2D Simulations of breaking wave impacts on a flat wall

14ème Ecole de Mécanique des Fluides Numérique
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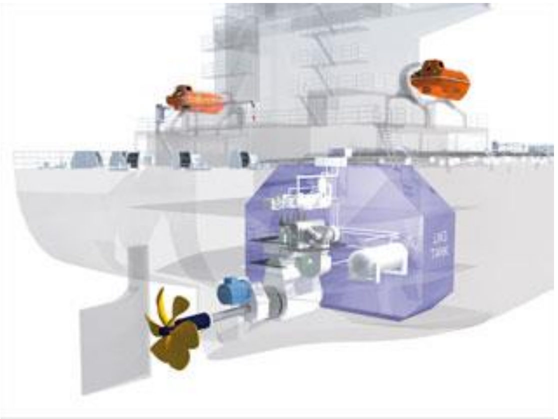
David Le Touzé (ECN)

Safety | Excellence | Innovation | Teamwork | Transparency

1 Industrial context: sloshing in LNG floating tanks

LNG tanks on floating structures



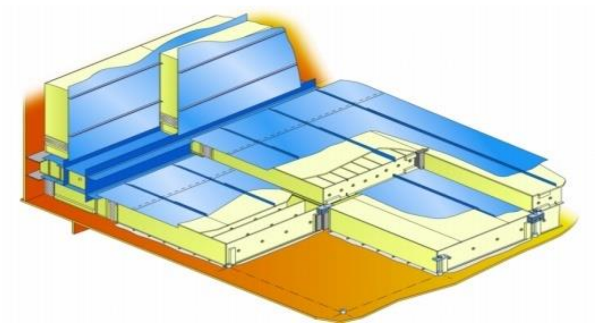
LNG carriers

Offshore applications

Small scale & bunkering

LNG membrane containment systems

- GTT (Gaztransport & Technigaz) is the designer of the LNG membrane containment systems



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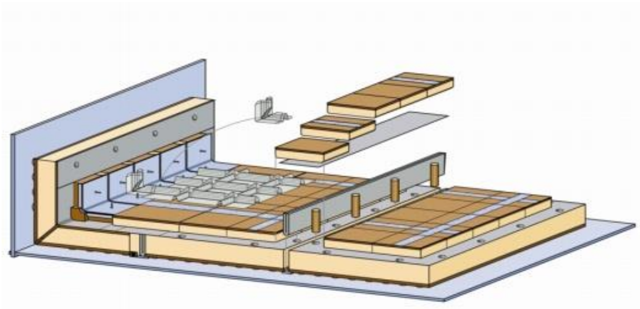
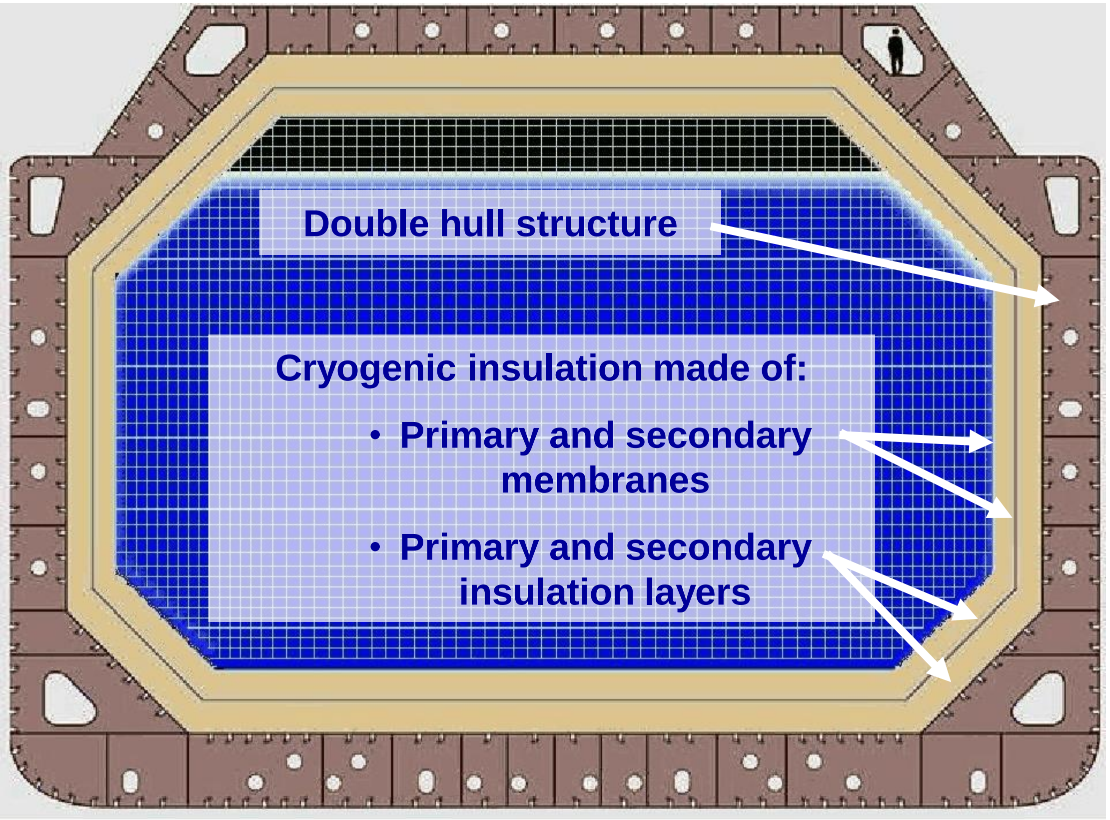


