Ondes de Choc dans les Mousses (Blast Waves in Aqueous Foams)

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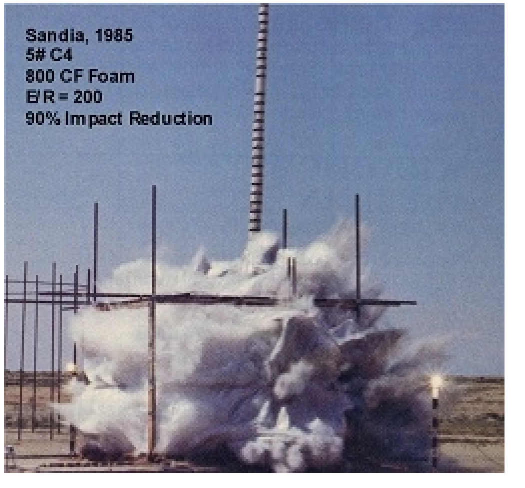
Centre de Mathématiques et de Leurs Applications

Introduction

- Blast waves in aqueous foams
  - Strong suppression of blast wave
  - Containment of materials
- Simulation
  - Detonation model
  - Modelling of flow in foam
  - Interface
- 7 equation multi-phase approach
  - Simpler droplet model
- EOS : Quicksteam
  - Also, Quickmethane
- Currently writing 2 journal articles (Quicksteam & VF III)



Images from www.aquafoam.com/BlastingExplosions.html

Motivation : Quicksteam

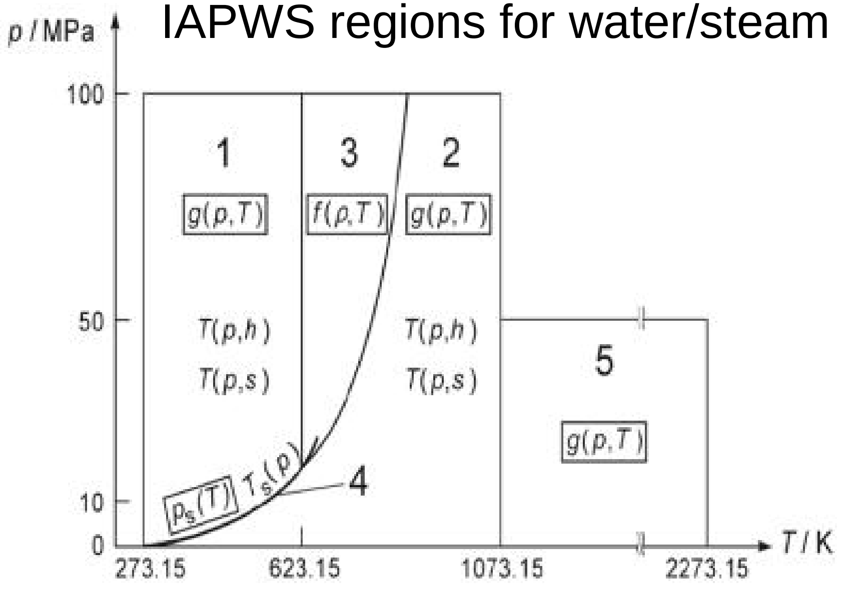
- Ideal gas and stiffened gas laws not good for :
  - Gasses near saturation
  - Liquids
    - Ratio of specific heats $\gamma = C_p / C_v$ not well defined for liquids
- Need more accurate method that better accounts for physics
  - Experimental measurements are well documented and tabulated for water [1] and methane [2]
  - Correlations of the tabulated data allow quick access to properties

1. W. Wagner & H-J Kretzschmar, International Steam Tables, 2nd ed., 1998.
2. U. Setzmann & W. Wagner, J. Phys. Chem. Ref. Data, 20(6), 1991

Quicksteam and Quickmethane

- Quicksteam/methane
  - Correlate equation of state experimental measurements
  - Uses Gibbs or Helmholtz free energy
- Selecting region : Water
  - Region 1, liquid
  - Regions 2 and 5, vapour (steam)
  - Region 3, liquid/vapour
  - Region 4, saturation curve
  - In most cases fixing to region 1 for liquid and 2 for gas will produce the most stable simulation
- Automatic for methane after choice of ρ
- Beyond the region boundaries
  - Necessary in gas/liquid mixtures when temperatures cross saturation curve

