EXPERIMENTAL STUDY OF SHOCK STRUCTURE IN AQUEOUS FOAMS AND THE UNSTEADY SHOCK EMERGENCE AT A FOAM/AIR BOUNDARY

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ABSTRACT

The interactions of shock waves initially in atmospheric air (Mach Numbers < 2.4) with aqueous foams (5 < foam density < 90 kgm^{-3}) have been investigated experimentally. In addition to the characterisation of general behaviour, two particular topics are reported.
i) The evolution of waves in aqueous foam has been explored, including the appearance and development of double-fronted compressive structures for a restricted range (incident shock Mach Number > 1.7, foam density > 30 kgm^{-3}) of initial conditions; possible mechanisms for the formation of double-fronted waves are discussed.
ii) The non-steady wave refraction at a foam/air boundary and the formation of a weakened transmitted shock in the downstream air has been studied; the strength of the transmitted wave is found to be a function of the upstream shock strength and the foam density.

INTRODUCTION

In earlier work[1] we reported the results of a preliminary study of shock wave interactions with aqueous foams. The objectives of the present contribution are to continue the general characterisation of the various interactions and, in particular, (i) to explore the development and structure of compressive waves within the foam and (ii) to examine the unsteady evolution of the shock wave emerging downstream of a foam/air boundary.

Little quantitative experimental work has been reported in the literature. Apart from our own earlier work[1] and the generally qualitative work referred to therein, some Russian[2,3] and Japanese[4] work which observed double-fronted structures may be noted here. Borisov et al[2] indicate the absence of adequate physical models of wave/foam interactions, a situation which appears still to be true. More generally Bethe[5] set out a theoretical framework for the discussion of wave behaviour in materials with an arbitrary equation of state, including the appearance of split waves, while the more recent work of Thompson et al[6] on condensing/evaporating liquid-vapour transitions induced by wave phenomena and of Cramer[7] on related behaviour in the gas phase are relevant. Our earlier work[1] invoked an equivalent ideal gas with high density and high heat capacity as a model of the foam. Such an approach has severe limitations; it cannot describe the evaporation/condensation processes which may be associated with the wave structure, nor can it easily assimilate more detailed information on the foam characteristics. Further information on wave structure and behaviour in foams is presented here and mechanisms for the appearance of double-fronted waves are discussed.

Some characteristics of the non-steady refraction process as the shock reforms in air downstream of a foam/air boundary and the dependence of its strength on upstream shock strength and foam density are reported.

EXPERIMENTAL

The shock tube employed in the present work was the 127mm diameter, horizontal facility used and briefly described in the earlier work[1]. Aqueous foam was again generated by passing pressurised nitrogen and a surfactant solution through a bed of packed beads to give a foam with small bubbles (mean diameter 0.22 mm) and an average density of 60 kgm^{-3}. In situ drainage of the foam under gravity before a run resulted in a significant vertical density gradient (up to 30 kgm^{-3}) for these relatively high density foams. Running the shock tube in reflected shock mode transforms the foam into one less dense (10-30 kgm^{-3}) with larger bubbles (mean diameter 0.35 mm). Tests at lower foam densities were carried out in this reformed foam.

Foam density was usually determined by weighing a sample of known volume, while the bubble size was estimated by photography of a sample held between microscope slides.

Pressure records were obtained from piezo-electric transducers (Kistler 600 and 700 series) on a horizontal diameter at 9 axial locations along the tube (including 5 locations in the foam-containing 2.14 m test section), with the facility for additional data from different circumferential positions at specific axial locations. Optical access permitted laser (5 mW He:Ne) tracking of the foam/air boundary in the downstream flow. Figure 1 indicates the arrangement of the instrumentation. Experimental data were sampled digitally at rates up to 2 MHz and stored for subsequent analysis via a DEC MINC-11 mini computer; the latter also provided automatic control of shock tube running.

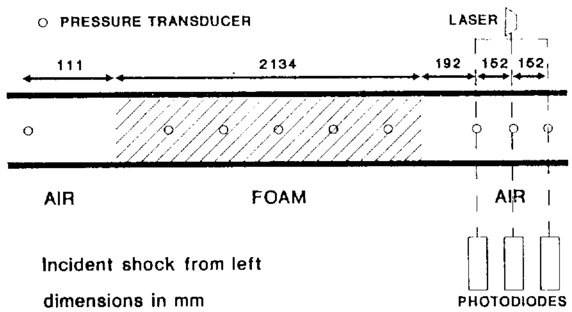

Fig. 1. Experimental facility and measurement positions

RESULTS AND DISCUSSION

Initial conditions were invariably atmospheric pressure and temperature. Incident shock speeds in air upstream of the foam were in the range $1.37 < M_S < 2.4$. The mean foam density was varied between 5 and 90 kgm^{-3}.