MARK III

LNG membrane containment systems

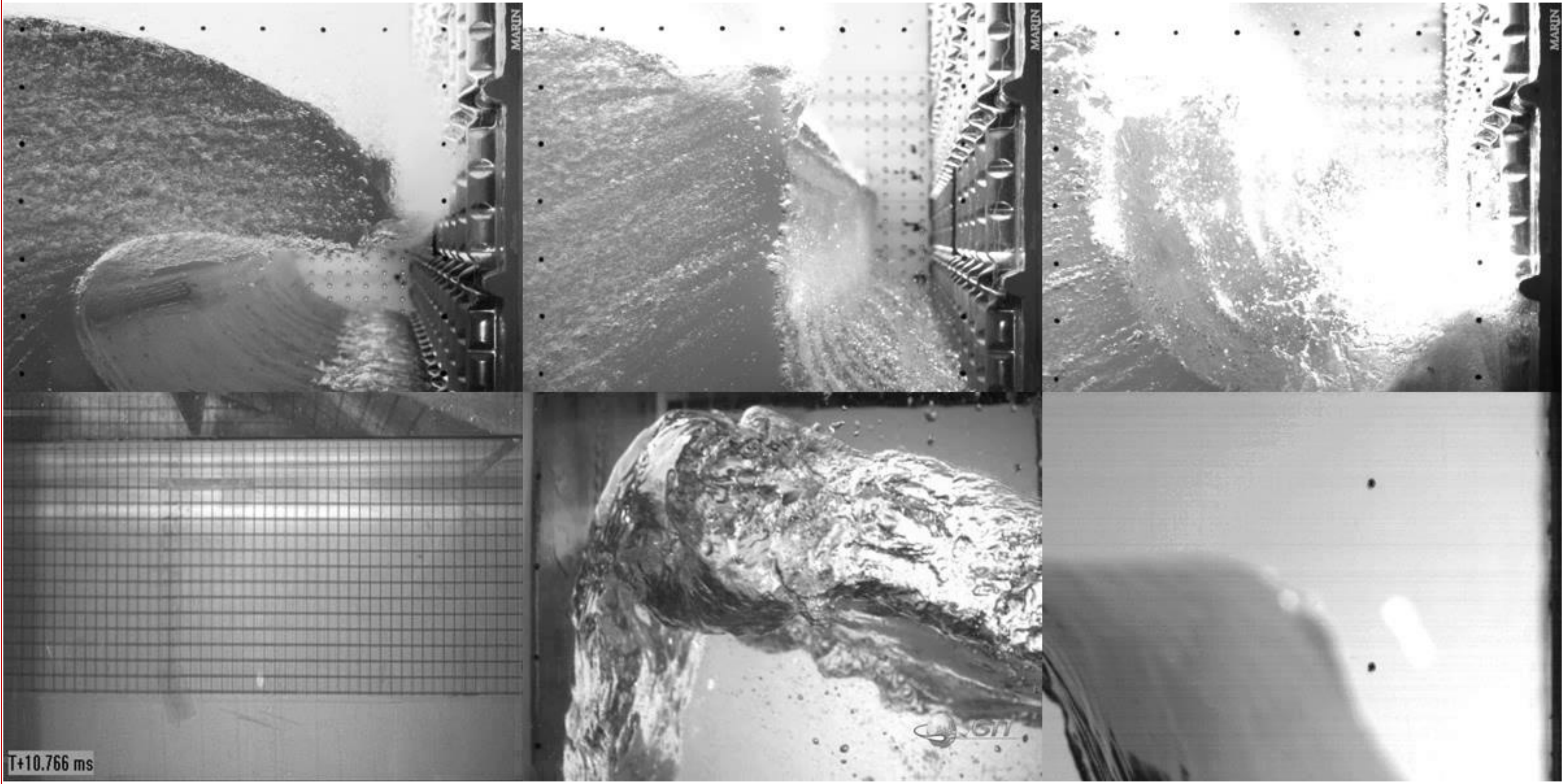
- **Objectives of sloshing studies:**
  - Determine the design loads for the containment system
  - Determine the design loads for the pump towers



