Influence of liquid and gas properties on impact pressures for a rectangular liquid patch impact

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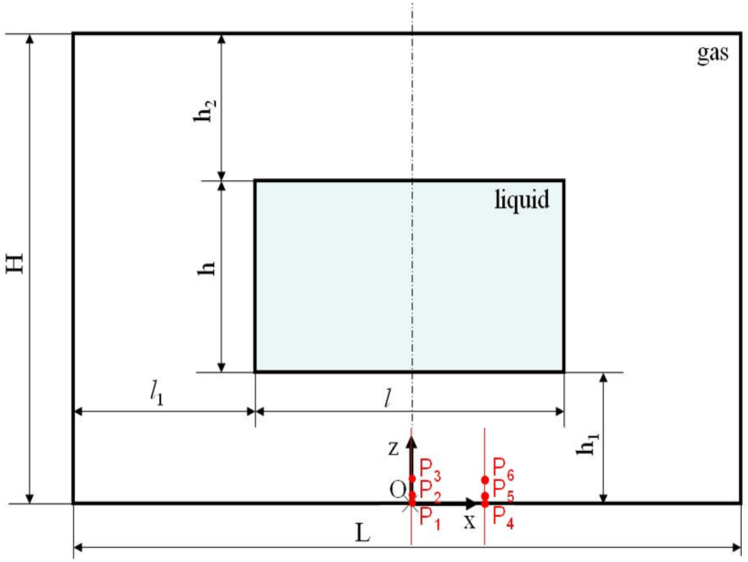
17th Int. Workshop on trends in numerical and physical modeling for industrial multiphase flows

Outline

- Test case description
- Numerical model
- Flow description
- Influence of physical properties on maximal pressure
- Energy considerations
- Conclusions and perspectives

Test case

- Systematic study
  - Geometrical properties



Length	(m)
H	15
h	8
h_1	2
h_2	5
L	20
l	10
l_1	5

Ref. point	*X (m)*	*Z (m)*
P_1	0	0
P_2	0	0.1
P_3	0	0.5
P_4	2.5	0
P_5	2.5	0.1
P_6	2.5	0.5

Test case

Systematic study

Physical characteristics

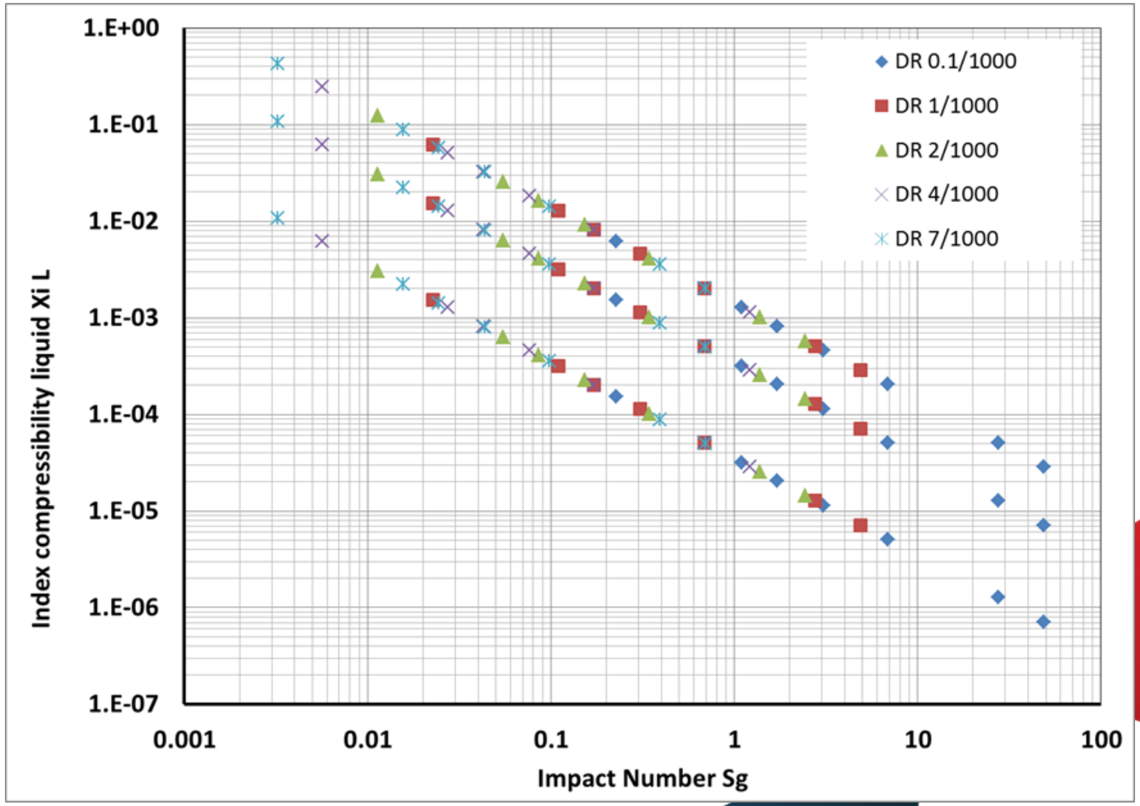
Gas speed of sound (m/s)	150	200	400	600	800	1000	2200

Liquid speed of sound (m/s)	1500	474	237

Density ratio	0.1/1000	1/1000	2/1000	4/1000	7/1000

Non dimension numbers

- Density ratio (DR) $$DR = \frac{\rho_{0G}}{\rho_{0L}}$$
- Gravity Impact number $$S_g = \frac{\rho_{0L} L_0 g}{p_0}$$
- Liquid compressibility index $$\chi_L = \frac{p_0}{\rho_{0L} a_{0L}^2}$$



Mathematical model

- Euler equations for compressible fluids
  - Conservation laws

Mass conservation: $\mathcal{L}_{v^o}(\rho) + \operatorname{div}\left(\rho(\boldsymbol{v} - \boldsymbol{v}^o)\right) = 0$

Momentum conservation: $\mathcal{L}_{v^o}(\rho\boldsymbol{v}) + \operatorname{div}(\rho\boldsymbol{v} \otimes (\boldsymbol{v} - \boldsymbol{v}^o) + p\mathbb{I}) = S$

ALE transport operator:

$$\mathcal{L}_{v^o}(f) = \frac{\partial f}{\partial t} + \operatorname{div}(f\boldsymbol{v}^o)$$

Impact : no viscosity (compressible Euler equations)
Impact : Isentropic assumption (energy equation not coupled)

  - Equations of state

Gases: classical Laplace equation
Liquids: isentropic stiffened gas EoS

$$p = \frac{\rho_0 a_0^2}{\gamma}\left(\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right)$$

  - ALE formulation

Point motion: $\frac{d\boldsymbol{x}}{dt} = \boldsymbol{v}^o$

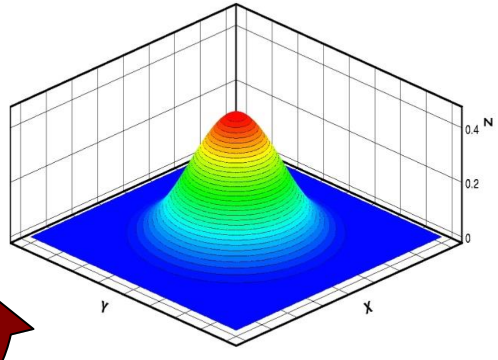
Volume evolution: $\frac{dw}{dt} = w\operatorname{div}(\boldsymbol{v}^o)$

