A computational parameter study for the 3D shock-bubble interaction, with and without modeled soap film

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Shock-bubble interaction: previous and current work

Previous experimental studies:

- Shock strengths: $1.05 \leq M \leq 4$
- Density contrast: $-0.75 \leq \text{At} \leq 0.5$
- Bubble gases: He, Kr, Ar, R22
- Film material

Previous numerical studies:

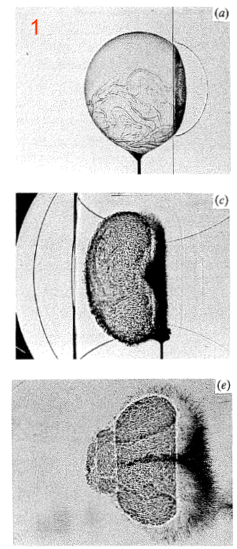
- Euler equations
- 2D resolution: $R_{30} - R_{900}$
- 3D resolution: R_{90}
- Methods: FCT, TVD, Godunov, WENO
- Adaptive gridding

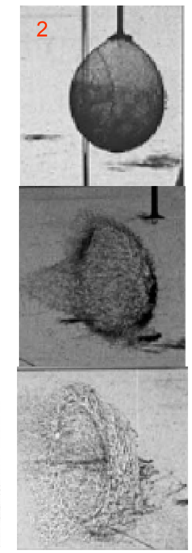
Previous 2D numerical parameter studies:

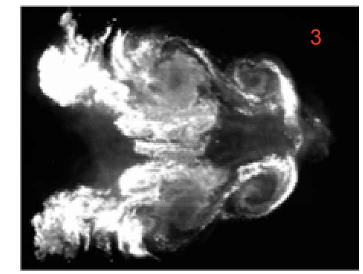
- Astrophysical regime, R_{120}
- Shock tube regime, R_{50}

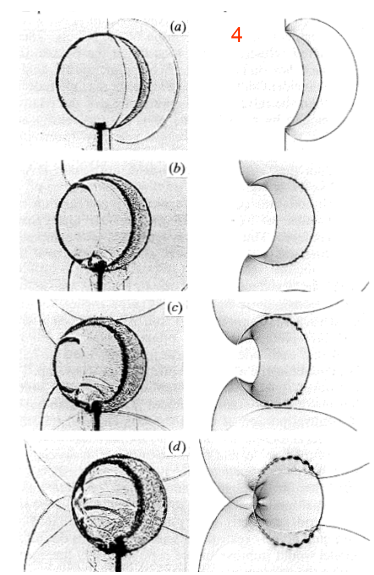
Current study:

- Shock strengths: $1.13 \leq M \leq 5$
- Density contrast: $-0.75 \leq \text{At} \leq 0.61$
- 3D resolution: R_{128}

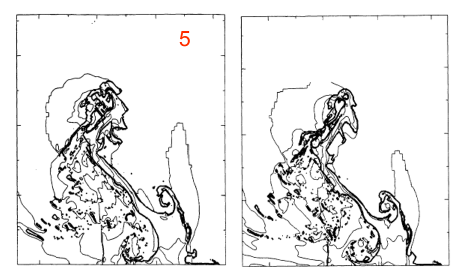


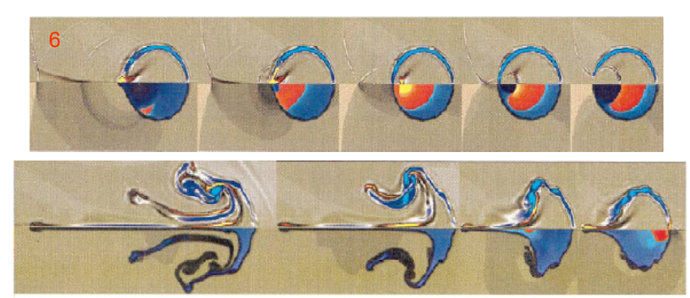


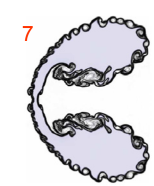




shock motion







1. Haas and Sturtevant, *JFM*, 1987
2. Layes, et al., *PRL*, 2003
3. Ranjan et al., *PRL*, 2005
4. Quirk and Karni, *JFM*, 1994
5. Klein, et al., *Ap.J.*, 1994
6. Zabusky and Zeng, *JFM*, 1998
7. Marquina and Mulet, *JCP*, 2003

Parameter study setup: numerical method

To simulate this problem in 3D, we have used the AMR code, *Raptor* (LLNL):

- 3D compressible Euler equations are solved, with a gamma-law EOS.

- Operator-split, piecewise-linear, second-order Godunov method (Collela, 1985).
  - Cell-centered initial data are traced along characteristics to cell-edges, using monotonized slopes (4^{th} order minmod limiting), to obtain L,R cell edge values.
  - Resulting L,R states at cell interfaces are input to an approximate Riemann solver.
  - Resulting Godunov state is used to compute fluxes.
  - Solution is update by an explicit conservative update.

