UCRL-CR-126749

S/C- B295120

**Final Report for CAFDA Project Entitled
"Experimental and Numerical Investigation of Accelerated Fluid Interfaces"**

J. A. Greenough
D. L. Marcus
J. W. Jacobs

RECEIVED
JAN 11 1999
OSTI

March 26, 1997

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

FINAL REPORT FOR CAFDA PROJECT ENTITLED

“Experimental and Numerical Investigation of Accelerated Fluid Interfaces”

J.A. Greenough and D.L. Marcus
Center for Computational Sciences and Engineering
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

J.W. Jacobs
Department of Aerospace and Mechanical Engineering
University of Arizona
Tucson, AZ 85721

INTRODUCTION

The main thrust of this collaborative effort can be summarized as an attempt to use the strengths of physical experiments and numerical simulations in understanding the dynamics of accelerated interfaces. Laboratory experiments represent the true nature of the physical processes and the simulations represent a model of these processes. We have taken the first steps toward this goal through development and calibration of new experimental techniques as well as validation and direct, systematic, and quantitative comparison with computational results. This report summarizes accomplishments made towards these goals. More detailed information is provided in reprints appended to this document.

SHOCKED 2D CYLINDRICAL JET

One of the important goals of this collaboration was to carry out calculations of shock accelerated diffuse cylinders which could be compared with previous Caltech experiments. Dr. Greenough has completed calculations of a 2D shocked cylindrical helium cylinder. Three sets of calculations have been completed with a factor of two refinement between each set. Performing these calculations and doing the preliminary analysis has uncovered a number of interesting features. These were the focus of an oral presentation at the 20th International symposium on shock Waves held at California Institute of Technology, July 23-28, 1995 [1].

During the short times of the experiments, times on the order of the shock passage through the gas jet, an interesting quadrupole configuration in the baroclinic production of vorticity has been observed. This is in sharp contrast to the characteristic dipole configuration observed in the vorticity field. The details of this observation were the focus of an oral presentation at the 5th International Workshop on The Physics of Compressible Turbulent Mixing, July 18-21, 1995 held at the University at Stony Brook [2]. Detailed and closely spaced in time snapshots of the flowfield have been collected for post-processing. The results obtained from these series of calculations will be the body of a paper that will follow in a timely fashion and be submitted to a refereed journal and prepared as a laboratory technical report. These documents will acknowledge the CAFDA support as well as be available for the CAFDA directors review.

We also obtained actual Helium mole fraction data from J. Budzinski at Los Alamos National Laboratory on the Helium jet experiments. He used Rayleigh scattering to measure the mole fractions for a series of Mach numbers both with and without reshock. The above calculations are for a single Mach number (1.095) that matches that experimentally studied by Prof. Jacobs using PLIF techniques. We have found, from the refinement study, that very high resolution was

necessary to obtain near correct long time mole fractions. This is a comment on the smearing of the volume fraction profiles by the shock wave. It bolsters our contention that Adaptive Mesh Refinement (AMR) provides the means necessary to counteract the effects of interface smearing. That is, adding sufficient refinement reduces the smearing effect to a negligible level.

INCOMPRESSIBLE RICHTMYER-MESHKOV EXPERIMENTS

Dr. Marcus and Prof. Jacobs with a University of Arizona Research Assistant, Charles Niederhaus, have begun work on the coupled numerical and experimental study of incompressible Richtmyer-Meshkov instability. The experimental component of this work has progressed on several fronts: (1) Existing videotape records of previously conducted experiments have been analyzed. Subsequently, a paper has been written and published in the *Physics of Fluids*. (2) The existing experimental apparatus has been refined by the addition of a digital image acquisition system to record the instability development and an accelerometer to simultaneously record the acceleration history of the liquid system. (3) Planar laser induced fluorescence imaging has been implemented to produce much clearer views of the interface and improve the accuracy of interfacial amplitude measurements.

Figure 1 is a schematic of the experimental apparatus. Richtmyer-Meshkov instability is generated by bouncing a thin rectangular tank containing two liquids (fresh water and a salt solution) off of a fixed spring. The container is mounted to a linear rail system which constrains its motion to the vertical direction, and a controlled initial surface shape is given to the system by oscillating the rails in the horizontal direction. After it is released, the container falls vertically and bounces off of the spring which is fixed at the end of the track. The instability then evolves as the container travels upward and downward until it bounces a second time. The two fluids thus experience a "shockless" impulsive acceleration, followed by a short period of zero acceleration, which mimics the conditions in shock tube experiments which utilize two gases. The motion of the interface is recorded using a video camera which travels with the moving container.

In the original experiments, the output from the video camera was recorded using a video cassette recorder (VCR). A number of experiments were conducted prior to the start of the project. During the first year of the project the videotape records from these runs were analyzed by utilizing a frame grabber to digitize video frames from the VCR. Instability amplitudes and initial growth rates were also measured from the captured video frames. It was found that the duration of the impulsive acceleration in these experiments is sufficiently long, that agreement with Richtmyer's linear stability theory, which assumes an acceleration pulse in the form of a delta function, could not be obtained. This analysis was therefore extended to consider a finite duration acceleration pulse with the distribution expected from a simple spring-mass system. The results of this analysis provided much better agreement with the initial growth rate measurements. In addition, a model was developed based on the assumption that the instability at late times resembles the flow generated by a row of alternating signed line vortices. This model was found to agree well with late time amplitude measurements. A paper describing this work has recently been published in the *Physics of Fluids* [3].

