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SHOCK WAVE PROPAGATION AND ATTENUATION IN FOAMS

by

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SUMMARY

Shock wave propagation and attenuation is of great practical and theoretical importance. Strong pulsating pressure fields, detonation processes, flame propagation, protection from blast waves are a few examples of areas of common interest. Foams and particularly liquid foams, show a peculiar characteristic of low reflectivity, low velocity of propagation of sound, high diffusion lossess and high frictional losses, when subjected to shock waves. Experiments have shown that a shock wave entering a liquid foam enclosed in a pipe, will reach the other end of it, reflect from the closed solid end but for all practical purposes, will not reappear again. The bubble diameter plays a role similar to the mean molecular path in gases, thus increasing the shock thickness by several orders of magnitude and changing it into a compression wave. This effect is further magnified by the diffusion processes which are discussed in terms of probabilistic concepts suggested by G.I. Taylor and the shape of the diffused wave can be predicted. A coordinate system is proposed based on the total impulsive forces, time duration of the impulse and mean pressure losses. By this method, using appropriate power laws, the dissipative qualities of foams can be assessed and compared. Tests with thin-walled honeycombs inserted in the foam medium indicate possibilities of greatly increasing the dissipation of shock wave energy into heat.

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INTRODUCTION

The propagation of shock and sound waves in liquid-gas media attracted early the attention of scientists, particularly those involved in Naval Research and submarine wake detection. Early papers in this field are due to A. Mallock (1) and A. B. Wood (2). Liquid-gas foams possess unusual characteristics of which the most important are: i) low velocity of sound; ii) low reflectivity; iii) thermodynamical properties favouring highly irreversible processes; iv) high heat capacity; v) bubble-structure in which the bubble diameter plays somewhat a role similar to the molecular free path in gases vi) a high viscosity increased by the effects of bubble motion. Most of the work in this field was concerned with foams having a low void fraction α (volume of gas/volume of mixture) which occurs in marine applications. It seems that not enough attention has been paid to the peculiar characteristics enunciated above, particularly for high void fractions. Such foams can be very stable if prepared from adequate liquid materials. Many applications are possible in this field like protection from blast and shock waves, control of detonation and flame propagation, sound absorption, nuclear reactor safety problems, etc. Also liquid-gas foams have the advantage that they can be generated in abundance in a very short time. A long term research programme was initiated at the University of Calgary to study the behaviour of foams in relation to shock waves.

PRELIMINARY PHYSICAL CONSIDERATION

The Velocity of Sound

A typical curve of the velocity of sound in foam plotted against the void fraction α is shown in Fig. 2. One observes a pronounced minimum between two extremes i.e. $\alpha = 0$ corresponding to pure liquid and $\alpha = 1$ to pure gas. Several authors suggested formulas of varying degree of sophistication. The simplest one is that of Mallock (1) who assumed $C^2 = B/\rho$ where B is the bulk modulus of the foam and ρ its density. This brings out the essential fact in this respect that a foam behaves very similarly to a gas. The drastic reduction in sound velocity can be explained by the effect of bubbles which convey to the foam the character of a compressible gas, yet the contained liquid gives it an exceptionally high density. More refined formulas assume either isothermal compression (3, 4) or adiabatic compression (3) as a function of the void fraction α resulting in expressions $C^2 = \frac{P}{\rho\alpha}$ and $C^2 = \frac{\gamma P}{\rho\alpha}$, respectively. Campbell and Pitcher (4) deduced a more complicated expression which after a few simplifications can be reduced to the isothermal case. Fig. 2 shows two curves computed for the foam used in this Laboratory.*) One observes that the isothermal and adiabatic assumptions play in this case, a minor role, also that the measured and computed sound velocities for $\alpha \simeq 0.934$ are very close to each other. Microphones were used to measure the sound velocity during the tests in this Laboratory.

