ATTENUATION OF SHOCK WAVES IN LONG PIPES BY ORIFICE PLATES,
ROUGH WALLS, AND CYLINDRICAL OBSTACLES*

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NOTICE

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Introduction

Providing blast protection for urban populations is one of the most important problems of civil defense, one which has been under study at the Oak Ridge National Laboratory for the past several years. A requirement set at ORNL for blast shelters is that, whatever their nature, they should be interconnected so as to permit movement of people and supplies. It soon became clear that the interconnecting tunnels themselves could serve as shelters, and this led to the concept of an underground grid of interconnected tunnels. E. P. Wigner described such a tunnel-grid system in detail in the proceedings of a 1965 symposium of the American Association for the Advancement of Science on civil defense.¹

Access to the tunnels in this system is through air locks, which prevent shock waves from reaching the interior of the tunnel complex. Unfortunately, air locks are expensive. Blast doors, an alternative to air locks, may also be expensive and furthermore do not permit continuous access to the tunnels. We have therefore examined other ways of protecting the interiors of long open tunnels from shock waves. Baffling the tunnel entrances with orifice plates is a way of doing this, and one purpose of this paper is to report experiments exploring its effectiveness.

A second purpose is to report the results of experiments on the attenuation of shock waves by artificially roughened walls and by cylindrical obstacles placed in the path of the shock. In addition to possible practical applications these experiments may have, they serve, together with the experiments on the orifice plates, to support a rough empirical correlation of shock attenuation with the Fanning friction factor of fully developed turbulent flow in the same pipe at the Reynolds number of the flow behind the shock front.

Finally, a third purpose of this paper is to describe the four-inch shock tube in which the experiments were carried out. It is driven by an explosive mixture of propane and oxygen, and exhibits some interesting gas-dynamic effects that are worthy of note.

Equipment

The shock tube consists of lengths of schedule-40, 4-inch iron pipe (wall thickness: 0.237"); schedule-80, 4-inch Hastelloy pipe (wall thickness: 0.337"); and schedule-XX, 5-inch stainless steel pipe (wall thickness: 0.750"). The different sections of pipe, which vary from 2 to 8 feet in length, are joined with Grayloc (Gray Tool Co.) flanges. Grayloc flanges are much more convenient than screwed connections, and minimize the manipulation involved in changing the pipes around. Each section of pipe rides on its own steel cart, so that the pipes can be moved simply by loosening the Grayloc flanges, wheeling the carts around, and retightening the Grayloc flanges.

A quick-release Grayloc flange clamps the membrane separating the explosive gas mixture from the rest of the shock tube. Only one bolt has to be loosened to free the quick-release flange, after which it rides smoothly out of the way on a counter-weighted cable. Since the membrane has to be changed after every explosion, the quick-release flange is a great convenience.

The membrane is made of polyethylene reinforced by Dacron scrim. A four-inch-diameter span will support a static pressure of 100 psi, so the driver section may be pressurized to increase the explosive yield.

Piezoelectric quartz transducers (Kistler 603A, 606L, and 613F) measure pressure as a function of time at various positions down the shock tube. Two oscilloscopes, one capable of handling two simultaneous signals (Techtronix 453) and one capable of handling four (Techtronix 535A) display the amplified output of the transducers. Their faces are

photographed with Polaroid cameras. Thus we can record pressure-time histories at up to six points in the shock tube simultaneously.

The transducers, which differ from one another in size, are all mounted in standardized bushings made from one-inch bolts. One-inch nuts have been welded to the wall of the schedule-40 pipe every four inches and the pipe wall drilled out. These holes are plugged with solid bolts except at the measuring stations, where the transducers are mounted in their bushings. Measuring stations can thus be changed merely by interchanging two bolts.