In the present work, data for pressure ratios in the range 2-20 and wave speeds in the range 100-350 ms^{-1} in the foam have been collected. Depending on the initial conditions either single- or double-fronted compressions are propagated to the foam from the air/foam boundary.

Figure 2 illustrates the history of what will be called a double-fronted wave as determined by pressure measurements at four stations along the trajectory in a single experiment with an incident shock Mach Number 2 and a foam density of 60 kgm^{-3}. Typically, the results show that the wave transmitted into the foam is a steep fronted compression with, characteristically, a pressure overshoot in the leading structure (see Figure 2), which attenuates as the wave evolves on progression further into the foam.

Some deceleration is also usually evident; in this experiment the wave speed decays from 190 to 140 ms^{-1}.

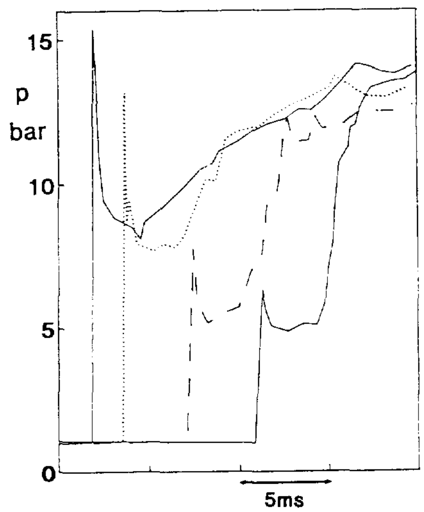

Fig. 2. p(t) for double-fronted wave at positions 150, 460, 1080 and 1700 mm into foam (ρ_F = 60 kgm^{-3}, incident shock Mach Number (MI) = 2.0)

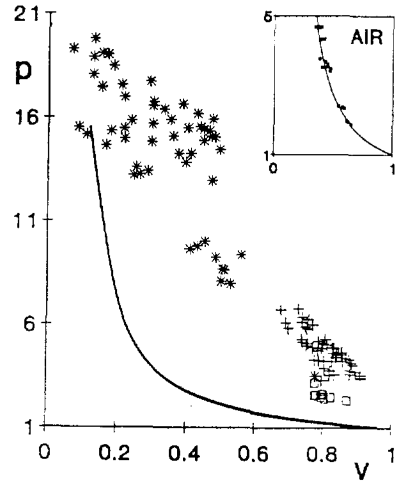

Fig. 3. Normalised p-v data for packed-bed generated foams (40 < ρ_F < 90 kgm^{-3}) derived via equation (1) from wavespeed and pressure rise across first wave (+), total double wave (*) or single wave (□). --- Clausius model, ρ_F = 60 kgm^{-3}.

Presentation of the data on a p-v plot, such as Figure 3, requires manipulation of the pressure ratio and wave speed information using conservation of mass and momentum, assuming steady, one-dimensional flow, to give

$$v/v_o = 1 - (p - p_o)v_o/W_s^2 \qquad (1)$$

where v is specific volume, p is absolute pressure, W_s is the wave speed in the foam and subscript o indicates the initial state. Although the conditions of steadiness and one-dimensionality may not be satisfied for the waves propagating in the foam, equation (1) provides a convenient method of representing the experimental data in the p-v plane. The inset to Figure 3 gives an indication of the quality of data obtainable from the facility when used to run shocks in air at similar initial conditions; the experimental data are seen to correlate closely with ideal gas predictions and thus lend confidence to measurements taken in the foam.

The data points in Figure 3 form three groups: those derived from single-fronted waves, those derived from the leading pressure rise of a double-fronted wave and those derived from the total pressure rise of a double-fronted wave. Such features were present for a limited range of initial conditions. No wave splitting was observed in the lighter shock-generated foams (<30 kgm^{-3}), irrespective of the pressure ratio, and only above a critical pressure ratio (>3), in the denser foams. Borisov et al.[2] reported that wave splitting was only observed when the wave speed was less than the speed of sound of the gas phase of the foam. This information with our results permits tentative identification of the conditions necessary to observe wave splitting: in summary the conditions are 3 (this work) < pressure ratio < 30 (Borisov et al.[2]); foam density > 30 kgm^{-3} (this work).