The Acoustic Impedance

If the shock wave propagates in the gas in which the acoustic impedance is $Z_g = C_g \rho_g$ and impinges on the foam interface where $Z_f = C_f \rho_f$ (C and ρ refer to the velocity of sound and density respectively) it can be shown that i) the str ngth of the transmitted shock (see Fig. 1) is equal to the reflected one (ΔP_5) ii) $(\Delta P_5 - \Delta P_1)/\Delta P_1 = (Z_f - Z_g)/(Z_f + Z_g)$ where ΔP_5 = transmitted or reflected over-pressure, ΔP_1 = incident over-pressure. It follows that if $Z_f > Z_g$, what is the usual case then after the shock has entered the foam, $\Delta P_5 > \Delta P_1$. Generalizing further when the shock propagates <u>within</u> the foam of uneven constitution an imaginary interface can be drawn between two hypothetical foam regions, the rate of growth of $Z = f(\alpha)$ within the foam determines if the shock becomes stronger or weaker along its trajectory. On Fig. 2, $\rho = f(\alpha)$ has also been shown, it is obviously a linear function. The velocity of sound can be approximated by an even function of α. The product of the two functions ρ C becomes again an odd function of α with an inflection point within $0 < \alpha < 1$. The results so obtained for the foam used in this laboratory are shown in Fig. 3 where the inflection point occurs close to $\alpha = 0.75$. It follows that, say, for a linear distribution of α with the distance X the amplification or attenuation of the shock propagating within the foam will depend upon the sign of $\frac{d^2Z}{d\alpha^2}$ which is different on both sides of the inflection point. It also follows that if the drastic reduction of the velocity of sound in the vicinity of $\alpha = 1$ would not follow exactly the formulae of $C = f(p,\alpha,\rho)$, given above but some linear relation α, two inflection points, a maximum and a minimum of $Z = f(\alpha)$ would appear resulting in an inversion of the acoustic impedance within $0 < \alpha < 1$.

*) A commercially available aerosol foam composed of K-Na soaps, coconut oil, water, and a mixture of 87% of isobutane and 13% of propane. Mean bubble diameter $d_b = 0.00345''$.

The Thickening of the Shock Front

When a shock travels in the foam its thickness increases by several orders of magnitude which is an important asset in attenuation. There are several reasons for it all of which may contribute to this phenomenon: i) The Reynolds No based on the bubble diameter is a measure of the shock thickness, (5,6)(similarly to the Reynolds No. based on free molecular path which is usually taken as a measure of shock thickness in gases (7)). ii) The equation of state of a foam is not known for the whole range of α. One may be justified to apply van der Waal's reasoning: The ideal gas equation $Pv = RT$ has to be corrected and allowance has to be made for the "forces of cohesion" which cause a decrease in pressure, therefore pressures in the original ideal gas equation have to be increased by (a/v^2). Similarly, allowing for the "volume of the molecules", the volume has to be decreased by the co-volume b. Reading the "forces of cohesion" as surface tension forces acting on the bubble-enclosed gas and volume of liquid as "volume of the molecules" a similar equation could result with its corresponding "pseudo critical point". It can also be shown (7) that if on the PV diagram $\frac{d^2P}{dv^2}$ changes sign from positive to negative the shock waves broaden and expansion waves steepen. This situation might occur in the vicinity of the critical point or its replica in the foam. iii) The structure of the foam results in the scattering of the wave. In a different context i.e. diffusion of a shock wave in turbulent atmosphere this problem was attacked by G.I. Taylor in a paper not generally available until the publication by G.K. Batcheler of all Taylor's works (8). His reasoning is statistical and quite general. It can be applied in a variety of circumstances. Our analysis indicates that this last contribution is probably the most important in explaining the extraordinary broadening of the shock propagating in the foam.

Viscosity

As the shock progresses between the walls of a tube containing the foam, viscous effects are very important because of the dissipative work done on the boundaries of the system. These forces would decrease the impulse maintaining a constant, positive time duration. This should be clearly distinguished from the diffusion process described at (iii) above in which the impulse remains constant but the pressure decreases due to the increase of the time. Both processes are irreversible, and contribute to the attenuation. Viscosity is increased in the foam by the appearance of the "second coefficient of viscosity" also introduced for the first time by G.I. Taylor and R.O. Davies (9, 10) in connection with gas bubble motion in a viscous fluid. It follows that if one would increase the viscous effects by say submerging a thin-walled honeycomb in the foam, the work upon the boundaries would increase substantially and pressures would drop. Both effects are normally present: Diffusion and friction.

