Evaluation of Fluiddynamic Loads on RPV Internals During Blowdown

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INTRODUCTION

The blowdown from a pressure vessel containing steam-water mixtures was the object in the past of a large number of theoretical and analytical studies, essentially owing to the relevance of this issue in nuclear reactor safety.

Different aspects of blowdown were investigated at "Dipartimento di Costruzioni Meccaniche e Nucleari" of Pisa University since 1972, mainly with regard to the evaluation of two-phase critical flow (D'Auria, 1983), the jet impingement and shape (D'Auria, 1984), the friction pressure drops in critical conditions (Vigni, 1984). Large system codes have been used for the interpretation of the experiments and to validate the implemented models (D'Auria, 1984; Ambrosini, 1987).

Among the problems connected with blowdown analysis, the evaluation of loads on components internal and external with respect to the main vessel is an important goal in the safety analyses of nuclear power plants, in the hypothesis of guillotine break of the largest pipes near the RPV. Large deformations and loss of functional integrity may be the result of fluiddynamic loads in the very early stage of presumed large break LOCA; this prevents or makes less efficient the intervention of the engineered safety features directly affecting the core integrity.

In this paper the main outcomes of a research having as main objective the last item are discussed. In particular (Vigni, 1973), a series of experiments were performed aiming at the evaluation of loads on a simple model of internal structure (plate with a central hole). Both ambient temperature water and saturated steam-liquid mixtures were considered, in a pressure range varying between 2.0 and 7.0 MPa. The experimental part of the research was carried out utilizing the PIPER vessel in which depressurization waves were created by the controlled break of proper rupture disks. The advanced thermalhydraulic codes RELAP5/MOD2 (Ransom, 1985) and CATHARE V1.3 (Boulet, 1987) have been recently applied to the analysis of the experimental results.

EXPERIMENTAL FACILITY AND TESTS DESCRIPTION

PIPER vessel.

The pressure vessel utilized in the experiments is shown in Fig. 1. Volume and height are 0.09 m^3 and 3 m, respectively; the vessel can operate with water in saturation conditions up to 10 MPa. Two nozzles, equipped with a fast opening rupture disk device, are installed in the upper and lower part of the facility (Fig. 1). Electrically heated rods supported by the lowest flange are used to warm up the liquid and to pressurize the vessel. In the frame of the present research a plate with a central hole and the related support (Fig. 2), were placed inside the vessel.

The instrumentation included piezoelectric pressure transducers and thermocouples mounted along the axes of the vessel and of the exit nozzles. Two longitudinal and two transversal strain gauges were welded to the external surface of the plate support device (D'Auria, 1978). In order to measure only the mechanical deformations along the axis of the cylindrical shell (following the propagation of the depressurization wave from the lower nozzle to the vessel) the strain gauges were connected to the Wheatstone bridge circuit, self-compensating for temperature and bending. In this way, possible strains due to thermal stresses cannot be eliminated; however this load is subsequent to the temperature transient of the fluid and it appears when the fluiddynamic load has gone out. The measurement device was qualified through static loading and unloading cycles.

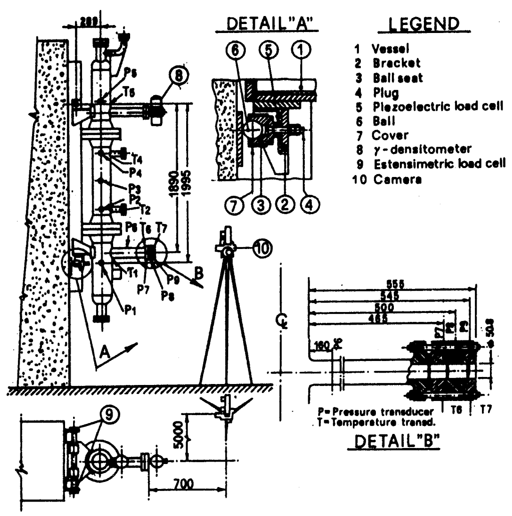

Fig. 1 - PIPER vessel and blowdown nozzle.

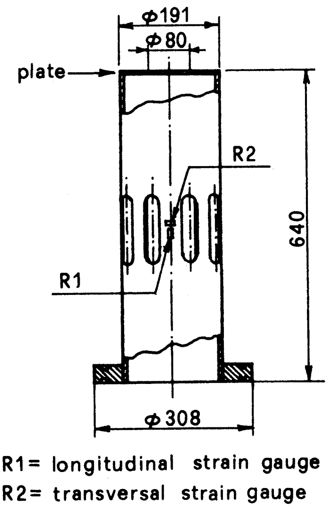

Fig. 2 - Plate and support device.