The fact that bounce length was found to be of importance in these experiments suggests that a more detailed knowledge of the acceleration pulse received by the bouncing container is required. Therefore, funds from the current contract were utilized to purchase an accelerometer which was subsequently mounted to the container in the experimental apparatus. Tests were performed utilizing the accelerometer with an existing computer and A/D converter to characterize the acceleration pulse. Results from these tests indicated that the acceleration profile contained a large high-frequency component which is probably the result of oscillations

in the spring and tank support system generated by the impact of the container with the spring. As a result of this finding, a substantial effort was directed toward eliminating these unwanted vibrations. We found that these oscillations were significantly reduced by utilizing rubber pads at the points where the tank is mounted to its support structure, and at the location where the support structure makes contact with the spring. In addition, we have obtained a stiffer spring which significantly shortens the pulse length and thus reduces the importance of the acceleration distribution to the developing instability.

Funding from this contract has also been utilized for the improvement of the image acquisition capability of the experiments. One of the major shortcomings of the previous experiment was that the video signal was recorded and stored using a VCR. This process resulted in a significant loss of quality and resolution in the captured video images. This problem has been rectified by the purchase of a digital video acquisition system consisting of a computer and frame grabber. This system allows the real-time capture of the video frames at the full camera resolution, thus increasing the resolution of the captured images by more than a factor of two. The implementation of this system required the building of delay and trigger circuitry to synchronize the start of data collection with the container release, and a considerable amount of computer programming. Figure 2 is a sequence of images acquired using the new acquisition system. This sequence more clearly shows the evolution of the interface from a simple sinusoidal shape, to one exhibiting the mushroom structures commonly observed in Richtmyer-Meshkov and Rayleigh-Taylor instabilities with small to moderate Atwood numbers. After growing to considerable size, these structures are destroyed by the second container bounce, as the flow rapidly erupts into turbulence. These results were presented at the 5th International Workshop on The Physics of Compressible Turbulent Mixing [4].

In viewing the images in figure 2, a slight amount of three-dimensionality (i.e. variation across the smallest tank dimension) is evident. This variation causes some of the features of the flow to be obscured, but more importantly, it complicates the measurement of interfacial amplitude. Planar Laser Induced Fluorescence (PLIF) is capable of improving the accuracy of these measurements by producing views of only a thin cross section of this flow. Funds were, therefore, also used to implement PLIF in this study. This was accomplished by using an existing 2 W Argon-ion laser, whose beam was spread into a sheet using a cylindrical lens. The light sheet was then passed through the transparent top of the fluid container using a pair of mirrors. A fluorescent dye (fluorescein) was then introduced into the heavy salt solution in place of the standard dye, which then became visible only when illuminated by the laser light sheet. Experiments were then carried out as before. Figure 3 shows a time sequence using the PLIF technique. Note that these images reveal more clearly the process of vortex formation and the wrapping of the interface around the vortex cores. Also note the appearance of small wall vortices which are masked in the standard dye technique (figure 2). However, most importantly, the location of the interface is much more clearly defined in these photographs, thus allowing much more accurate measurements of interfacial amplitude. Figure 4 is a plot of measured amplitude versus time for three experiments, where time is scaled in this plot with the theoretically predicted growth rate using measured acceleration histories. Note that these measurements collapse much more readily onto a single curve than do measurements from the standard dye technique [3]. Also shown on this plot are lines indicating the growth predicted by the linear stability theory and the late time vortex model discussed above. Again much better agreement with the two theoretical models is attained with the PLIF measurements.

Part of the motivation for this study is to explore the efficacy of simple interface capturing strategies (resolving a fluid-fluid interface via solution of the mass conservation equation using a robust advection scheme) as compared to interface tracking procedures (full reconstruction of a distinguished interface at each time step and using the resultant volume fraction data to update the density field). Preliminary calculations have been completed by Dr. Marcus which indicate that, for the parameter range spanned by the experiments, capturing provides an adequate

representation of the evolving interface. The initial conditions for this calculation are a sinusoidally perturbed interface separating fluids with upper and lower densities of 1000 kg/m^3 and 1367 kg/m^3 , and were chosen to match one of experiments conducted at the University of Arizona. In addition, the acceleration of the interface is modeled as half-period sine function with a duration of 57 ms, peaking at an acceleration of 133.1 m/s^2 , which also approximates that of the experiments. The interface has been smeared across several zones to simulate the effect of thin diffusive layer between the two fluids and inhibit grid-scale perturbations from growing. The amplitude of the initial perturbation was taken from the photograph of the experiment as 13.5% of the wavelength. After an initial period of brief quiescence, the interface begins to grow into the characteristic mushroom shape. Qualitative observation of the growth rate shows good agreement between the experiment and the calculation.