Candidate explanations which should be considered in any attempt to account for the double-fronted waves observed in the present results include (1) the non-steady interactions emanating from the upstream air/foam boundary; (2) the non-one-dimensional behaviour of the wave system which is known to be induced by transverse gradients in properties; (3) non-equilibrium relaxation of the foam in two time-dependent stages, reflecting the different responses to the propagating wave of the lamellae and Plateau borders in the foam, in a manner similar to that postulated by Mori et al.[4] for very light foams; and (4) features consequential on phase changes or other physical factors such as high heat capacity, present in the fluid, which may lead to an anomalous Hugoniot.

It may be that contributions from all four possibilities are present in our observations, but at this stage the stronger contenders appear to be options (3) and (4). For present purposes, because this work indicates the phenomena are occurring over a restricted range of conditions, attention is confined to the fourth possibility.

Wave splitting is a well documented phenomenon in solids[8] when phase changes are present, in a few special cases of liquid/vapour phase transitions and in the gas phase as recently discussed theoretically by Cramer[7]. The split wave phenomena may be related to an anomalous Hugoniot function, featuring a region of negative curvature[6], which can be caused by phase change, plastic yield[8] and a high heat capacity[7] in real gases. All three factors are plausible causes of wave splitting in a foam.

Modelling the data, as plotted on Figure 3, requires an appropriate equation of state or equivalent input. It is evident from the inset that modelling air as an ideal gas works well. Attempts to parallel this procedure for the foam have been less successful. Regarding the foam as a mixture of nitrogen, behaving as an ideal gas, and water with no permitted evaporation, gives a Clausius form for the equation of state in which the finite molecular volume of a real gas becomes the liquid volume

$$p\,(v - \phi/\rho_\ell) = R(1 - \phi)\,T \qquad (2)$$

where R is the specific gas constant for nitrogen, ϕ is the liquid mass fraction and ρ_ℓ is the liquid density; heat capacities are typical of the foam. The high heat capacity so introduced, which is closer to that of a liquid, results in much smaller temperature changes than in a gas. The curve in Figure 3 is the Hugoniot function based on this model. Data from the experiments are not adequately modelled, reasons for which may be the previously intimated need for an anomalous Hugoniot which requires a more complex equation of state (eg van der Waals), and/or failure of the assumptions on which equation (1) is based. Progress in this direction awaits further experimental evidence and future modelling exercises.

The refraction and emergence of the wave from the downstream foam/air boundary is particularly important because in many practical situations the main concern is not with the details of wave propagation within the foam, important though that may be in its own right, but with the mechanism of the transfer of energy into an adjoining medium.

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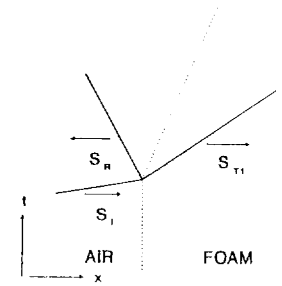

Fig. 4. Schematic diagram o
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Fig. 5. Behaviour downstrea
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In the present work the early evolution of the emergent wave has been studied. Pressure measurements of the wave structure at a series of stations in the downstream flow have been supplemented by laser attenuation measurements to track the trajectory of the foam/air interface; the experimental arrangement is that shown schematically in Figure 1.

Impedance considerations indicate that a compressive wave (ideally a shock) in the foam will, under the conditions of our experiments, interact with the foam/air boundary to produce a reflected expansion (R) and a weakened transmitted wave (ST2 - again, ideally, a shock), as shown in Figure 4. Figure 5 is from an experiment having a single-fronted wave in the foam and shows typical pressure profiles from the three downstream stations indicated in Figure 1 and an optical attenuation record obtained at the middle position. The plateau in the pressure traces may be associated with the transmitted wave ST2. The extinction in the optical record may be associated with the arrival of the foam/air boundary: under the conditions of the experiment illustrated in Figure 5, the foam boundary is moving at approximately 300 ms^{-1}. The foam must therefore act as a significant reservoir of kinetic energy.

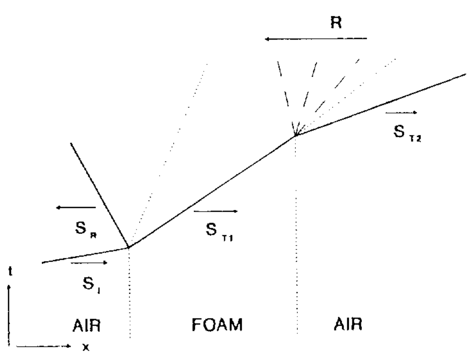


Fig. 4. Schematic diagram of idealised wave system.