IAPWS regions for water/steam



The 7 equation Bestion model

- Solve for v = (δ, $\alpha_g\rho_g$, $\alpha_l\rho_l$, $\alpha_g\rho_g U_g$, $\alpha_l\rho_l U_l$, $\alpha_g\rho_g E_g$, $\alpha_l\rho_l E_l$)
- Newton's method to solve equation for T_g, P, T_l

$$R_0 = \frac{(v_0 + v_1)e_a(T_g, P)}{2} + \frac{(v_1 - v_0)e_s(T_g, P)}{2} - v_5 + \frac{v_3^2}{2v_1}$$
$$R_1 = \alpha_l(T_g, P)\rho_l(T_l, P) - v_2$$
$$R_2 = e_l(T_l, P) - \frac{1}{v_2}\left(v_6 - \frac{v_4^2}{2v_2}\right)$$

  - Similar equation with R_1 and R_2 for Euler
- Added switch to control phase change

$$Q_{il} = 0 \text{ if } (T_l < T_{\text{sat}} \text{ and } \alpha_v < \alpha_{\text{min}})$$
$$Q_{iv} = 0 \text{ if } (T_g > T_{\text{sat}} \text{ and } \alpha_v > \alpha_{\text{min}})$$

choose $\alpha_{\text{min}} = 10^{-3}$

The 7 equation Bestion model

- Drag force for dispersed phase

$$C_{\mathrm{drag}} = \theta_\rho \frac{C^*}{r^*} \frac{\alpha_w \alpha_g \rho_w \rho_g}{\rho} |u_g - u_w|$$

where $\rho \equiv \alpha_g \rho_g + \alpha_w \rho_w$ and $\theta_\rho = \rho/(\alpha_g \rho_w)$.

  - Dispersed liquid : droplets
  - Dispersed gas : bubbles
- When blast wave passes, foam structure destroyed leaving droplets

Test cases

- Return to equilibrium
  - 7 equation Bestion model
- Block of liquid
  - Euler model with interface reconstruction
- Water hammer
  - 7 equation Bestion model

Return to equilibrium

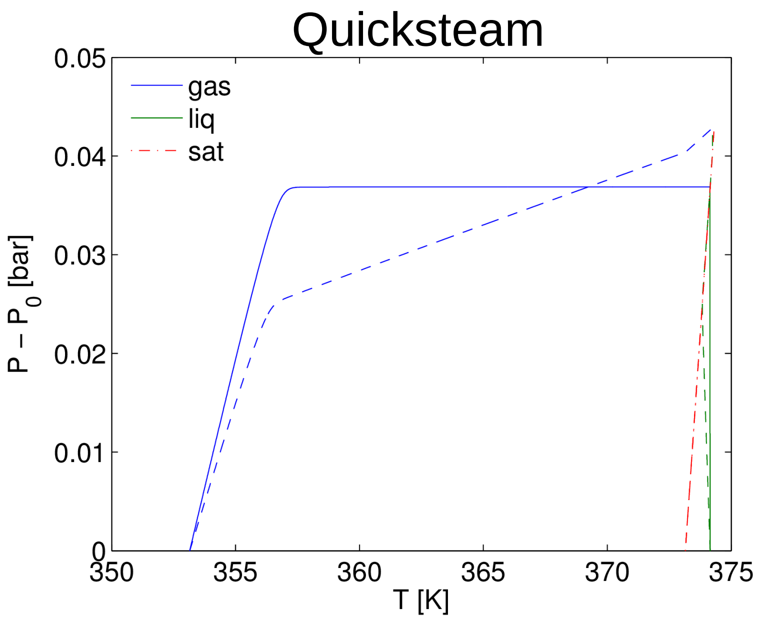
- Intuitive test, looking for correct behaviour
  - i.e. return to saturation curve
- Initially