Numerical model

Smoothed Particle Hydrodynamics

- Particle approximation

$$\Pi^h(f)(x) = f * W(x) = \int_{R^d} f(y)W(x-y,h)dy$$



Gauss function : statistical estimation

- Conservation laws

$$\boxed{\frac{d}{dt}(w_i\phi_i) + w_i \sum_j w_j\left(F_i + F_j\right).\nabla W_{ij} = w_i S_i}$$

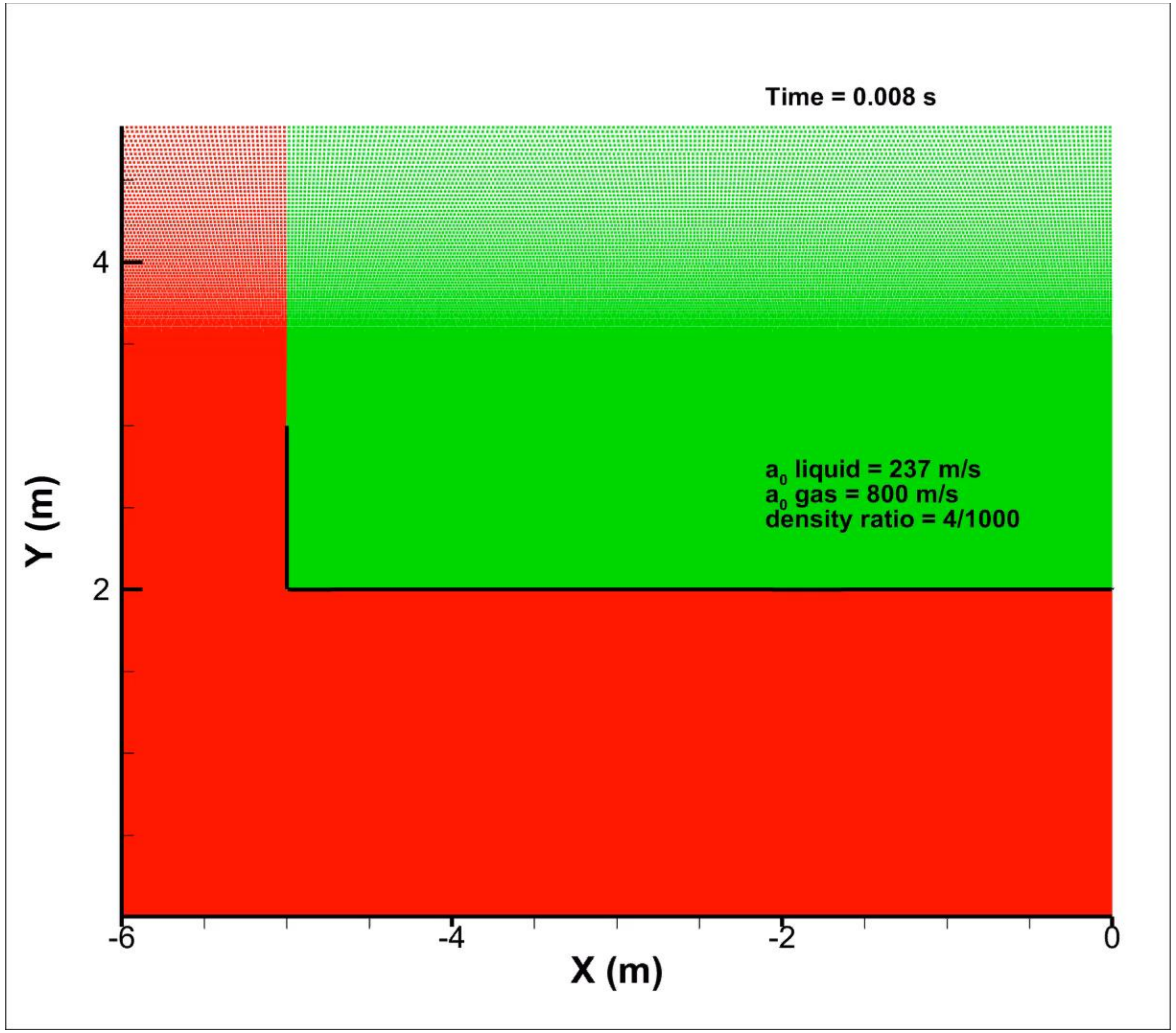
Discrete scheme equivalent to Finite Volume schemes
Upwind with Riemann solver
Higher order scheme with MUSCL reconstruction

- Lagrangian evolution

$$\frac{d\boldsymbol{x_i}}{dt} = \boldsymbol{v_i}$$

$$\frac{dw_i}{dt} = w_i \sum_j (\boldsymbol{v_j} - \boldsymbol{v_i}) \cdot \nabla W_{ij}$$

Flow description



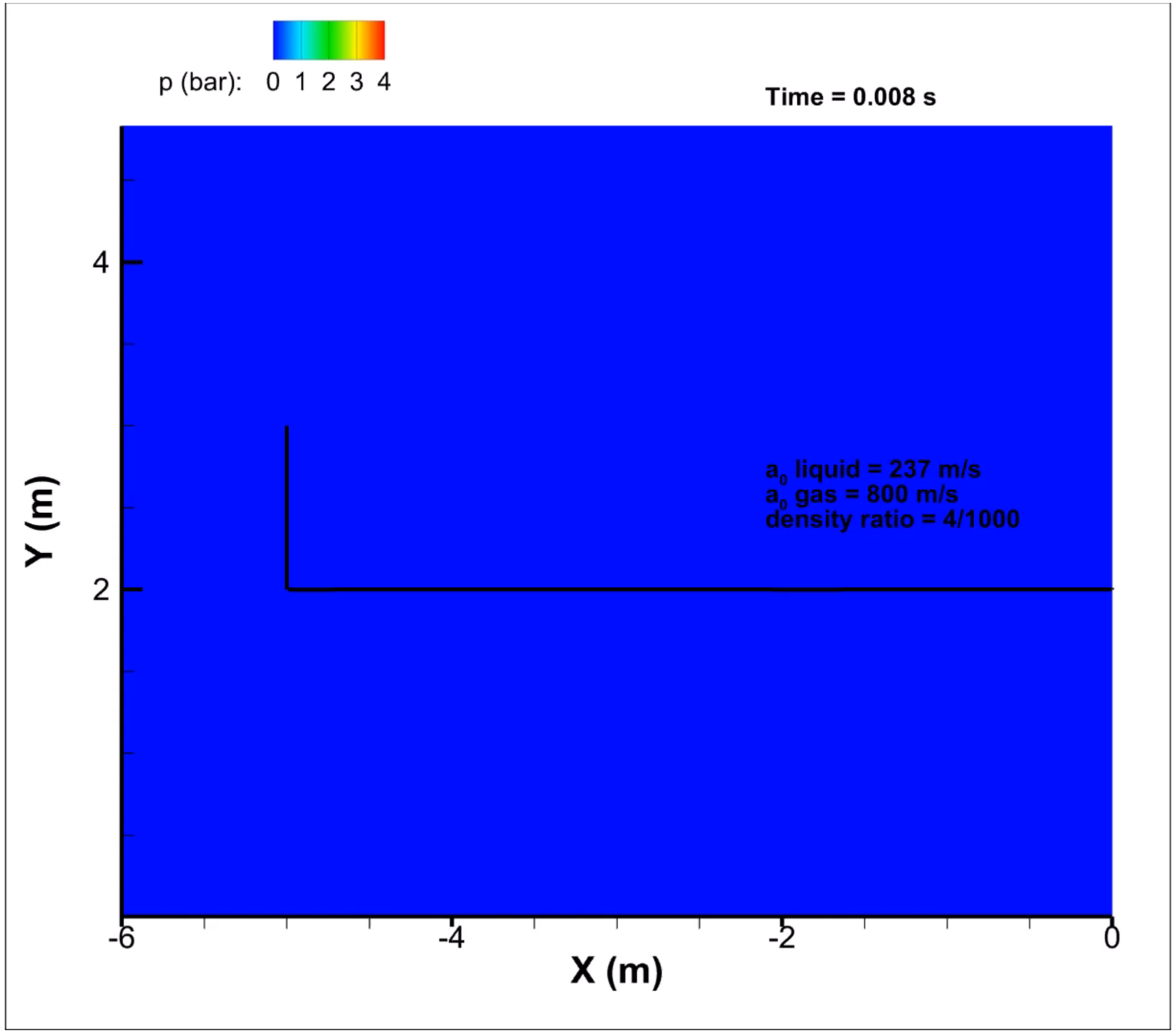
Before impact

- Liquid acceleration
- Progressive deformation of free surface
- Gas escape
- Gas pocket formation
- Free surface instabilities

