VALIDATION OF A CAVITATION MODEL AND ITS APPLICATION TO CONTAINMENT LOADING EXPERIMENTS

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The author previously presented a model of bulk cavitation, for use in conjunction with fast reactor containment codes, in which the growth of the individual vapour bubbles is calculated for each fluid cell.
Specimen cases of the application of the model to containment experiments were also presented but these were confined to simple rigid geometries.

In this paper evidence for the validity of the model is obtained from comparison with the results of two purpose-designed cavitation experiments available in the literature, and the model is then applied to a wider range of containment geometries than hitherto.
For the more complex geometries agreement with experiment is found to be significantly better with the cavitation model.

The paper ends with a discussion of the significance of this result for real reactors, which leads to the conclusion that cavitation is probably as important there as it is in models.

1. Introduction

Previous publications /1-3/ have argued that dynamic cavitation of the coolant is an important feature of the containment process in LMFBRs in that it affects the extent to which the energy contained in the pressure waves emitted by a reactor core undergoing an HCDA is transformed into the energy of deformation of structures essential for the satisfactory containment of the post-explosion situation. The local growth and collapse of cavitation bubbles under the influence of tensions and pressures arising elsewhere in the reactor system is essentially a dissipative process since it converts pressure energy and kinetic energy to heat, and so in general it can be expected to improve the calculated performance of a containment structure under a given HCDA loading. There are however significant impedance mismatch and resonance effects at fluid-structure boundaries and to make an accurate evaluation of the response of any particular structure it is necessary to carry out a complete calculation using one of the well-known containment codes /4, 5/ modified to include the physical behaviour of cavitating coolant.

Qualitative analysis of the progression of the pressure waves which originate in the expanding core (supported in part by calculations) indicates that the chief regions of coolant where cavitation can be expected are at free surfaces, where it arises from the reflection of pressure waves, in the neighbourhood of the axis, caused by the convergence of reflected waves in roughly symmetric geometries, and in strata bordering deformable wetted structures both internal and external. As a consequence we can expect to see the most significant effects of cavitation manifested in the pressures arising from roof impact and in the strain histories of deformable structures. Coincidentally the roof loadings and the structural deformations are generally considered to be the key points in containment analysis /5/. Refs. /1-3/ also proposed a dynamic cavitation model for use in reactor containment codes, in which the bubbles were assumed to be inertially controlled, independent and uniformly distributed. Justification for these assumptions was drawn both from relative magnitude arguments and from a more detailed bubble growth model which included additional transfer effects such as heat and mass diffusion and phase changes at the bubble surface. The importance of obtaining experimental information both to justify these assumptions and to provide essential parameters in the model, in particular the number of bubbles per unit mass of fluid (N) and the effective tensile strength of the fluid (P_{cav}) was repeatedly stressed, and the paucity of relevant experimental data lamented.

Recently the results of two sets of experiments designed specifically to investigate dynamic cavitation have become available. In the remainder of this paper sections 2 and 3 briefly describe the experimental arrangements and procedures and compare the results with the predictions of the analytical model mentioned above (SIMON). It is concluded that the model is validated in a sense to be defined later, and approximate values for N and P_{cav} are obtained. In section 4 the SIMON model is embedded in the Lagrangian containment code

ASTARTE [4] and the combination applied to the analysis of firstly a model test with rigid tank geometry from the COVA series of experiments [6] and secondly a flexible round-bottomed vessel experiment from the same series. The influence of cavitation on the roof pressure histories and the vessel deformations are discussed for each experiment. Section 5 completes the paper with an attempt to extend the conclusions drawn from these simplified model comparisons to real reactor situations.

2. Open Tank Experiments

Information concerning a series of experiments in which explosive charges submerged in water were detonated in open tanks has appeared fairly recently [7]. In the sub-series of experiments which investigated the early stages of cavitation an array of Kerr-cell cameras using flash-bomb illumination was employed to obtain a sequence of high-quality photographs at intervals of about 3.5 μs of the upper 50 mm of the water directly above the charge. In these photographs the water, which had been demineralised but not microfiltered, was subjected to an upcoming spherically-expanding shock which was reflected at the free surface as a tension front. In successive photographs the spherical surface of the tension front could be seen propagating downwards and behind it in the inverted cap of liquid subjected to tension the cavitation bubbles could be observed to grow. The experiments were carried out in an open tank large enough for shocks reflected at the tank walls and bottom to be well away from the tension region for the times of interest, and for the cavitation to take place completely free from the influence of walls or other material interfaces where bubbles could form preferentially.