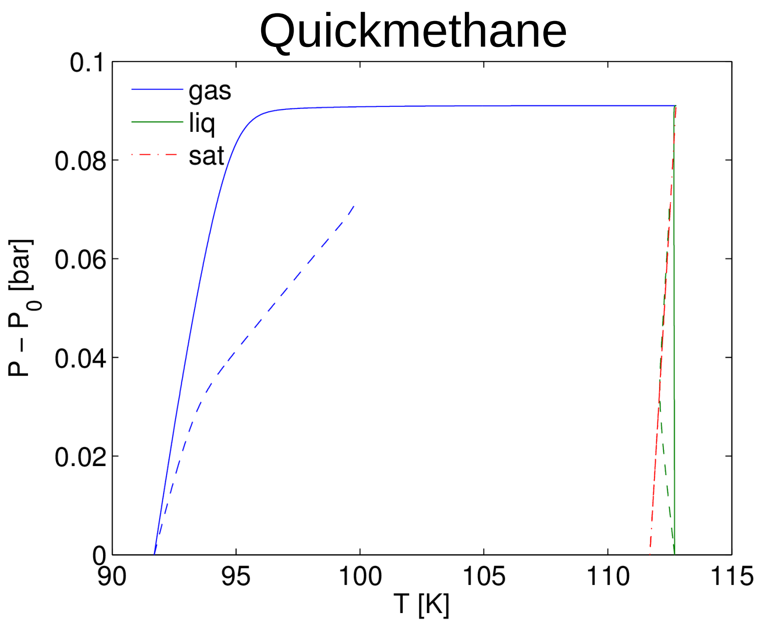
  P_0 = 1.014 bar

  $T_l = T_{sat}$ +1

  $T_g = T_{sat}$ - 20

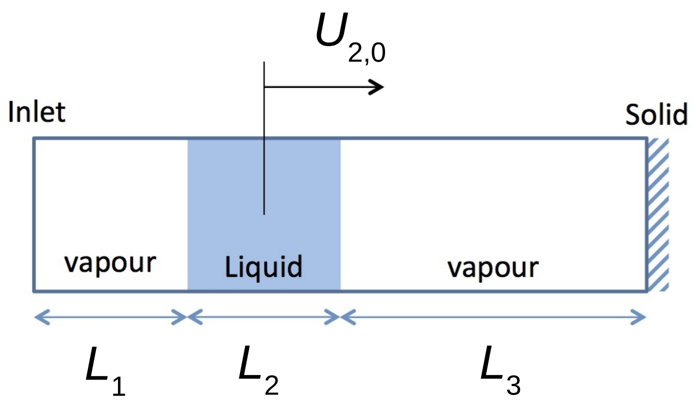
- Single cell, $U_g = U_l = 0$
- Solid : $\alpha_l = \alpha_v = 0.5$, $\alpha_a = 0$
- Dashed : $\alpha_l = \alpha_v = 1/60$, $\alpha_a = 58/60$
- Temperatures return to saturation curve
- Methane (dashed) does not : $\alpha_v \rightarrow 0$