During impact

- Compression of gas pocket
- oscillations of gas pocket

Flow description

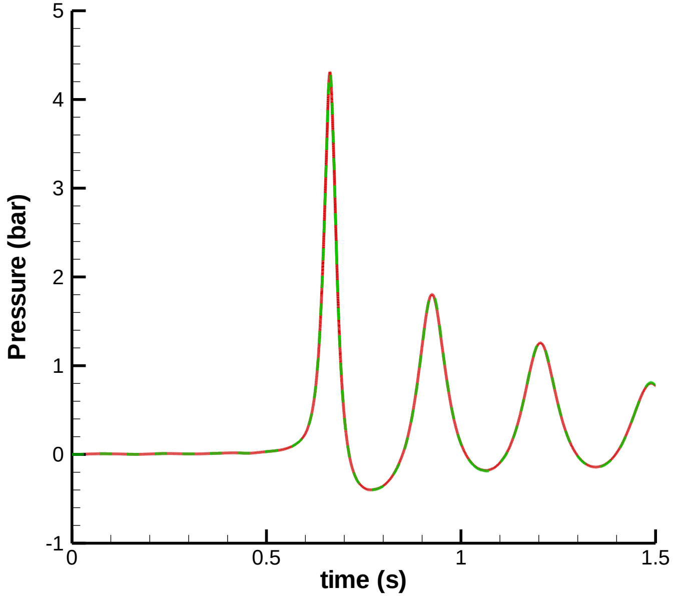


Before impact

- Pressure almost 0

During impact

- Compression of gas pocket
- Pressure oscillations inside gas pocket and liquid



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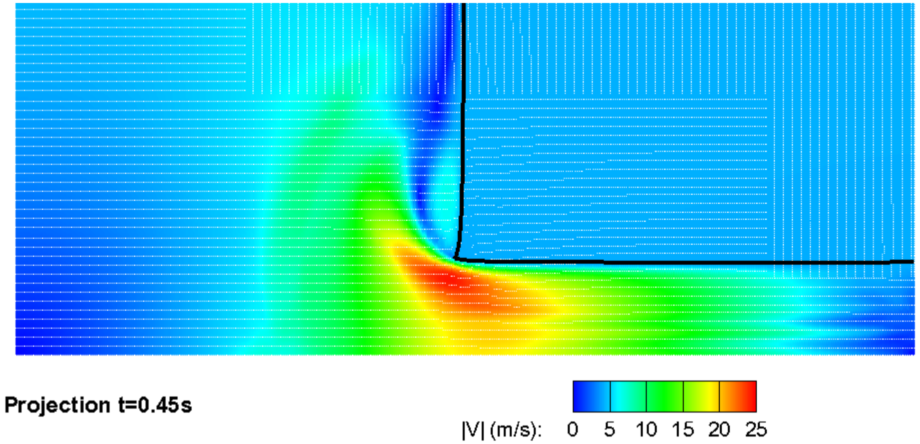
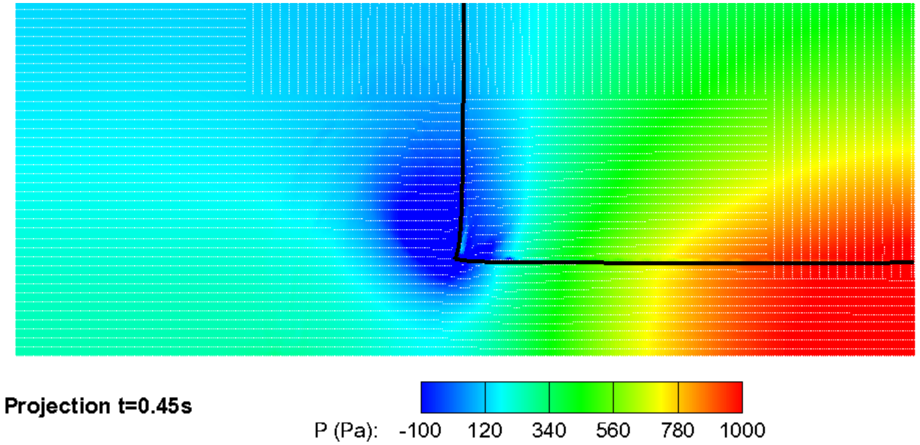
Flow description

- Is there always a gas pocket?



Projection t=0.45s



Projection t=0.45s

- Boundary conditions for gas
  - u = 0 m/s on x=0
  - p = Patm on 'outlet' (gas free to escape)

P=0 → **$P=\rho V^2/2$**

- Gas pocket entrapment due to BC
  - Size of the gas pocket influenced by gas properties (DR, Mach)
  - Mix of ELP3 (pure gas compression) and ELP1 (pure liquid acoustic wave)

Influence of physical properties on maximal pressure

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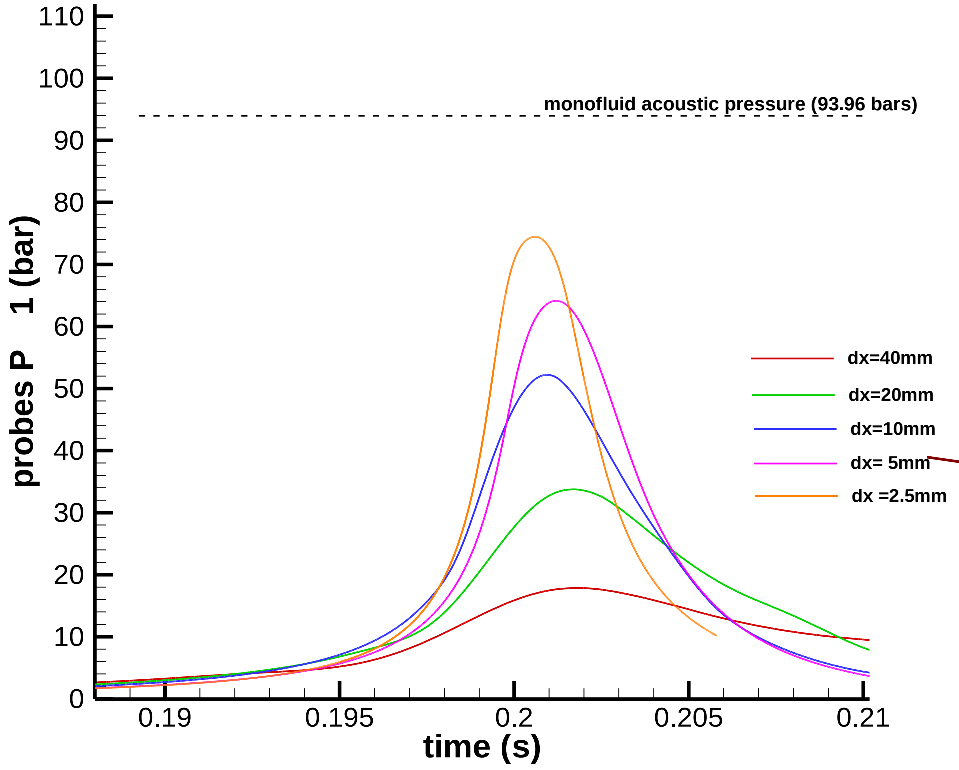
Particle size sensitivity study