The explosive mixture used in the experiments reported below consists of 79% oxygen and 21% propane. It results from charging the driver section by flushing it thoroughly with compressed oxygen, bleeding it down to atmospheric pressure through a small valve, and then admitting 20-cm-Hg of propane under pressure through a diffusing tube. The gauge pressure of the driver at detonation is then 20 cm-Hg. The gas mixture is detonated by a .22-caliber blank cartridge discharged into it by a rifle mounted in the end cap of the shock tube.

Results: Bare Tube

The shock overpressure in the bare shock tube is the reference by which we judge the attenuation produced by the different kinds of baffles. Fig. 1 shows shock overpressures measured at various distances X down the tube; X is measured from the end cap, and is plotted divided by L , the length of the driver section. These overpressures were measured by timing the flight of the shock between a pair of transducers located four inches apart and converting the measured shock velocity to overpressure using the Rankine-Hugoniot equations.

The points shown are averages of several measurements. The variation about the mean is about 10%; the error bars in Fig. 1 have arbitrarily been chosen to correspond to an error of $\pm 10\%$. The square point at $X/L = 4.8$ deviates from the circular points near it, probably owing to friction losses:

it represents a position 2.6 times as far down the pipe as is represented by a circular point with the same X/L .

The flow has been calculated² numerically by the method of von Neumann and Richmyer³ starting at the instant the detonation front reaches the membrane. Prior to that, the explosive disturbance consists of a Chapman-Jouguet detonation followed by a rarefaction wave. Behind the rarefaction is a region of stationary burned gas of uniform pressure

and density.⁴ In the calculations, the ratio of specific heats γ of air was taken to be 1.4, but that (γ') of the burned gas was taken to be 1.2.* The curve in Fig. 1 is normalized to a yield of 1.26 kcal/g of reactants, or about 70% of what is expected from the stoichiometric combustion of propane and oxygen to carbon monoxide and water vapor. This yield is equivalent to a yield of 6 g TNT per running foot of driver section.

The experimental points and the calculated curve both show a prominent plateau in the neighborhood of 3-5 driver length down the tube. The plateau is caused by the eventual forward expansion of the stationary gas behind the detonation front. This forward expansion catches up with the shock front in the vicinity of $X/L = 3$ and supports the shock front for about two driver lengths, as can be seen from time sequences of pressure, density, and velocity profiles given in reference 2.

Fig. 1. Peak Overpressure as a Function of Distance Down the Shock Tube.

*For powerful Chapman-Jouguet detonations, γ' , the velocity of detonation U , and the heat released per gram of reactants Q are related by the equation⁵ $U = [2(\gamma'^2 - 1)Q]^{1/2}$. For the stoichiometric combustion of propane and oxygen to carbon monoxide and water vapor, $Q = 1.83$ kcal/g. According to measurements quoted by Lewis and von Elbe,⁶ the detonation velocity of such a stoichiometric mixture is very close to 2.50 km/sec and nearly independent of pressure. Using these values, we find $\gamma' = 1.19$.

Results: Baffled Tubes

Four sets of experiments were carried out with orifice plates, the sets differing in either spacing or inner diameter of the orifice plates. In three sets of experiments, the inner diameter of the orifice plates was 3-1/8" and the spacing either 4", 8", or 12". In the fourth experiment, the spacing was 4" and the inner diameter 2-1/2". In the experiments using a four-inch spacing, space for 31 orifice plates was provided, but in fact only 28 were used, numbers 8, 16, and 24 having been removed. This was done so that clear spaces eight inches wide were available in which the transducer pairs could be mounted without having an orifice plate between them. No such omission was necessary with the eight- or twelve-inch spacing. Sixteen baffles were used with the eight-inch spacing and 12 baffles were used with the twelve-inch spacing. In the experiments carried out with the 3-1/8" orifice plates, the first orifice plate was placed 9'8" from the end cap of the shock tube; the length of the driver in these experiments was 37". Two driver lengths were used in the experiments carried out with the 2-1/2" baffles, 37" and 95". With the smaller driver, the first baffle was located at 10' 3", with the larger, at 15'2". The shock overpressure was measured at intervals of approximately 2'6".

