Experimental and computational investigations of shock-accelerated gas bubbles


Wisconsin Shock Tube Laboratory
Fusion Technology Institute
University of Wisconsin-Madison

*Lawrence Livermore National Laboratory
AX- Division
Overview

- Planar shock wave accelerates spherical soap bubble: Ar inside, N₂ outside, $A_{\text{init}}=0.176$

- Time evolution of geometrical properties

- Mach number effects
  - $M=2.88$, $u_p=745$ m/s, $A_{\text{shock}}=0.00216$
  - $M=3.38$, $u_p=907$ m/s, $A_{\text{shock}}=-0.0219$

- Laboratory and computational experiments

- Comparison with RAPTOR (2D and 3D model)
Details of R-M experiment

Planar shock wave
Spherical soap bubble D = 5 cm
Driver: He    Driven: N₂    Test: Ar

Initial conditions:
Continuous white light from the front
Motion picture at 220 fps

Post shock:
Mie-scattering from the soap
film acting as flow tracer
2 laser pulses
2 images per run on same frame
Initial conditions

In free fall, bubble exhibits almost no left to right motion

Deduce that front to back motion is also negligible

Laser sheet intersects bubble in diametral plane
Shock Accelerated Bubble M#2.88

$t = 25 \mu s$

$t = 55 \mu s$

$t = 65 \mu s$

$t = 170 \mu s$
Shock Accelerated Bubble M#2.88

$t = 200 \mu s$

$t = 240 \mu s$

$t = 280 \mu s$

$t = 295 \mu s$
Shock Accelerated Bubble M#2.88

$t = 305 \mu s$

$t = 390 \mu s$

$t = 400 \mu s$

$t = 460 \mu s$

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Shock Accelerated Bubble M#2.88

$t = 520 \, \mu s$

$t = 570 \, \mu s$
Shock Accelerated Bubble M#2.88

$t = 740 \mu s$

$t = 776 \mu s$

$t = 895 \mu s$
Shock Accelerated Bubble M#3.38

$t = 42 \mu s$

$t = 84 \mu s$

$t = 90 \mu s$
Shock Accelerated Bubble M#3.38

$t = 146 \mu s$

$t = 158 \mu s$

$t = 226 \mu s$
Shock Accelerated Bubble M#3.38

$t = 226 \mu s$

$t = 324 \mu s$

$t = 324 \mu s$
2-D Computational experiments

- **Raptor code (LLNL)**
- **Navier-Stokes; Godunov with PLM; Richardson’s error estimation**
- **2-D cross section (w/ axial symmetry)**
- **Grid:**
  - 3 AMR levels (4,4,2)
  - $\Delta x_{min} = 0.078$ mm
- **$M = 2.88,3.38$**
- **2-inch-dia. Ar bubble in $N_2$ initially at 98.274 kPa**
- **No soap film; sharp interface**
- **Richardson on only while shock interacts**
- **Times given relative to initial shock-bubble interaction (±4 μs error)**
Qualitative laboratory/computational comparison M#2.88

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Qualitative laboratory/computational comparison M#3.38
Qualitative laboratory/computational comparison M#3.38

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Geometrical features

- Length scale: bubble diameter $D$
- Time scale: $\tau = D/u_p$

(u$_p$ = particle velocity behind shock)
Width growth rate

- M2.88 computational
- M2.88 experiment
- M3.38 computational
- M3.38 experiment
Height growth rate

- M2.88 experiment
- M3.38 experiment
- M2.88 computational
- M3.38 computational
Vortex diameter growth rate

![Graph showing vortex diameter growth rate with markers for M3.38 experiment, M2.88 experiment, and M2.88 computational.](image)

**Figure:** Vortex diameter growth rate

- **M3.38 experiment**
- **M2.88 experiment**
- **M2.88 computational**
Experiments vs. computations (H$_2$; M=2.88)
Height growth rate (power law fit)

- M2.88 experiment
- Power law 1.3
- Power law 1.2
- Power law 1.15
2D Simulation with different initial conditions