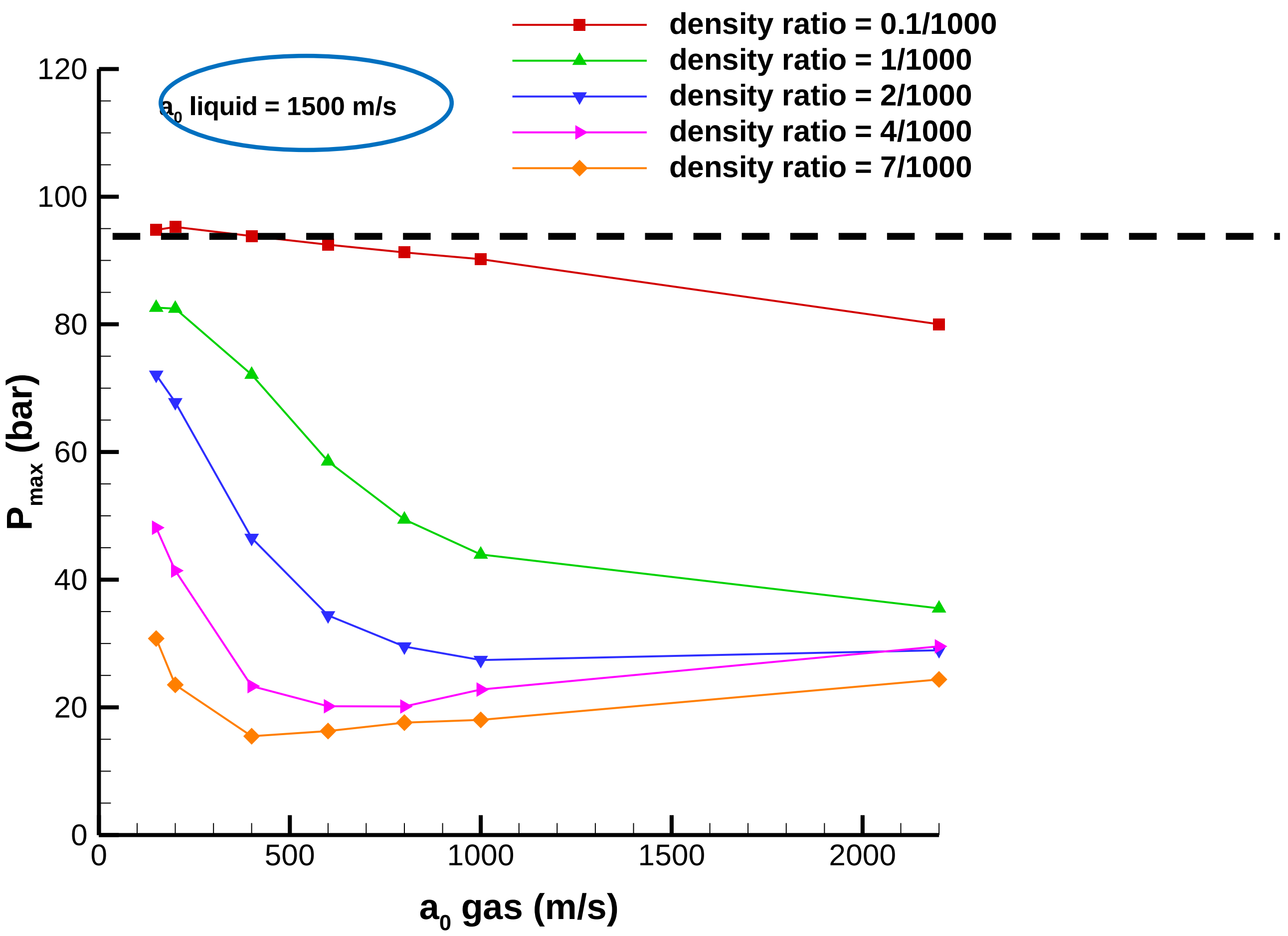
- Convergence study for S_g=1



Indicative acoustic pressure

Δx [mm]	h1/Δx [-]	n points [-]
40	50	100.10^3
20	100	150.10^3
10	200	300.10^3
5	400	900.10^3
2.5	800	3000.10^3

Pmax with constant a0L (liq. speed of sound)



$$p_{acoustic} = \rho_{0L} a_{0L} \sqrt{2gh_1}$$

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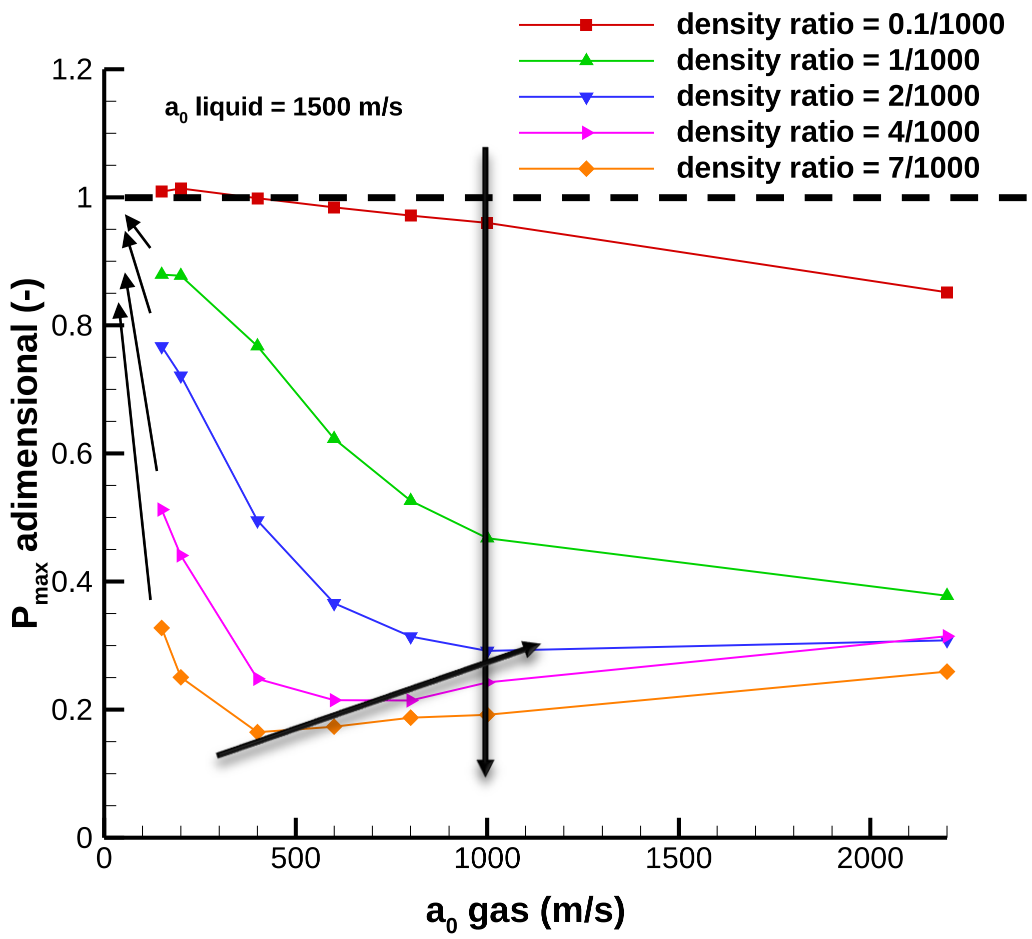
Pmax with constant a0L (liq. speed of sound)



