Vorticity Deposition and Density Structure Generation in Colliding Blast Wave Experiments

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Abstract

Experiments that involve colliding blast waves should involve the deposition of vorticity and the eventual generation of density structure as a result. The generation of vorticity is fundamental to hydrodynamics and is of interest for a number of reasons. Various 2D numerical simulations are presented which show the formation of density structure in simple blast wave interactions ranging from the strongly asymmetric to the symmetric case.

1 Introduction

There are a number of different approaches to studying the physics of strong explosions or blast waves using high powered lasers. Nanosecond duration pulses can irradiate a small solid target in a ambient gaseous medium, or one can use clustered gas targets with short-pulse lasers as two examples. The understanding of blast wave physics is important because they are so central to important astrophysical objects, particularly supernovae.

One interesting feature of certain blast wave experiments is that some experiments indicate that the blast waves either have a lot of internal mixing, magnetic field generation, or non-radial structure generation. All three imply the generation of another fundamental hydrodynamic quantity : vorticity. In an ideal blast wave (both spherical and cylindrical) there should be no vorticity. It is therefore interesting to ask how this vorticity gets generated.

In Symes' 2010 report [1] on a series of blast-wave experiments utilizing cluster media, good evidence for the generation of blast waves with copious irregular internal density structure in clustered hydrogen gas was presented. It is, however, difficult to ascertain the cause of vorticity generation in this experiment. In this report we suggest that it may be of interest to further utilize the capability to study colliding blast wave [2]. In the case where the system can we well described by pure hydrodynamics, a binary pair of asymmetric blast waves should lead to the formation of a strong vortex ring and an associated spiracular density structure. It would be of considerable interest to see to what extent we can model vorticity deposition in blast wave experiments based on cluster media.

2 Theory

Consider the case of two colliding blast waves. Now imagine that we make this highly asymmetric, so that one blast wave is launched from a region of much higher pressure. On coming into contact the pressure associated with the stronger blast wave is still much higher than the other. In this limiting case the weaker blast wave should be essentially passive and have no other effect than to act as a cold density inhomogeneity. The stronger blast wave will behave as a powerful shock wave, and if we assume that it has a much larger radius than the weaker blast wave, will also behave as a quasi-planar shock.

The problem of a planar shock wave interacting with a 'bubble' is well known in the fluid dynamics literature (see the review by Ranjan and others [3]), and has been investigated experimentally under normal conditions. As the transmitted shock propagates through the bubble it will deposit vorticity via the baroclinic mechanism. The bubble undergoes deformation and collapse as fluid is drawn in from the side that the shock is incident on. A vortex ring is formed and the subsequent action of the Kelvin-Helmholtz instability produces spiracular density structures.

If one is justified in reducing the two blast wave or two explosion problem to a shock-bubble interaction, then the formation of such a vortex ring and the associated density structure should occur. In what follows we test this idea using 2D numerical simulations employing a code that solves the equations of ideal hydrodynamics. Here we work solely within the framework of ideal hydrodynamics. This may or may not be a good approximation to an actual blast-wave experiment, and we regard this as an examination of a solution to an idealized problem and not a simulation of an actual experiment.

Simulation	x_{h1}	x_{h2}	P_{h1}	P_{h2}	R_{h1}	R_{h2}	f_1
A	0	50	40000	8000	15	5	0.98
B	0	50	40000	16000	15	5	0.93
C	0	45	40000	4000	15	15	0.91
D	0	45	40000	2000	15	15	0.95

Table 1: Table of Simulation Parameters

3 Simulations

3.1 Set-Up

In order to study vorticity deposition and its consequences, we have carried out two dimensional hydrodynamic simulations using the ARCTURUS code. In the configuration used in this study, ARCTURUS solves the inviscid Euler equations for an ideal gas using the scheme of Ziegler/Kurganov-Noelle-Petrova [**?**, **?**]. We have exploited the fact that the inviscid Euler equations can be cast in dimensionless form by choosing $\tilde{\rho} = \rho/\rho_0$, $\tilde{u} = u/c_0$, $\tilde{P} =)/(\rho_0 c_0^2)$, $\tilde{x} = x/L$, and $\tilde{t} = c_0 t/L$. The parameters ρ_0, c_0, and L are a characteristic density, sound speed and scale-length respectively. Henceforth we will drop use of the tilde and refer only to the dimensionless quantities.