PUBLICATIONS RESULTING FROM THIS PROJECT

- [1] J.A. Greenough, J.B. Bell, P. Colella, E.G. Puckett and J.W. Jacobs, "A numerical study of shock acceleration of a diffuse helium cylinder," *Proceedings of the 20th International Symposium on Shock Waves*, California Institute of Technology, Pasadena, CA, July 23-28, 1995, B. Sturtevant, J. E. Sheperd and H. Hornung (ed.) World Scientific (1996) 617-622.
- [2] J.A. Greenough, and J.W. Jacobs, "A numerical study of shock-acceleration of a diffuse helium cylinder," *Proceedings of the Fifth International Workshop on Compressible Turbulent Mixing*, University at Stony Brook, New York, July 18-21, World Scientific (1996) 338-345.
- [3] J.W. Jacobs, and J.M. Sheeley "Experimental study of incompressible Richtmyer-Meshkov instability," *Phys. Fluids*, **8**, 405-415 (1996).
- [4] J.W. Jacobs, M.A. Jones, and C.E. Niederhaus, "Experimental studies of Richtmyer-Meshkov instability," *Proceedings of the Fifth International Workshop on Compressible Turbulent Mixing*, University at Stony Brook, New York, July 18-21, World Scientific (1996) 195-202.

Figure 1. The experimental apparatus.

Figure 2. A sequence of images showing the development of the instability in a typical experiment. Times relative to the point of first contact with the spring are: (a) -15 ms, (b) 18 ms, (c) 68 ms, (d) 118 ms, (e) 185 ms, (f) 235 ms, (g) 285 ms, (h) 352 ms, (i) 402 ms, (j) 452 ms, (k) 519 ms, (l) 569 ms. The second spring contact occurs between (j) and (k).

Figure 3. A sequence of PLIF images showing the development of the instability in a typical experiment. Times relative to the point of first contact with the spring are: (a) -46 ms, (b) 21 ms, (c) 88 ms, (d) 154 ms, (e) 221 ms, (f) 288 ms, (g) 355 ms, (h) 421 ms, (i) 488 ms, (j) 555 ms, (k) 621 ms, (l) 688 ms. The second spring contact occurs between (k) and (l).

Figure 4. A plot of measured amplitude compared with predictions of linear instability theory and a simple vortex model.

A numerical study of shock acceleration of a diffuse helium cylinder *

J. A. Greenough, J. B. Bell and P. Colella
Center for Computational Sciences and Engineering
Lawrence Livermore National Laboratory
Livermore, CA USA 94550

E. G. Puckett
Department of Mathematics and Institute of Theoretical Dynamics
University of California
Davis, CA USA 95616

J. W. Jacobs
Department of Aerospace and Mechanical Engineering
University of Arizona
Tucson, AZ USA 85721

Abstract: The development of a shock-accelerated diffuse helium cylindrical inhomogeneity is investigated using a new numerical method. The new algorithm is a higher-order Godunov implementation of the so-called multi-fluid equations. This system correctly models multiple-component mixtures by accounting for differential compressibility effects. This base integrator is embedded in an implementation of adaptive mesh refinement (AMR) that allows efficient increase in resolution where the computational effort is concentrated where high accuracy, or increased resolution, are required. Qualitative and quantitative comparison with previous experimental data is excellent. The simulations show that counter-sign vortex blobs are deposited in the jet core by baroclinic generation of the curved shock wave as it traverses the jet. This vorticity deposition occurs over timescales that scale with the shock passage time ($\sim 10\mu\text{sec}$). Three phases of development are identified and characterized. The first is the weak-deformation (WD) phase, where there is weak distortion of the helium jet due to weak vorticity-induced velocity effects. The second phase is the strong-deformation (SD) phase where there is large distortion for the jet and the vortex blobs due to large induced-velocity effects. The last is a relaxation/reorganization (RR) phase where the vorticity field reorganizes into

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48. Additional support under contract W-7405-Eng-48 by the Applied Mathematical Sciences Program and the HPCC Grand Challenge Program of the Office of Scientific Computing at DOE, Defense Nuclear Agency under IACRO 94-831 and the Center for Advanced Fluid Dynamics Applications under contract B295120.

a point-like vortex pair.

Key words: Shock accelerated diffuse interfaces, Multi-fluid methods, Adaptive methods

1. Introduction

The evolution of interfaces accelerated by shock waves has been the focus of investigations for many years. This class of problem has applications in such disparate fields as inertial confinement fusion (ICF) and high-speed combustion. The literature is rich in studies on the stability of plane interfaces (Richtmyer, 1960), (Meshkov, 1969), (Zaitsev et al.), and (Brouillette et al., 1988). The stability of curved interfaces has received similar attention culminating with the study of (Hass et al., 1987), where cylindrical or spherical shapes, constructed from soap bubbles or nitrocellulose membranes, were filled with either a light or heavy gas and then accelerated by a shock wave. This last study and the previous works relied on such membranes to separate gases. A different class of experiment on acceleration of gaseous cylinders was developed by (Jacobs, 1993) and (Jacobs, 1992) that was free from the effect of membranes and used a planar laser-induced fluorescence (PLIF) technique allowed for excellent visualization of the flow and quantitative information regarding mixing.