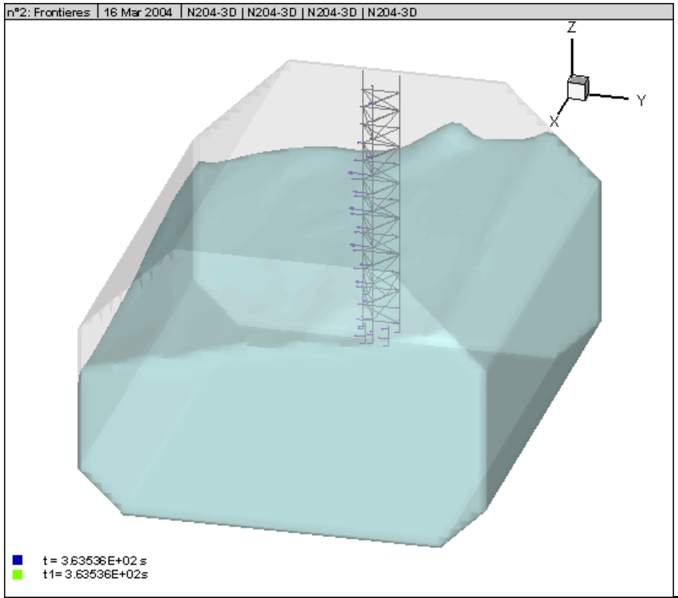
Sloshing model tests

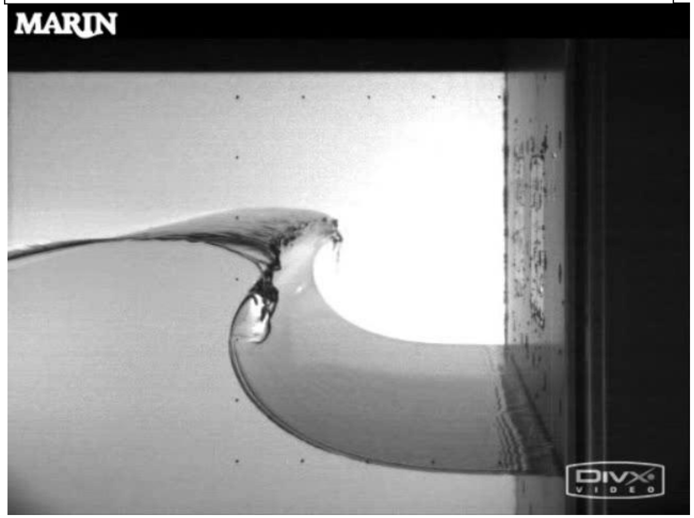
2 Context of wave impacts

Different types of tests carried out in order to understand sloshing physics



Phenomenology of a liquid impact

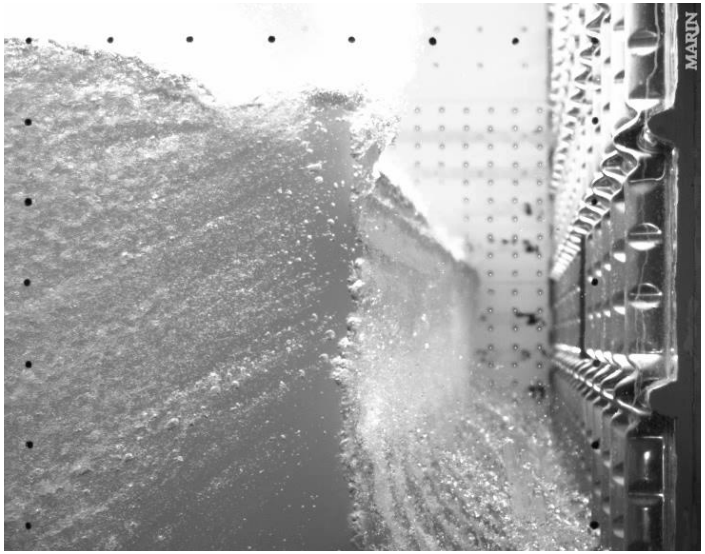


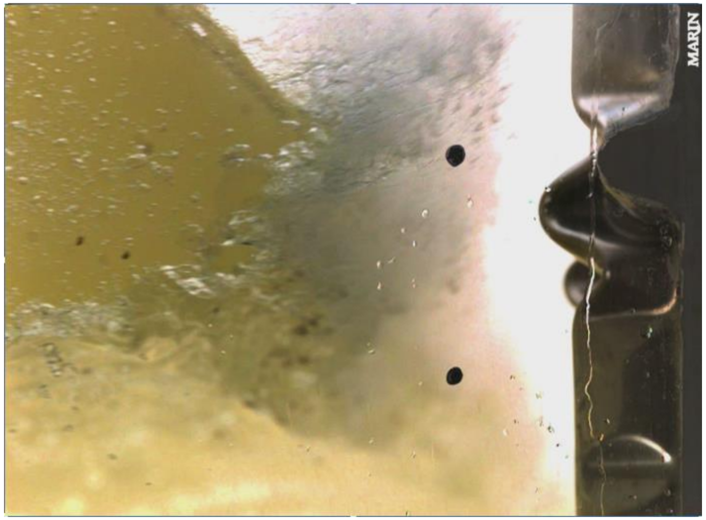


- Global flow
  - Global flow is governed by gravity (Froude)
- Local behavior during impacts
  - Transfer of mechanical energy from liquid to gas
  - Gas compression during escaping and possible entrapment
  - Phase transition during gas compression
  - Rapid change of liquid momentum when avoiding the wall
  - Possible creation of pressure wave
  - Fluid-structure interaction
  - Free surface instabilities

HydrOcean ENSTA Bretagne ECN

Phenomenology of a liquid impact





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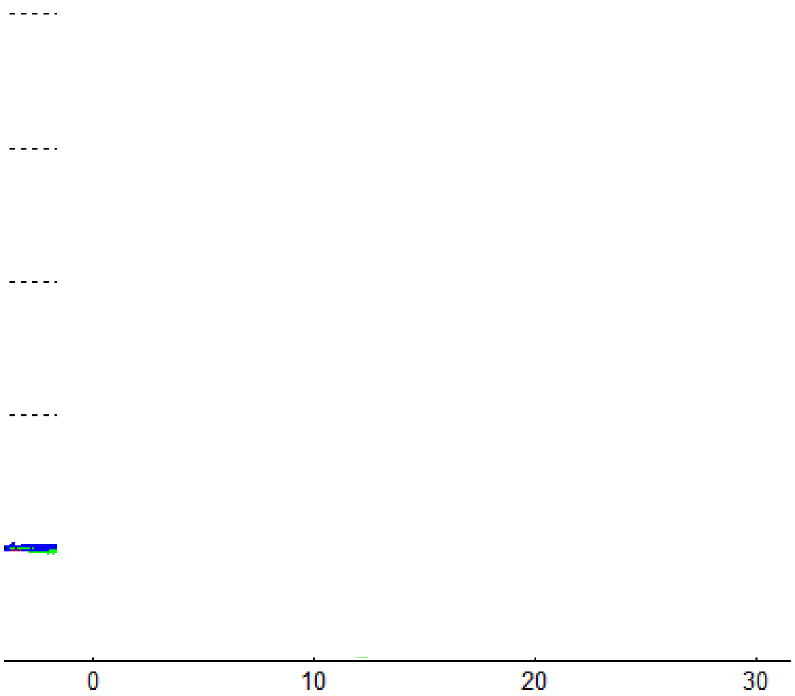
  - Rapid change of liquid momentum when avoiding the wall
  - **Possible creation of pressure wave**
  - **Fluid-structure interaction**
  - **Free surface instabilities**