$$p_{acoustic} = \rho_{0L} a_{0L} \sqrt{2gh_1}$$

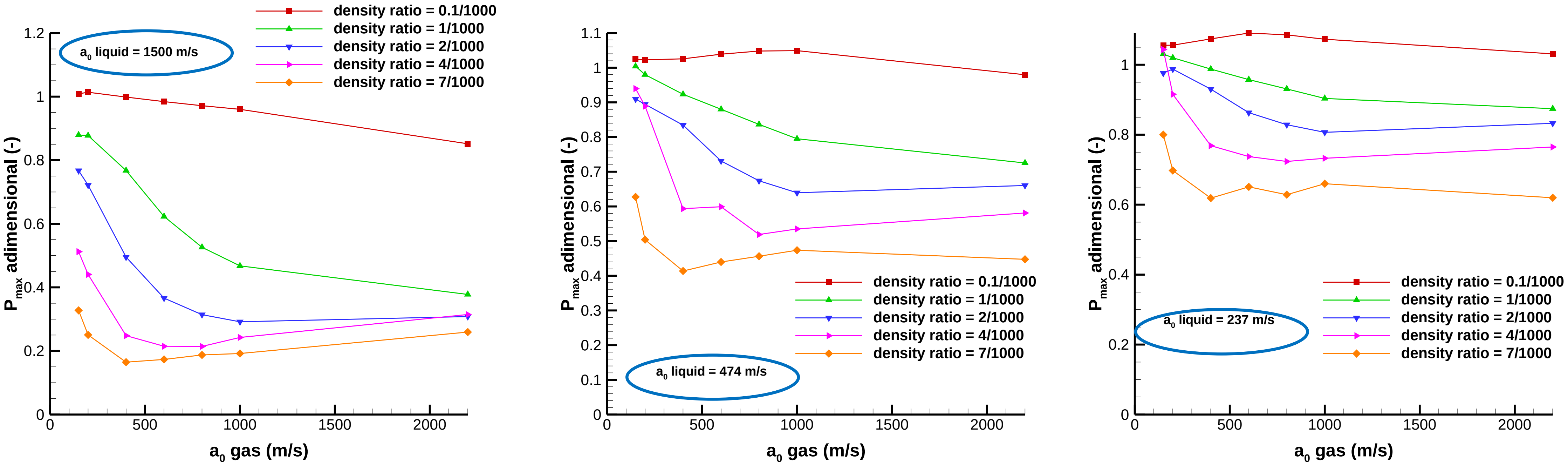
$P_{max} \rightarrow P_{ac}$ as DR → 0 (no matter a0g)

P_{max} ↘ as DR ↗

$P_{max} \rightarrow P_{ac}$ as a0g → 0 (to be confirmed)

P_{max} lowest not for $P_{0g} \rightarrow \infty$

Pmax with constant a0L (liq. speed of sound)



P_{max} → P_{ac} as DR → 0 (no matter a0g)

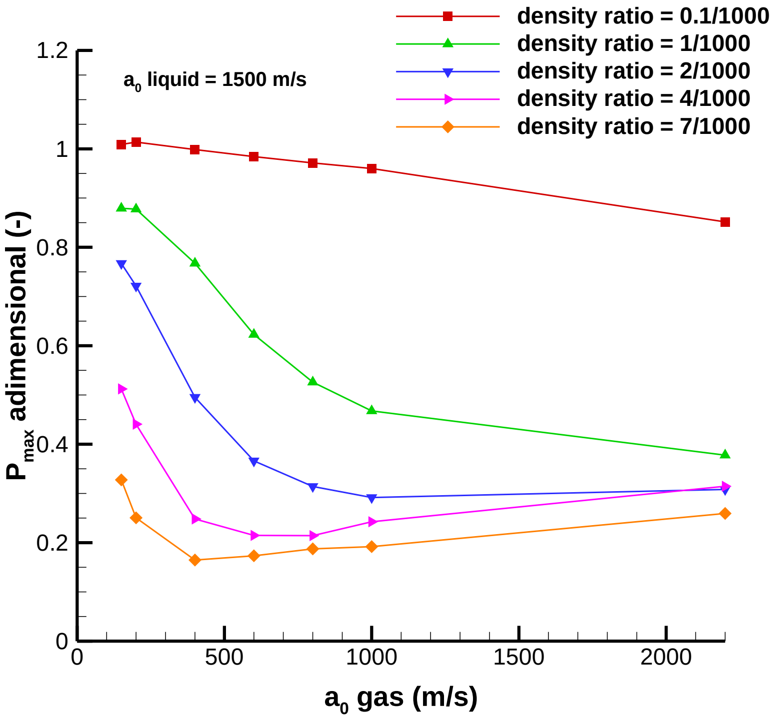
P_{max} ↘ as DR ↗

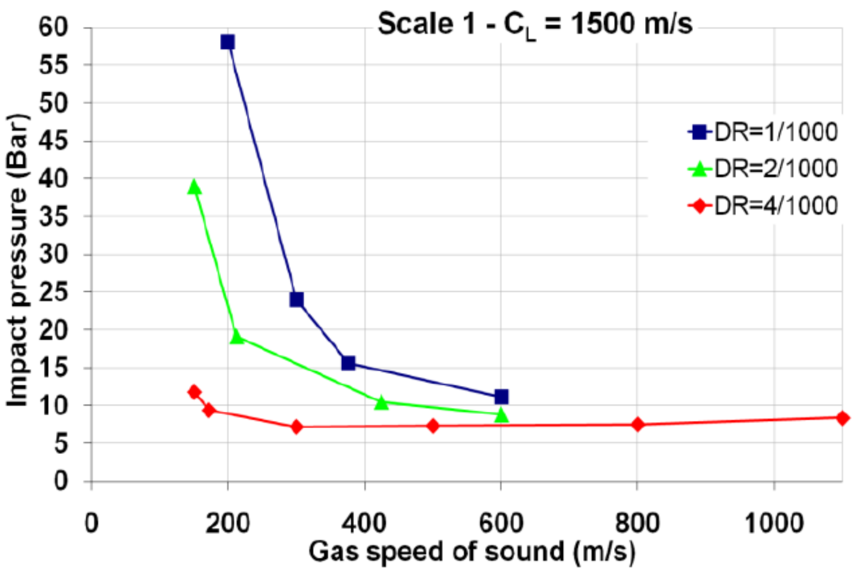
P_{max} → P_{ac} as a0g → 0 (to be confirmed)

Lowest P_{max} influenced by a0l (ELP1/ELP3 coupling)

Pmax with constant a0L (liq. speed of sound)