Block of water

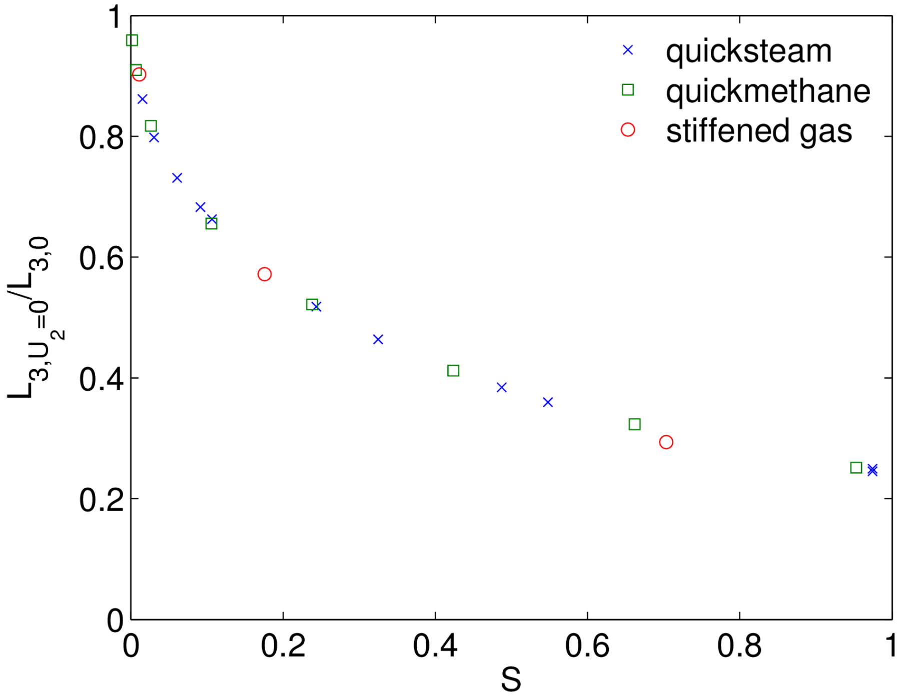
- Tests compressibility effects
- With Interface capturing between liquid and vapour
  - Condensate
- Dimensionless groups
  - Bagnold number $S = \dfrac{\rho_L U_{2,0}^2 L_2}{2 P_0 L_3}$



Collapse using Bagnold number

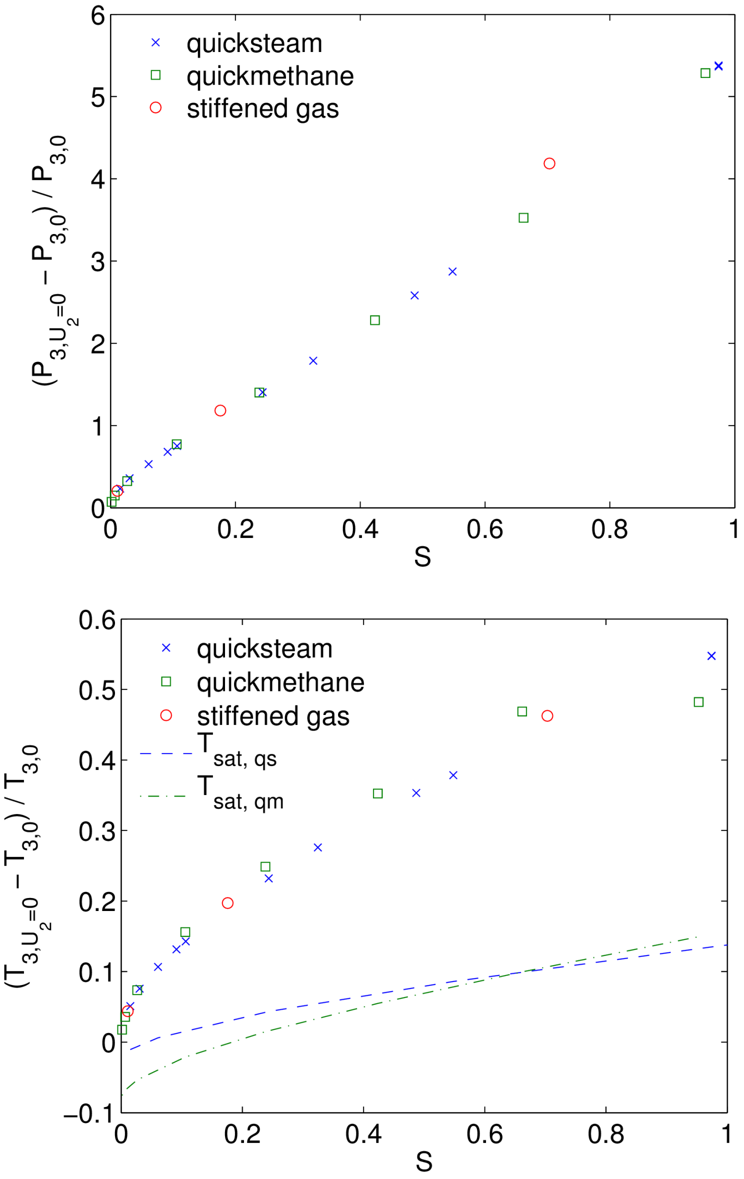
- Range of $U_{2,0}$, L_2, L_3
  - Quicksteam
  - Quickmethane
  - Stiffened gas
- Bagnold number defined as :