The present simulations use a high-resolution adaptive method designed for multi-fluid flows with initial mixed layers. In this paper, the development of the helium mole fraction and vorticity field will be examined. Extensive comparisons with experimental data have also been completed as well as development of a new conceptual model describing this flow, but cannot be described here due to space limitations.

2. Multi-fluid system and numerical method

The equations used for this study are the so-called multi-fluid equations as developed by (Colella et al., 1995) and also described in (Puckett et al., 1992). This system is based on a volume-of-fluid approach, where the fraction of a cell volume occupied by a distinguished fluid is followed during the flow evolution. The basic assumptions in this approach are that there is pressure equilibrium within a cell, a single velocity vector for both fluids, and that all changes of state are adiabatic. The equations are given as

$$\frac{\partial f^\alpha}{\partial t} + \nabla \cdot (u f^\alpha) = f^\alpha \frac{\hat{\Gamma}}{\Gamma^\alpha} \nabla \cdot u \quad (2.1)$$

$$\frac{\partial}{\partial t} (f^\alpha \rho^\alpha) + \nabla \cdot (u f^\alpha \rho^\alpha) = 0 \quad (2.2)$$

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (u u \rho) + \nabla p = 0 \quad (2.3)$$

$$\frac{\partial}{\partial t} (f^\alpha \rho^\alpha E^\alpha) + \nabla \cdot (u f^\alpha \rho^\alpha E^\alpha) + p f^\alpha \frac{\hat{\Gamma}}{\Gamma^\alpha} \nabla \cdot u + f^\alpha \frac{\rho^\alpha}{\rho} u \cdot \nabla p = 0 \quad (2.4)$$

where f^α , ρ^α , and E^α are the volume fraction, density, and total energy density of fluid component α . The volume fraction is defined as $f^\alpha = \Lambda_\alpha / \Lambda$ where Λ is the volume of the cell and Λ_α is the volume of the cell occupied by fluid α . Γ^α is the sound speed gamma for fluid α , and $\hat{\Gamma} = 1 / \sum_\alpha (f^\alpha / \Gamma^\alpha)$ represents fraction weighted Γ for the mixture.

The pressure that appears in the above system is defined to be a thermodynamically consistent pressure and defined as $p = \sum_i \hat{\Gamma} (f^i p^i / \Gamma^i)$, where p^α is the partial pressure of component α . Note that the formulation is sufficiently general to allow real gas equation of state (EOS) systems described by pressure given as a function of density and internal energy.

The solution procedure for the system is a higher-order Godunov method following that of (Colella, 1984) and detailed in (Greenough, et al., 1995). This base integrator for the multi-fluid system is embedded within an implementation of adaptive mesh refinement (AMR). This methodology is based on the original work of (Berger & Oliger, 1984) and later (Berger & Colella, 1989). This is a means for managing a refined grid heirarchy composed of logically rectangular grid patches that allows for efficient increases in resolution by focusing the computational accuracy where errors are deemed large, or in regions where high resolution is required.

3. Problem setup

The initial conditions for this problem are taken from (Jacobs, 1993). The shock wave Mach number is 1.094 in air. In (Budzinski, 1992), a Ralieg scattering technique is used to measure the actual molar concentrations of helium. It shows the initial profile is Gaussian in shape with a core concentration of approximately 80% helium. The initial half radius is set as, $r_{\text{half}} = 0.2$, where it is defined as the distance where the helium mole fraction is half the center value. The density ratio between air and helium is $\rho_{\text{helium}} / \rho_{\text{air}} = .138$.

The computational domain is 9cm wide by 27cm long with a base grid of 36 cells wide by 108 cells long. There are two levels of refinement with the first level is a factor of 4 more refined than the base grid and the second level is a factor of 8 more refined than the first level of refinement. This gives an effective grid resolution of $\Delta x_{\text{fine}} = \Delta y_{\text{fine}} = 0.0078125\text{cm}$. The shock is initialized in air at a distance of $3r_{\text{half}}$ from the jet. All boundaries are inflow/outflow type.

4. Results and discussion

4.1. Flow visualization

Figures 1 and 2 show the evolution of the mole fraction of helium and the development of the vorticity field, respectively. Figure 1a shows the initial conditions and the initial mixed layer. At $88\mu\text{sec}$, figure 1b, there is a flattening of the jet and a generally weak deformation of its original circular structure. From here out to about $400\mu\text{sec}$, spanned in time by Figs. 1c through f, there is strong deformation of the jet as it is inverted and transformed into the vortex pair. After $400\mu\text{sec}$, from Fig. 1g on, the flow evolves as a well defined vortex pair. Comparing these results with those given in (Jacobs, 1993), the agreement is exceptional.

Based on these observations and for ease and clarity of later exposition, we define three phases of development. The first is the weak-deformation phase (WD) that occurs over short times out to about $90\mu\text{sec}$. The second is the strong-deformation phase (SD) that occurs after WD out to about $400\mu\text{sec}$. The last is the relaxation/reorganization (RR) phase that occurs after SD.

