DEVELOPMENT AND VALIDATION OF A 2D TURBULENT MIX MODEL

David L Youngs

AWE, Aldermaston

UK

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Problems of interest

- Compressible flow with interfaces between fluids of widely differing densities.
- High Reynolds No.
- Turbulent mixing at interfaces. Due to RT instability, RM instability. KH instability also important.

Need to model turbulent mixing in flows which are on average 1D or 2D.

Strategy for Numerical Simulation

- 3D Large Eddy Simulation (LES) impractical for real complex applications but can be successfully applied to simplified problems.

- High-resolution 3D LES is applied to simplified problems for which experimental results are available.

- A combination of 3D simulation results and experimental data is then used to set model coefficients used in a turbulence model (RANS model).

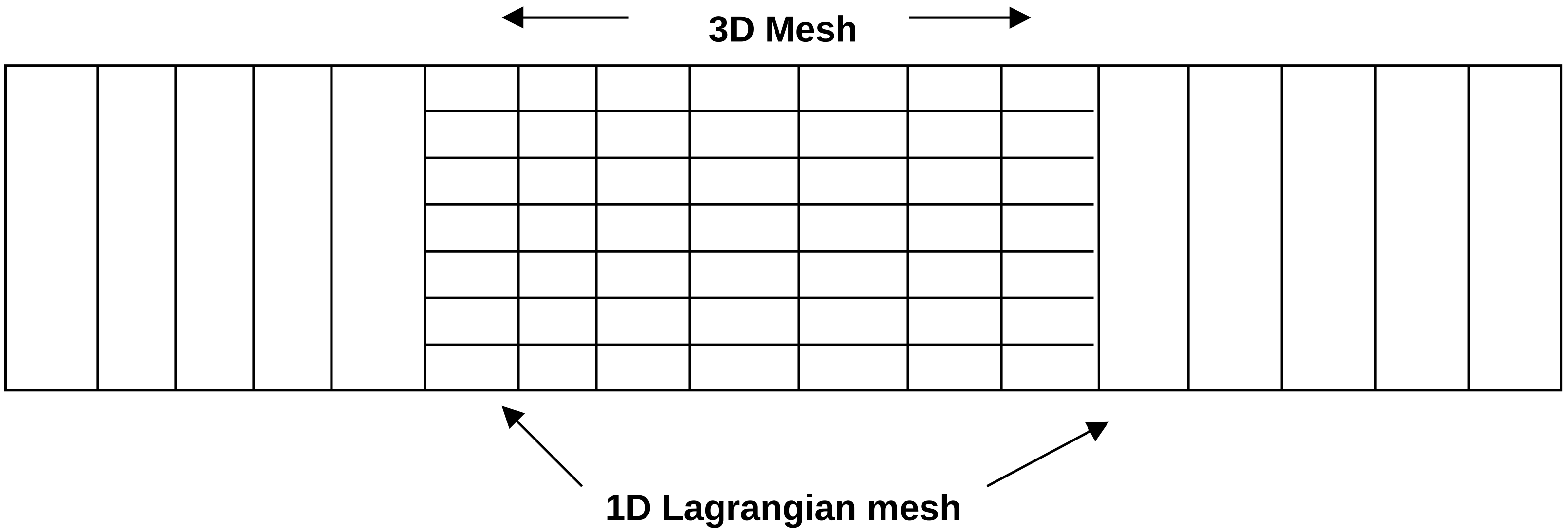
- The turbulence model is used to calculate the average mixing behaviour in 1D and 2D numercial simulations of complex real applications.

TURMOIL 3D

- Simple 3D compressible Eulerian hydrocode used for turbulent mixing studies (LES).

- Same numerical method as the AWE 2D and 3D Eulerian production codes, but without interface tracking.

- Moving mesh option:-



Used for shock tube applications

- Explicit numerical method ideally suited to parallelisation. Low Mach no. calculations used to approximate incompressible flow.

- **Lagrangian phase - non-dissipative except in the presence of shocks. Quadratic artifical viscous pressure used.**

- **Rezone or Advection phase.**
  Monotonic advection method of Van Leer used for all fluid variables.

- **Monotonic advection considered essential for problems considered here with shocks and initial density continuities.**
  $\Rightarrow$ **non-linear dissipation at high wave numbers.**

- **Example of MILES (Monotone Integrated Large Eddy Simulation).**

- **No need for an additional sub-grid dissipation model.**

THE 2D TURBULENCE MODEL (RANS MODEL)

Implemented in a 2D Eulerian hydrocode (which also has the moving mesh option)

Novel form of turbulence model - based on modelling the dynamics of the large scale structures (bubbles of light-fluid, drops of heavy fluid) rather than 1st or 2nd order closure assumptions for the fluctuating quantities)

Combines three basic ideas

1. **Mixing induced by a pressure gradient or shock on fluids of different density.**
2. **Turbulent diffusion in the presence of concentration gradients.**
3. **Exchange of mass between the initial fluids is used to model the decay of concentration fluctuations [2].**

Uses multiphase flow equations with turbulent diffusion terms added [1].

Bouyancy - drag model used to calculate initial behaviour - approximate representation of the initial conditions[3].

References: 1. D.L.Youngs, Laser and Particle Beams, vol 12, p725 (1994)
2. D.L. Youngs, Proceedings of 5th IWPCTM, Stony Brook(1995)
3. J.C.V. Hansom et al., Laser and Particle Beams, vol 8, p51(1990)

The simple incompressible RT problem $(\rho_1,\ \rho_2,\ g\ \text{constant})$ is the key problem for fixing the turbulence model coefficients.

Loss of memory of initial conditions tends to occur $\rightarrow$ self-similar mixing with length scale gt^2:

Bubble penetration $h_1 = \alpha \dfrac{\rho_1 - \rho_2}{\rho_1 + \rho_2}\, gt^2$

α ~ 0.05 to 0.06

(AWRE Foulness, LLNL (LEM), Chelyabinsk 70)

TURMOIL3D calculations with short-wavelength initial perturbations (growth purely by mode coupling) give α ~ 0.03, less than observed.

Need to add long wavelength initial perturbations:-

$$\sigma^2 = \int_0^\infty P(k)\, dk$$

where $\left\{ \int_{2\pi/\lambda}^{\infty} P(k)\, dk \right\}^{\frac{1}{2}} = \varepsilon \lambda$

ε = 0.0005 gives self-similar growth with α ~ 0.05. It is assumed that this corresponds to a typical experimental situation.

Model coefficients are chosen to fit the key quantities for RT mixing

α : **growth rate coefficient**

$\frac{D}{P}$: $\frac{\text{turbulence KE dissipated}}{\text{Loss of potential energy}}$

θ : **molecular mixing fraction**

$$\frac{\int \overline{f_1 f_2}\, dz}{\int \bar{f}_1 . \bar{f}_2\, dz}$$

Values used are based on TURMOIL3D calculations (800 x 400 x 400 zones, ε = 0.0005): -

α	=	0.05
D/P	=	0.4 (no experimental data)
θ	=	0.7 (some experimental confirmation)

Still leaves one key degree of freedom

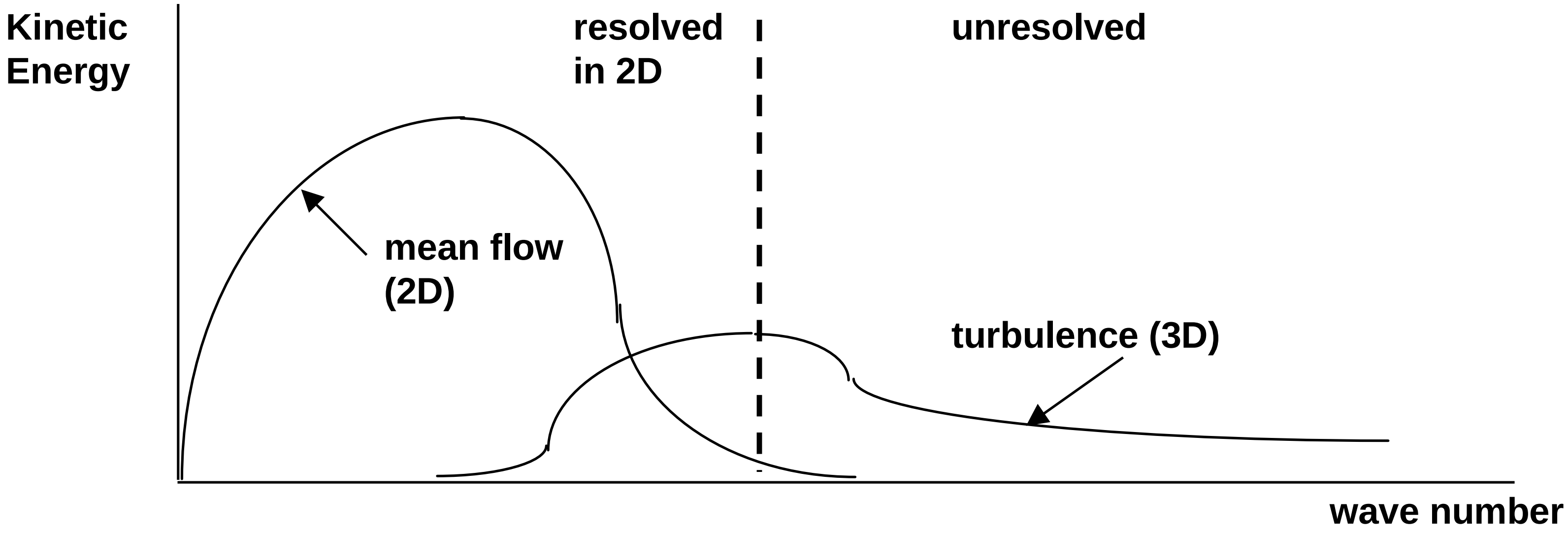
$$\Delta = \frac{\Delta u_D}{\Delta u_D + \Delta u_P}$$

