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TITLE GENERATING STRONG SHOCK WAVES WITH A SUPERSONIC PERISTALTIC PUMP

AUTHOR(S) R. Menikoff, T-14
K. S. Lackner, T-3

SUBMITTED TO Proceedings of the APS 1991 Topical Conference on Shock Compression on Condensed Matter, Williamsburg, VA, ~~June~~ 17-20, 1991

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Generating Strong Shock Waves with a Supersonic Peristaltic Pump

R. Menikoff and K. S. Lackner*

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

An axially phased implosion of a cylindrical tube with a phase velocity exceeding the sound speed of the fill material acts as a peristaltic pump which drives a shock wave along the axis. The region behind the onset of the phased implosion forms a converging-diverging nozzle. When appropriately designed the flow approaches a steady state in which the shock is planar and propagates near the nozzle entrance. The steady-state flow and the approach toward it have been derived in a one-dimensional model. The steady-state nozzle flow is well characterized: uniform across the channel, simple and predictable in the axial direction. The flow in the converging section is very stable and not affected by the flow in the diverging section. These properties form the basis of an alternative shock tube design which is not limited in pressure by material strength of the tube wall. Experiments with a simple design have corroborated the theoretical predictions. A super-shock tube, in which the phased implosion is driven by high explosives, can reach extremely high pressures and energy densities. With a well characterized drive system, measurements of the steady-state shape of the nozzle can be used to determine the equation of state along an isentrope behind the axial shock.

1. Introduction

A supersonic peristaltic pump is a means of generating very strong, planar shock waves in dense gases or liquids. This pump works by radially imploding a shock tube in an axially phased manner. The phased implosion causes a constriction to travel along the length of the tube. Since the phase velocity exceeds the sound speed of the fluid within the tube, a shock wave forms and propagates in front of the point of maximum constriction.

Viewed in the frame of reference traveling at the phase velocity, the fluid flow reduces to the flow through a converging-diverging nozzle. In contrast to the standard nozzle theory, for the supersonic peristaltic pump the shape of the nozzle is a dynamical degree of freedom. For a slender nozzle, the flow is well approximated by the 1-D equations for duct flow with the cross sectional area varying in both space and time. In [1] it was shown that the flow approaches a stable steady state. The shape of the nozzle, the position of the shock relative to the nozzle entrance and fluid profile behind the shock can be accurately calculated from an ordinary differential equation (ODE).

The supersonic peristaltic pump extends the range of shock tubes to shock waves of higher densities and pressures exceeding the material strength of the tube wall. The radial implosion not only provides the energy to drive the shock but also confines the flow in the converging section of the nozzle. The flow is not sensitive to details of the driving conditions. The relative position of the shock is determined mainly by the energy balance between the work done on the shock tube by the radial implosion and the energy required to drive the shock. Furthermore, the converging section of the nozzle decouples from the flow behind the nozzle throat and downstream fluctuations do not affect the converging section of the nozzle. With its well characterized flow and inherent stability, the supersonic peristaltic pump is an excellent generator of strong planar shocks. Recent work on developing an explosively driven shock tube generator based on the principle of a phased implosion is reported elsewhere in these proceedings.[2,3]

We briefly outline the 1-D model for the flow in the supersonic peristaltic pump in section 2. The steady state equations are described in section 3. The variation of the steady state solution with the equation of state and initial working fluid density is analyzed in section 4. A quasi steady adiabatic approximation describing the approach to the steady state flow is presented in section 5. We conclude in section 6 with a discussion of the supersonic peristaltic pump.

* This work was supported by the U. S. Department of Energy.

2. Theory

For a slender nozzle with a sound speed large compared to the implosion velocity of the wall, the flow behind the shock has little radial dependence and is therefore approximately one-dimensional. As shown in [1], the flow can be modeled by the duct flow equations

$$\partial_t(\rho A) + \partial_z(\rho A v) = 0\,, \qquad (2.1)$$

$$\partial_t(\rho A v) + \partial_z(\rho A v^2 + PA) = P\partial_z A\,, \qquad (2.2)$$

$$\partial_t(\rho A \mathcal{E}) + \partial_z(\rho A \mathcal{E} v + PAv) = -P\partial_t A\,. \qquad (2.3)$$

The cross sectional area, A, of the shock tube couples the equations for the fluid flow inside the tube to the equations describing the dynamics of the shock tube wall.