EXPERIMENTAL RESULTS AND THEIR ANALYSIS

Fig. 4 shows a typical sample of measurements done in our laboratory using the foam described above and shock strenghs of about 1.4. Tests were carried out in a flame tube. Eight pressure transducers were connected to a recording system. Time resolution was of the order of 1 μsec. The I.D. of the flame tube was 2.0" and the length of the shock trajectory in the foam varied between 15" - 68". The ordinate represents the ratio between the $(\Delta P_5)_n$ transmitted in the foam (see Fig. 1) at any station n and the original $(\Delta P_5)_1$ in the foam. It is quite remarkable to observe how much pressures attenuate. This effect is increased by an order of magnitude introducing a 2" and again an 8" long thin walled aluminum honey-comb submerged in the foam. The average diameter of the hexagonal cells was in this case 1/4".

The above results can be analysed in more precise terms. A coordinate system is proposed specially for this purpose. Typical examples are shown in Figs. 5a and 5b. The ordinate represents on both cases the ratio I/I_1 which is the ratio between the impulse measured at any station in the foam to the original impulse in the foam. In Fig. 5a the abscissa represents the ratio between $(\Delta\bar{p})_{tot}/\Delta_{P5}$ i.e. between the total mean pressure deficiency (see Fig. 1) and the original mean over pressure. The word total implies total losses: due to friction and diffusion or any other causes. If no losses would occur the points along the successive station would not progress to the right. Fig. 5b shows the same ratio I/I_1 plotted against T_1/T where T refers to the time duration of the impulse above the ambient pressure. For pure diffusion processes the increase of the time would be associated with a constant impulse I_1 and the points would progress from the right top corner to the left along the upper abscissa. As friction is also involved in the process the curve is inclined downwards. A further sophistication of this method of presentation is shown in Fig. 6. Both friction and diffusion are always present but the degree of their interaction varies accordingly to the case. An empitical relation can be assumed namely that

$$\frac{T_1}{T} = 1 - \left[\frac{(\Delta\bar{P})_{tot}}{(\Delta\bar{P})_5}\right]^m$$

where the exponent m varies from case to case; $(\Delta\bar{P})_{tot}/(\Delta\bar{P})_5$ is always smaller than unity. With an increasing m, $[(\Delta\bar{P})_{tot}/(\Delta\bar{P})_5]^m$ tends to zero and T_1/T tends to unity. This implies that no diffusion takes place only friction is responsible for the decrease in the impulse I. In the other extreme when $m \rightarrow 0$ the R.H.S. of the above equation tends to zero. This implies an increase in the positive time duration T ($T \rightarrow \infty$) and a drop of the impulse represents the case of pure diffusion. It follows that if one plots I/I_1 against $(\Delta\bar{P})tot/(\Delta\bar{P})_5$

using the above relation and inserting T_1/T as well as the exponent m as a parameter, two families of lines can be drawn within this frame. Superimposing this coordinate system upon Fig. 5a the intensity of losses due to friction and due to diffusion are immediately analysed. It also facilitates to classify each individual case by finding the appropriate exponent m. It has been observed using this system of analysis that stronger shocks were following a steeper path downwards in the, Fig. 5a, coordinate-system. This should be expected as higher velocities would be associated with higher friction losses; motion along the diagonal implies pure friction losses only. Fig. 7 shows the effect of immersing an 8" long honeycomb into the foam. One observes superimposing a transparency of Fig. 6 that along the honeycomb the losses are almost entirely due to friction and correspond to a constant time ratio $T/T_1 = 0.5$. Upstream of the honeycomb however, both effects are present and the interaction between triction and diffusion can be characterised by the exponent m = 1.7.

CONCLUSION

The analysis of tests points out at the main causes of unusual behaviour of shock propagation in foams. The intense attenuation effects at high values of the void fraction α have been previously pointed out by the authors in (11) where a shock entering the foam and reflecting from the endplate could not be detected at the end of its trajectory by any type of available transducer. A rational foundation has been laid to analyse various types of foams using an appropriat coordinate system especially introduced for this purpose. Attention is also drawn on the importance of the acoustic impedence and the equation of state in describing such processes.