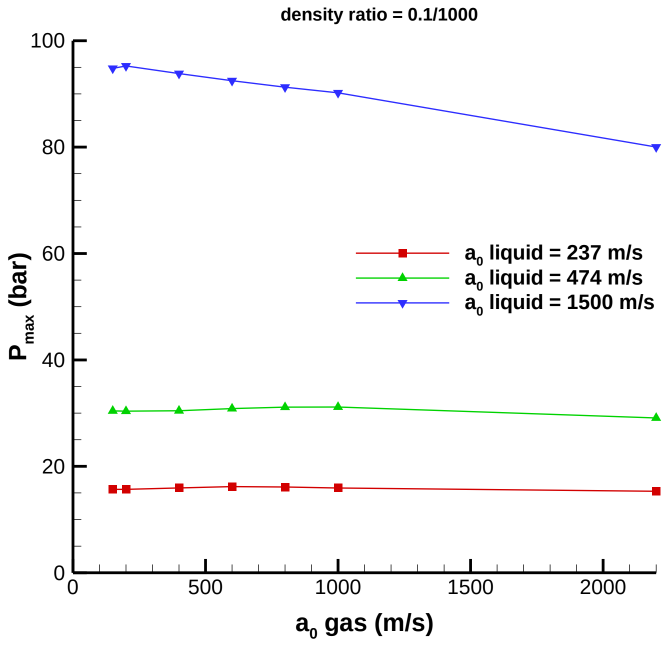
- Comparison with Flux-IC results (2009)

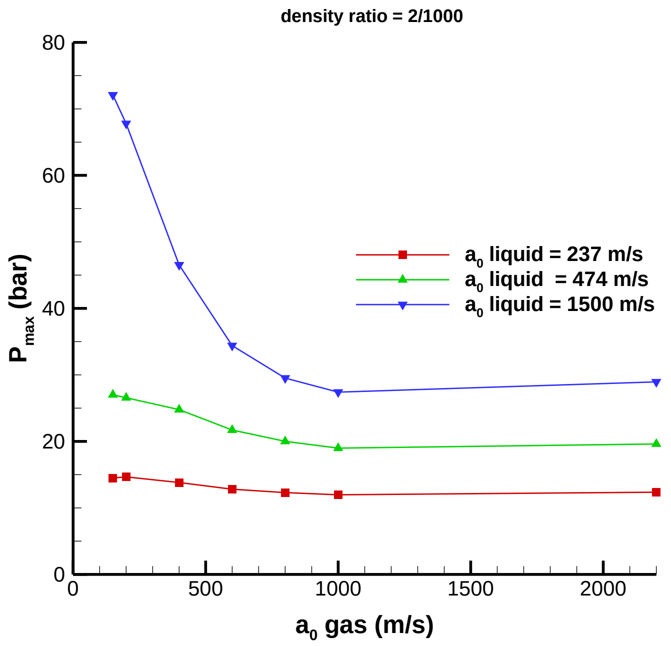


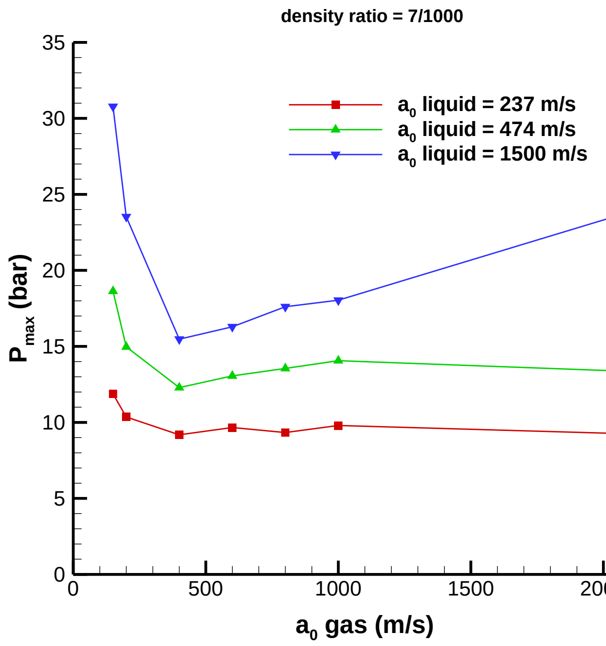


> Same trends

Pmax with constant DR (density ratio)







Weak influence of a0g for small DR

- No coupling between ELP1 and ELP3
- Pure ELP1 regime

Weak influence of a0g for <u>small</u> a0L

- No coupling between ELP1 and ELP3
- Pmax is lowered compared to acoustic Press.

Strong influence of a0g for <u>large</u> a0L

- coupling between ELP1 and ELP3

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Energy transfers

Energy transfer

Phase 1: incompressible gas escape

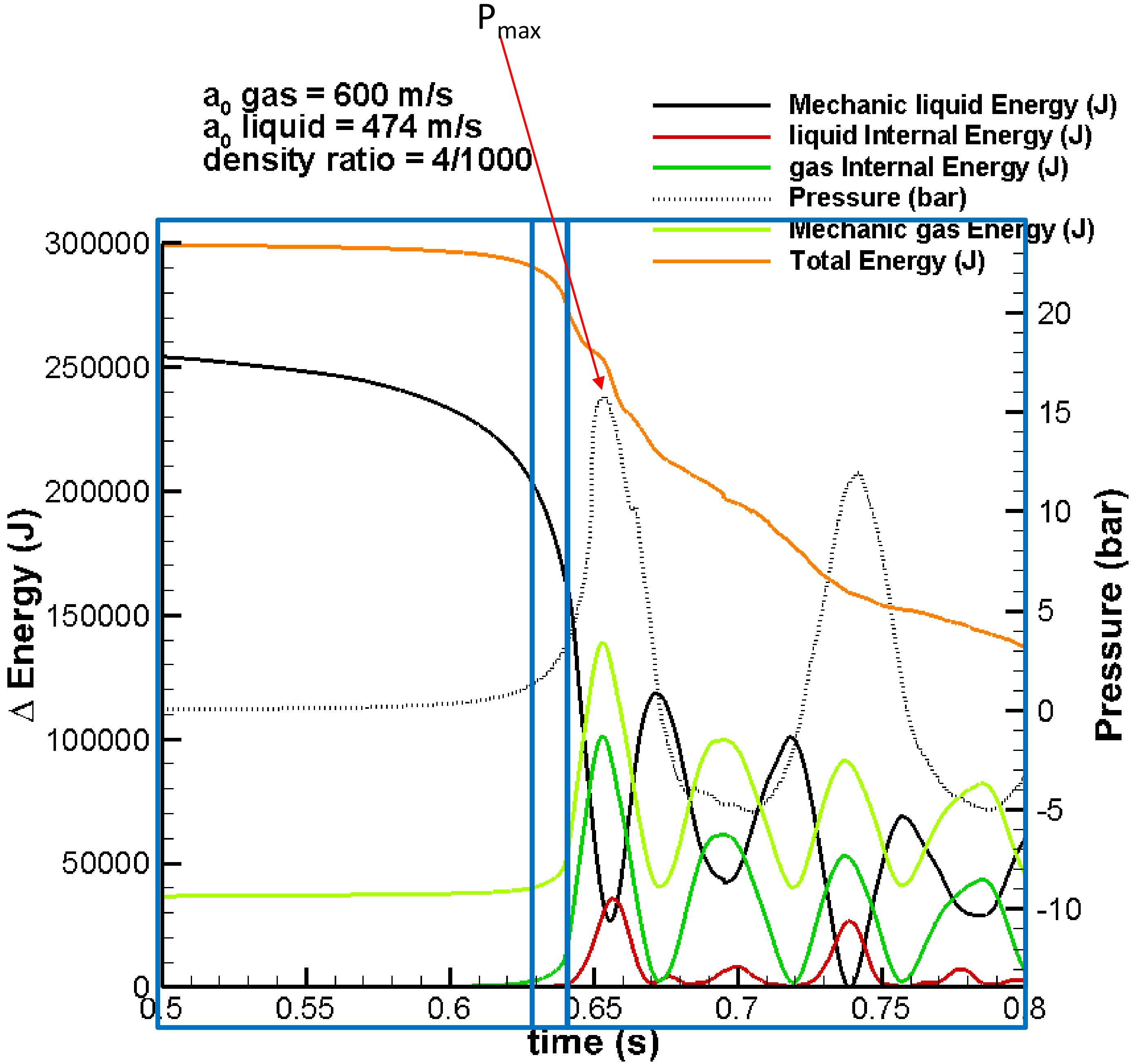
- No gas internal energy var.
- Dominated by mech. energy transfer
- Incompressible phase
- Influence of DR only