$$S = \frac{\rho_L U_{2,0}^2 L_2}{2 P_0 L_3}$$



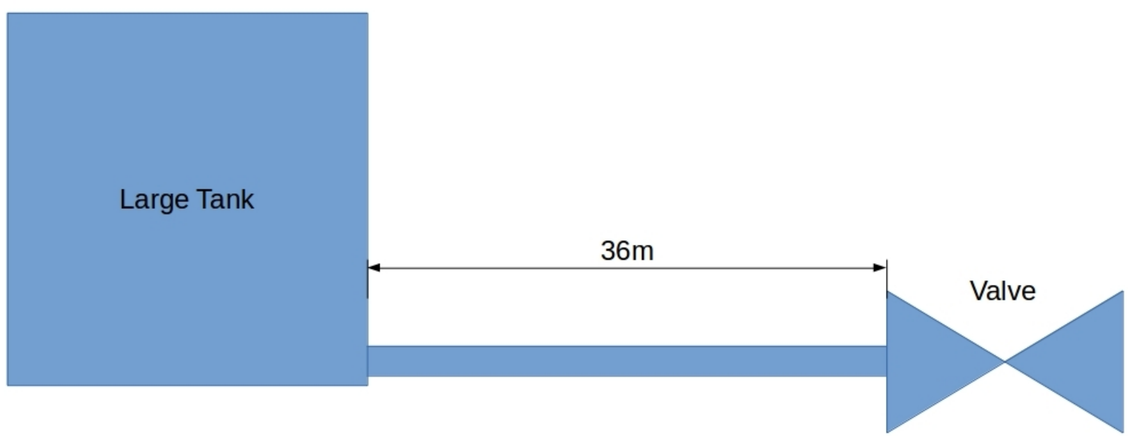
Pressure and temperature

- Properties approx constant inside each separate fluid
- Collapse with Bagnold
- $T_3 > T_{sat}$
  - No phase change



Water hammer

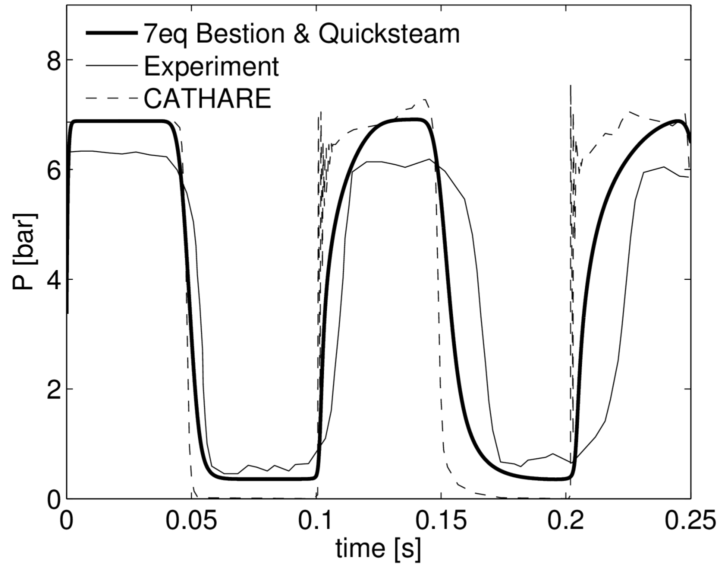
- Tank connected to a pipe with valve at end
  - Valve is suddenly closed
  - Pressure wave propagates back towards the tank and is reflected
  - Phase change possible depending on initial parameters