Gas-pocket impact during sloshing model tests

- Pressure signals from a column of 27 sensors



Gas-pocket impact during sloshing model tests

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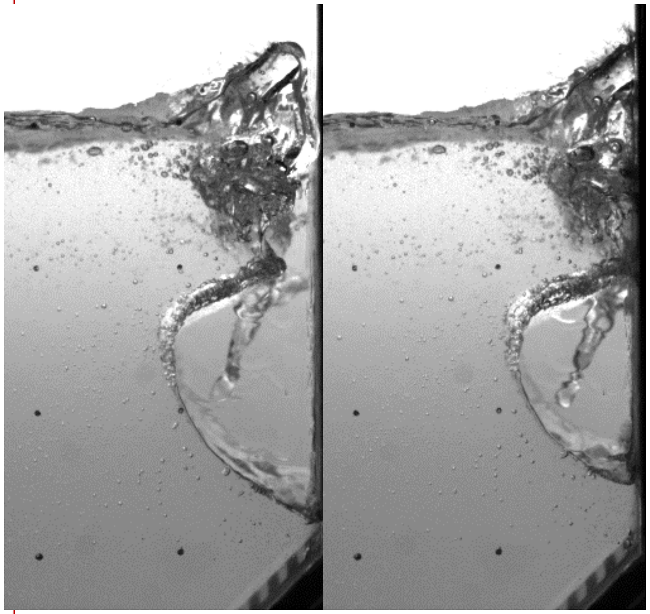