Phase 2: compressible gas escape

- Internal & mech. Gas energy var.
- Compressible phase
- Competition between gas escape and compression
- Influence of a_{0g} at escape ($Mach_g$)

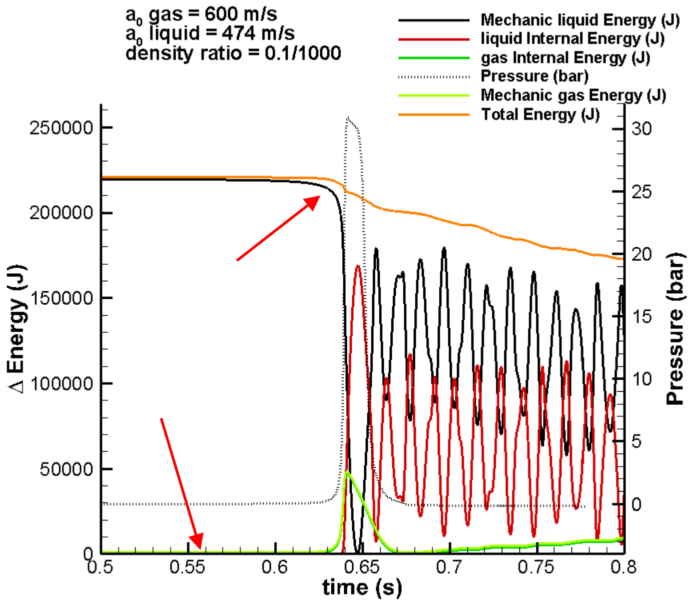
Phase 3: compressible gas pocket

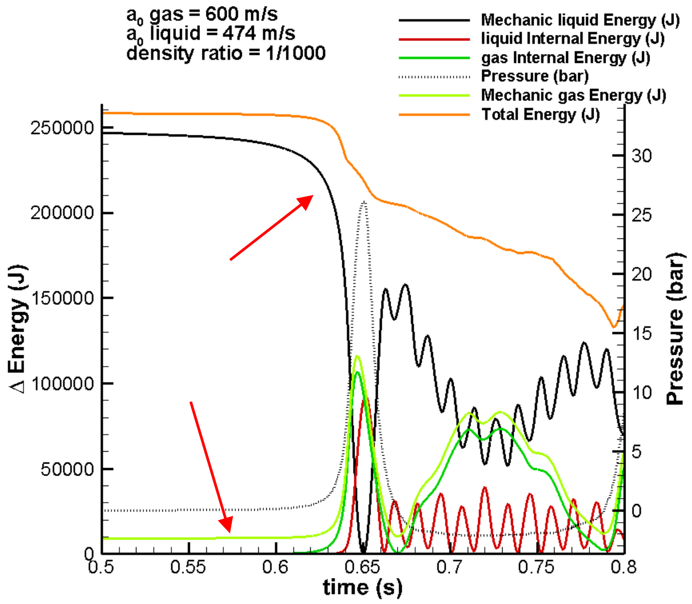
- Internal & mech. Gas energy var.
- Internal Liquid energy var.
- Compressible phase