- Integrator is embedded in the block-structured adaptive mesh refinement (AMR) framework of Berger and Oliger (1984) and Rendleman et al. (1998)
  - Nested hierarchy of increasing resolution rectangular sub-grids
  - Refinement in space and time
  - Fully parallelized

- Extended to 2D, 3D by the operator splitting technique of Strang (1964)

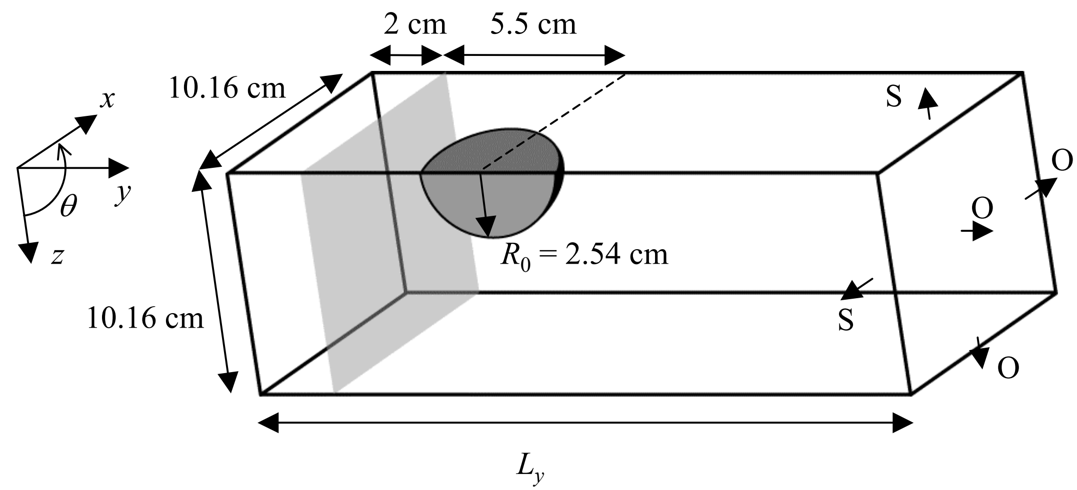
- Extended to multiple materials where the interface is captured following the VOF method of Miller and Puckett (1996)

- Turbulence model is implicit: MILES (monotone-integrated large-eddy simulation).

Parameter study setup: initial condition and computational grid

Grid:

- 3D Cartesian mesh
- 2 levels of refinement, 4× each
- ¼ symmetry
- Finest level resolution: R_{128}
- ~10^7 cells total



Boundary conditions:

- Outflow on outer lateral surfaces (exclude wall reflections)
- Symmetry on inner lateral surfaces

Refinement criterion:

- Density gradients
- All bubble fluid ($f_1 > 0$)

Initial condition:

- Planar shock of specified strength moving along y-axis, incident on quiescent spherical bubble.
- Ambient and bubble gas properties specified at standard atmospheric conditions.
- Bubble surface smoothed using a sub-grid VOF technique.

Parameter study setup: 12 scenarios

Scenario number	Gas pair	M	At	η_0	η_{post}	Previous work
1 2 3	Air-helium	1.20 1.50 1.68	-0.757	0.138	0.119 0.102 0.095	Experimental (Layes, et al)
4 5 6	N_2-argon	1.33 2.88 3.38	0.176	1.426	1.379 1.152 1.109	Experimental (Ranjan, et al)
7 8 9	Air-krypton	1.20 1.50 1.68	0.486	2.892	2.949 2.933 2.885	Experimental (Layes, et al)
10 11 12	Air-R12	1.14 2.50 5.00	0.613	4.173	4.731 8.181 9.786	Numerical (Zabusky and Zeng)

Diagnostics:

- Velocity of bubble and primary vortex ring
- Bubble dimensions
- Bubble volumetric compression
- Extent of bubble-ambient mixing
- Circulation