In our model the constriction of a cylindrical tube is caused by a traveling pressure pulse on the outside of the shock tube wall

$$P_a(z,t) = \tilde{P}_a(z - v_\phi t)\,, \qquad (2.4)$$

where v_ϕ is the phase velocity. We assume that the shock tube wall is thin and approximate it by a mass layer.

The motion of the shock tube wall follows Newton's law:

$$\sigma \frac{\partial^2}{\partial t^2} R(z,t) = 2\pi R(z,t)\left[P(z,t) - P_a(z,t)\right]\,. \qquad (2.5)$$

Here σ is the mass per unit length of the wall.

3. Steady-State Solution

In the frame of reference moving with the phase velocity, the steady-state solution consists of a stationary axial shock near the nozzle entrance followed by a transonic nozzle flow. The steady-state nozzle flow determines the fluid pressure as a function of the radius ratio, $P = P_N(R/R_s)$ with R_s the radius at the shock front. Above a critical radius ratio, P_N has two branches, a supersonic and a subsonic branch. The critical point is the sonic point below which there are no stationary solutions.[1]

We emphasize that P_N and the critical radius ratio, R_s/R_*, are independent of the shape of the nozzle and only depend on the equation of state of the fluid inside the shock tube. Consequently, the shape of the nozzle is determined by a single ordinary differential equation

$$\sigma v_\phi^2 \frac{d^2}{dz^2} R(z) = 2\pi R(z)\left[P(z) - P_a(z)\right]\,, \qquad (3.1)$$

where

$$P(z) = \begin{cases} P_0\,, & \text{for } z_s < z\,; \\ P_N^{\rm sub}(R(z)/R_s)\,, & \text{for } z_* \le z \le z_s\,; \\ P_N^{\rm super}(R(z)/R_s)\,, & \text{for } z < z_*\,. \end{cases} \qquad (3.2)$$

The boundary conditions require that R is the initial tube radius and dR/dz vanishes at the nozzle entrance. Furthermore, at the minimum radius which is reached at $z = z_*$, the flow must be sonic, $R(z_*) = R_*$. As in an eigenvalue problem, the position of the shock front provides the additional degree of freedom necessary to satisfy these three boundary conditions simultaneously.

4. Dependence of the Steady State on Working Fluid Parameters

For applications it is desirable to have the axial shock propagate at the nozzle entrance. This can be achieved by an appropriate choice of the working fluid density. We have used the steady-state Eqs. (3.1) and (3.2) for a parametric study of the variation of the shock position with density and the variation of the optimal density with the stiffness of the equation of the state.

For the model it is assumed that the applied pressure only depends on the distance from the nozzle entrance. In realistic applications, where the traveling pressure pulse is generated by a detonation wave sweeping along the shock tube, the pressure is slightly affected by the trajectory of the tube wall. Here, the fixed pressure pulse which would be obtained on a rigid wall provides one limiting case. The other corresponds to the energy limit, where the driver supplies a fixed amount of energy to the shock tube. We have chosen the phase velocity $v_\phi = 0.9$, the inital wall radius $R_0 = 0.5$, the wall mass $\sigma = 1$ and the applied pressure as "half" a Gaussian, $P_a(z) = 0$ for $z > 0$ and $P_a(z) = P_0 \exp(-\frac{1}{2}(z/z_0)^2)$ for $z \le 0$ with $z_0 = 1.5$ and $P_0 = 0.334$. With units for length, time, mass and pressure of cm, μs, g and Mb, the model parameters approximate the explosively driven phased implosion experiment described in [1]. For simplicity, we use an ideal gas equation of state for the working fluid.

In figure 1, the nozzle shape, the applied pressure and fluid pressure, and the axial velocity (in the comoving frame) and sound speed are shown for a $\gamma = 5/3$ gas with initial density $\rho = 0.5$ in the optimal case when