$\Delta u_D =$ **mixing velocity due to turbulent diffusion**

$\Delta u_P =$ **mixing velocity induced by pressure gradient**

Results shown here for $\Delta = 0.4$

TYPICAL 2D TURBULENCE MODEL APPLICATION



Mean flow (2D) : calculated
Turbulence (3D) : modelled

Points of concern

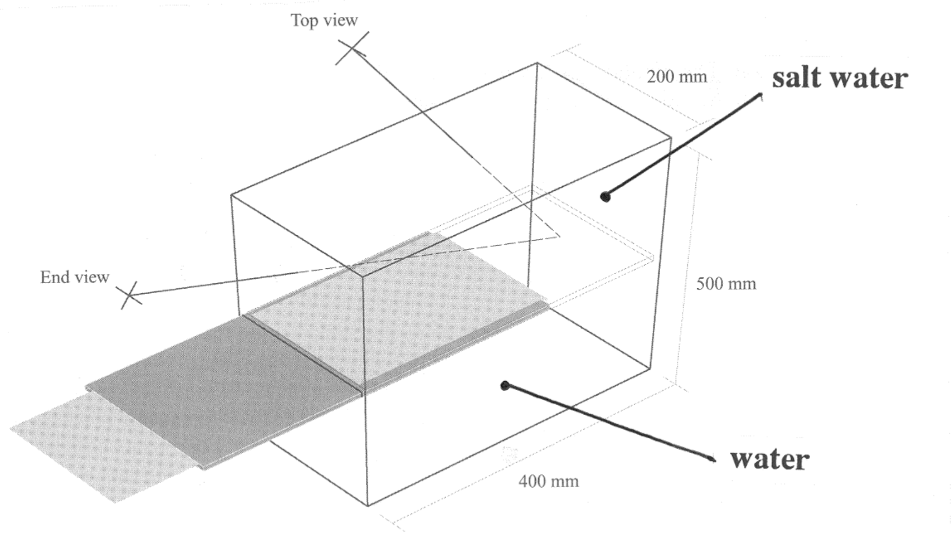
(a) Likely to be some overlap between the mean flow scales and the turbulence scales - is double counting an issue?

(b) Some of the turbulence scales are resolved (but only in 2D). Does this matter?

(c) Does the turbulence model give the correct spatial distribution in a complex 2D situation.

RAYLEIGH-TAYLOR EXPERIMENT (CAMBRIDGE UNIVERSITY)

Dalziel, Linden, Youngs, JFM 1999

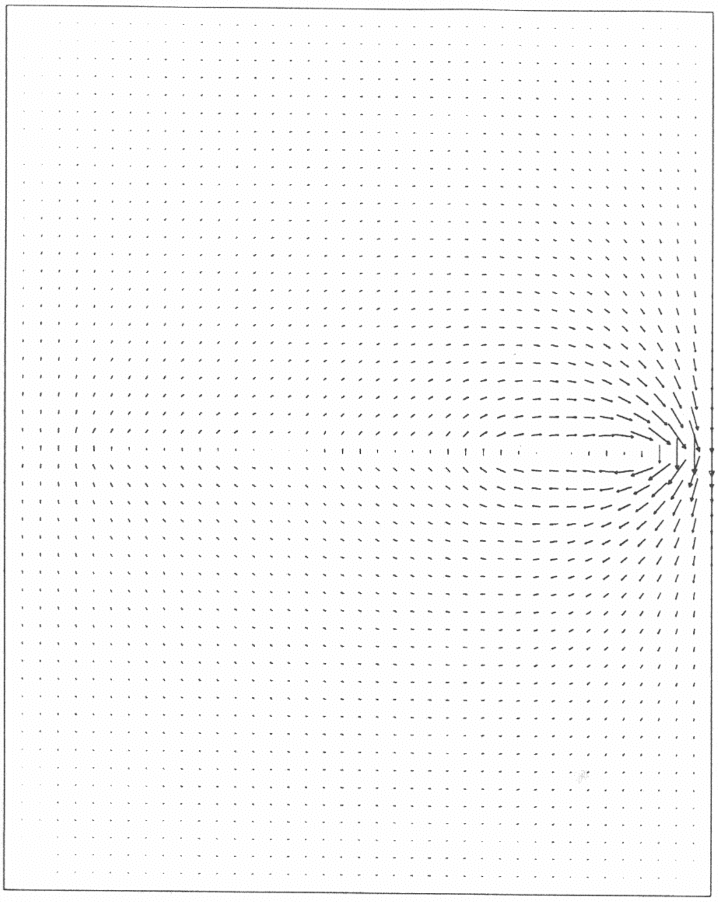


3D calculation : 400 x 320 x 160 zones

- **Random perturbation ($\varepsilon = 0.0005$)**
- **2D initial velocity field used to represent effect of barrier removal $\Rightarrow$ 2D on average**

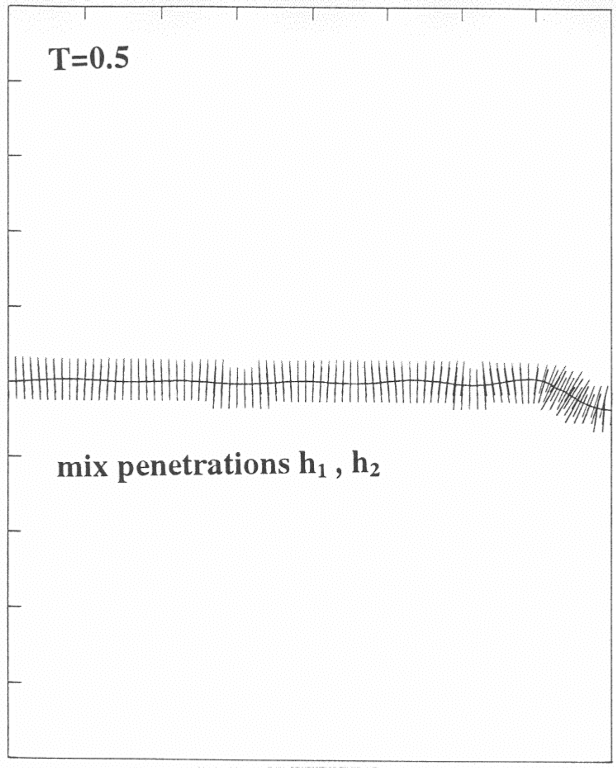
2D turbulence model calculation

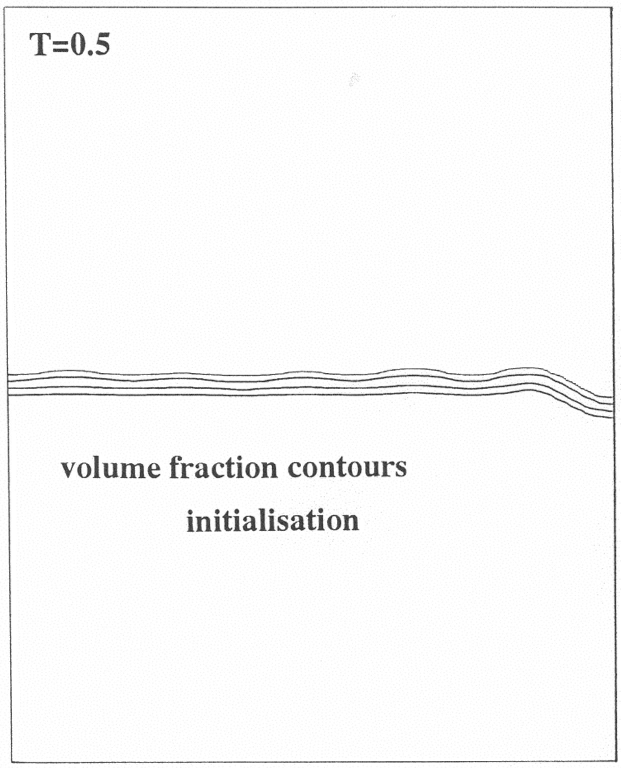
- **100 x 80 zones**
- **barrier perturbation included**