Flow visualization: low Mach number

Helium bubble in air

At = -0.757

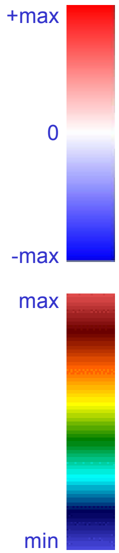
$M = 1.2$

Krypton bubble in air

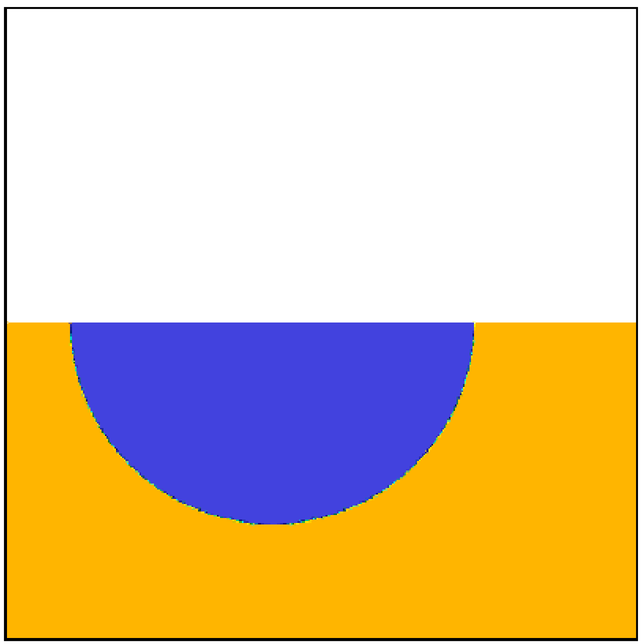
At = 0.486

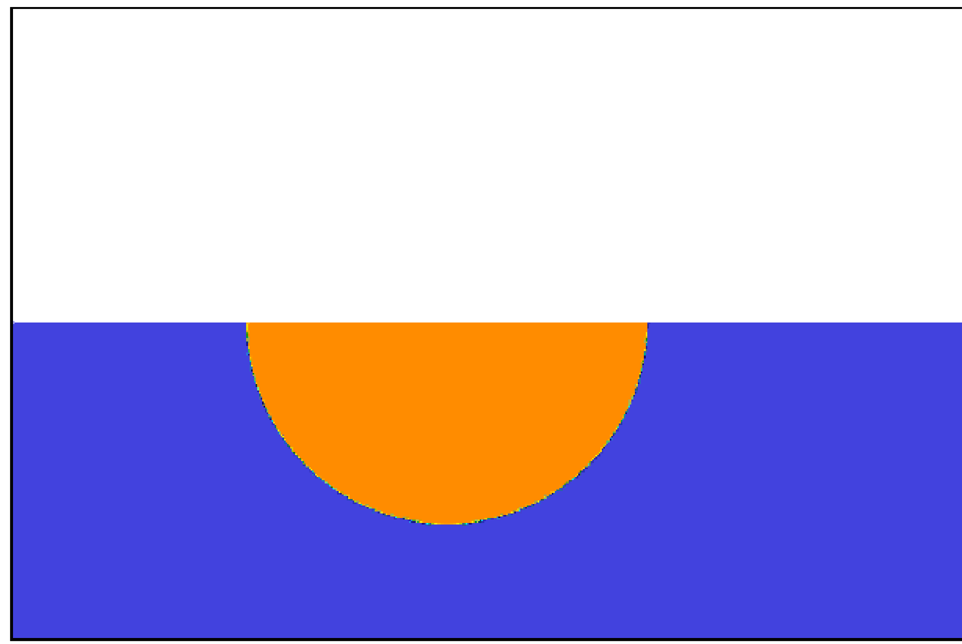
$M = 1.2$

Vorticity magnitude



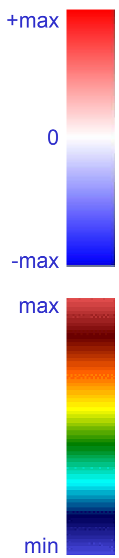
Density





Flow visualization: high Mach number

Vorticity magnitude

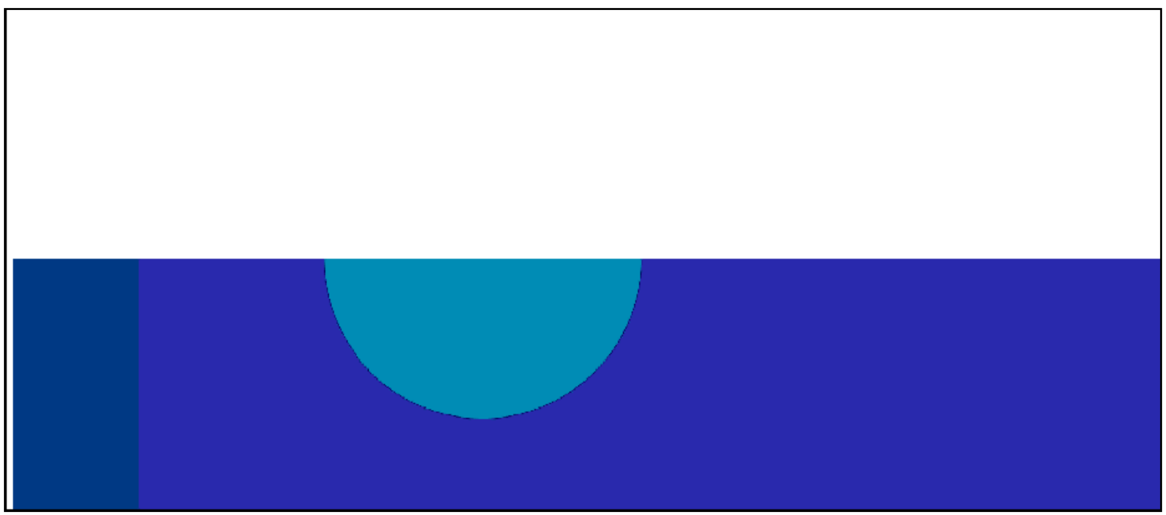


Density

R12 bubble in air

At = 0.613

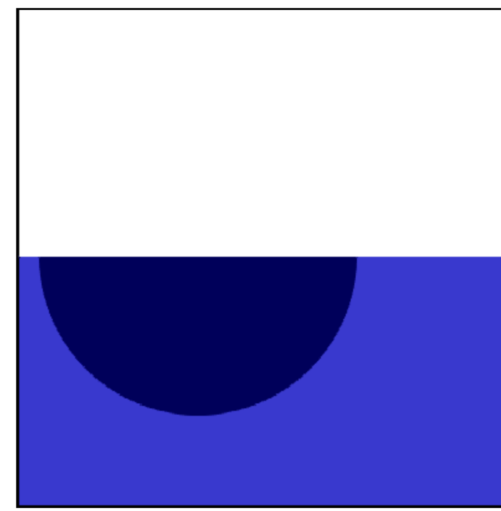
$M = 2.5$



Argon bubble in N_2