The initial conditions consist of a uniform, static, ambient medium ($\rho = 1$,$\mathbf{u} = 0$, $P = 1$) that fills nearly the entireity of the domain except for two hot spots. These are two uniform circular regions centred at $x = x_{h1}$ and $x = x_{h2}$ respectively ($y = 0$). These are of the same density as the ambient medium ($\rho = 1$), but substantially higher pressure (P_{h1} and P_{h2} respectively). The fluid is also initially static in the hot spots. The hot spot radii are denoted by R_{h1} and R_{h2}. The boundary conditions are outflow boundaries in both x and y, although the simulations were only carried out up to a point by which the shock front had not reached either boundary. The simulations are run up to t =3.0–3.6. Here we will report on a set of sample simulations. The key parameters of these simulations are in Table 1.

3.2 Results

In figures 1–4 we show a time sequence of the density (plotted in log form) in run A.

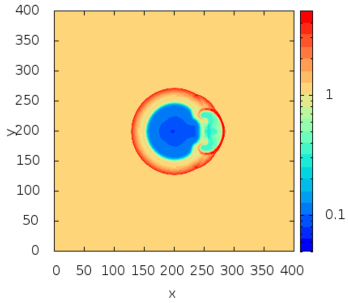

Figure 1: $\log_{10}$ plot of ρ in run A at t =0.6.

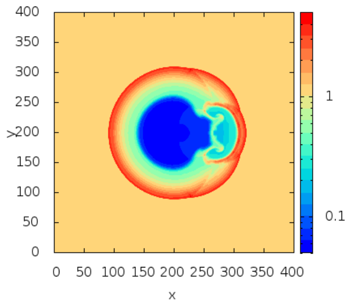

Figure 2: $\log_{10}$ plot of ρ in run A at t =1.4.

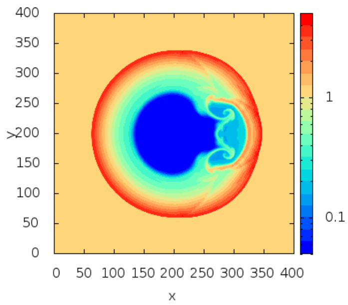

Figure 3: $\log_{10}$ plot of ρ in run A at t =2.2.

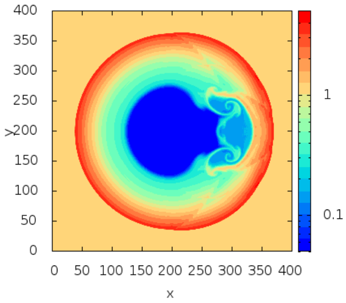

Figure 4: $\log_{10}$ plot of ρ in run A at t =3.0.

This illustrates the general history of these simulations. At early times the shock from the stronger explosion overtakes the weaker one, and the cavity of the weaker 'blast wave' is collapsed and material is driven into it. What is not apparent from the density plots is the deposition of vorticity. The presence of the vortex ring is however apparent as the simulation progresses and the associated spiracular structure forms (Kelvin-Helmholtz instability).

In figures 5–8 we show a series of close ups of the remnant of the weaker blast wave at late time (actual times indicated in captions).

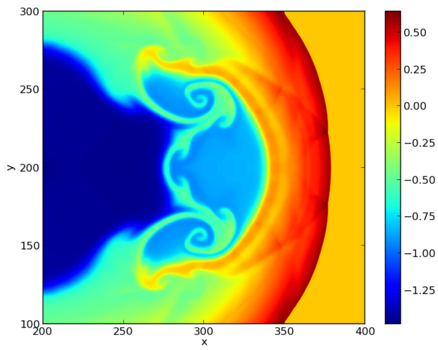

Figure 5: $\log_{10}$ plot of ρ in run A at t =3.4 showing a close up on remnant of the weaker blast wave.

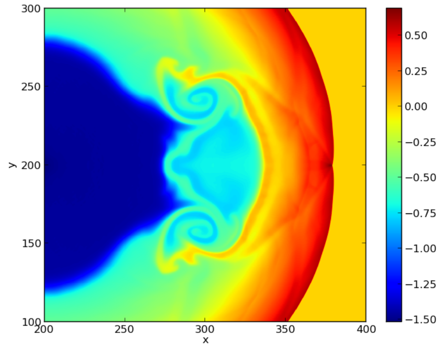

Figure 6: $\log_{10}$ plot of ρ in run B at t =3.6 showing a close up on remnant of the weaker blast wave.

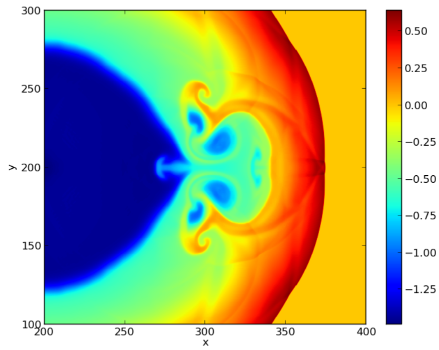

Figure 7: $\log_{10}$ plot of ρ in run C at t =3.4 showing a close up on remnant of the weaker blast wave.