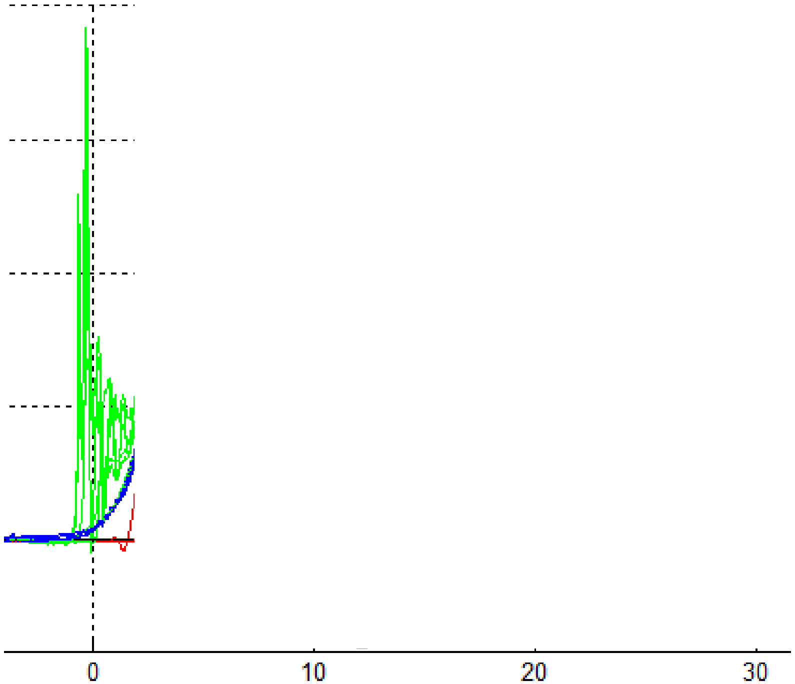

Gas-pocket impact during sloshing model tests

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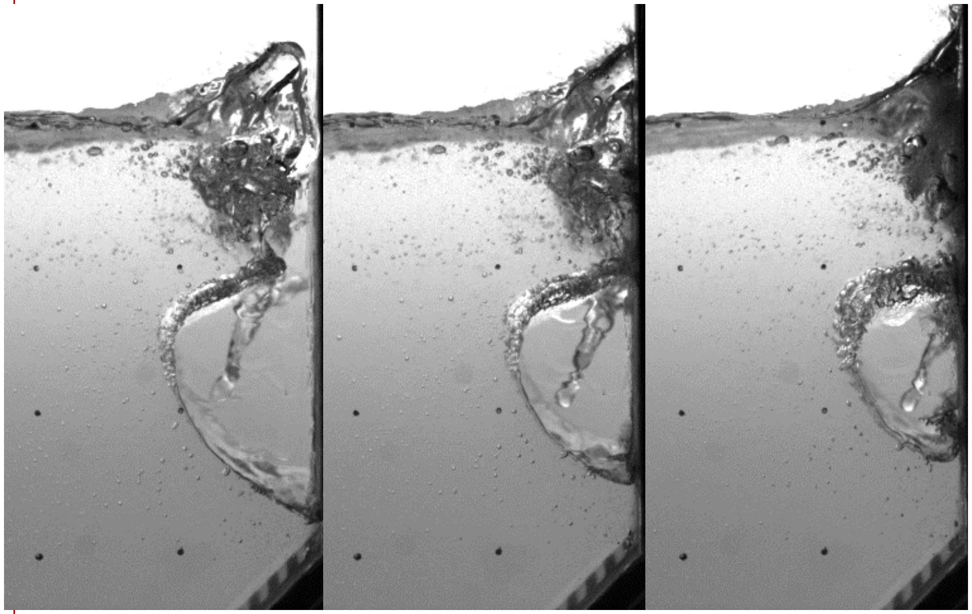