<u>Test modalities and initial conditions.</u>

The water initially charged into the vessel was pressurized by injecting high pressure nitrogen or by electrical power supply to the heating rods. In this last case, saturation conditions were achieved with steam present in the upper part of the vessel. The lower nozzle was used in all the experiments. The diameter and the L/D ratio were maintained the same in all the tests, respectively equal to 0.05 m and to 11.0.

Typical experiments were initiated by the rupture of the double disk device in Fig. 1. Break time was measured in the range 3-5 milliseconds. The overall blowdown duration (time necessary to the RPV pressure to achieve the ambient value) lies between 2 and 10 seconds, depending upon the initial mass inventory, the water temperature (saturation or ambient values) and pressure.

The initial values of fluid pressure and temperature as well as of mass inventory are summarized in Tab. I.

OUTLINE OF CODE MODELS

RELAP5/MOD2 and CATHARE V1.3 are advanced thermalhydraulic system codes extensively used for the evaluation of transient behaviour of nuclear power plants (D'Auria, 1989). Both are based on a six partial differential equations system which is solved by a nearly implicit and by a completely implicit numerical method in the case of RELAP5/MOD2 and CATHARE, respectively. The constitutive relationships, known as closure equations, also differentiate the two codes.

The input models (nodalizations) simulating the PIPER vessel have been developed according to the instructions contained in the user manuals; the rather small duration of the phenomena to be calculated (few milliseconds) has been considered.

The RPV has been nodalized by 41 and 25 nodes in the CATHARE and RELAP5 models, respectively; the number of meshes for the nozzle are 24 and 14 for the two cases. The plate present in the vessel has been simulated by a geometric discontinuity. The imposed maximum time step holds 10^{-4} seconds. Finally, the rupture disk assembly has been nodalized by a control valve in the RELAP5 and by a proper boundary condition in the CATHARE input deck; opening time has been varied in the range 1-10 milliseconds.

RESULTS FROM THE ANALYSIS

Tests scenario.

It appears worthwhile to present an overall view of the tests scenarios even to better define the particular aspects addressed in this work.

With reference to tests 701 and 702 of Tab. I, the fluid pressure trends and the jet thrusts on the vessel supporting frame are reported in Figs. 3 and 4, respectively. The much faster depressurization rate can be noted in the case of liquid initially at ambient temperature, owing to the lack of vapor production (Fig. 3); even the total impulse on the vessel constraints is much smaller in this case (Fig. 4).

TEST N°	p_o (MPa)	T_o (K)	M_o (Kg)	x_o (-)
203	2.10	300	55.0	-0.4410
303	3.10	300	56.0	-0.5180
502	5.10	300	52.0	-0.6530
701	7.17	300	55.0	-0.7890
201	2.10	488	55.0	0.0047
302	3.10	508	55.4	0.0062
501	5.10	538	55.4	0.0087
503	5.10	538	27.5	0.0518
504	5.10	538	55.0	0.0090
702	7.17	560	55.8	0.0099

Tab. I - Initial conditions for the considered tests.

The analysis of experimental data demonstrated that significant loads on the internal plate only occur in the first few milliseconds following the break opening and are due to the propagation of the depressurization wave, generated by putting into communication the high pressure fluid with the environment at ambient conditions. Subsequent fluiddynamic loads caused by the pressure drop through the plate are negligible and hidden, in the case of hot water conditions, by thermal stresses occurring in the plate supporting devices. For

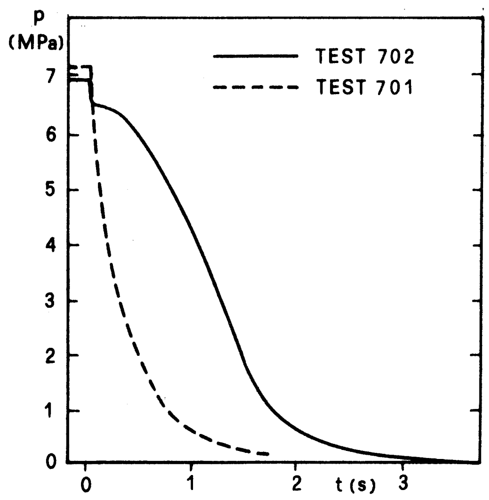

Fig 3 - Measured RPV pressure trends.