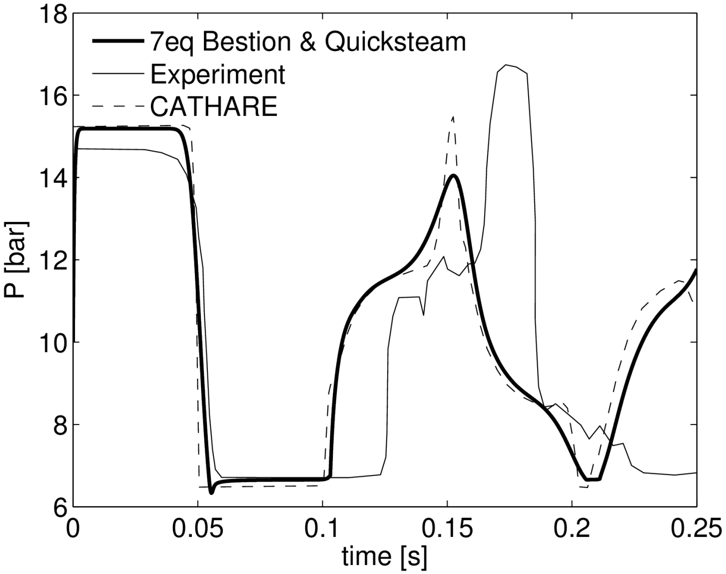
Water hammer

- Experimental and simulation results available [2]
- Good match with CATHARE code
  - CATHARE also uses steam tables
  - No phase change P_{min} higher than CATHARE code
- Match to experimental data can be improved by altering initial condition to account for physical effects [2]

Without phase change



With phase change



2. G. Serre & D. Bestion, Two-Phase Water-Hammer Simulation with the CATHARE Code, 9th International Conference on Nuclear Engineering ; Nice, Acropolis (France) ; 8–12th April 2001.

Applications

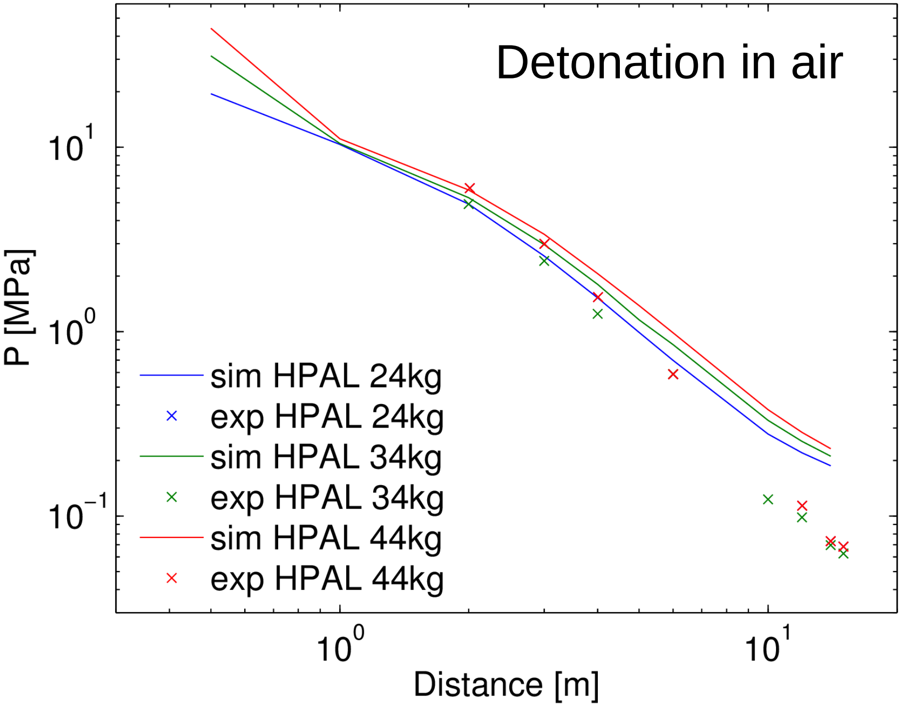
- Article title : Quick recovery of equation of state values for fluid flow simulation using Quicksteam and Quickmethane
- Attenuation of shock waves in aqueous foams
  - Pressures beyond Quicksteam's limits
    - Code not yet capable of these pressures...
    - Could apply stiffened gas or stretch
- Also used to study sloshing methane tanks
  - Liquid compressibility plays important role
  - Work of Matthieu Ancellin