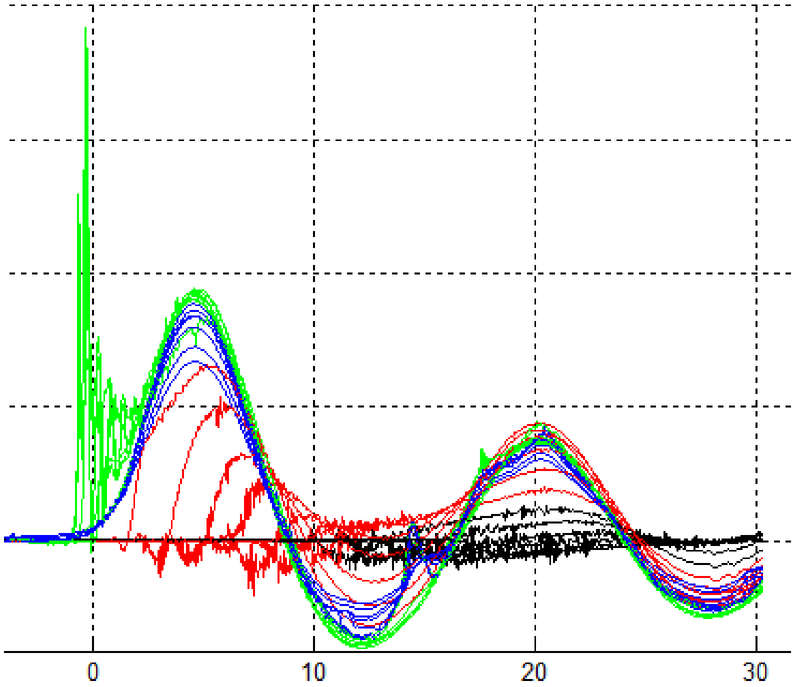

Gas-pocket impact during sloshing model tests

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