The overpressures measured in these experiments are plotted in Fig. 2, which is a replica of Fig. 1. Shown also are curves obtained by applying to the curve in Fig. 1 a correction factor $C = \exp(-0.30 f \Delta X/D)$, where f is the Fanning friction factor for fully developed turbulent flow in the baffled section of the pipe at the Reynolds number of the flow behind the shock front, ΔX is the distance from the beginning of the baffled section to the point of interest, and D is the diameter of the pipe.

It is tacitly assumed that the friction factor is constant over the range of Reynolds numbers covered. The Reynolds number of the flow behind a 100-psi shock in a four-inch pipe is about 6×10^6 ; for a

10-psi shock it is about 10^6 . In a smooth pipe,⁷ the friction factors corresponding to these Reynolds numbers differ only by about 32%; thus the variation of f about a suitable mean is only of the order of 16%. For rough pipes,⁷ the variation is even less. In fact, for an equivalent sand roughness of more than 10^{-4} , the friction factor is constant above a Reynolds number of 10^6 .

Arredi⁸ and Möbius⁹ have reported measurements of the friction factor for configurations of orifice plates. Their measurements cover the range of inner diameters and spacings used in our experiments. By interpolating in their data, we find $f = 0.21, 0.15$, and 0.12 for $3\text{-}1/8$ " orifice plates according as their spacing is 4", 8" or 12", and $f = 0.78$ for the 2.5" plates at a 4" spacing. The data indicate that f is nearly constant above a Reynolds number of 10^4 .

C provides a satisfactory correlation of the experiments, which cover a range of about a factor of six in friction factor. In order to try to cover a wider range of friction factors, we performed an experiment in which the friction factor was reduced an order of magnitude below the smallest value it had in the experiments with the orifice plates. The wall of the shock tube was artificially roughened by cutting a V-thread in it with an apex angle of 60° and a pitch of 0.125". Thus the depth-to-pitch

Fig. 2. Peak Overpressure in a Tube Containing Orifice Plates. The black points are taken from Fig. 1, the open points refer to positions inside the baffled section. From left to right, the five lower curves refer, respectively, to 2.5" orifice plates with a 7'11" driver, 2.5" plates with a 3'1" driver, and 3.125" plates with a 3'1" driver (rightmost three curves). The lower curves have been calculated by applying the factor C to the upper curve.

ratio is 0.866 and the depth-to-diameter ratio in a four-inch pipe is 0.0271. Schiller¹⁰ has reported values of f for various "Löwenherz" threads (metric threads with a depth-to-pitch ratio of 0.75 and flats at top and bottom equal to one-eighth of the pitch). In one of his experiments, the depth-to-diameter ratio was 0.0286; the corresponding value of f was about 0.013. Schiller's data also indicate that f becomes constant above a Reynolds number of 10^5 .

Shown in Fig. 3 are results of experiments carried out with the threaded wall; the driver length was 37" and the threaded section began 9'8" from the end cap. Shown also is a curve obtained by applying C for $f = 0.013$ to the curve of Fig. 1. Agreement is not bad, although the curve lies slightly above the mean course of the points. The comparison of the factor C with the data is complicated by the presence of an unexplained

fine structure in the experimental points that takes the form of a slight minimum near $X/L = 4$ and a slight maximum near $X/L = 6$. If instead of using the curve in Fig. 1 as the reference pressure to which to apply the correction C , we use the actual measured points in the bare tube, the correlation is significantly worsened.

In the last set of experiments, aluminum dowels 1/2" in diameter and 2-1/2" long obstructed the flow. The dowels were screwed rigidly into a base plate containing a triangular array of holes shown in Fig. 4. Five different patterns were used, all of which are also shown in Fig. 4. The full-density pattern contains 8 dowels per diameter of length; of the

Fig. 3. Peak Overpressure in a Tube With a Threaded Wall.

remaining four patterns, two correspond to two-thirds density, and two to one-third density.