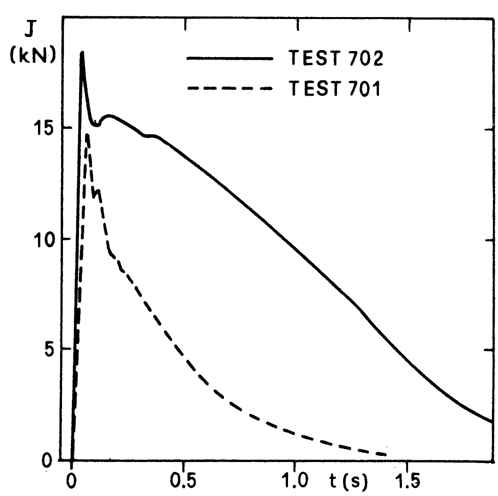

Fig. 4 - Measured trends of jet thrust.

this reason only the initial few milliseconds are considered in the analysis hereafter.

Loads on the internal plate.

The depressurization wave originated at the break propagates along the nozzle and, afterward, inside the vessel. Three-dimensional phenomena are foreseeable inside the RPV, including scattering and reflection of the wave. The attenuation of the amplitude depends upon the compressibility of the fluid and the elasticity of the vessel walls. Saturated fluid is expected to create larger damping than subcooled water.

The peak load on the PIPER internal structure occurs when the depressurization wave reaches the bottom end of the plate and the upper end is still subjected to the initial pressure.

Typical trends from the strain gauge transducers are shown in Fig. 5. Similar signals have been measured for the differential pressure between stations P1 and P5 in the RPV (Fig. 1). The maximum values of the load obtained by strain gauge (F) and of the quantity DpA are plotted in Fig. 6 as a function of the test pressure. The maximum load on the plate (F) versus the maximum jet thrust (J) is shown in Fig. 7. Two main considerations outcome from the analysis of the above figures:

- the values of F and of Dp almost coincide in the case of subcooled liquid blowdown, while the latter value is much larger than the former in presence of saturated fluid (Fig. 6); this testifies of the damping of the depressurization wave when traversing the saturated liquid inside the blowdown nozzle and up to the lower face of the internal plate;
- the link between F and J is nearly linear in the case of subcooled liquid, lower values of F occur in presence of saturated fluid confirming the presence of larger dissipation mechanisms in the last situation.

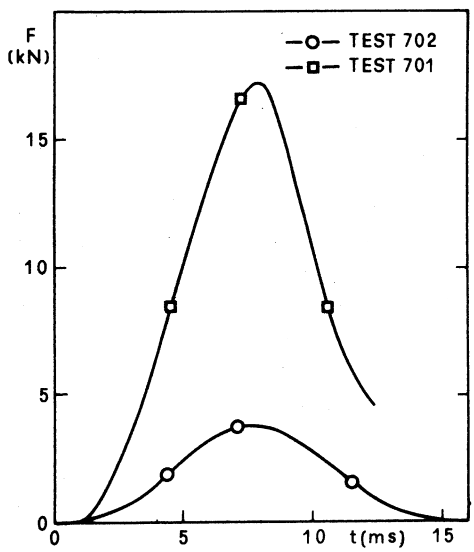

Fig. 5 - Trends of loads on the internal plate measured by strain gauges.

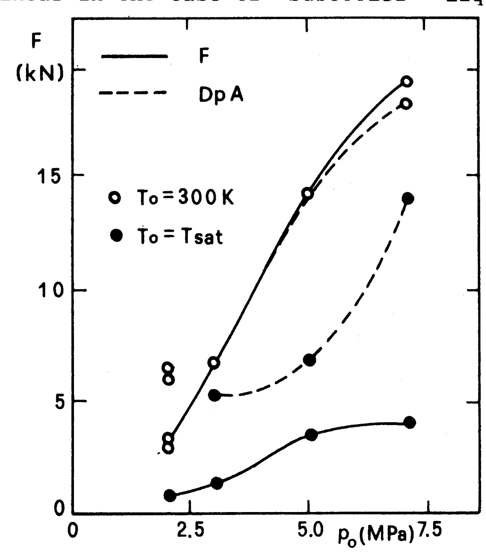

Fig. 6 - Maximum load on the internal plate vs. initial test pressure.

Codes application.

Essentially, two quantities calculated by the code can be compared with experimental data:

- the pressure difference p_5-p_1;
- the maximum load F, obtained in the calculations as product of the pressure

differential across the plate times the plate area.

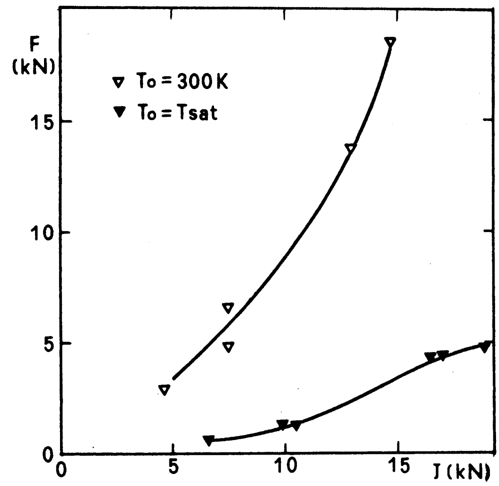

Fig. 7 - Maximum load on the internal plate vs. maximum jet thrust.