Model for barrier perturbation

Initial velocity field (2D)

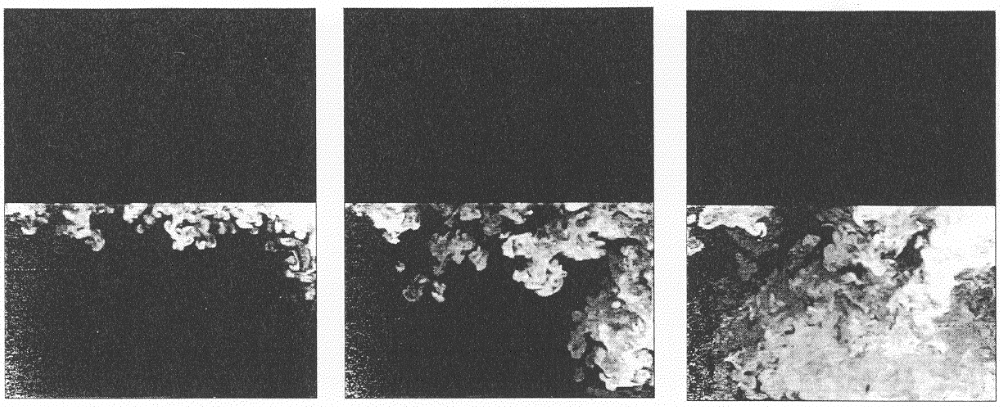




2D turbulence model calculation – run to t=0.5 with interface tracking and initial conditions model.

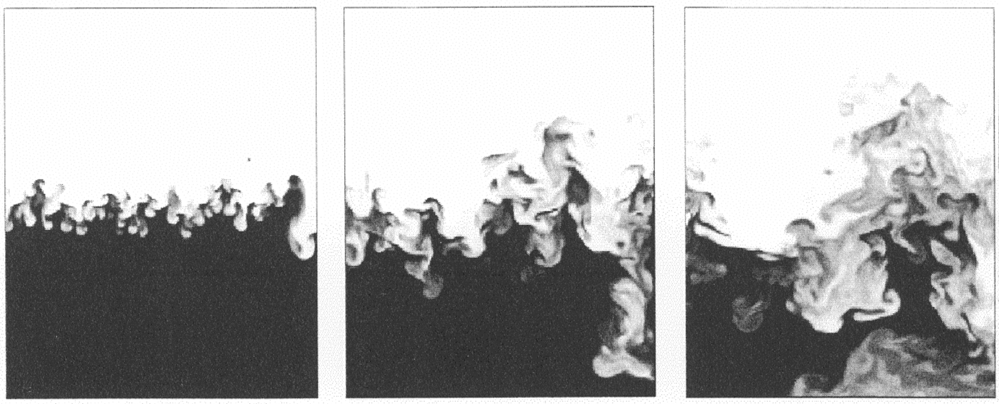
S. B. Dalziel, P. F. Linden and D. L. Youngs JFM 1999

(a) (b) (c)

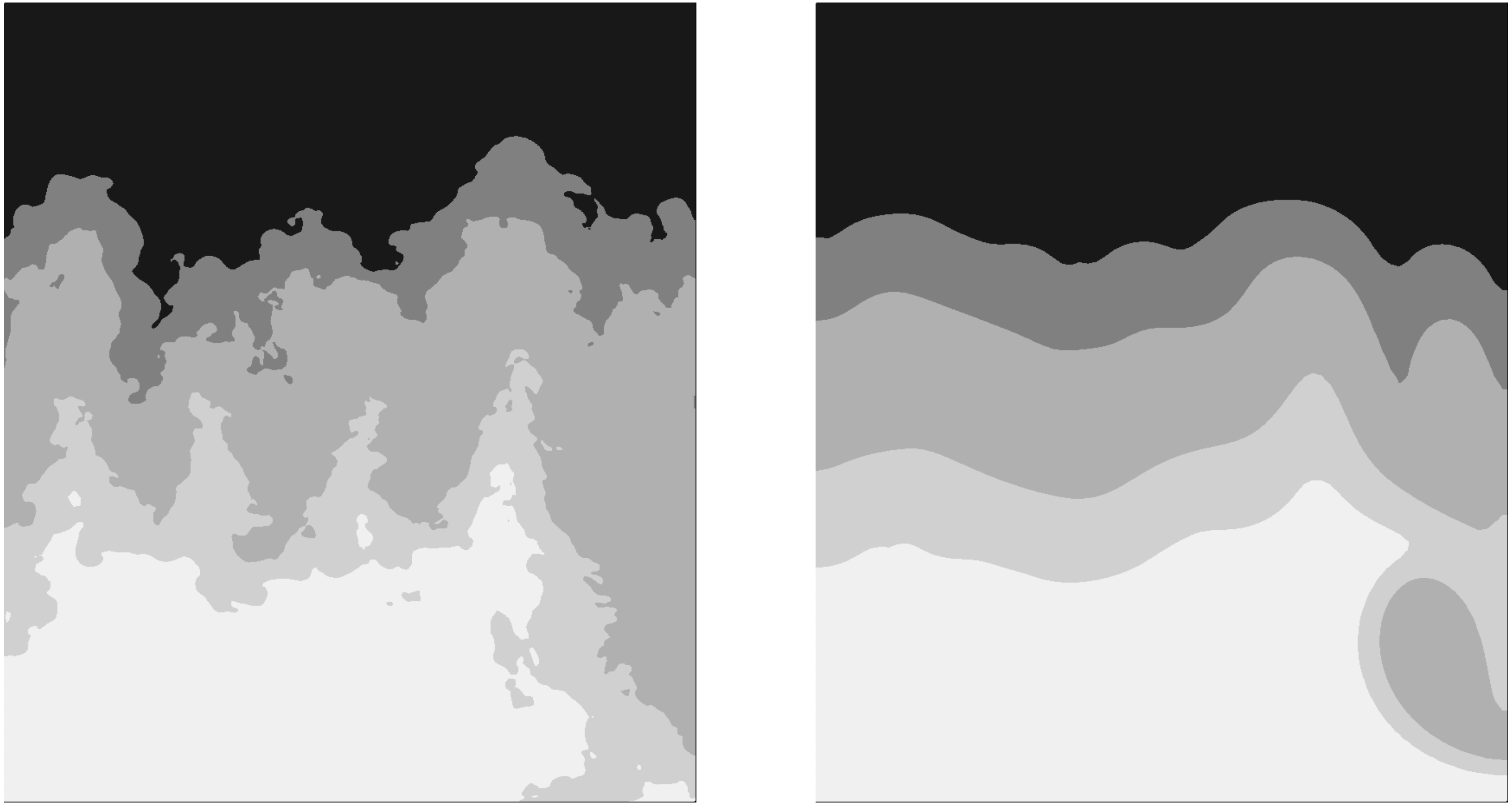


Experiment (lower half of tank)

3D Numerical Simulation (200x160x80 zones)