At = 0.176

$M = 2.88$

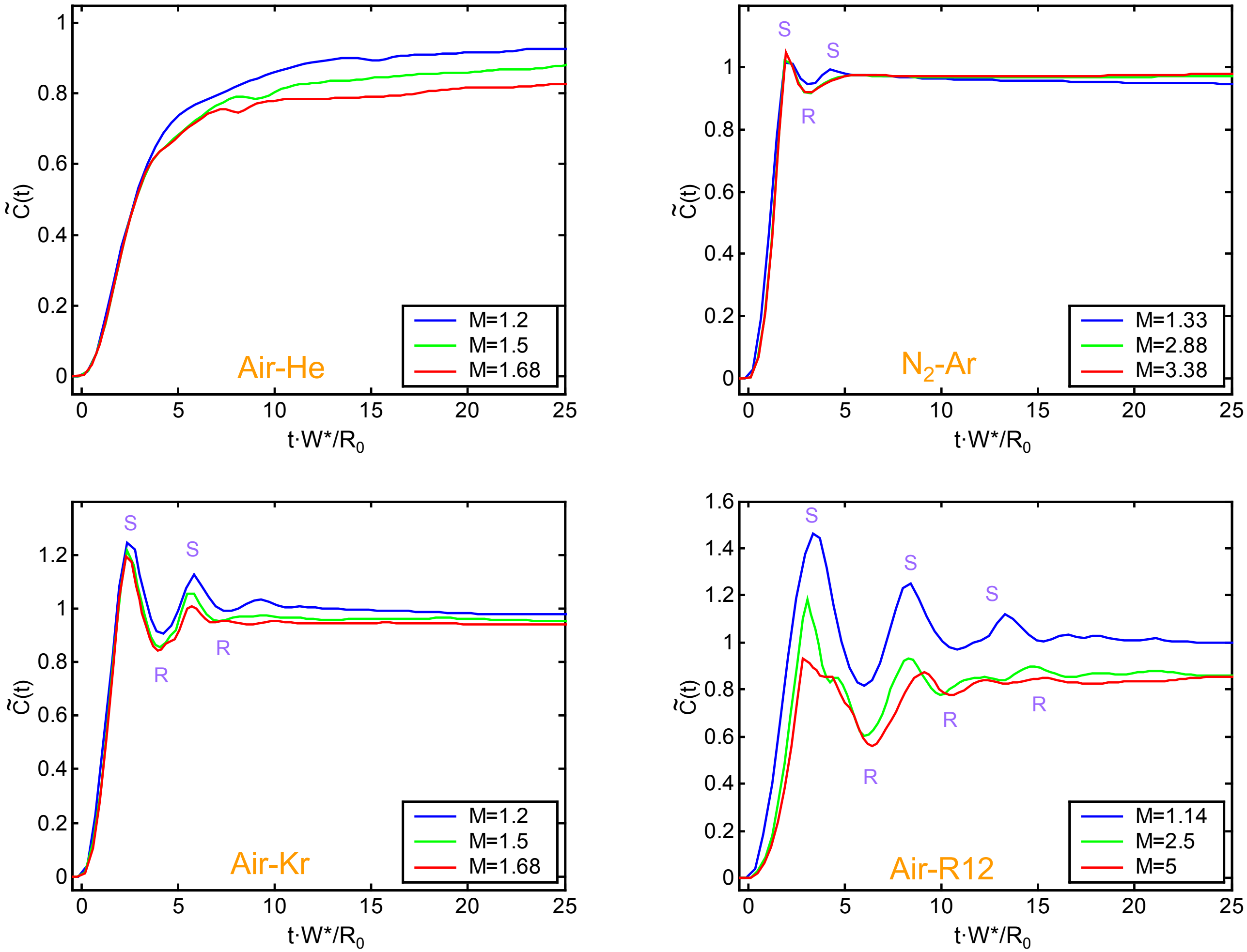


Integral diagnostics: bulk compression

Compression: $$C(t) = \frac{4\pi R_0^{\ 3}}{\iiint_D f_1(x,y,z,t)\,dV}$$ → Ratio of original bubble volume to concentration-weighted total volume at time t.

Normalization: $$C_f^{1\mathrm{D}} = \frac{V_0}{V_f} = \frac{\rho^*}{\rho_1} \qquad \widetilde{C}(t) \equiv \frac{C(t)-1}{C_f^{1\mathrm{D}}-1}$$

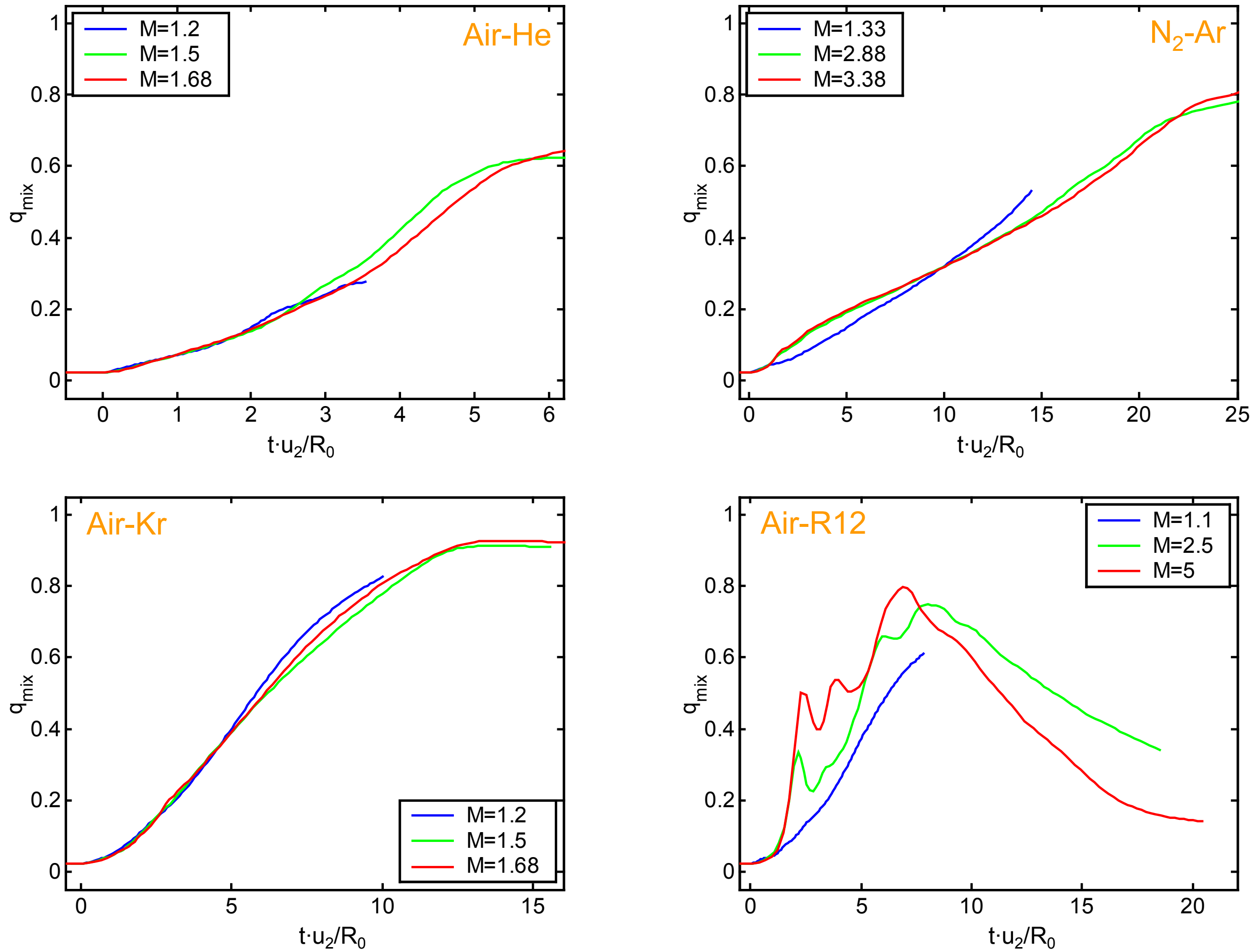
ρ^* computed from 1D gasdynamics (see Giordano and Burtschell, *POF*, 2006)