In the vorticity time sequence, Fig. 2a shows the shock, still essentially planar, leaving positive (in the upper half plane) vorticity behind it. By $66\mu\text{sec}$, Fig. 2b, the shock is well out of the jet core and two counter-sign circular vortex blobs are seen located in the jet core. During the WD phase, the vortex blobs remain essentially undistorted. This is due to the fact that vorticity induced velocity effects are very weak during the WD phase. Also, the blobs are deposited in the jet core over a timescale that scales with the shock passage time ($\sim 10\mu\text{sec}$). During the SD phase however, there are large induced-velocity effects that distort and stretch the vortex blobs into something like continuous finite thickness sheets. The underlying vortical field swirls these sheets so that they are reorganized, at later times, into a vortex pair. Note that during the SD phase, there is strong counter-sign vorticity appearing also oriented in sheets, ahead of the distorted blob. Although not shown here, this counter-sign production acts to modulate the overall circulation as it relaxes to a near constant value.

The development of this flow is seen to be determined by the interaction and evolution of the vortex blobs. Once they are present in the flow, they at first interact weakly (during WD), then interact strongly (during SD) as they change from blobs to more point-like vortices (during RR). During the course of the transformation in the vorticity field, the helium jet undergoes a similar transformation as shown. From a modeling point of view, this flow could be accurately depicted by the development of a vortex blob pair in an essentially circular helium jet (slightly flattened on the upstream side in reality). The

subsequent development could be predicted by their interaction and reorganization/relaxation to point vortices.

References

- R.D. Richtmyer 1960 Taylor instability in shock acceleration of compressible fluids. *Commun. Pure Appl. Maths* 23, 297-319.
- E.E. Meshkov 1969 Instability of the Interface of Two Gases Accelerated by a Shock Wave. *Izv. Akad. Nauk. SSSR Mekh. Ahidk. Gaza* 4, 1151-157, Russian: *Izv. Acad. Sci. USSR Fluid Dyn.* 4, 101-104.
- Zaitsev, S.G., Lazareva, E.V., Chernukha, V.V., & Belyaev, V.M. 1985 Experimental Investigation of the Hydrodynamic Instability of the Interface Between Media of Different Density in an Acceleration Field. Translated from *Teplofizika Vysokikh Temperatur* 23, 535-541.
- Brouillette, M. & Sturtevant, B. 1988 Shock Induced Rayleigh-Taylor Instability at a Continuous Interface. Abstract submitted to the Intl Workshop on the Physics of Compressible Turbulent Mixing, 24-27 October 1988, Princeton, New Jersey.
- Haas, J.-F. & Sturtevant, B. 1987 Interaction of weak shock waves with cylindrical and spherical inhomogeneities. *J. Fluid Mech.*, 181, 42-76.
- Jacobs, J.W. 1992 Shock-induced mixing of a light-gas cylinder. *J. Fluid Mech.* 234, 629-649.
- Jacobs, J.W. 1993 The Dynamics of Shock Accelerated Light and Heavy Gas Cylinders. *Phys. Fluids A* 5, 2239-2247.
- Colella, P., Ferguson, R.E., Glaz, H.M. 1995 Multifluid Algorithms for Eulerian Finite Difference Methods. Manuscript.
- Puckett, E.G. & Saltman, J.S. 1992 A 3-D Adaptive Mesh Refinement Algorithm for Multimaterial Gas Dynamics. *Physica D* 60, 84-104.
- Colella, P. 1984 A Direct Eulerian Muscl Scheme for Gas Dynamics. *SIAM J. Sci. Stat. Comput.* 6, 104-117.
- Greenough, J.A., Bell, J.B., Colella, P. 1995 An Adaptive Multifluid Interface-Capturing Method for Compressible Flows in Complex Geometry. *AIAA Paper* 95-1718.
- Berger, M.J. & Oliger, J. 1984 Adaptive Mesh Refinement for Hyperbolic Partial Differential Equations. *J. Comput. Phys.* 53, 484-512.
- Berger, M.J. & Colella P. 1989 Local Adaptive Mesh Refinement for Shock Hydrodynamics. *J. Comput. Phys.*, 82, 64-84.
- Budzinski, J.M. 1992 Planar Rayleigh Scattering Measurements of Shock Enhanced Mixing. Doctoral dissertation. California Institute of Technology.

Figure 1. A sequence showing the computed helium mole fraction evolution. Note that the shock arrival time at the jet is approximately $40\mu\text{sec}$ and all times reported are relative to the start of the calculation. (a) The initial jet, (b) $88\mu\text{sec}$, (c) $202\mu\text{sec}$, (d) $259\mu\text{sec}$, (e) $318\mu\text{sec}$, (f) $436\mu\text{sec}$, (g) $561\mu\text{sec}$, (h) $943\mu\text{sec}$, (i) $1182\mu\text{sec}$. The shock moves from left to right. The color bar to the right varies highest to lowest values from top to bottom.