The comparison between measured and calculated trends is given in Figs. 8 and 9. With reference to saturated water tests, the uncertainty bands are associated with the variation of break opening time in the range 1-10 ms.

The figures show that the wave propagation is simulated by both codes; nevertheless, CATHARE results are more adherent to the experimental trends while a too large damping of the pressure wave is calculated by RELAP5.

The Dp values calculated from top to bottom of the PIPER vessel and across the plate (Fig. 8), give an idea of the amount of damping in the saturated liquid; this also explains the measured data reported in Fig. 6 with main reference to the discrepancy between the

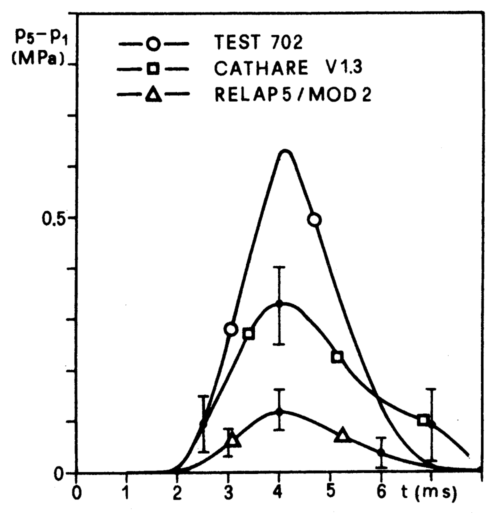

Fig. 8 - Measured and calculated trends of p_5-p_1.

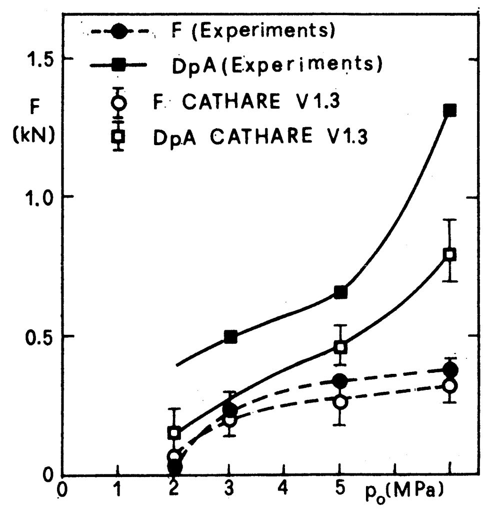

Fig. 9 - Measured and calculated max. load on the internal plate.

values of the force obtained by strain gauge and by pressure measurements.

The reported data also demonstrate the deficiency of the RELAP5 model in predicting the sonic wave progression; this appears to be due essentially to the numerical solution model. In particular, the "numerical viscosity" introduced to get, artificiously, real solutions from the set of balance equations seems to have a strong damping effect on the wave propagation. On the other hand, CATHARE data are in fairly good agreement with the experimental ones.

All the above results should be seen considering that a three-dimensional phenomenon such as the wave propagation from the exit nozzle toward the RPV interior is simulated by one-dimensional models. Still, the elasticity of the RPV is not considered in the theoretical models.

CONCLUSIONS

With reference to the whole set of experiments, it has been shown that two independent measurement methods (strain gauge and pressure difference) produce very similar results with subcooled liquid, while substantial differences occur in the case of saturated mixture. A strong attenuation of the depressurization wave explains the above difference.

The much higher value of the loads on the internal plate, in presence of subcooled liquid with respect to the case of saturated mixture, and the strong non linear dependence of the load upon initial pressure in the last conditions are the most significant results of the experiments.

The application of CATHARE V1.3 and RELAP5/MOD2, on one hand allowed a more complete understanding of the some wave propagation, on the other hand demonstrated the deficiencies of the RELAP5 model. The too high unphysical attenuation of the wave amplitude was identified as the main problem in this connection, even considering the 3-D characteristics of the phenomenon that are not simulated by any of the two codes.

SYMBOLS

A : Net area of the plate

F : maximum value of the load on the plate

M_o : initial fluid mass in the RPV

p_o : initial fluid pressure

J : maximum value of the jet thrust

Dp : maximum value of the pressure differential measured in stations P5 and P1

t : time

T_o : initial fluid temperature

x_o : initial fluid quality

ABBREVIATIONS

LOCA: Loss of Coolant Accident

MPI : (Italian) Ministry of Public Education

RPV : Reactor Pressure Vessel

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