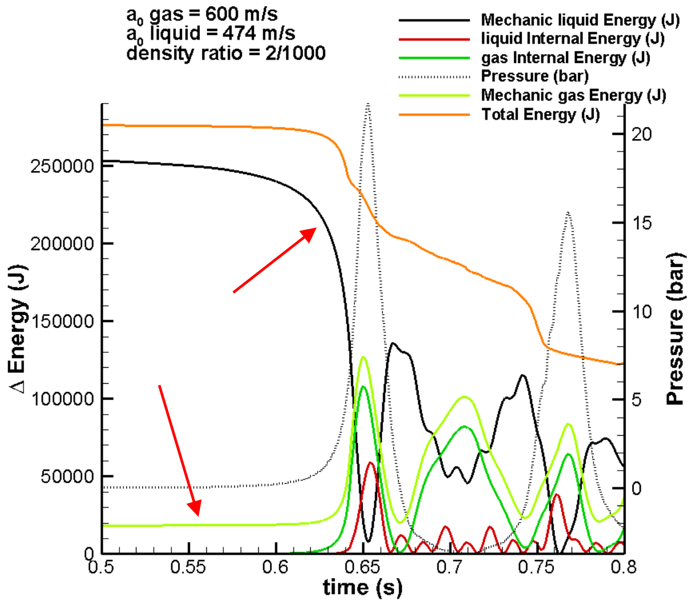


Energy transfer

Phase 1: influence of density ratio


a_0 gas = 600 m/s
a_0 liquid = 474 m/s
density ratio = 0.1/1000

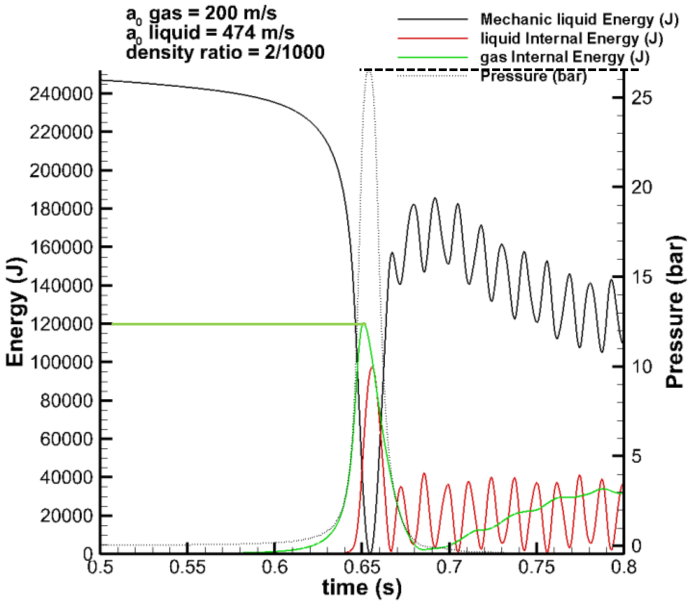

a_0 gas = 600 m/s
a_0 liquid = 474 m/s
density ratio = 1/1000

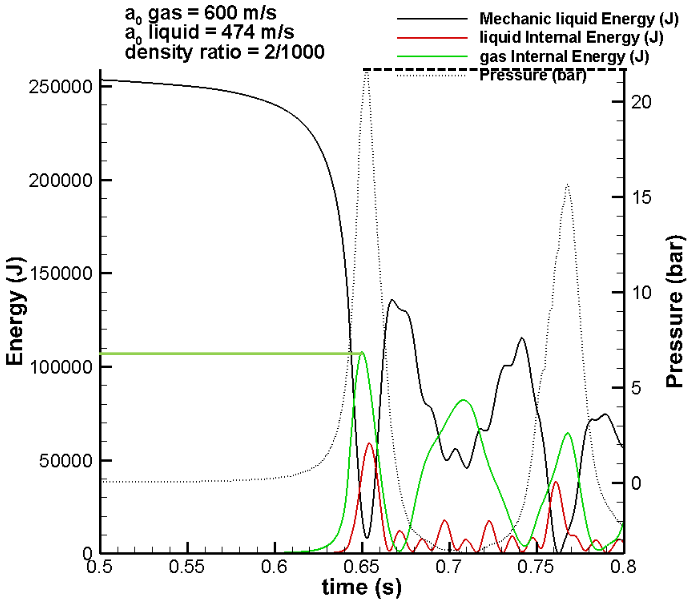

a_0 gas = 600 m/s
a_0 liquid = 474 m/s
density ratio = 2/1000

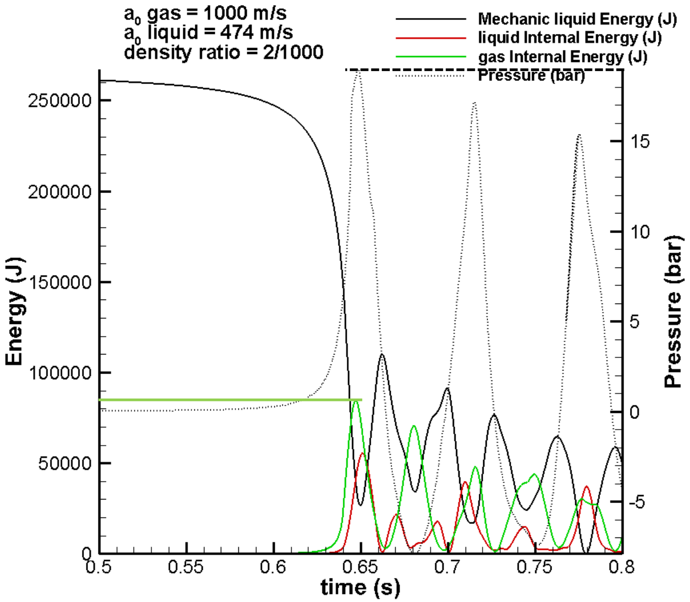
- DR increases mech. energy transfers between liquid and gas
- DR decreases the liquid kinematic energy: impact velocity is lowered
- DR decreases the P_{max}

Energy transfer

Phase 2: influence of gas speed of sound



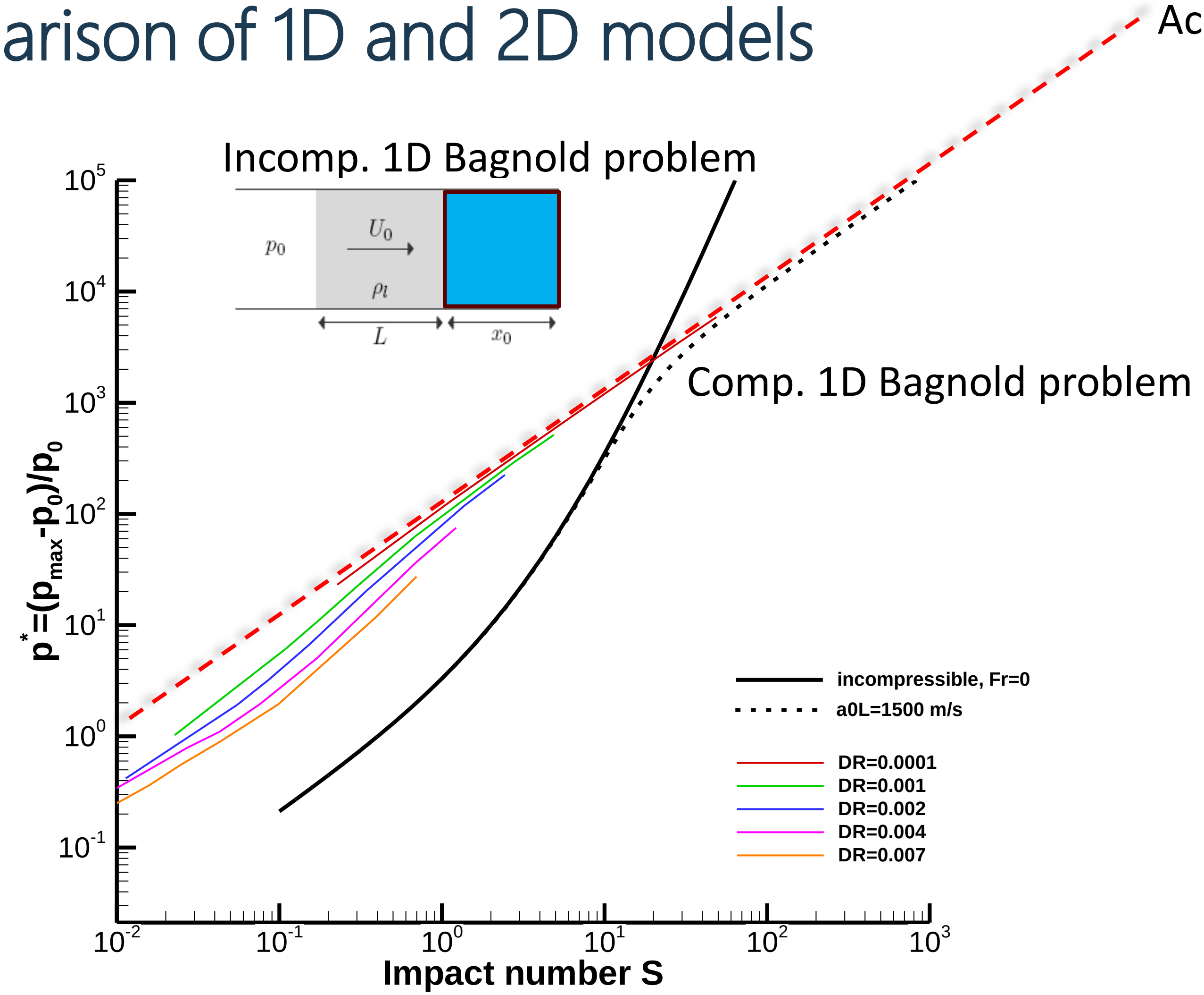


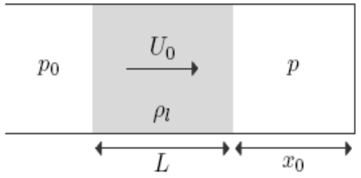


- a_{0g} decreases transfer of liquid mech. energy to gas internal energy
- Increase of gas ‘spring’ stiffness: more difficult to provide energy to the gas
- a_{0g} decreases the P_{max}

Global overview

- Comparison of 1D and 2D models





Conclusions

Small gas stiffness

- convergence of P_{max} towards liquid acoustic pressure
- Verified if DR → 0, or $a_{0G} \rightarrow 0$

Large gas stiffness through DR increase

- Strong influence of DR during main part of gas escape
- Increase of gas pocket size
- Increase of gas stiffness
- Double influence to lower impact pressure

Large gas stiffness through a_{0G} increase

- Increase of gas compressibility only
- Small influence on gas escape
- Less efficient than increase in DR, to reduce impact pressures

Liquid stiffness

- Small liquid stiffness: convergence of P_{max} towards liquid acoustic pressure (ELP1)
- Large liquid stiffness: increase of coupling between liquid and gas stiffness (Paradox!)

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Perspectives

Gas escape phase

- Understand the energy transfers due to DR, a_{0G}
- Influence of gas Mach number on gas escape
- Is it possible to predict the gas pocket size?
- Is it possible to divide the flow into incompressible and compressible phases
- Influence of gas on free surface shape for more general liquid shapes

Thank you for your attention