Violent flows III

- Full title 'Violent flow in aqueous foams III: Comparison with experimental measurements and test cases'
- Objective : Make predictions of blast wave attenuation for a given amount of explosive
- Problems
  - Multiple phenomena to be modelled
  - Extremely high pressures
- Test cases
  - Detonation code coupled to Euler solver
  - Shock tube with water droplets
    - Droplet equations
    - 7 equation Bestion
  - Comparison with Sandia correlations

Detonation coupled to Euler code

- Use detonation model of Massoni et al. [3]
- Take data from detonation simulation
- Apply as left boundary condition in Euler simulation
  - Air and water



3 J. Massoni & R. Saurel & A. Lefran¸cois & G. Baudin, Modeling spherical explosions with aluminized energetic materials, Shock Waves 16, 75–92, 2006.

Shock tube with water droplets

- Experiments from [4]
- Vertical shock-tube
- Water droplets created by jet
- Shock and jet timed to meet at C6
- Strong attenuation of pressure jump

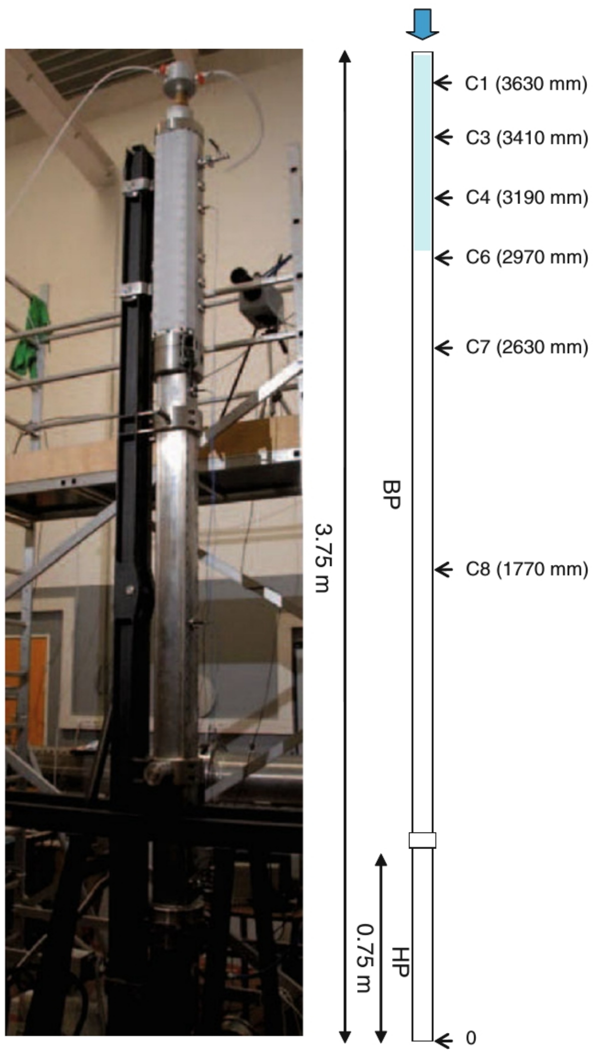
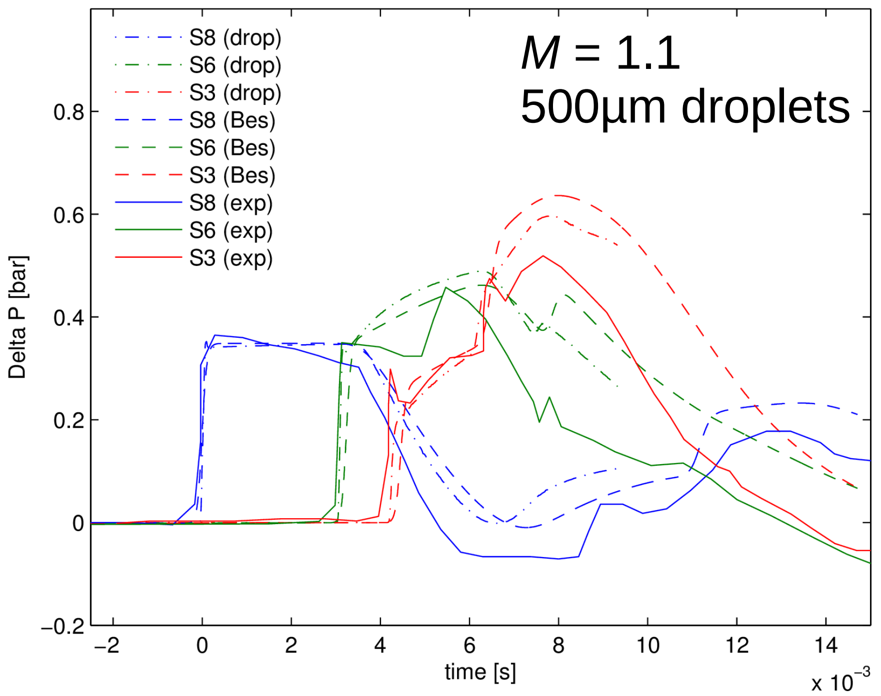