Integral diagnostics: mixing

Mixing: $q_{mix} = \frac{1}{V(t)} \iiint_D F_{10}^{90}\big(f_1(x,y,z)\big) f_1(x,y,z)\, dV \rightarrow$ Ratio of mixed volume at time t to total volume at time t

A cell is considered “mixed” if $0.1 \le f_1 \le 0.9$



Mixing trend in time collapses on timescale based on post-shock flow velocity u_2

Integral diagnostics: circulation

Circulation: $\Gamma = \oint_P \vec{u} \cdot d\vec{s} = \iint_S \vec{\omega} \cdot d\vec{A}$ $\rightarrow$ Area integrated vorticity at time t.

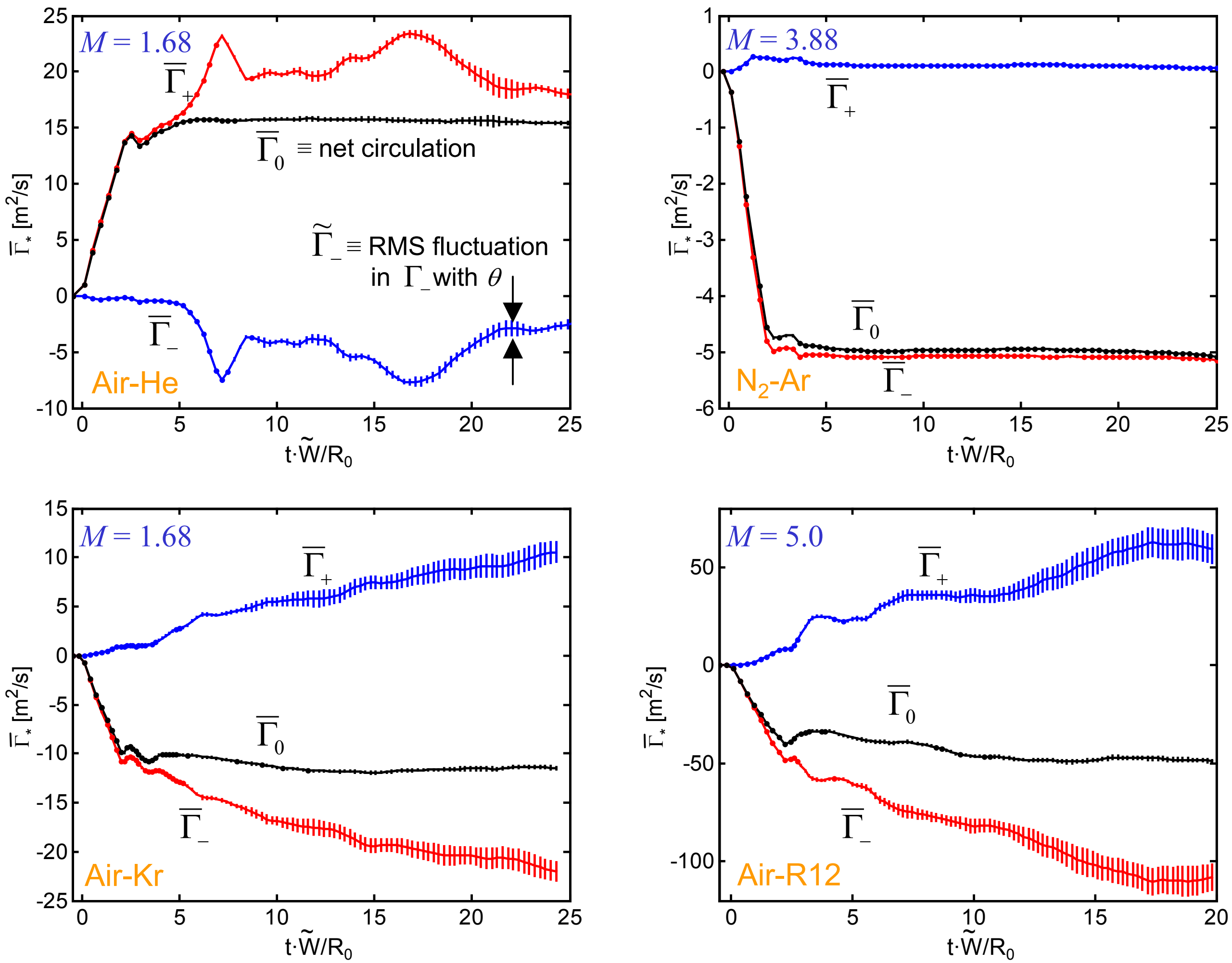
Circulation measured from simulations: positive, negative, and net, averaged over 48 θ–slices ($\overline{\Gamma}$), with RMS fluctuations ($\widetilde{\Gamma}$).

Red: "primary" circulation.