A graticule ruled in 1/10" (2.54 mm) squares was immersed vertically in the water perpendicular to the camera and directly over the charge, and by means of the length scale so provided it proved possible to count the active nucleation sites and to measure the bubble diameters in each layer of fluid and for each time, directly from the photographs.

This experimental technique, besides avoiding interface effects, is conceptually simple and effective, but as executed there were a number of difficulties and deficiencies. No measurement of the pressure profiles of the upcoming shock or the tension front were made. The photographic grain size and the finite depth of focus of the camera limited the accuracy with which bubble radii could be measured and bubble number densities estimated. Lastly, the technique of using multiple cameras and disposable apparatus (the wooden tank was reduced to matchwood in each experiment) together with the precise timing required to capture the shock photographically during the brief period in which it was reflected from the free surface meant that the experimental difficulties were formidable and only a few experiments of this type were performed. Hence statistical analysis of the results was not possible. The position of the shock and of the tension front are clearly visible on the photographs. From them it is found that the tension front and the shock both proceed with the same constant speed of $1590 \pm 10 \ ms^{-1}$.

Examination of the bubbles shows that the bubbles appear to be scattered randomly over the volume under scrutiny. They also differ in radius, there being in the early stages many small bubbles and a few larger ones in each cavitating layer (2.54 mm deep). Since the contribution of a bubble to the void fraction is proportional to the cube of its radius, it is found that the contribution of the many small bubbles to the void fraction may practically be neglected. From the macroscopic point of view the area density of "big" bubbles is the parameter of interest. To convert area densities to numbers of bubbles per unit volume or unit mass it is necessary to know the depth of view. In the early photographs this is determined by the depth of focus of the camera system (approx. 50 mm), which in this experiment is always smaller than the diameter of the imaginary disc formed by the intersection of each layer and the cap of cavitating liquid behind the tension front. The small bubbles present at this time blur into invisibility when they are outside the region of the depth of view. In the later photographs this is no longer true - the bubbles are now so large that when out of focus they appear as fuzzy blobs and still cover some part of the bright background field. In this case it is more convenient to assume that the bubbles are all of equal radius and are scattered randomly throughout the imaginary disc mentioned above. Measurement of the fraction of the background unobscured by the silhouettes of bubbles then allows the bubble number density to be calculated. Figs. 1 and 2 show the number of bubbles per unit mass and their mean radius as a function of depth below the free surface for times up to 15.46 μs (where time zero is taken as the time when the expanding shock meets the free surface) together with estimated error bands. Although a gradual rise in the number of bubbles in time seems discernable there is no consistent spatial distribution of this quantity, and the error bands are such that the hypothesis of a constant number of bubbles can be sustained, with $N = 3600/\mathrm{kg}$.

A trivial calculation indicates that with the number densities and radii appearing in the figures, the bubbles are on average some 3 diameters apart, so that the assumption that they do not interact is also justified to a first approximation. As regards the value of the tensile strength of the water, the tensions appearing in the experiment are so high (about - 60 MPa at the free surface) as to obscure any possible effect of the water's initial resistance to tension.

To analyse the experiment, the SIMON module was embedded in a one-dimensional Lagrangian code with a spherical geometry option, and the profile of the upcoming pressure wave was calculated from a knowledge of the mass and equation of state of the explosive charge (12.9 g RDX/TNT) and of the depth of the charge below the surface (216 mm). 101 meshes were employed, and the principal SIMON parameters were $N = 3600/\mathrm{kg}$, $P_{cav} = -1$ MPa, although this latter parameter had little effect on the results. Although the use of a spherical reflection does not model accurately the true situation of reflection at a plane, along the perpendicular from charge to free surface, and for short distances below the surface the errors are expected to be negligible.

Fig. 3 shows the calculated radial pressure profile at several times. As can be seen from the figure, the leading edge of the shock is smeared out over several millimetres instead of being sharp as expected physically. This is unfortunately necessary, since the common Lagrangian algorithms cannot cope with discontinuities in pressures and velocities. The calculated radii are compared with experiment in Fig. 2. From this figure it may be seen that the calculated radius is quite well predicted close to the free surface (the anomalously low value for the uppermost calculational cell is due to the finite mesh size) but the calculated rate of penetration of cavitation into the liquid seems rather too high. Excellent agreement in both profile and spot values is attained for T = 12 μs. Fig. 4 shows that calculated void fractions agree fairly closely with experiment for all times and positions, again except for the anomalous uppermost cell.