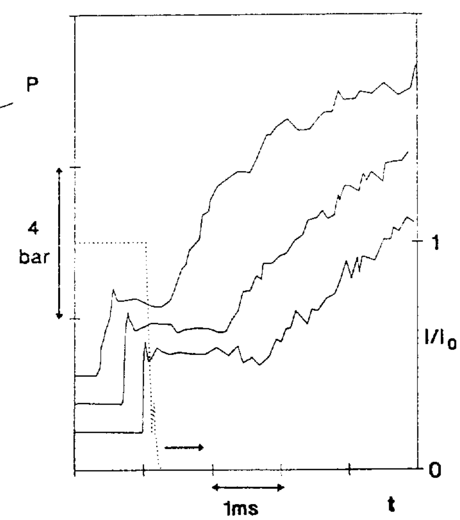
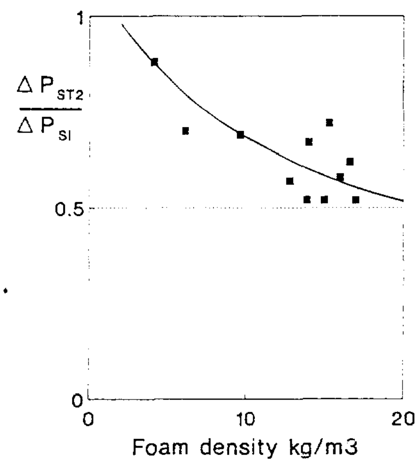


Fig. 5. Behaviour downstream of initial foam/air boundary; $\rho_F = 18kgm^{-3}$, MI = 2
---- p(t) at 192, 344 and 496 mm
- - - I(t) at 344 mm.

The wave strength of ST2 can be estimated from the plateau pressure and compared with the strength of the shock wave incident on the upstream air/foam boundary as shown in Figure 6. The curve on Figure 6 was obtained assuming an equivalent ideal gas model for the foam, incorporating the actual density and heat capacity, and calculating, by a method similar to that described by Gel'fand[9], the situation illustrated for ST2 in Figure 4. Strength reductions of 50% are observed at the higher foam densities.

In practice, of course, the evolution of the downstream wave system will be non-steady in at least two respects; one is associated with the non-centred nature of the real interaction at the foam/air boundary where a



finite acceleration time is required by the foam. The second is related to the longer timescales which will be needed for the expansion R to be reflected off the upstream air/foam boundary, propagate back through the foam as a compression, re-emerge from the downstream foam/air boundary and reach, and thus strengthen, the shock in the downstream flowfield. The timescales of these experiments were too short to exhibit the latter feature which, in the ideal case, would lead ultimately to a downstream shock strength equal to that of the incident wave.

Fig. 6. Strength of wave emergent downstream of foam/air boundary, showing variation with foam density for an incident shock Mach Number of 1.87: □ experiment; --- Equivalent ideal gas model.

CONCLUSIONS

This study of shock wave interactions with aqueous foams has revealed:
(1) double-fronted compression waves observed for aqueous foam densities > 30 kgm^{-3} and pressure ratios in the foam >3;
(2) candidate explanations for the above phenomenon include shock splitting, as observed in other media, and/or staged relaxation;
(3) the strength of the wave emergent in the downstream flow, as indicated by its pressure ratio, is less than that of the shock wave incident on the foam;
(4) the stronger the incident shock and/or the greater the foam density, the weaker, relatively, is the emergent wave.

ACKNOWLEDGEMENT

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REFERENCES

1 P.M. Weaver & N.H. Pratt, Shock Tubes and Waves (VCH, W. Germany 1988) p. 363
2 A.A. Borisov et al., Acta Astronautica, 5, 1027 (1978)
3 V.M. Kudinov et al., Progr Astro. and Aero., 87, 96 (1983)
4 Y. Mori et al., Int. J. Multiphase Flow, 2, 453 (1976)
5 H.A. Bethe, Office of Scientific Res & Dev., Rep. 545 (1942)
6 P.A. Thompson et al., J. Fluid Mech., 185, 385 (1987)
7 M.S. Cramer, J. Fluid Mech., 199, 281 (1989)
8 Y.B. Zeldovich & Y.P. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena Vol. II (Academic, N.Y. 1967)
9. B.E. Gel'fand et al., Comb. Expl., 17, 464 (1982)

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