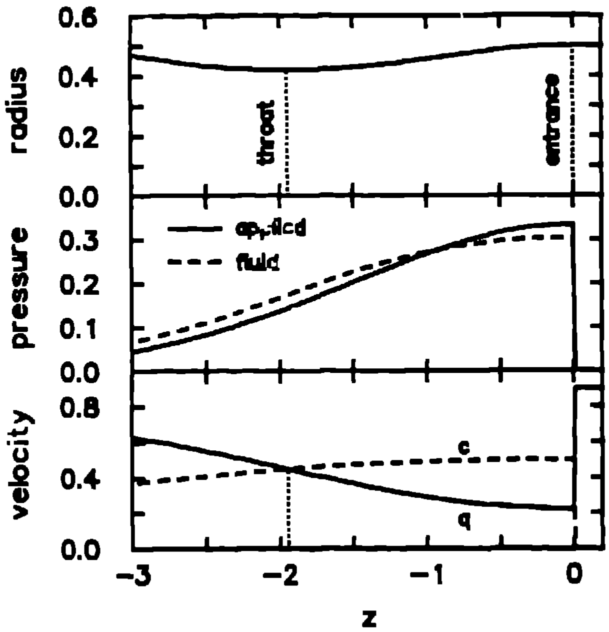

Fig. 1: Steady-Shock Solution, $\gamma = 5/3$

the axial shock is at the nozzle entrance. This illustrates two important points. First, a small constriction is sufficient to propagate the axial shock: $\Delta R/R = 17\%$ for $\gamma = 5/3$. Second, the fluid pressure inside the nozzle can track the applied pressure very closely. The deviation between the applied and fluid pressures increases with increasing wall mass.

The relative shock position as a function of density for $\gamma = 5/3$ is shown in figure 2. With a higher density, the axial shock falls back because more energy is needed to drive the flow. In figure 3 we varied the density in order for the shock to be at the nozzle entrance for different values of γ. A stiffer equation of state (larger γ) requires less energy to drive the flow. With a fixed pressure pulse the external energy transferred to the working fluid varies with the fluid parameters because the shape of the nozzle and hence $\int PdV$ changes.

5. Approach to Steady State

The 1 D model, Eqs. (2.1) (2.3) and (2.5), describes both the steady state and the approach to steady state after the axial shock has formed. The approach to steady state is characterized by a time constant. For the 2 D calculations of the experiment in [1], we have plotted in figure 4 the position of the shock front relative to the onset of the pressure pulse after eliminating high frequency noise introduced by the discretization. It

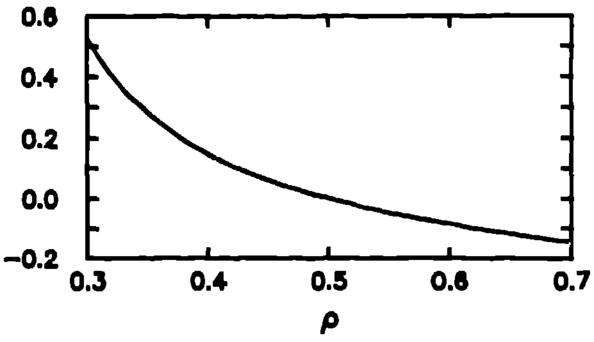

Fig. 2: Relative shock position as function of initial density for $\gamma = 5/3$ working fluid.

can be seen that the distance from the equilibrium position decays approximately exponentially. The time constant decreases as the equilibrium is approached from $\tau = 3.5\mu s$ for the range shown in the figure to $\tau \approx 1.2\mu s$ at equilibrium.

This behavior can be explained by a model in which the flow proceeds through a series of quasi-steady states. The quasi-steady states are solutions to the ODE, Eqs. (3.1) (3.2) for which the shock velocity and the phase velocity are different. The solution of the "eigenvalue" problem relates the shock velocity to the shock position. As a result of the stability of the axial shock, the shock velocity exceeds the phase velocity when the shock is behind its equilibrium position and falls below the phase velocity for a shock ahead of its equilibrium position.

In the adiabatic approximation the rate of change of the shock position relative to the onset of the pressure pulse is given by

$$\frac{dz}{dt} = v_s(z) - v_p . \qquad (5.1)$$

Near the equilibrium position, z_0, the right hand side of eq. (5.1) can be expanded in a Taylor series and gives to first order $(z - z_0)dv_s/dz(z_0)$. Therefore, the time constant is $\tau = -dv_s/dz(z_0)$. For the experiment in [1], the 2 D calculation and the quasi-steady approximation yield the same time constant within the accuracy of the calculations.