Figure 2. A sequence showing the vorticity evolution. Note that the shock arrival time at the jet is approximately $40\mu\text{sec}$ and all times reported are relative to the start of the calculation. (a) $44\mu\text{sec}$, (b) $66\mu\text{sec}$, (c) $88\mu\text{sec}$, (d) $141\mu\text{sec}$, (e) $202\mu\text{sec}$, (f) $259\mu\text{sec}$, (g) $318\mu\text{sec}$, (h) $436\mu\text{sec}$, (i) $1182\mu\text{sec}$. The shock moves from the left to right. The color bar to the right is centered with respect to the data. Values vary highest positive to highest negative from top to bottom.

A Numerical Study of Shock-Acceleration of a Diffuse Helium Cylinder *

Jeffrey A. Greenough¹ and Jeffrey A. Jacobs²

¹ Lawrence Livermore National Laboratory, Livermore, CA 94550

² Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, AZ 85721

Abstract

The development of a shock-accelerated diffuse helium cylindrical inhomogeneity is investigated using a new numerical method. The new algorithm is a higher-order Godunov implementation of the so-called multi-fluid equations. This system correctly models multiple component mixtures by accounting for differential compressibility effects. This base integrator is embedded in an implementation of adaptive mesh refinement (AMR) that allows efficient increase in resolution by concentrating the computational effort where high accuracy, or increased resolution, are required. Qualitative and quantitative comparison with previous experimental data is excellent. The simulations show that counter-sign vortex blobs are deposited in the jet core by baroclinic generation of the curved shock wave as it traverses the jet. This vorticity deposition occurs over timescales that scale with the shock passage time ($\sim 10\mu\text{sec}$). Three phases of development are identified and characterized. The first is the weak deformation (WD) phase, where there is weak distortion of the helium jet due to weak vorticity induced velocity effects. The second phase is the strong deformation (SD) phase where there is large distortion for the jet and the vortex blobs due to large induced velocity effects. The last is a relaxation/reorganization (RR) phase where the vorticity field is reorganized into point-like vortex pair.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48. Additional support under contract W-7405-Eng-48 by the Applied Mathematical Sciences Program and the HPCC Grand Challenge Program of the Office of Scientific Computing at DOE, Defense Nuclear Agency under IACRO 94-831 and the Center for Advanced Fluid Dynamics Applications under contract B295120.

1 Introduction

The evolution of interfaces accelerated by shock waves has been the focus of investigations for many years. This class of problem has applications in such disparate fields as inertial confinement fusion (ICF) and high-speed combustion. The literature is rich in studies on the stability of plane interfaces [1], [2], and [3]. The stability of curved interfaces has received similar attention culminating with the study of [4], where cylindrical or spherical shapes, constructed from soap bubbles or nitrocellulose membranes, were filled with either a light or heavy gas and then accelerated by a shock wave. This last study and the previous works relied on such membranes to separate gases. A different class of experiment on acceleration of gaseous cylinders was developed by [6] and [5] that was free from the effect of membranes and used a planar laser induced fluorescence (PLIF) technique for obtaining excellent visualization of the flow and quantitative information regarding mixing.

The present simulations use a high resolution adaptive method designed for multi-fluid flows with initial mixed layers. In this paper, the development of the helium mole fraction and vorticity field will be examined. Extensive comparisons with experimental data have also been completed as well as development of a new conceptual model describing this flow, but cannot be described here due to space limitations.

2 Multi-fluid System and Numerical Method

The equations used for this study are the so-called multi-fluid equations as developed by [7] and also described in [8]. This system is based on a volume-of-fluid approach, where the fraction of a cell volume occupied by a distinguished fluid is actually followed during flow evolution. The basic assumptions in this approach are that there is pressure equilibrium within a cell, there is a single velocity vector for both fluids and that all changes of state are adiabatic. The equations are given as

$$\frac{\partial f^\alpha}{\partial t} + \nabla \cdot (u f^\alpha) = f^\alpha \frac{\hat{\Gamma}}{\Gamma^\alpha} \nabla \cdot u \quad (2.1)$$

$$\frac{\partial}{\partial t} (f^\alpha \rho^\alpha) + \nabla \cdot (u f^\alpha \rho^\alpha) = 0 \quad (2.2)$$

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (u u \rho) + \nabla p = 0 \quad (2.3)$$

$$\frac{\partial}{\partial t} (f^\alpha \rho^\alpha E^\alpha) + \nabla \cdot (u f^\alpha \rho^\alpha E^\alpha) + p f^\alpha \frac{\hat{\Gamma}}{\Gamma^\alpha} \nabla \cdot u + f^\alpha \frac{\rho^\alpha}{\rho} u \cdot \nabla p = 0 \quad (2.4)$$

where f^α , ρ^α , and E^α are the volume fraction, density, and total energy density of fluid component α . The volume fraction is defined as $f^\alpha = \Lambda_\alpha/\Lambda$ where Λ is the volume of the cell and Λ_α is the volume of the cell occupied by fluid α . Γ^α is the sound speed gamma for fluid α , and $\hat{\Gamma} = 1/\sum_\alpha (f^\alpha/\Gamma^\alpha)$ represents fraction weighted Γ for the mixture.