It is concluded that the SIMON model achieves good predictions of void fractions with a suitable choice of the parameter N, at least when the tensions are high.

3. Shock Tube Experiments

As part of a collaborative effort with JRC-Ispra a small team at CENG Grenoble is performing a series of tests /8, 9/ of a quite different kind. In these tests a vertically-mounted composite shock tube consisting of two long aluminium rods sandwiching a transparent cell which contains the liquid under test is struck a downward blow at its lower end and the resultant upcoming tension wave is measured both below and above the cell by strain gauges mounted on the rods. The cell has an internal diameter such as to produce a good fit with the rods, and the seal is effected by O-rings. This type of experiment is very quick and simple, and a large number of tests have been performed. Since no photography is performed at present, preferential growth of bubbles at the surface of the rods and on the cell wall cannot be precluded a priori, but visual inspection of the bubbles after a test seems to indicate that bubbles form throughout the liquid volume, and in what follows it is assumed that the tests do reveal the response of a cylinder of water cavitating in the bulk under predetermined tension pulses. It is possible to compare transmission coefficients and pulse propagation speeds with and without cavitation in this apparatus simply by employing pressure pulses instead of tension pulses. In this way the perturbing effects of the deformable walls of the test cell may be isolated. The result /9/ is that the effective wave speed for both pressure and tension pulses in the water is 1040 ms^{-1}, and the total transmission coefficient (measured from peak pressures) is 0.15 - 0.16 in both cases. These results may be contrasted with the theoretical values of 1200 ms^{-1} and 0.36 respectively obtained from knowledge of the dimensions and elastic modulus of the cell. This lack of agreement with theory even for positive pressures makes comparison with calculations doubtful, and the situation is worsened by the fact that a lack of experimental reproducibility has been observed, transmitted tensions decreasing in magnitude in successive tests. We conclude that in its present state this type of experiment can serve only to supply the mean tensile strength of the water and to provide a rough check on the wave-propagation predictions of SIMON (i.e. the qualitative form of the transmitted pulse). In ref. /8/ it is found that the effective tensile strength of tap-water in this apparatus is - 0.5 MPa. In the open tank tests using demineralised water and much higher tensions, spray dome velocity measurements gave a strength of about - 2 MPa. For the water employed in containment model tests the value will probably lie between these two extremes. Fig. 5 shows the experimental and calculated input and output pressure signals for a liquid column 100 mm long, the experimental curves being taken from ref. /9/ and the calculated curves from SIMON with N = 10000 sites/kg. We observe that the shape of the transmitted pulse is quite well reproduced, while its magnitude is almost 100% too great, a fact connected with the difficulties regarding the transmission coefficient mentioned previously. The calculation correctly predicts the time at which the tension pulse becomes a pressure pulse, but considerably overestimates the peak pressure. The theoretical and experimental reasons for this are being investigated. The agreement in timing and tension pulse shape is regarded as encouraging.

To round off sections 2 and 3 it is concluded that SIMON provides a correct qualitative account of dynamic cavitation and is able to give a fair quantitative account of the main features of the phenomenon such as durations and void fractions. If validation is an iterative process between experiment and calculation, the model may be considered to have been validated to a first iteration.

4. Application to Model Tests

COVA /6/ experiment IT5 is a model test employing a rigid cylindrical vessel of aspect ratio 1.6. It has been calculated with the combinations ASTARTE /4/ + SIMON (N = 10000/kg), ASTARTE + SIMON (N = 250000/kg) and ASTARTE + cutoff of negative pressures (P_{min}). Fig. 6 shows the calculated and experimental pressure and impulse records at a gauge position on the vessel wall close to the roof. Only one set of SIMON curves appears since the differences between the two calculations are small. This point will be returned to in section 5. Impulses with SIMON and P_{min} agree closely, although both overpredict experiment at this position. The SIMON pressure record is significantly less spiky than that from P_{min} and hence is closer to experiment. More interesting are the results of calculations for COVA experiment IT9. This experiment has a deformable cylindrical tank with a hemispherical end-closure, and was calculated with ASTARTE using a pressure cutoff (P_{min}) and with ASTARTE + SIMON (N = 10000/kg). In the latter calculation cavitated regions are seen to form above the charge and in a thick layer along the vessel wall. By time 4 ms approximately 50% of the fluid volume is cavitated. After roof impact at 6 ms a wave of recompaction moves downwards from the roof. Simultaneously, the deformation of the upper part of the vessel produces an upward motion of the curved bottom of the vessel which induces a fresh layer of cavitated liquid along the vessel wall. By 12 ms some 20% of the liquid volume is cavitated.

