singularity level (b).

3.2 BLOWDOWN EFECTS

The transient is generated within a strong rupture at the edge of the piping system and corresponds to a pulse of despressurization P_{cav}-P_{atm}=P_o. The rupture happens in a breach (orifice) having a d<D diameter.

Data: P_o = 50bars; L = 50m; D = 0,10m; c = 2000m/s; f = 0,02; K_f = 10; K_s = 80; τ_1 = 0,316s; ω_1 = 19,8rad/s.

Figure 4 shows the evolution of the velocity at D (Fig. (4)a) point; and the pressure theoretical in D (Fig. (4)b) point, according to TRANS program. The velocity (analytical) represent a continuous average curve, tends to V_{lim}=31,62 m/s, having an asymptotic evolution [12,13,17] results.

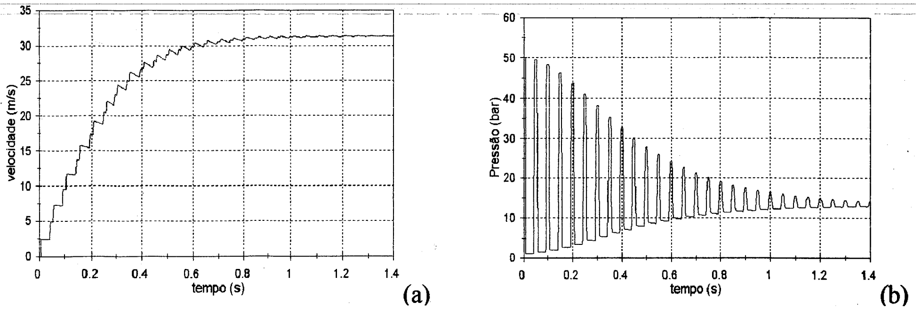

Figure 4 - Evolution of the velocity (a) and of the pressure (b) in the D point.

The second case (abrupt decompression effect): this case compare the results and predictions given by our models with experimental results (see Fig.5) [23].

Data: L = 1,22m; D = 0,103m; c = 1460m/s; f = 0,02; P_{cav} = 115,83bars; K_s = 0,73; β = 35,19; ω_1 = 61,44rad/s; τ_1 = 0,1023s; ω_0 = 201,75rad/s; τ_0 = 0,0311s; α=0.30; τ = 0.000836s; x(P_3) = 0,305m (of the cavity).

Figure 6 shows the pressures in (P_3) point (on the piping) distant from the x=0,305m of the cavity.

Figure 6 shows respectivily the results given by code TRANS (6)a, and experimental and calculated results obtained by code WHAMMOC II [23].

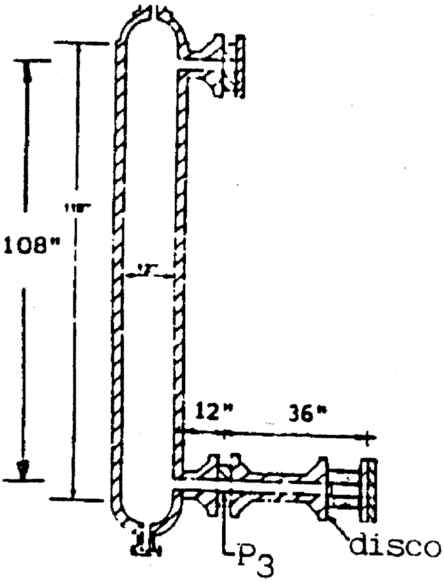

Figure 5 - Scheme of the test. [23]

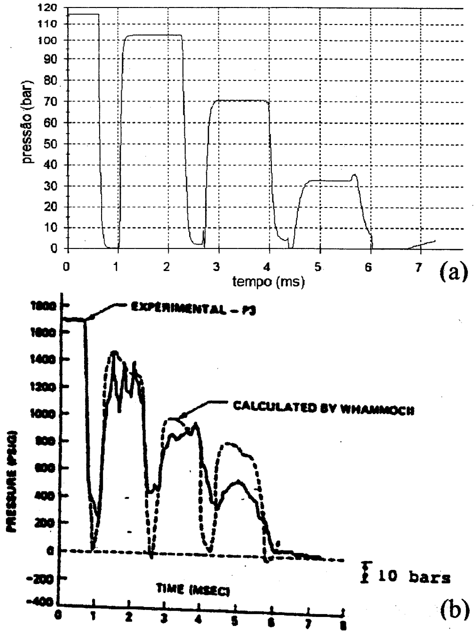

Figure 6 - Pressures in P_3 point - Results given by code TRANS (a) and literature [23](b).

4. CONCLUSIONS

Taking into account the analysis of the results obtained with TRANS program, is is possible to demonstrate that the program was able to supply detailed results reproducing expected real trends of transient phenomena of this kind.

The magnitude of the first wave reflected in the singularity, supplied by the program, corresponds exactly to the value obtained by the previously developed analytical solution.

The dampings due to abrasion are insignificant when compared with the dampings caused by the singularity. Thesé dampings were reduced even for high (K) values, since it is the effect of velocity which provokes more significant attenuations.

The fluid reaches a limit velocity to the extent it moves itself. Such limit velocity corresponds to the values calculated for the incompressible condition (analytical model).

Real flow values (P(t) and v(t)) vary around the incompressible flow.

The numerical results tend to the values obtained by the analytical model once the sound velocity in TRANS ($c \to \infty$, incompressible case) program increases.

5. ACKNOWLEGDEMENTS

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