Blue: opposite-signed circulation

$$\tilde{W} = \begin{cases} W_{tr}, & \eta_0 < 1.0 \\ W_0, & 1.0 \le \eta_0 \le 2.0 \\ \dfrac{2W_0}{1+\frac{\pi}{2}}, & \eta_0 > 2.0 \end{cases}$$

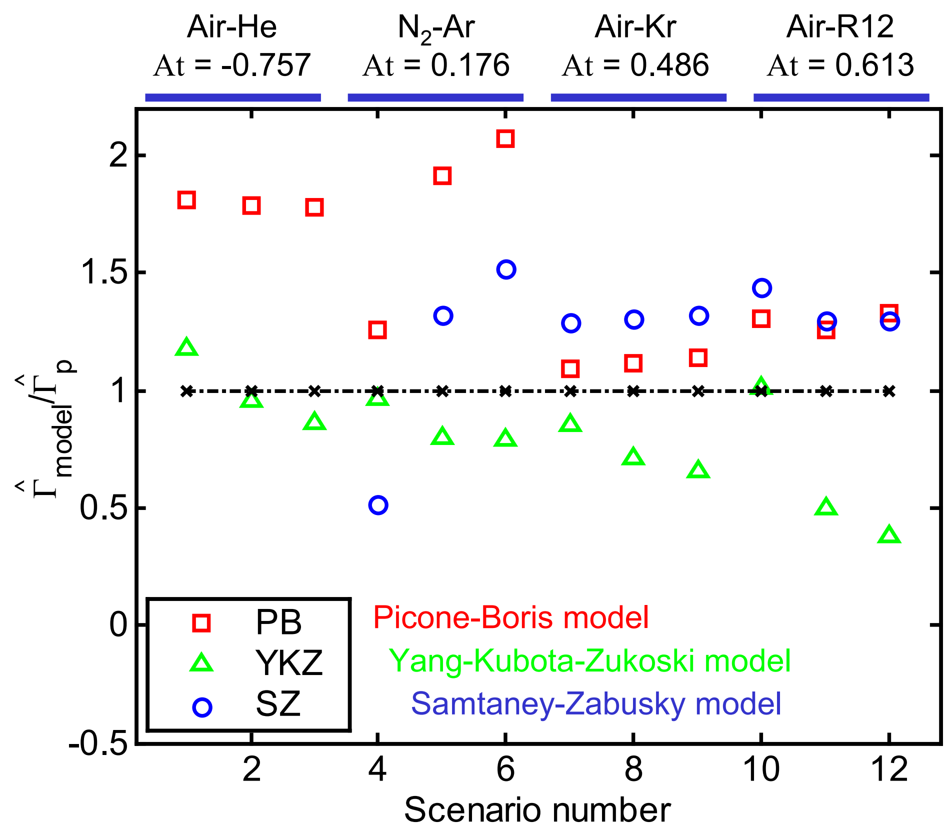
"Shock passage": $t \cdot \widetilde{W}/R_0 = 2$



Comparison to models:

$\hat{\Gamma}_p \equiv$ primary circulation at shock passage

"Shock passage": $\tilde{t} \cdot W/R_0 = 2$



Picone-Boris (PB), Yang-Kubota-Zukoski (YKZ):

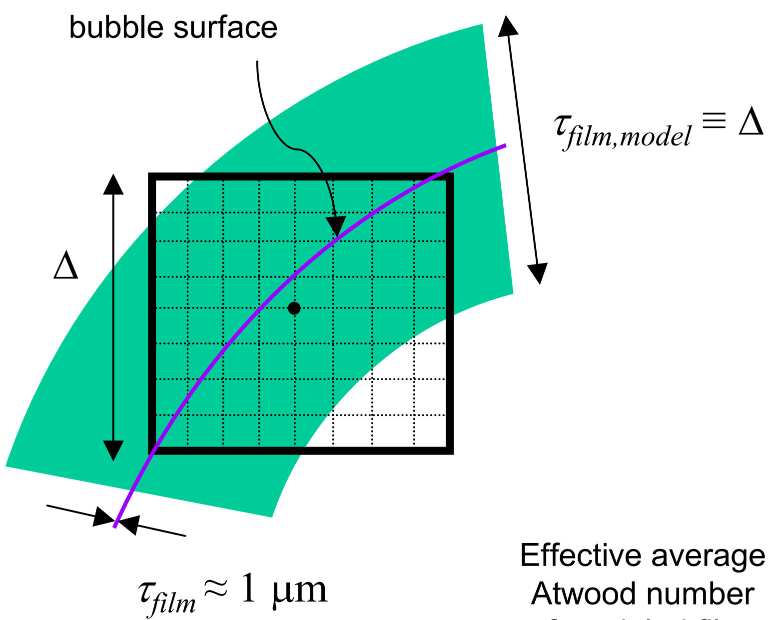
- Based on integrated baroclinic torque
- Bubble shape, density ratio, shock front assumed constant

Samtaney-Zabusky (SZ):

- Asymptotically-motivated approach
- Based on general scaling laws obtained from shock-polar analysis
- "Heavy" bubbles ($\mathrm{At} > 0$) only

Film effects: model for film material in IC

Mass-conserving, subgrid model for film material:



Effective average Atwood number of modeled film, relative to air:

$$\text{At}_f \approx 0.6$$

- Add 3rd fluid to simulation, in spherical concentric cladding region on bubble surface:
  - "Film" molecular mass: 18.016
  - "Film" gamma: 1.327
- Make "film" region as thin as possible:

$$\tau_{film,model} \equiv \Delta$$

- Apply fixed scaled density to all "film" material:

$$\rho_3 = \frac{m_\mu}{V_\Delta} = \rho_{\text{liq}} \frac{V_\mu}{V_\Delta}$$

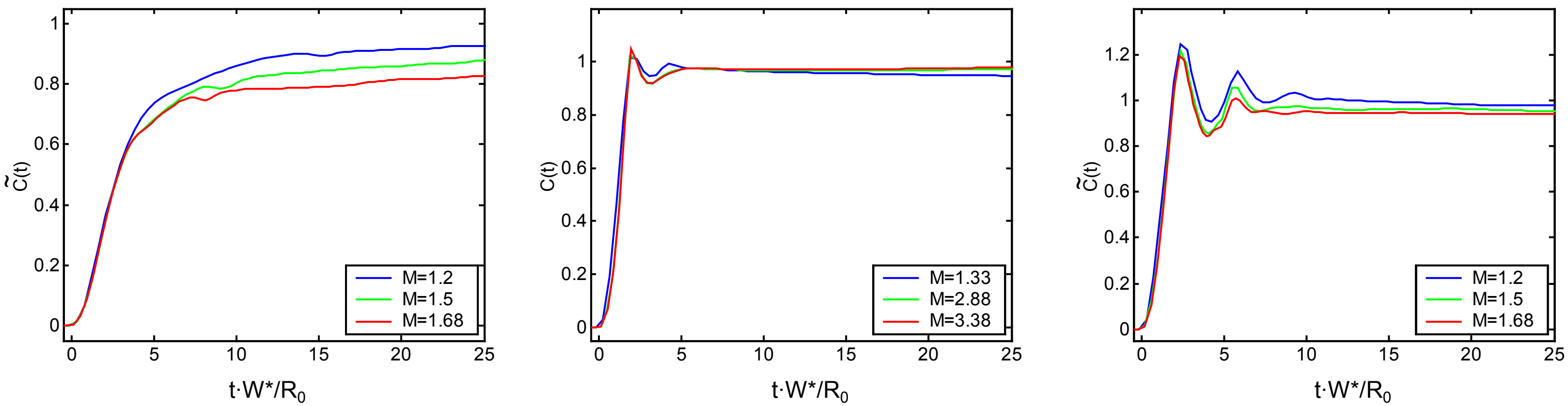
- Subdivide cell for sampling
- Query subcell center locations relative to inner and outer radii of "film" region
- Tally subcells in/out of film region
- Compute "film" VF and total density for the cell

- Provide rough estimate of the effects due to the perturbation in the initial density field.
- Determine under what conditions these effects may be significant or negligible.

Film effects: integral diagnostics

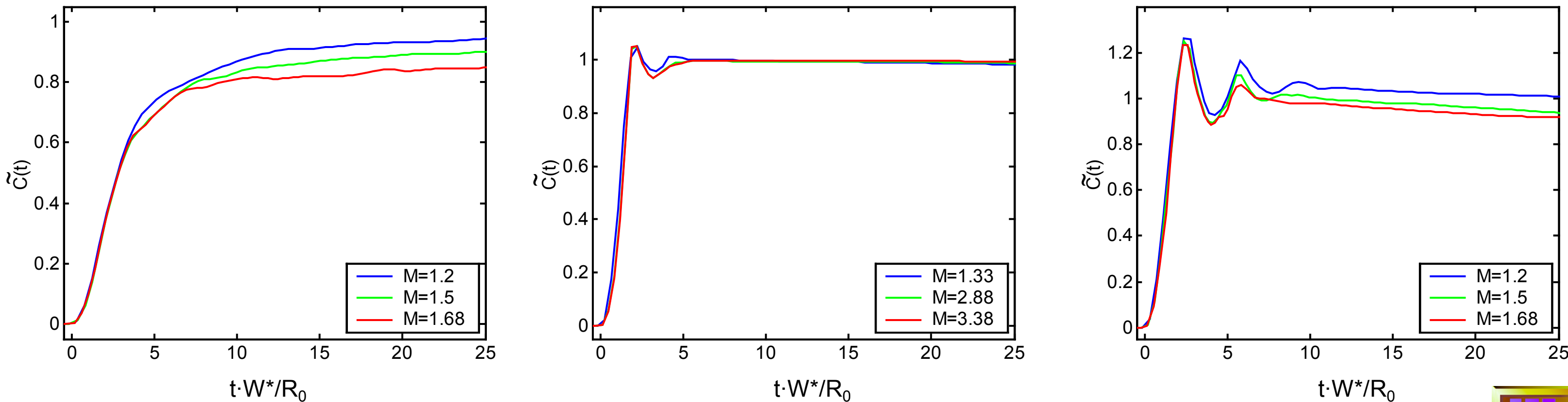
Compression: $C(t) = \dfrac{1}{4\pi R_0^{\,3}} \iiint_D f_1(x,y,z,t)\,dV \;\rightarrow$ Normalization: $C_f^{1D} = \dfrac{V_0}{V_f} = \dfrac{\rho^*}{\rho_1}$ $\quad \widetilde{C}(t) \equiv \dfrac{C(t)-1}{C_f^{1D}-1}$