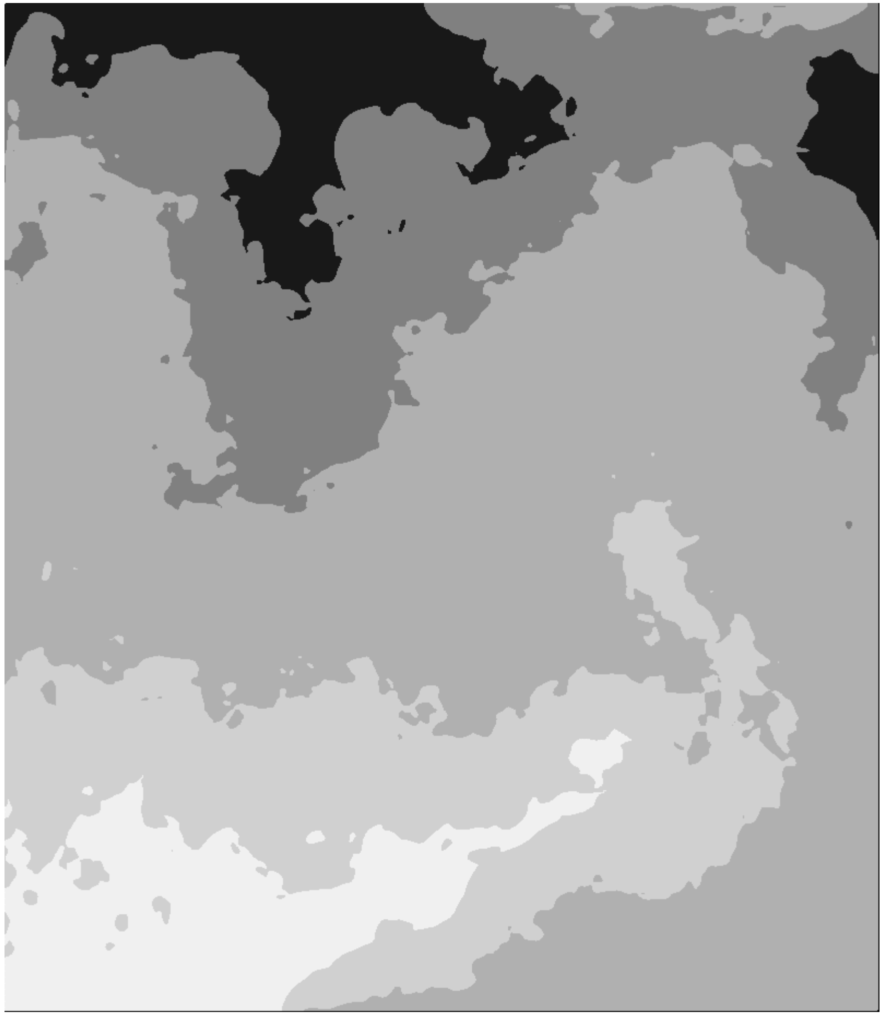


T=1.0 T=2.0 T=3.0



3D simulation at t = 2.0 2D turbulence model at t = 2.0

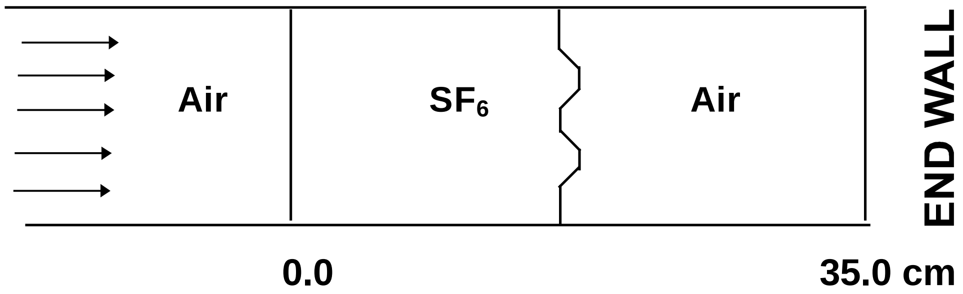
Mean volume fraction contours: 0.05, 0.25, 0.75, 0.95



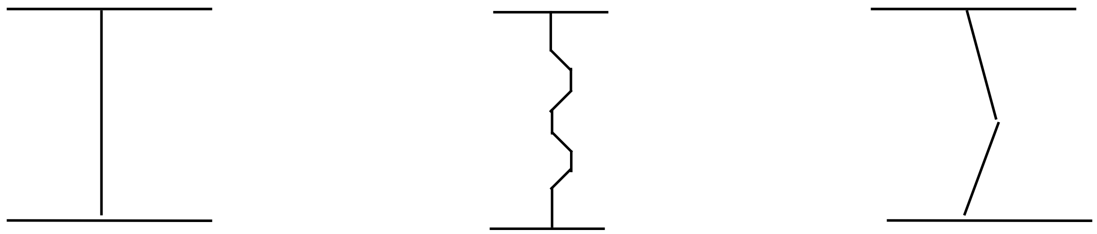
3D simulation at t = 3.0

2D simulation at t = 3.0

SHOCK TUBE EXPERIMENT (AWE)



Cross-section 20 x 10 cm



(a) flat (b) double bump (c) chevron

Moving mesh option used (semi-Lagrangian calculations)

3D LES:

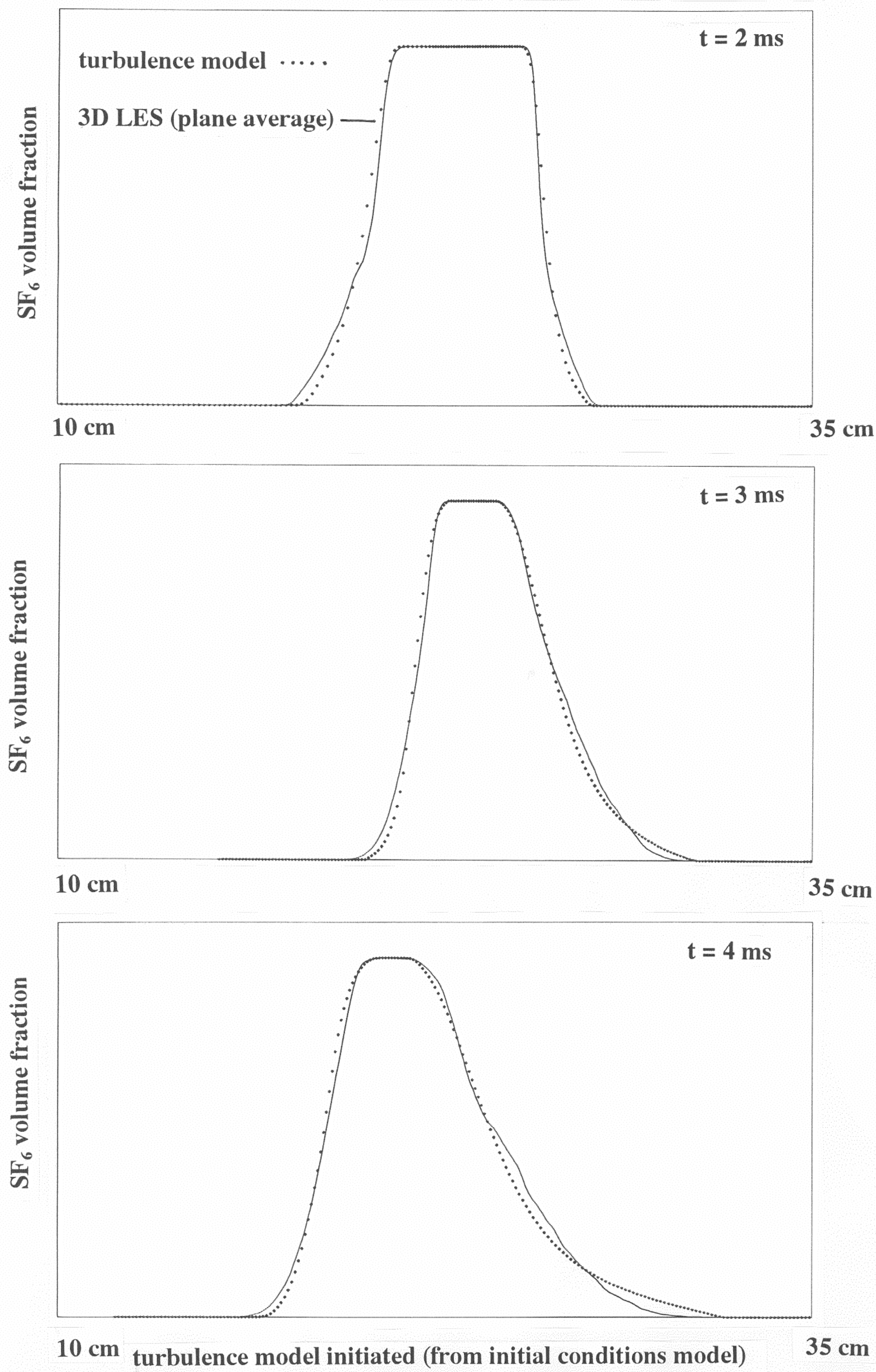
400 x 320 x 160 zones
random interface perturbations (models effect of membrane rupture)