- **Film**
- **Sharp interface**
- **Rounded interface**
- **Diffuse interface**

280 µs
2D Simulation with different initial conditions

- Film: 590 µs
- Sharp interface: 558 µs
- Rounded interface: 558 µs
- Diffuse interface: 558 µs

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Height growth rate M#2.88
Width growth rate $M\#2.88$

![Graph showing width growth rate $M\#2.88$ with different interface conditions and experimental data.](image)
Conclusions from comparison with 2D simulation

- Observed bubble distortion, formation of vortex ring
- Measured growth rates of relevant large scale features
- Axial compression and expansion is observed
- Growth rate predicted are good for early timings
- No upstream vortex or jet is observed in simulation
- Absence of small scale features in simulation

- Need 3-D numerical simulations
3-D Computational experiments

- **Raptor code (LLNL): 3-D**
- Euler (no artificial viscosity used in 3-D runs); Godunov with PLM; Richardson’s error estimation
- 3-D Cartesian, ¼ symmetry about bubble center
- Grid:
  - 2 AMR levels (4,4)
  - $\Delta x_{min} = 0.195$ mm (factor of >2 coarser than 2-D runs)
- $M = 2.88$
- 2-inch-dia. Ar bubble in N2 initially at 98.274 kPa
- Film:
  - Thickness: 1 cell-width
  - Density: $0.1$ g/cm$^3$
- Times given relative to initial shock-bubble interaction (±4 ms error)
3-D Computational experiments

- Shock propagates along the $y$-axis
- Bubble is centered at $(0, y_{center}, 0)$
- Results are viewed using 3 planar slices: one perpendicular to each axis, at a selected location on that axis.
- $x$-$y$ and $z$-$y$ plots are shown at $z = 0$ and $x = 0$ locations, respectively.
- $x$-$z$ plots are shown at a $y$ location selected to be near the main vortex ring (indicated by red line).
Qualitative laboratory/3-D computational comparison

Ar vol. fraction

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<th>Value</th>
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<tr>
<td>1.00e-00</td>
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M = 2.88

t = 170 μs
Qualitative laboratory/3-D computational comparison

$t = 187 \mu s$

$x-y$ plane

$x-z$ plane

Total density (g/cm$^3$)

$t = 170 \mu s$

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Qualitative laboratory/3-D computational comparison

$t = 286 \mu s$

$x-y$ plane

Ar vol. fraction

1.00e-00
8.57e-01
7.14e-01
5.71e-01
4.29e-01
2.86e-01
1.43e-01
0.00e+00

$x-z$ plane

$z-y$ plane

$t = 280 \mu s$

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Qualitative laboratory/3-D computational comparison

$t = 286 \mu s$

$x-y$ plane  
$x-z$ plane

Total density (g/cm$^3$)

- 6.20e-03
- 5.47e-03
- 4.74e-03
- 4.01e-03
- 3.29e-03
- 2.56e-03
- 1.83e-03
- 1.10e-03

$t = 280 \mu s$

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Width growth rate

- M2.88 Computational
- M2.88 experiment
- M3.38 computational
- M3.38 experiment

\( W/D \) vs. \( t/\tau \)
Height growth rate

![Graph showing height growth rate with data points and lines for M2.88 Computational, M2.88 experiment, M3.8 Computational, and M3.38 experiment.](image-url)
Conclusions

• Developed new bubble-release technique
• Used strong (M>2.5) shocks
• Observed bubble distortion, formation of vortex ring
• Measured growth rates of relevant large scale features
• $\tau=D/u_p$ appears to be appropriate time scale
• 3D simulation with film resolved internal structures and small scale perturbations.

• Need full 3-D numerical simulations
• Develop “tomography” experiment
• Develop experiment to measure species concentration
Initial conditions

In free fall, bubble exhibits almost no left to right motion

Deduce that front to back motion is also negligible

Laser sheet intersects bubble in diametral plane