ACKNOWLEDGEMENT

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REFERENCES

1. Mallock A., "The Damping of Sound by Frothy Liquids," Proc. Roy. Soc A84, 391, 1910.
2. Wood, A. B., "A Textbook of Sound," 360, Macmillan Company, New York, 1941.
3. Hamilton, L. J., "Propagation of Pressure Waves in Two-Phase Media," Ph.D. Thesis, The University of California, U.S.A., 1968.
4. Campbell, I. J. and Pitcher, A. S., "Shock Waves in a Liquid Containing Gas Bubbles," Proc. Roy. Soc., Sec. A, 243, 534, 1958.
5. Wijngaarden, L. V., "On the Structure of Shock Waves in Liquid-Bubble Mixtures," Appl. Sci. Res. 22, 366, July 1970.
6. Miura, M., "Weak Shock Waves in a Liquid Containing Gas Bubbles," Journal of The Physical Society of Japan, Vol. 32, No. 3, 851, March, 1972.
7. Shapiro, A. H., "The Dynamics and Thermodynamics of Compressible Fluid Flow," Vol. I, 125 - 132, Ronald Press, N.Y., 1953.
8. Taylor, G. I., "The Propagation of Blast Waves Over the Ground," Scientific Papers, Vol. 3, Edited by G. K. Batchelor, 274, 1963.
9. Taylor, G. I., "The Two Coefficients of Viscosity for an Incompressible Fluid Containing Air Bubbles," Proc. Roy. Soc. A226, 34, 1954.
10. Davies, R. O., "Note on the Volume Viscosity of Water Containing Bubbles," Proc. Roy. Soc. A226, 39, 1954.
11. de Krasinski, J. S. and Khosla, A., "Shock Attention in Non-Homogeneous and Porous Media," Proc. Third International Symposium on Military Applications of Blast Simulators, Schwetzingew, W. Germany, Sept., 1972.