The pressure that appears in the above system is defined to be a thermodynamically consistent pressure and defined as $p = \sum_i \hat{\Gamma} (f^i p^i / \Gamma^i)$, where p^α is the partial pressure of component α . Note that the formulation is sufficiently general to allow real gas EOS systems described by pressure given as a function of density and internal energy.

The solution procedure for the system is a higher-order Godunov method following that of [9] and detailed in [10]. This base integrator for the multi-fluid system is embedded within an implementation of adaptive mesh refinement (AMR). This methodology is based on the original work of [11] and later [12]. This is a means for managing a refined grid hierarchy composed of logically rectangular grid patches that allows for efficient increases in resolution by focusing the computational accuracy where errors are deemed large, or in regions where high resolution is required.

3 Problem Setup

The initial conditions for this problem are taken from [6]. The shock wave Mach number is 1.094 in air. In [13], a Raleigh scattering technique is used to measure the actual molar concentrations of helium. It shows the initial profile is Gaussian in shape with a core concentration of approximately 80% helium. The initial half radius is set as, $r_{\text{half}} = 0.2$, where it is defined as the distance where the helium mole fraction is half the center value. The density ratio between air and helium is $\rho_{\text{helium}}/\rho_{\text{air}} = .138$.

The computational domain is 9cm wide by 27cm long with a base grid of 36 cells wide by 108 cells long. There are two levels of refinement where the first level is a factor of 4 more refined than the base grid and the second level is a factor of 8 more refined than the first level of refinement. This gives an effective grid resolution of $\Delta x_{\text{fine}} = \Delta y_{\text{fine}} = 0.0078125\text{cm}$. The shock is initialized in air a distance of $3r_{\text{half}}$ from the jet. All boundaries are inflow/outflow type.

4 Results and Discussion

4.1 Flow Visualization

Figure 1 and 2 shows the evolution of the mole fraction of helium and the development of the vorticity field, respectively. Figure 1(a) shows the initial conditions and the initial mixed layer. At $88\mu\text{sec}$, figure 1(b), there is a flattening of the jet and a generally weak deformation of its original circular structure. From here out to about $400\mu\text{sec}$, spanned in time by figures 1(c) through (f), there is strong deformation of the jet as it is inverted and transformed into the vortex pair. After $400\mu\text{sec}$, from figure 1(g) on, the flow evolves as a well defined vortex pair. Comparing these results with those given in [6], the agreement is exceptional.

Based on these observations and for ease and clarity of later exposition, we define three phases of development. The first is the weak deformation phase (WD) that occurs over short times out to about $90\mu\text{sec}$. The second is the strong deformation phase (SD) that occurs after WD out to about $400\mu\text{sec}$. The last is the relaxation/reorganization (RR) phase that occurs after SD.

In the vorticity time sequence, figure 2(a) shows the shock, still essentially planar, leaving positive (in the upper half plane) vorticity behind it. By $66\mu\text{sec}$, figure 2(b), the shock is well out of the jet core and two counter-sign circular vortex blobs are seen located in the jet core. During the WD phase, the vortex blobs remain essentially undistorted. This is due to the fact that vorticity induced velocity effects are very weak during the WD phase. Also, the blobs are deposited in the jet core over a timescale that scales with the shock passage time ($\sim 10\mu\text{sec}$). It turns out that as the shock traverses the density stratification that the peak baroclinic production (by two orders of magnitude relative to all other values in the field) occurs at the curved shock. That means that at each instant in time, as the shock progresses across the jet that it acts as a strong source of vorticity. The result is what is shown in figure 2(b); the vortex blob pair. There is secondary production in the post shock region, but over times on the order of the shock passage time, these are weak secondary effects. During the SD phase however, there are large induced velocity effects that distort and stretch the vortex blobs into continuous finite thickness sheets of vorticity. These sheets are swirled around and reorganize, at later times, into a point-like vortex pair. Note that during the SD phase, there is strong counter-sign vorticity appearing that is also oriented in sheets, ahead of the distorted blob. Although not shown here, this counter-sign production acts to modu-

late the overall circulation as it relaxes to a near constant value. During the late time relaxation phase, the signed baroclinic production is essentially in balance leading to the circulation approaching a constant state.

The development of this flow is seen to be determined by the interaction and evolution of the vortex blobs. Once they are present in the flow, they at first interact weakly (during WD), then interact strongly (during SD) as they change from blobs, to point-like vortices (during RR). During the course of the transformation of the vorticity field, the helium jet undergoes a similar transformation as shown above. From a modeling point of view, this flow could be accurately depicted by the development of a vortex blob pair in an essentially circular helium jet (slightly flattened on the upstream side in reality). The subsequent development could be dictated by their interaction and reorganization/relaxation to point vortices.

4.2 Vortex Blob Deposition

Figure 3 shows a composite of the vorticity, the baroclinic generation, and the total density at two instants in time separated by $4\mu\text{sec}$. The figures from top to bottom are aligned spatially. The three frames on the left are all at $49\mu\text{sec}$ and the three on the right are all at $53\mu\text{sec}$. In the frames on the left, the shock wave is curved and the shock leading edge is coincident with the peak helium concentration.