Fig. 6 View of the general experimental set-up and scheme of the shock tube with the locations of the different stations of measurements

4 G. Jourdan, et al., Attenuation of a shock wave passing through a cloud of water droplets, Shock Waves 20, 285–296, 2010.

Shock tube with water droplets

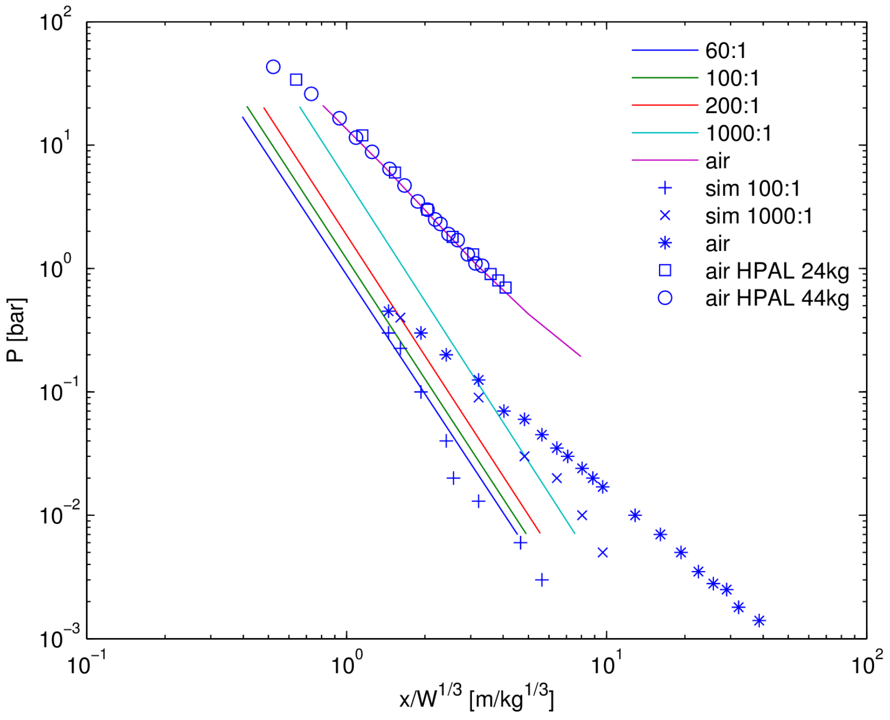
- Varying shock strength, α_l and droplet size
- Droplet model used by Jordan et al. [4]
- Results from droplet model and 7 equation Bestion
  - Both models match experiment well at $M = 1.1$



$M = 1.5$ also works, but 1.8 does not. High pressure problem needs to be rectified...

Sandia empirical data fits

- Detonation code at high pressure with Euler
- Low pressure using 7 equation Bestion
- Necessary to control T_g and P behind shock front
  - Negative values
  - using energy and mass sources
    - Would be energy and mass in real explosion



Conclusions

- Quicksteam and Quickmethane improve accuracy and robustness of multiphase simulations
  - 3 test cases
  - Article in preparation
- Good comparison with Sandia correlation for air at high pressure
- Reproduced trend for Sandia foam at low pressure
- Need to increase pressures in 7 equation Bestion model
  - Use numerical solution of Jordan matrix when matrices becomes singular