wavelengths 0.5 to 5 cm
s.d 0.01 cm

2D turbulence model calculation

200 x 160 zones
initial conditions model
a_o = 0.02 cm, λ_0 = 0.5 cm

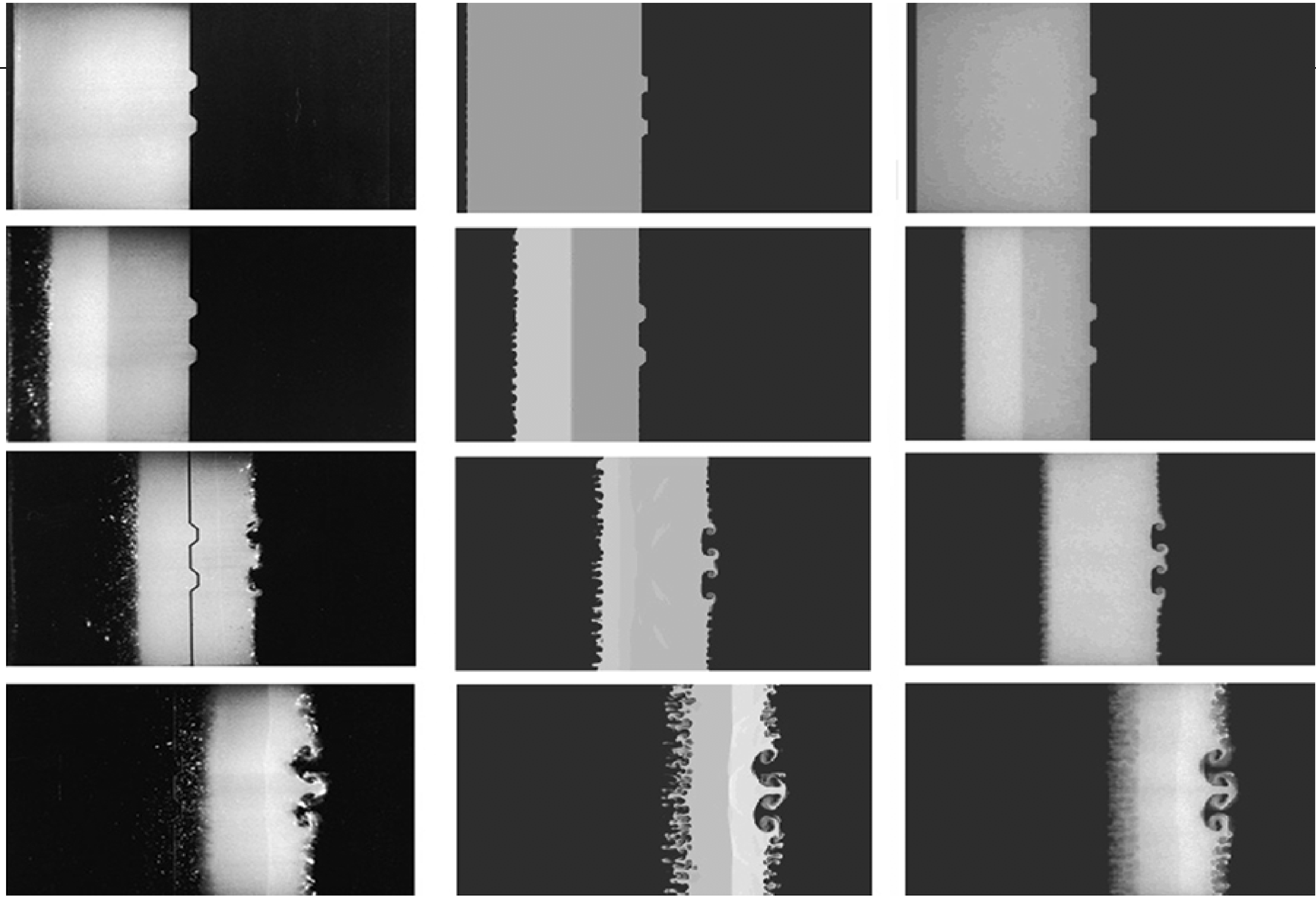
Shock tube experiment : flat interface



turbulence model initiated (from initial conditions model)
at t = 0.2 ms (first interface), t=1.1 ms (second interface)
initial molecular mixing fraction = 0.5

AWE Shock Tube Experiment

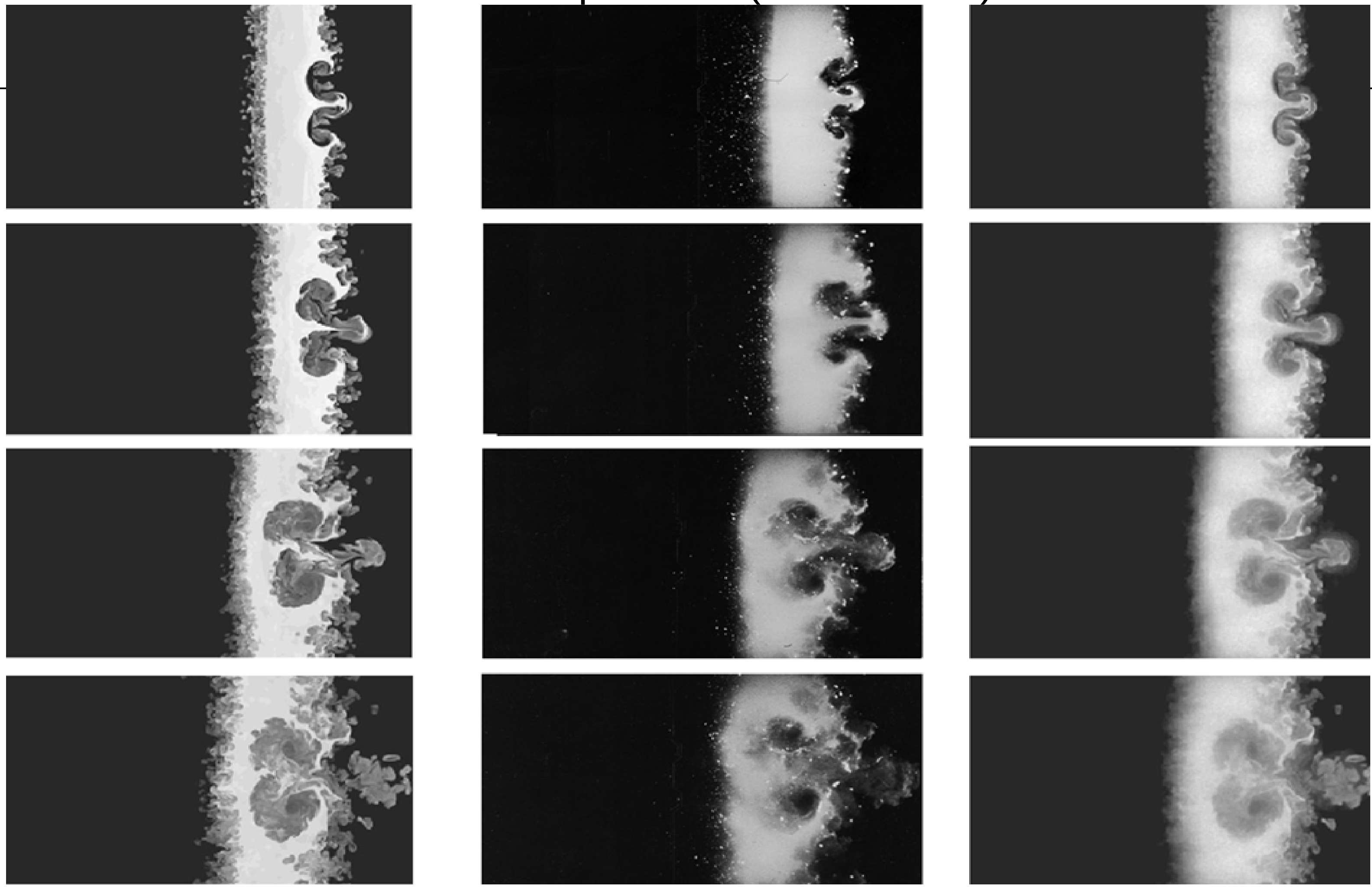
Double Bump results (0.0 - 1.9 ms)



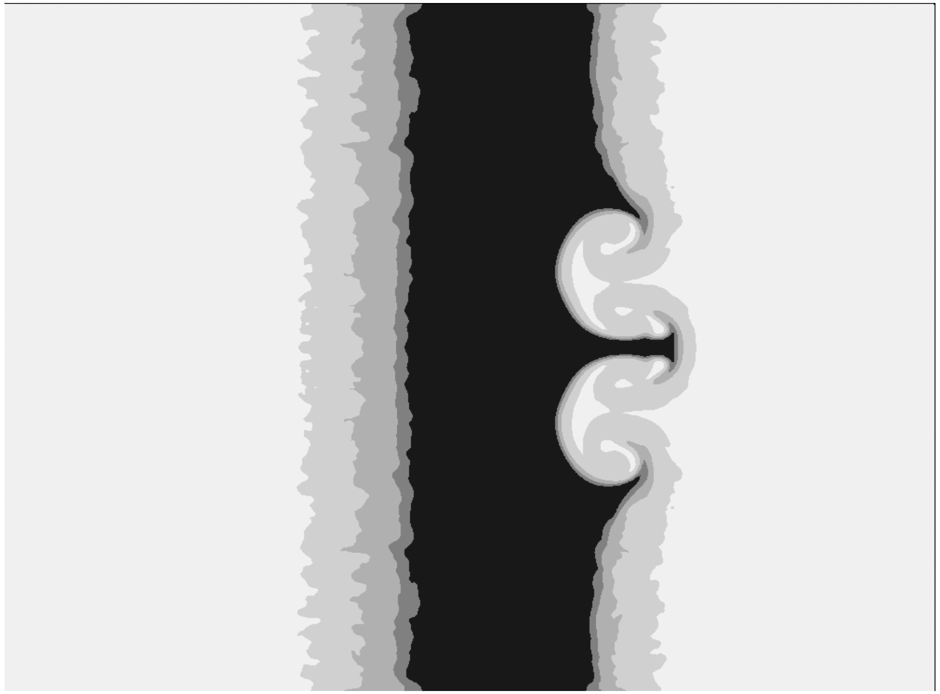
Experiment | 3D simulation | 3D simulation (scattered image)