No film model



Air-He | N_2-Ar | Air-Kr

Film model activated

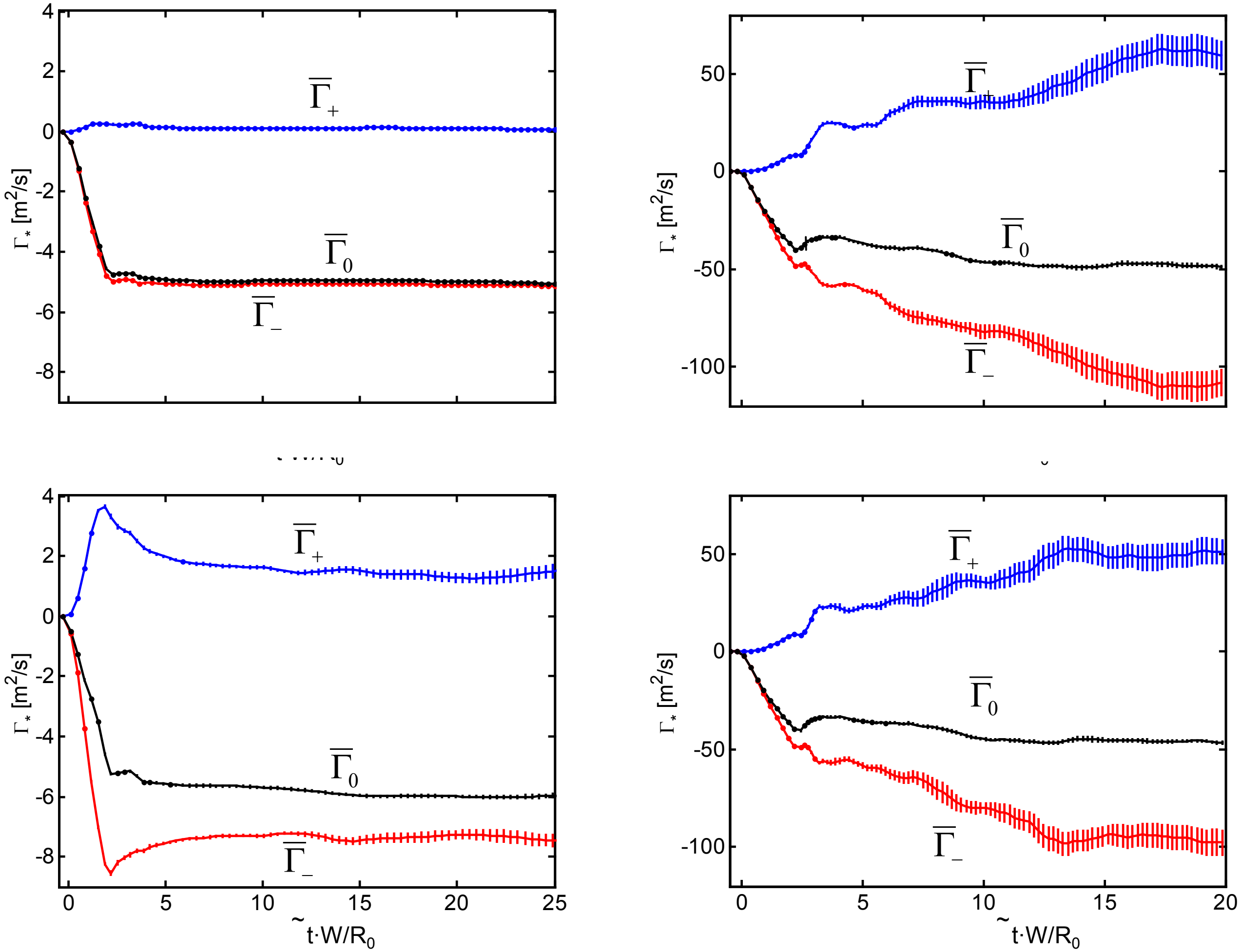


Circulation: $\Gamma = \oint_P \vec{u} \cdot d\vec{s} = \iint_S \vec{\omega} \cdot d\vec{A}$ → Net strength of vortex rings generated in shock-bubble interaction.

N_2-Ar, M = 3.38 Air-R12, M = 5.0

No film model

Film model activated



Red: “primary” circulation.

Blue: opposite-signed circulation

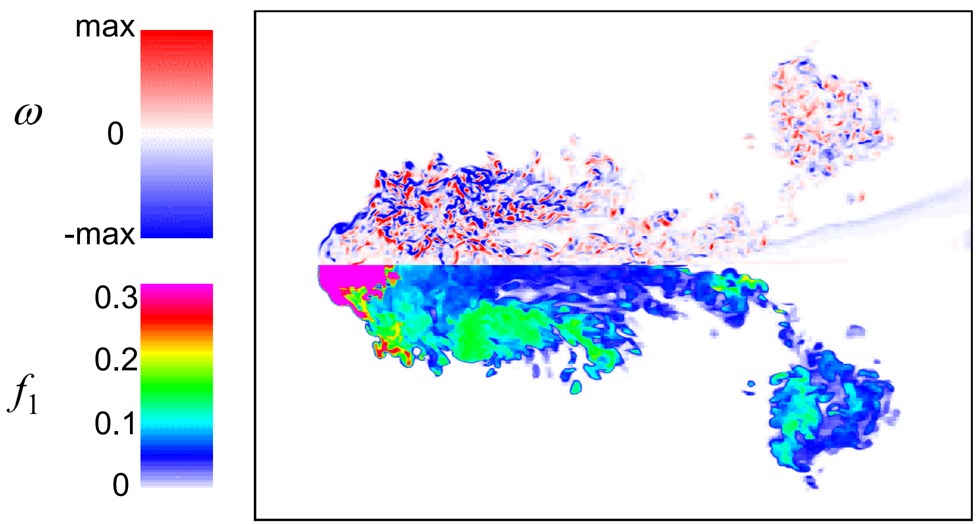
Conclusions and future work

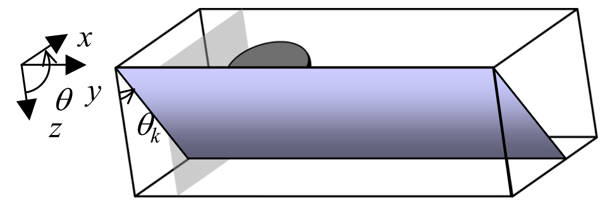
Parameter study results, summarized:

- Successful Mach-number scaling and timescaling for compression.
- Scaling laws and models more elusive for circulation.
- Difficulty of correlating behavior across Atwood numbers.
- Significance of secondary effects.
- Accelerated vortical growth with modeled film material, at low Atwood number only.

Remaining tasks:

- Perform convergence study
- Characterize turbulent features of the shock-bubble interaction
- "Tune" integral diagnostics, to achieve desired and appropriate measurement





R12 bubble in air
At = 0.613
$M = 5.0$
$tW_0/R_0 = 25$