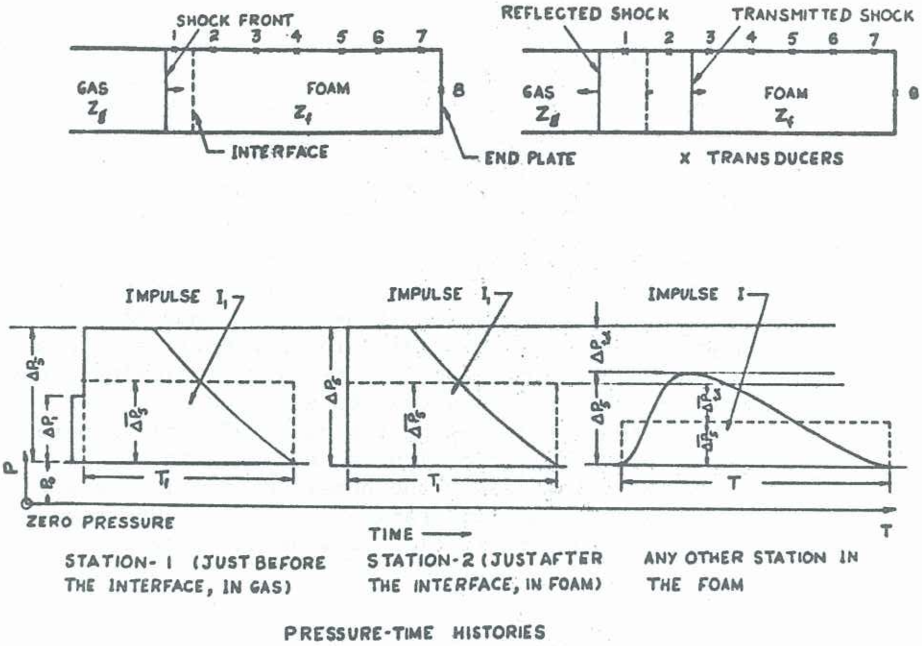

Fig. 1. Shock-foam Interaction

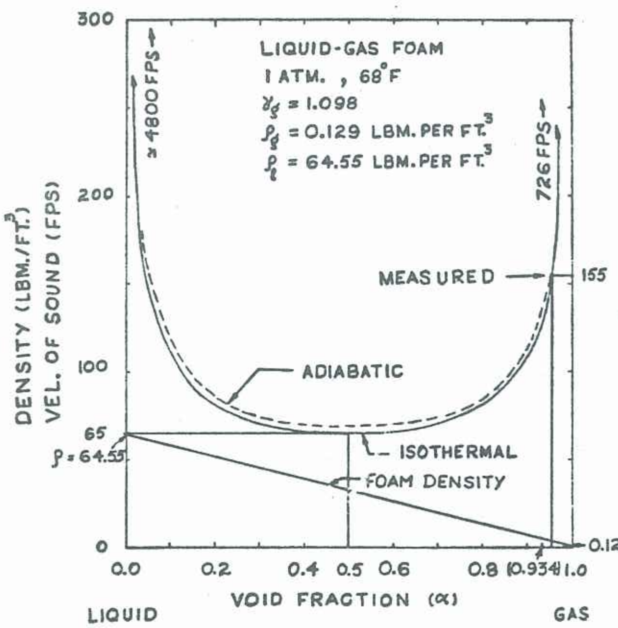

Fig. 2. Density and Velocity of Sound as f(α)

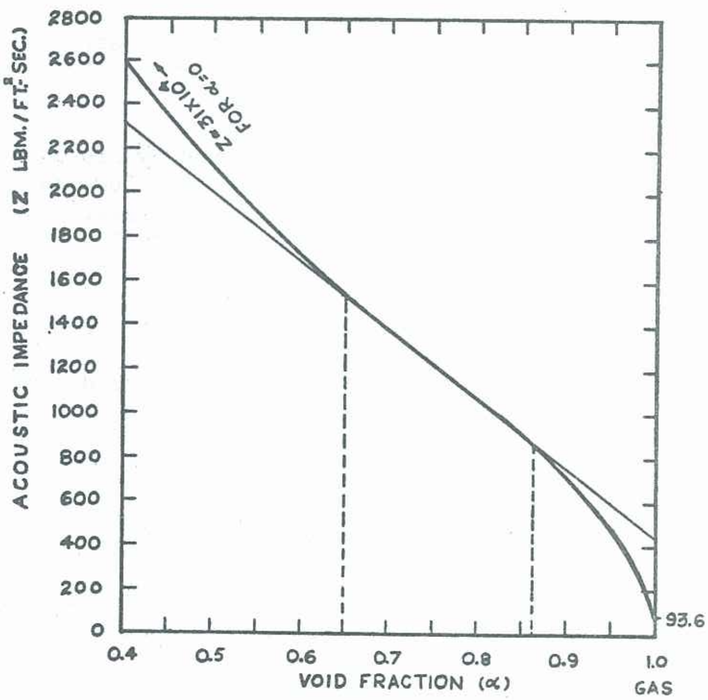

Fig. 3. Acoustic Impedance as f (α)