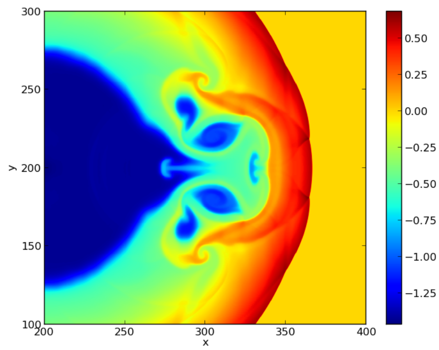

Figure 8: $\log_{10}$ plot of ρ in run D at t =3.0 showing a close up on remnant of the weaker blast wave.

This shows that there are subtle variations in the morphology of the remnant of the weaker blast wave depending on the exact parameters chosen. In some cases (C and D) the ‘roll-up’ of material in the cavity does not appear to become so highly developed (in contrast to A and B), however the roll-up of the compressed shell of the weaker blast wave is perhaps more prounced. Nonetheless, it is clear that the deposition of vorticity and the affect this has on the density structure is not highly dependent on very specific choices of parameters.

Finally it is interesting to examine the symmetric case. This is shown for two blast waves (P_h =2000,$R_h = 15$) in figure 9.

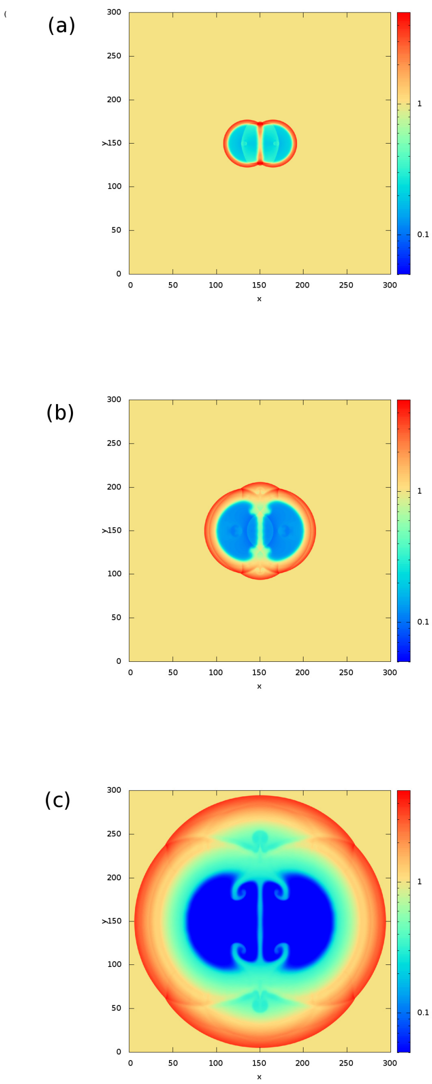

Figure 9: $\log_{10}$ plots of ρ in a symmetric case (t =0.5,1.5, and 9 respectively).

Interestingly what we observe here is that, although the problem is entirely symmetric, and neither blast wave cavity undergoes collapse as such, we still observe density structuring arising from vorticity deposition, in particular the KH roll-up that can be seen in the final snap-shot. The collapse of a weaker cavity is not essential to vorticity deposition, which arises from the propagation of the transmitted shocks through the cavities of the blast waves. Clearly this still occurs in the case of two colliding blast waves, as there are still transmitted shocks. Therefore there must still be vorticity deposition. Although the ’wall’ between the two cavities is not driven into the other, the KH instability eventually results in the development of KH roll-up.

4 Conclusions

We have argued that blast wave collisions should result in vorticity deposition and consequently structure generation. One might expect this to be particularly clear in the case where the two blast waves are asymmetric, as behaviour should eventually resemble that of shock-bubble interactions. We have presented 2D numerical simulations using ideal hydrodynamics which demonstrate this. We also show that even in the symmetric case, the vorticity deposition can still lead to structure generation. The Kelvin-Helmholtz instability remains a subject of investigation in its own right, and observable density structuring provides additional information about vorticity deposition and shock propagation in experiments. Whilst vortcity deposition and the associated density structuring have not been deeply studied in blast wave experiments (e.g. [1] and [2]), the planning of future experiments might want to consider examining the issue of vorticity.

References

[1] D.R.Symes et al., *HEDP*, **6**, 274-279 (2010)

[2] R.A.Smith et al., *Plasma Phys.Control.Fusion*, **49**, B117-B124 (2007)

[3] D.Ranjan et al., *Annu.Rev.Fluid Mech.*,**43**, 117-140 (2011)