Shown in Figs. 5 a-e are overpressures measured at various positions down the tube for these five patterns. In all cases, the driver section was 37" long and the dowel-filled section of pipe began at 10'0". Three curves

Fig. 4. Packing Patterns for the Aluminum Dowels.

Fig. 5 a-c. Peak Overpressure in a Tube Containing Cylindrical Obstacles in Packing Patterns a, b, and c.

Fig. 5d,e. Peak Overpressure in a Tube Containing Cylindrical Obstacles in Packing Patterns d and e.

are drawn in each figure, but before we consider them, let us compare the different sets of points. The two sets of points corresponding to two-thirds density agree with one another fairly well, although there appear to be some differences in fine structure. The set of points corresponding to full density also agrees with these two, in contradiction to the expectation that it would equal the pressure in the bare tube corrected by a factor C , equal to the three-halves power of the factor $C_{2/3}$ that applies to two-thirds density. It appears that the local flow perturbations introduced by the dowels interfere with one another, and thus affect the value of the friction factor. Comparison of Figs. 5d and 5e, both referring to one-third density, shows further effects of such flow interference.

Not only does the friction factor vary with the pattern of dowel packing, but it may also vary with the Reynolds and Mach numbers of the flow. The Reynolds number of the flow behind a 100-psi shock moving into air at STP is about 7.7×10^5 when computed with the half-inch diameter of the aluminum dowels; the corresponding flow Mach number (flow velocity

divided by ambient sound speed) is about 1.9. The corresponding numbers for a 10-psi shock are about 1.3×10^5 and 0.39, respectively. These overpressures roughly define the range covered in the experiments reported in Figs. 5. In this range, the skin friction coefficient c_f of isolated infinite cylinders lies between about 1.0 and 1.5.¹¹ Since the skin friction coefficient is referred to the projected area of the cylinders, rather than the wetted surface of the pipe, f is related to c_f by the equation

$$\frac{f}{c_f} = \frac{d h N}{\pi D}$$

where d is the diameter of the cylinders, h is their height, N is the number of cylinders per unit length of pipe, and D is the diameter of the pipe. Finally, it is worth noting that the skin friction factor of cylinders may depend somewhat on the length-to-diameter ratio.

The three curves in Fig. 5 are based on values of f of 0.230, 0.153, and 0.0765. If we deduce a value of c_f from the best-fitting curve for each of the patterns (a) - (e), we find the values 0.76, 1.14, 1.14, 2.28, and 1.16, respectively. These values are roughly consistent with the range of values quoted above, but without more accurate values of the skin friction coefficient no better test of the factor C is possible.

Finally, we consider again the square point at $X/L = 4.8$ in Fig. 1. As mentioned earlier, this point, which corresponds to a distance down the tube of 38', is probably low because of frictional resistance. If we use the nearby circular points, which correspond to distances down the tube of about 15', to find the pressure at $X/L = 4.8$ in the absence of friction, we find it to be about 115 psi. The friction factor f of the bare tube is then about 0.007, which is not unreasonable for aged iron pipe.⁷ (Actually, this value of f is only a crude estimate, since a slight change in the measured overpressure causes a much larger change in f .) A friction

factor of 0.007 could mean that the rightmost circular points are slightly low. Thus their trend in the absence of friction might be nearly parallel to the line of slope -1 in Fig. 1, a possibility that must be borne in mind.

In their study of wall effects in shock tube flow, Emrich and Wheeler¹² also employed an exponential formula for the attenuation of the overpressure. Their relaxation length, 420 diameters, corresponds to a friction factor of 0.008, in good agreement with what we have obtained above. It should be noted, however, that their value is an average of a large number of relaxation lengths measured in a variety of shock tubes, and that the individual values vary by as much as a factor of three from their average.

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