In the vorticity field at $49\mu\text{sec}$, figure 3(a), the early stages of positive and negative vortices are seen just behind the curved shock. The baroclinic production field at this time, figure 3(c), shows the peak values are located at the curved portion of the shock wave within the jet. Note that these maxima are about 2 orders of magnitude greater than all other values in the field. This production along the curved shock wave is the mechanism for generating the vortex blobs. At each instant in time, the baroclinic generation due to the curved shock in a stratified density field acts as a strong source term in the vorticity evolution equation (positive in the upper half plane and negative in the lower half plane). The result over the time of the shock passage is the counter-signed vortex blobs as shown in 3(d). The peak vorticity values occur in the blobs. Note that the baroclinic generation behind the shock wave within the jet only weakly modulates the blob vorticity distribution. By $53\mu\text{sec}$ the shock has passed beyond r_{half} and the peak generation of circulation is over.

References

- [1] R.D. Richtmyer 1960 Taylor instability in shock acceleration of compressible fluids. *Commun. Pure Appl. Maths* **23**, 297-319.
- [2] E.E. Meshkov 1969 Instability of the interface of two gases accelerated by a shock wave. *Izv. Akad. Nauk. SSSR Mekh. Ahidk. Gaza* **4**, 1151-157 [Russian: *Izv. Acad. Sci. USSR Fluid Dyn.* **4**, 101-104.
- [3] Zaitsev, S.G., Lazareva, E.V., Chernukha, V.V., & Belyaev, V.M. 1985 Experimental investigation of the hydrodynamic instability of the interface between media of different density in an acceleration field. Translated from *Teplofizika Vysokikh Temperatur* **23**, 535-541.
- [4] Haas, J.-F. & Sturtevant, B. 1987 Interaction of weak shock waves with cylindrical and spherical inhomogeneities. *J. Fluid Mech.*, **181**, 42-76.
- [5] Jacobs, J.W. 1992 Shock-induced mixing of a light-gas cylinder. *J. Fluid Mech.* **234**, 629-649.
- [6] Jacobs, J.W. 1993 The dynamics of shock accelerated light and heavy gas cylinders. *Phys. Fluids A* **5**, 2239-2247.
- [7] Colella, P., Ferguson, R.E., Glaz, H.M. 1995 Multifluid algorithms for eulerian finite difference methods. Manuscript.
- [8] Puckett, E.G. & Saltzman, J.S. 1992 A 3-d adaptive mesh refinement algorithm for multimaterial gas dynamics. *Physica D* **60**, 84-104.
- [9] Colella, P. 1984 A direct eulerian muscl scheme for gas dynamics. *SIAM J. Sci. Stat. Comput.* **6**, 104-117.
- [10] Greenough, J.A., Bell, J.B., Colella, P. 1995 An adaptive multifluid interface-capturing method for compressible flows in complex geometry. AIAA Paper 95-1718.
- [11] Berger, M.J. & Oliger, J. 1984 Adaptive mesh refinement for hyperbolic partial differential equations. *J. Comput. Phys.* **53**, 484-512.
- [12] Berger, M.J. & Colella P. 1989 Local adaptive mesh refinement for shock hydrodynamics. *J. Comput. Phys.*, **82**, 64-84.
- [13] Budzinski, J.M. 1992 Planar rayleigh scattering measurements of shock enhanced mixing. Doctoral dissertation. California Institute of Technology.

Figure 1: A sequence of the computed helium mole fraction evolution. Note that the shock arrival time at the jet is approximately $40\mu\text{sec}$ and all times reported are relative to the start of the calculation. (a) The initial jet, (b) $88\mu\text{sec}$, (c) $202\mu\text{sec}$, (d) $259\mu\text{sec}$, (e) $318\mu\text{sec}$, (f) $436\mu\text{sec}$, (g) $561\mu\text{sec}$, (h) $943\mu\text{sec}$, (i) $1182\mu\text{sec}$. The shock moves from left to right. The color bar to the right varies highest to lowest values from top to bottom.

Figure 2: A sequence of the vorticity evolution. Note that the shock arrival time at the jet is approximately $40\mu\text{sec}$ and all times reported are relative to the start of the calculation. (a) $44\mu\text{sec}$, (b) $66\mu\text{sec}$, (c) $88\mu\text{sec}$, (d) $141\mu\text{sec}$, (e) $202\mu\text{sec}$, (f) $259\mu\text{sec}$, (g) $318\mu\text{sec}$, (h) $436\mu\text{sec}$, (i) $1182\mu\text{sec}$. The shock moves from the left to right. The color bar to the right is centered with respect to the data. Values vary highest positive to highest negative from top to bottom.

Figure 3: A short time composite sequence at 49 μsec of the (a) vorticity, (c) baroclinic generation, and (e) total density and at 53 μsec of the (b) vorticity, (d) baroclinic generation, and (f) total density. Note that the shock wave moves from left to right and the figures are aligned spatially.