6. Discussion

The 1 D model makes it possible to easily survey the parameter space for the flow in a supersonic peristaltic pump. For simplicity we have used an ideal law gas for the working fluid. However, our method is

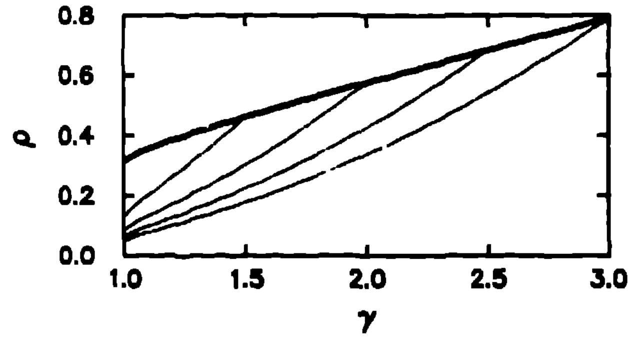

Fig. 3: Density as function of γ for shock to propagate at the nozzle entrance. Heavy line corresponds to a fixed pressure pulse. Light lines correspond to pressure pulses limited to constant energy.

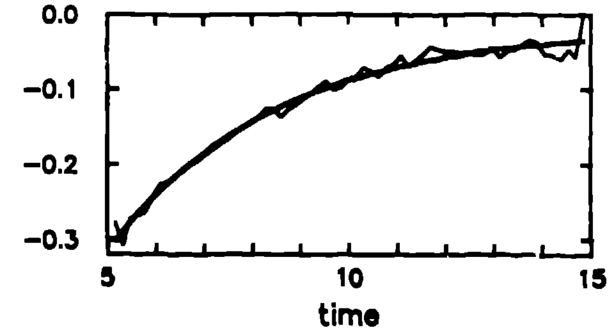

Fig. 4: Relative shock position as function of time for numerical simulation of experiment in [1]. The heavy line represents an exponential fit to the calculation.

not restricted to an ideal gas. Indeed, in [1] a realistic equation of state was used for a comparison with experimental data.

Currently, an explosively driven fast shock tube based on the principle of a supersonic peristaltic pump is being developed.[2,3] The inherent stability of the flow in the converging section of the nozzle results in a reliable and reproducible generator of strong planar shocks. In particular, the boundary layer between the working fluid and the shock tube is swept out the nozzle before it can grow to a significant fraction of the cross-sectional area of the tube. Hence, the fluid behind the axial shock is well suited for applications such as the acceleration of a projectile to high velocity for equation of state measurements or other fluid experiments.

With a well characterized drive system, the equation of state of the working fluid along an isentrope through the shocked state can be determined by measuring the nozzle shape, for example, with a flash X-ray. In particular, the average adiabatic exponent is determined from the critical radius ratio. It is noteworthy that such a shock generator operates in the pressure range of interest for the detonation products of a high explosive.

Finally, there is a striking similarity between the steady state solution of the model equations for the supersonic peristaltic pump and the Zeldovich von Neumann Doering model equations for a one dimensional Chapman Jouguet detonation wave.[5] The flow in the converging nozzle and the reaction zone of a detonation wave both exhibit a shock followed by a smooth region of decreasing pressure ending in a state which is sonic relative to the shock front. The propagating wave in both cases decouples from the flow behind the sonic point. The energy supplied by the applied pressure corresponds to the energy released by the chemical reaction.

The theory of the supersonic peristaltic pump and its experimental verification have laid the foundation for a super-shock tube. This extends the experimentally accessible range for the study of high pressure and high temperature hydrodynamical phenomena. We believe the applications for this new tool will be as varied as those for gas driven shock tubes.

References

1. R. Menikoff, K. S. Lackner, N. L. Johnson, S. A. Colgate, J. M. Hyman and G. A. Miranda, *Shock Wave Driven by a Phased Implosion*, Phys. Fluids **A 3** (1991), pp. 201–218.
2. J. K. Meier and J. F. Kerrisk, *An Introduction to the Fast Shock Tube*, these proceedings.
3. J. F. Kerrisk and J. K. Meier, *Comparison between Fast Shock Tube Calculations and Tests*, these proceedings.
4. R. Courant and K. Friedrichs, *Supersonic Flow and Shock Waves*, (Interscience, New York, 1948
5. R. Menikoff and K. S. Lackner, *Fluid Flow in a Supersonic Peristaltic Pump*, Proceedings Workshop on Viscous and Numerical Approximation of Shock Waves, Ed. M. Shearer, 1990