AWE Shock Tube Experiment

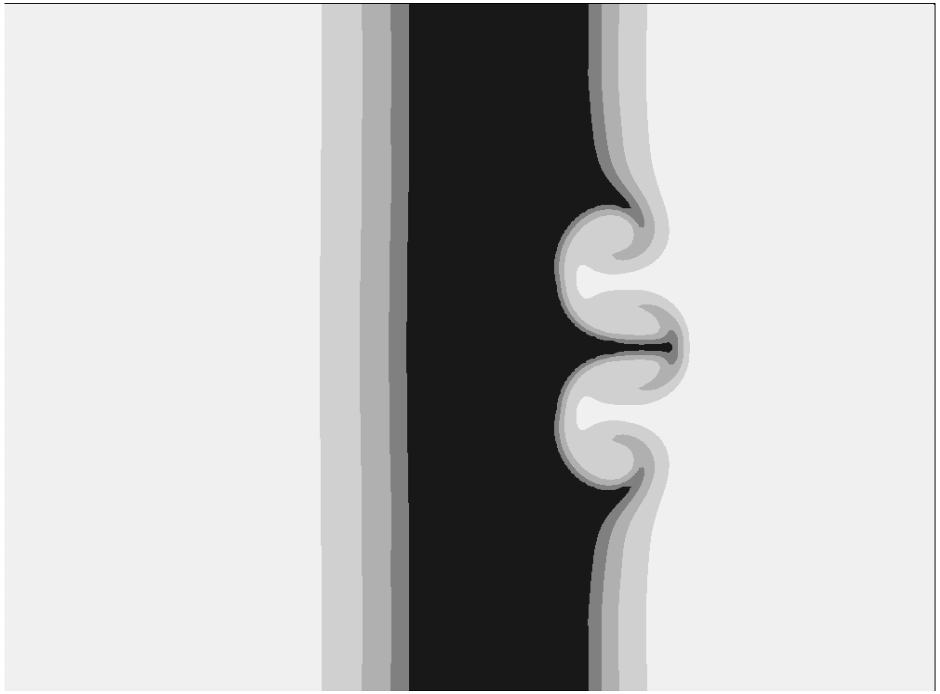
Double Bump results (2.2 - 3.9 ms)



3D simulation | Experiment | 3D simulation(scattered image)



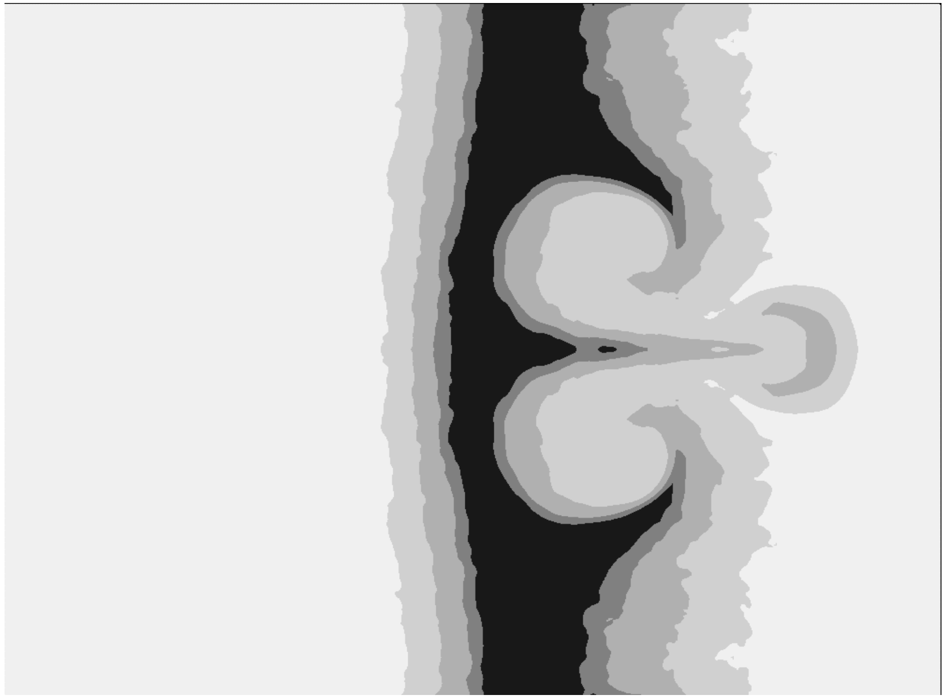
3D simulation at t = 2.0ms

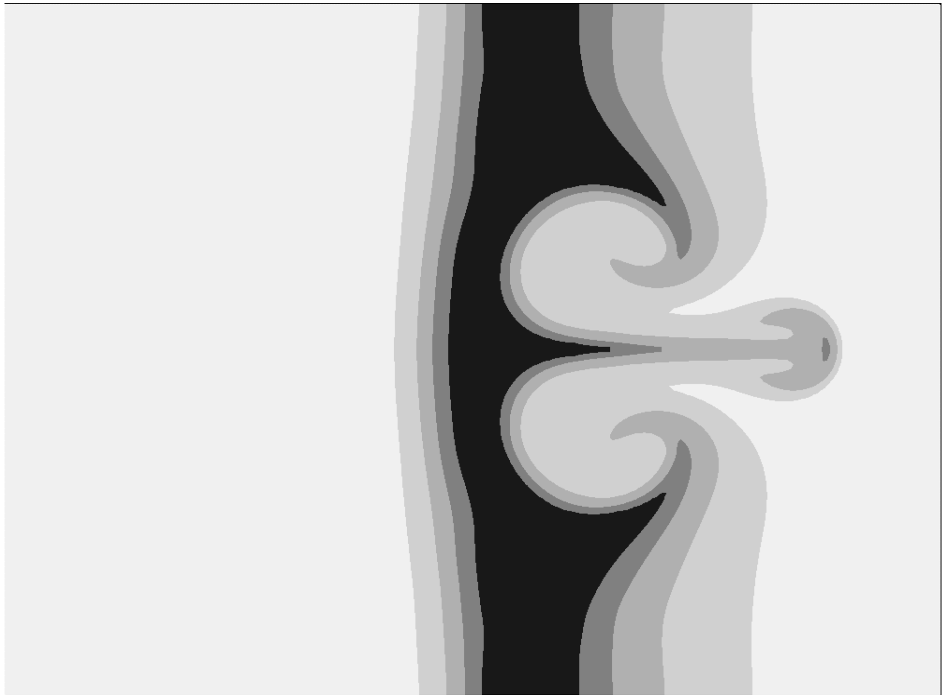


2D turbulence model at t = 2.0ms

Double bump experiment

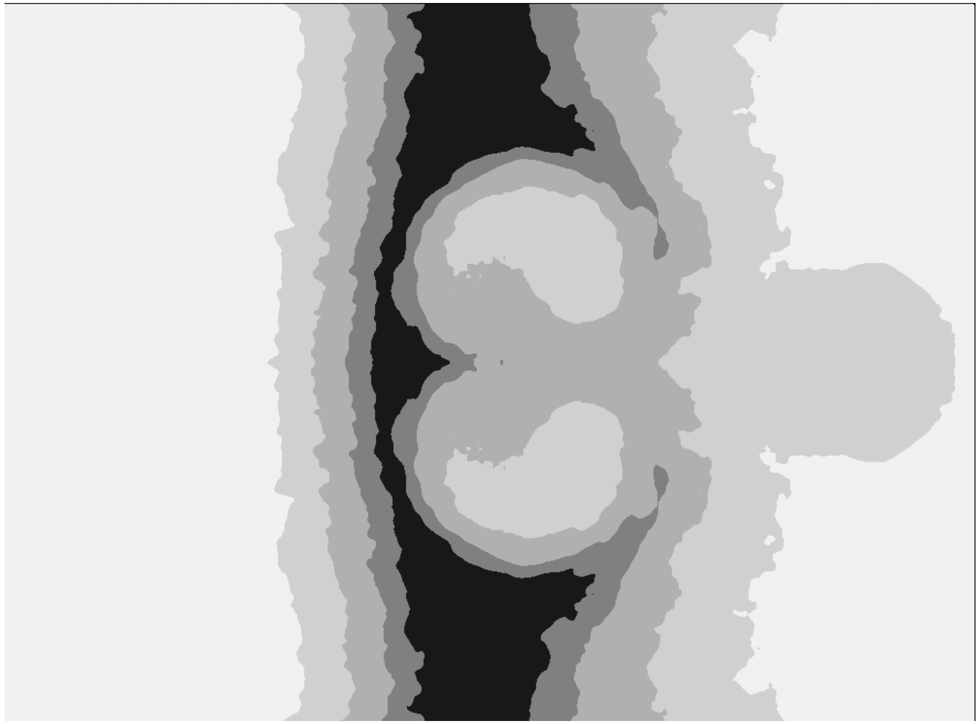
mean volume fraction contours: 0.05, 0.3, 0.7, 0.95