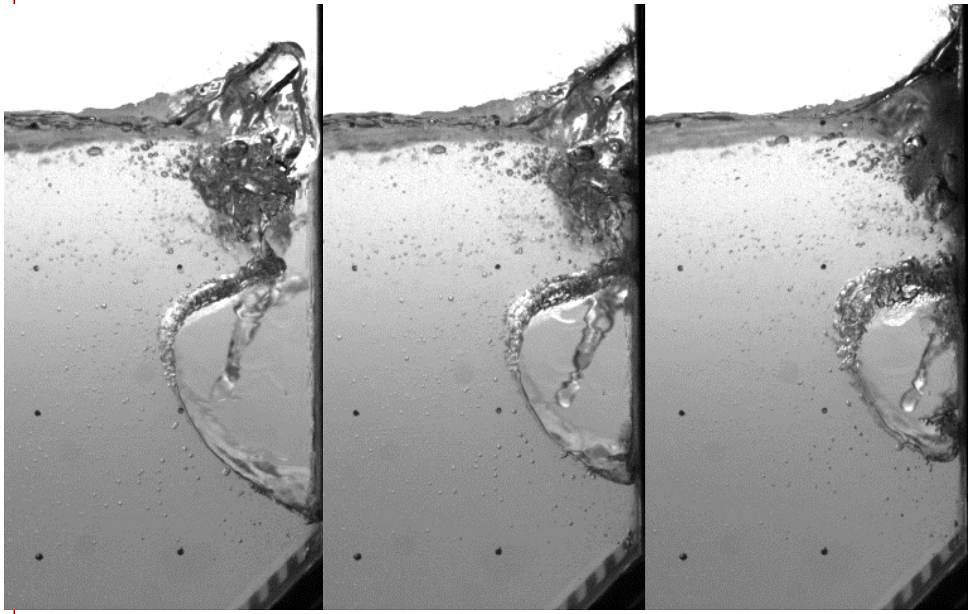
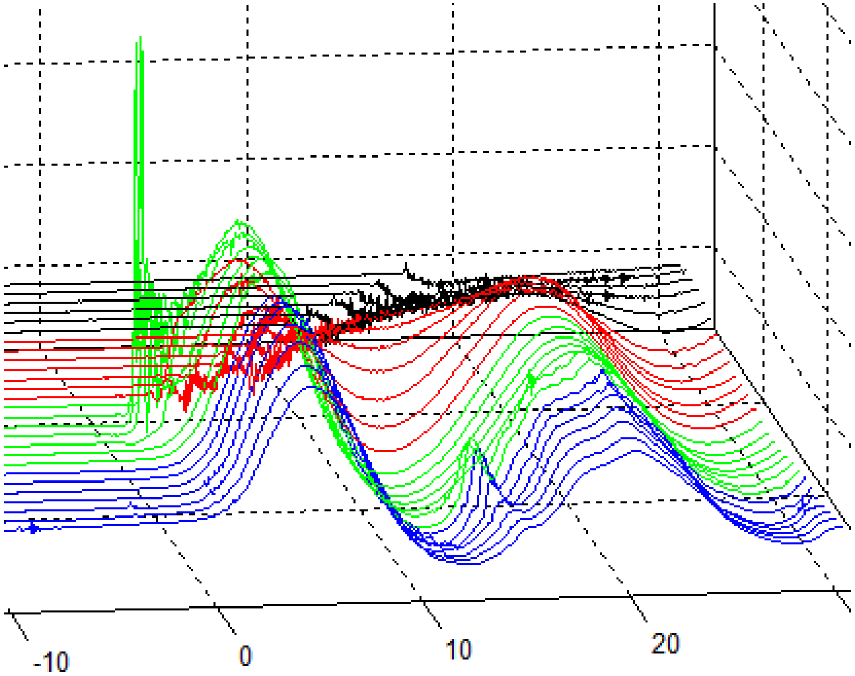
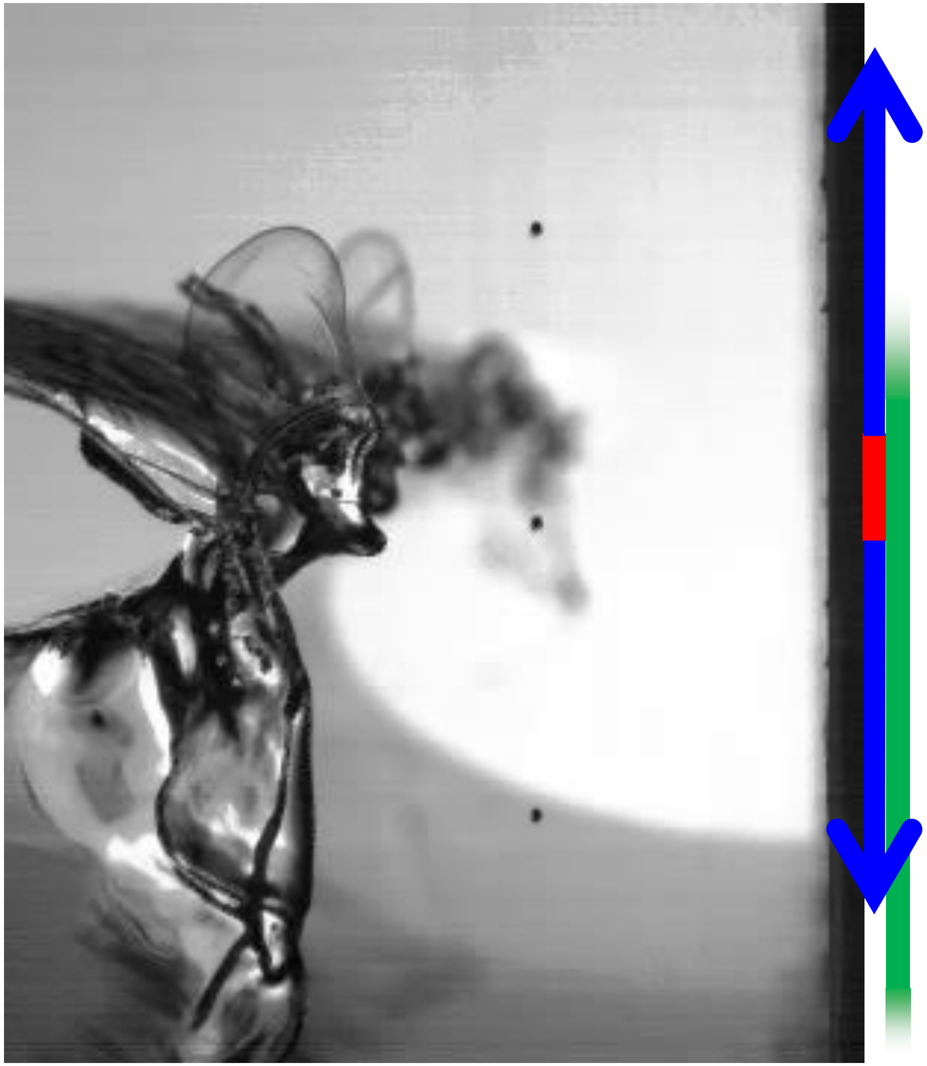