Fig. 7 shows the calculated final hoop strains for comparison with experiment. It may be seen that although neither calculation provides a good prediction of the experiment, the SIMON results are closer in general form, and in particular produce better predictions of the strains of the hemispherical bottom and the position of the maximum hoop strain.

5. Extension to Reactors

It was shown in ref. /3/ that for exact scaling from models to reactors, if the reactor coolant has N bubbles/kg and the linear scale of the reactor is F times that of the model, then the model should have NF^3 bubbles/kg. The results of the two calculations of experiment IT5 reported in the previous section are interesting for this reason, since an increase in N by a factor of 25 made almost no difference to the calculated pressures and impulses. This suggests that if the nucleation site density is "large enough" then good scaling properties can be expected. If this is accepted we may transfer experience with models directly to full-scale reactor structures. The pressure pulse arising from an expanding core bubble is expected to be much broader than the shock-waves emitted by explosives in model tests, and in consequence the cavitation which is calculated to occur near the free surface in models may not appear in reactors. On the other hand, the cavitated stratum which develops parallel to deformable structures in models should also appear in reactor geometries. We may therefore expect the deformations of these structures to be modified by the presence of the neighbouring cavitated layer as occurs in experiment IT9. In more complex geometries with internal structures cavitation can logically be expected to play a more central role.

To conclude, the SIMON module for dynamic cavitation has been validated to a first approximation against two experiments of quite different types, and application of the model to COVA experiments has shown the power of cavitation to modify roof impact pressures and vessel strains. These results seem capable of extension to real reactor situations.

References

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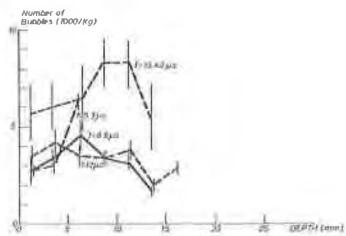

Fig. 1 Number of bubbles per unit mass as a function of depth (Open tank experiment)

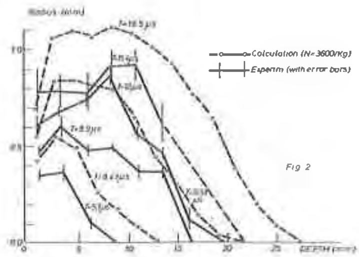

Fig. 2 Mean radius of bubbles as a function of depth

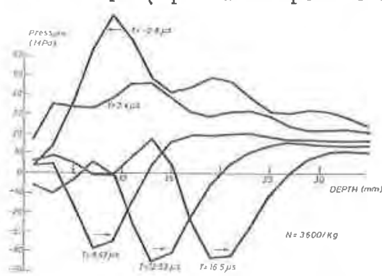

Fig. 3 Calculated pressure profiles (open tank experiment) N = 3600/kg, P_{cav} = - 1 MPa

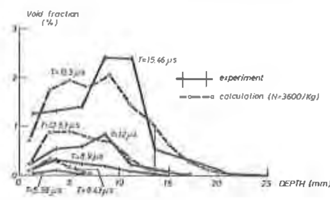

Fig. 4 Void fraction as a function of depth

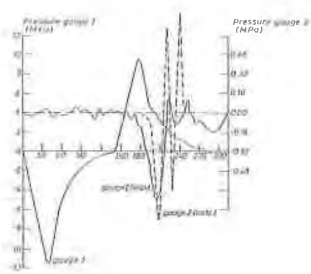

Fig. 5 Shock tube experiment. Experimental and calculated tension pulses

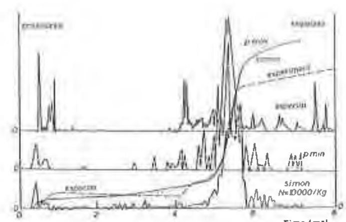

Fig. 6 COVA experiment IT5. Pressures and impulses at wall, height 980 mm

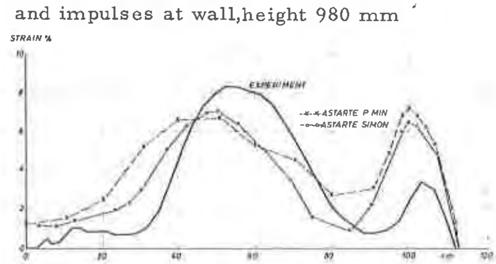

Fig. 7 COVA experiment IT9. Final hoop strains