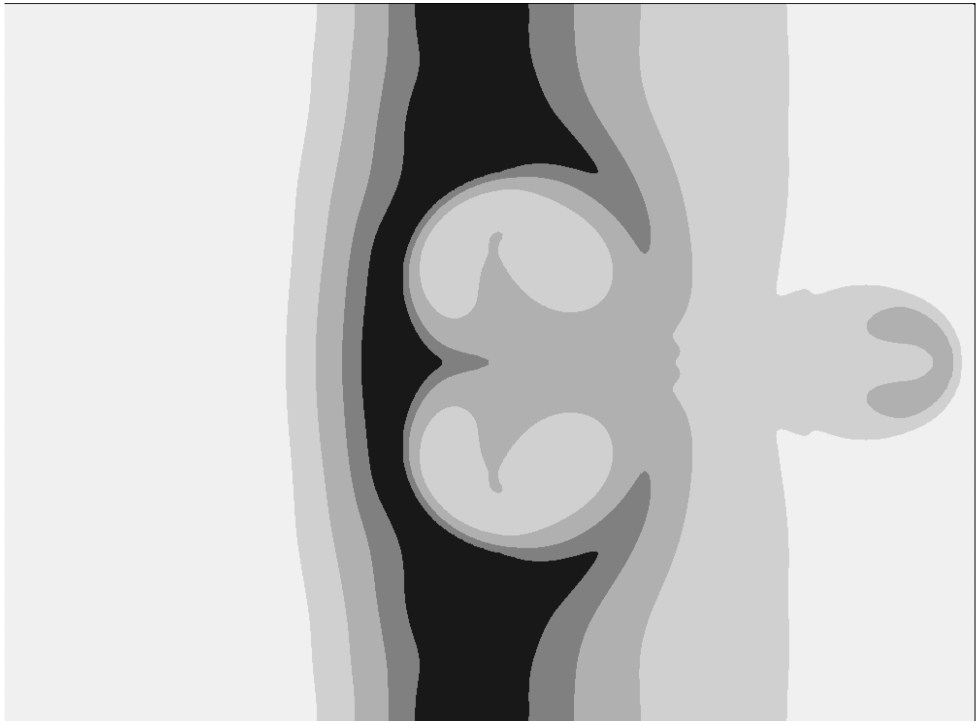




3D simulation at t = 3.0ms

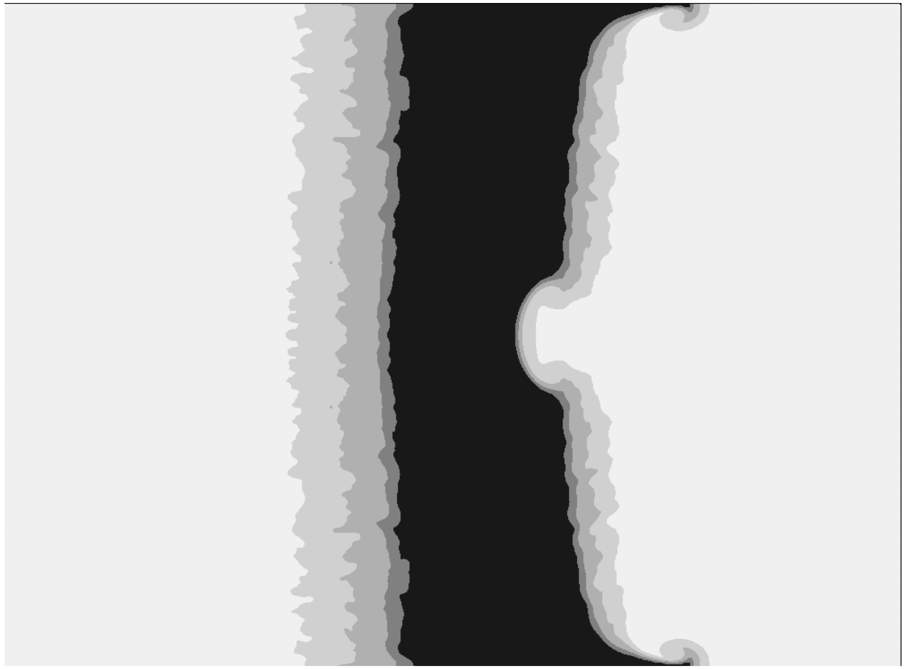
2D turbulence model at t = 3.0ms

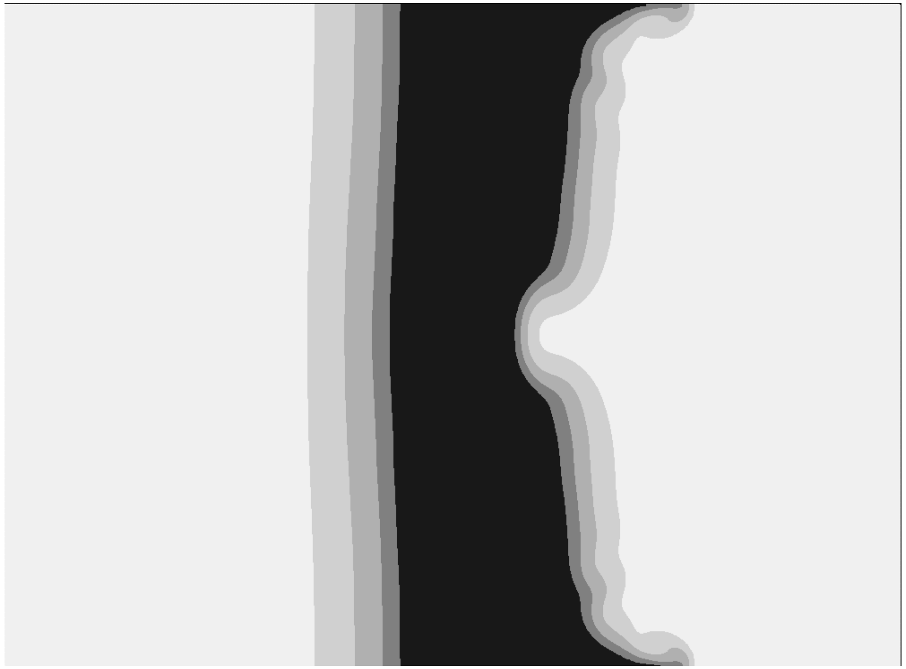




3D simulation at t = 4.0ms

2D turbulence model at t = 4.0ms

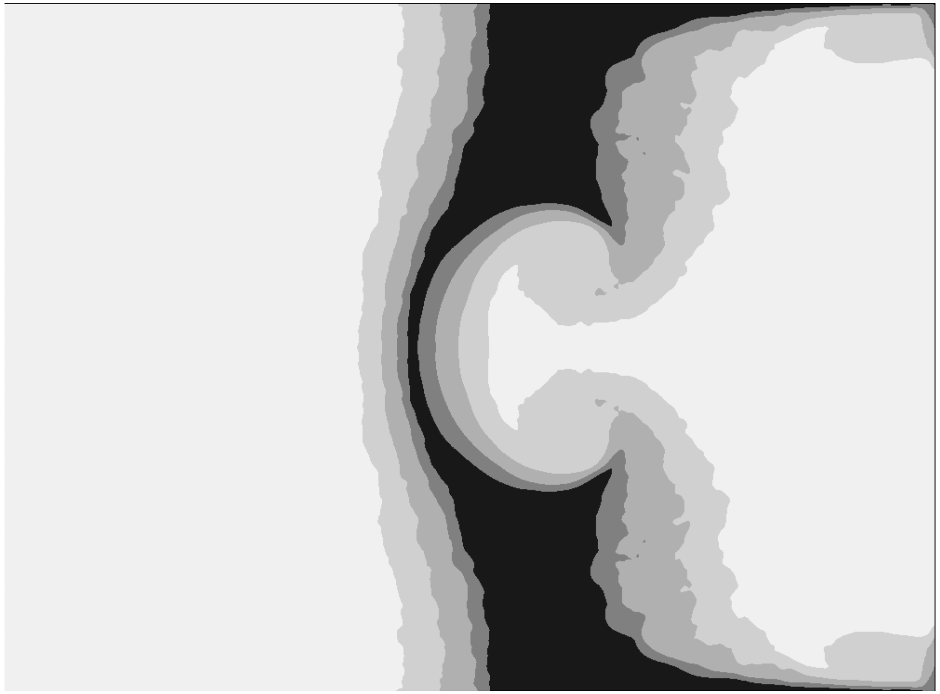


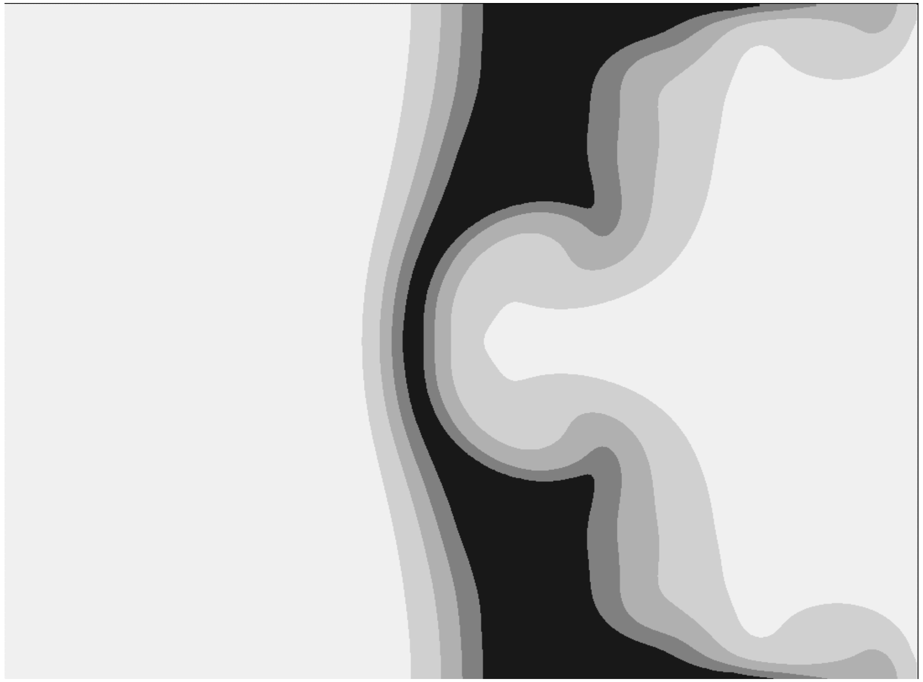


3D simulation at t = 2.0ms   2D turbulence model at t = 2.0ms

mean volume fraction contours: 0.05, 0.3, 0.7, 0.95

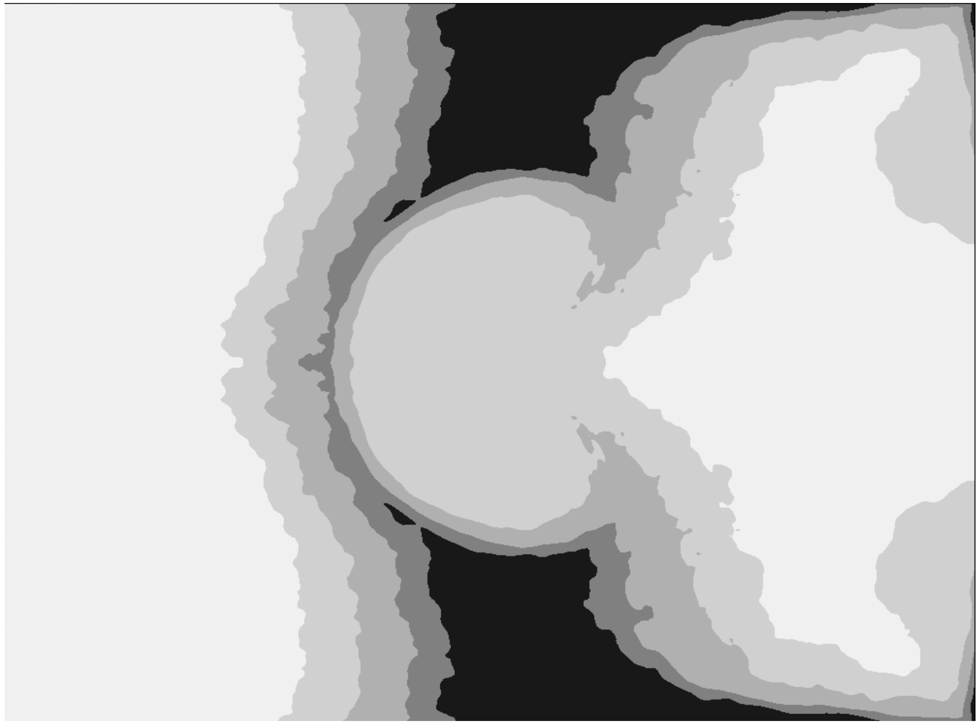
Chevron experiment

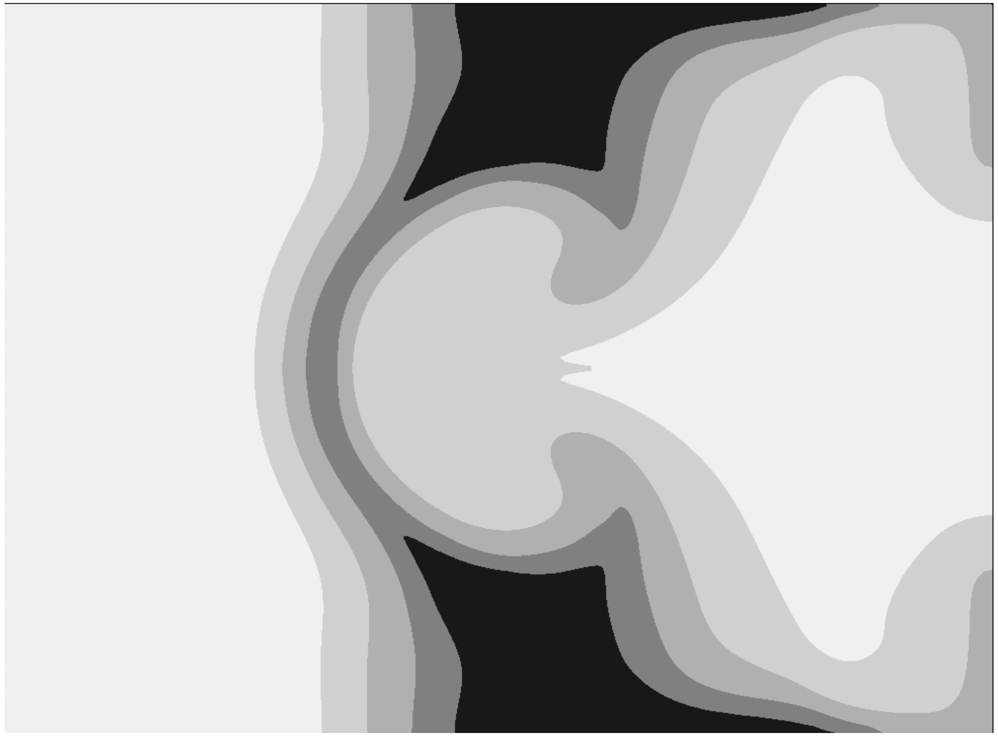




3D simulation at t = 3.0ms

2D turbulence model at t = 3.0ms





3D simulation at t=4.0ms

2D turbulence model at t=4.0ms

FINAL REMARKS

- **The 2D turbulence model based on the equations of multiphase flow, using a single set of model coefficients has given satisfactory results for**

  RT self-similar mixing
  A 2D RT experiment
  The double-bump shock tube experiment
  The chevron shock tube experiment

- **3D LES for simplified problems, in conjunction with experimental data, is making a very valuable contribution to the validation of the turbulence model.**

- **In the near future (after AWE's next supercomputer procurement) a more detailed comparison, (including 2D distributions of k and θ) will be made between the 2D turbulence model results and higher resolution LES.**