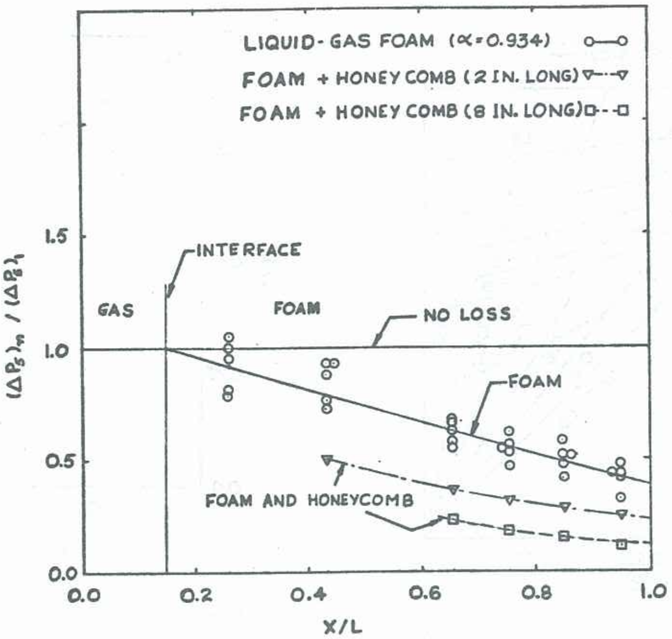

Fig. 4. Shock Attenuation along the Trajectory in the Foam

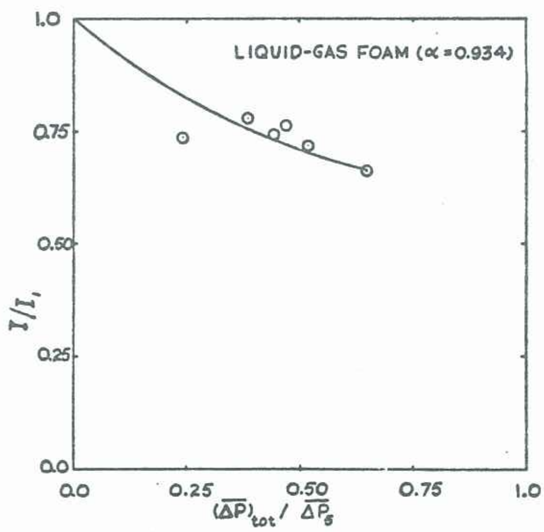

Fig. 5 a) The drop of impulse as Function of the Pressure Losses

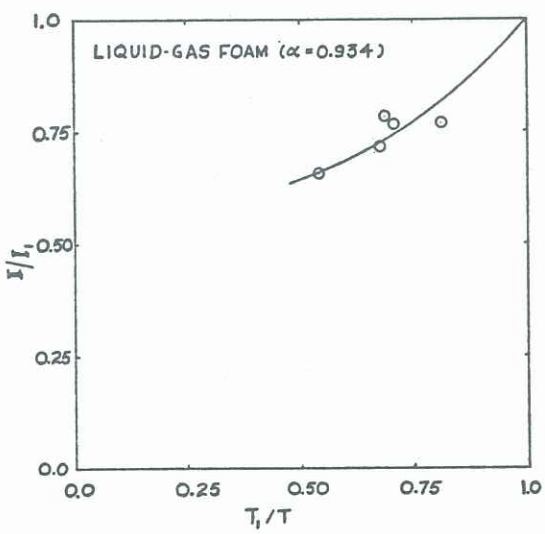

Fig. 5 b) The drop of Impulse as Function of the Increase of Positive Time Duration

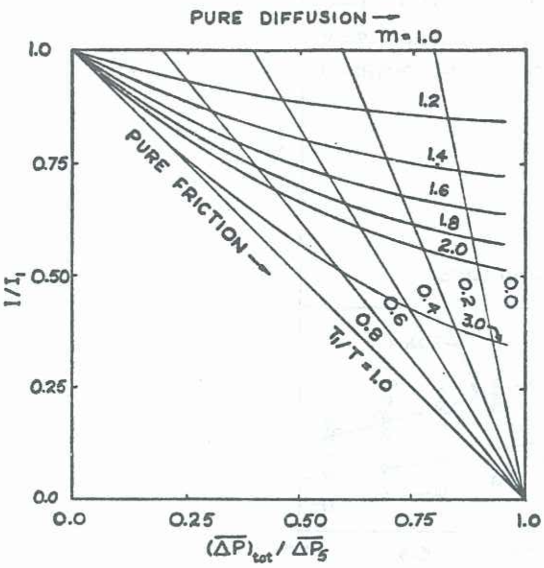

Fig. 6 The Proposed Coordinate System

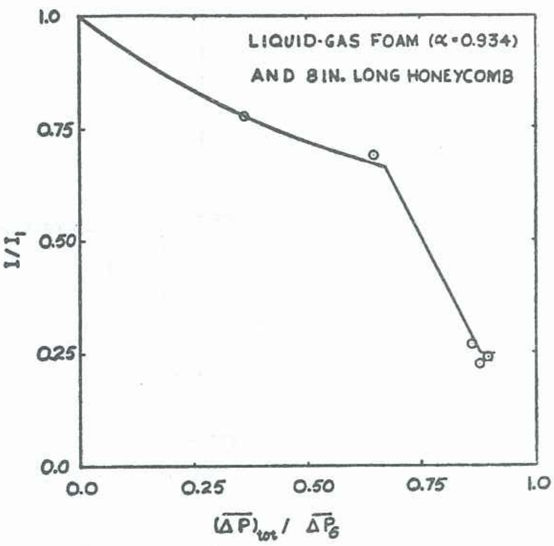

Fig. 7 Losses in foam and in a Foam-Immersed Honeycomb