Elementary Loading Process (ELP)

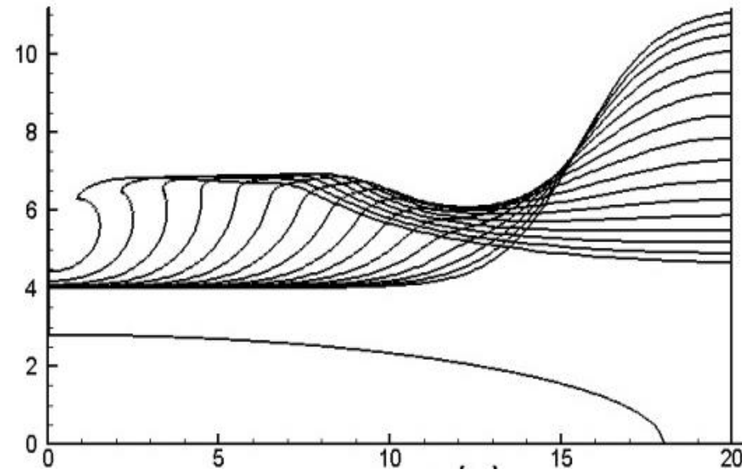


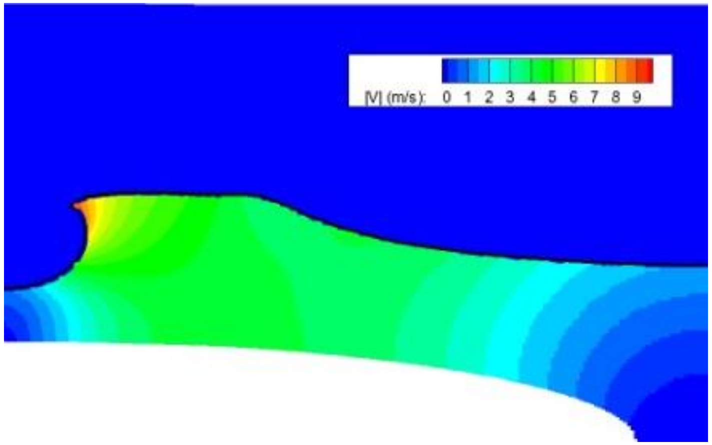
- Direct impact — ELP1
- Building jet — ELP2
- Compression of escaping or entrapped gas — ELP3

3 Numerical strategy, Software presentation, Waves selection

General strategy for wave impact simulation

- **FSID: wave generation and propagation** ENSTA Bretagne
  - Highly non linear free surface flows
  - Potential code based on:
    - Desingularized technique
    - Transformal mappings
  - Liquid phase only (no gas)
  - Objective:
    - Create simply wave impact conditions
  - Means:
    - Arbitrary shape of the initial free surface
    - Bathymetry
- **SPH-Flow: impact simulation** HydrOcean ECN
  - Restart with FSID data at a late stage
  - Gas starts at rest

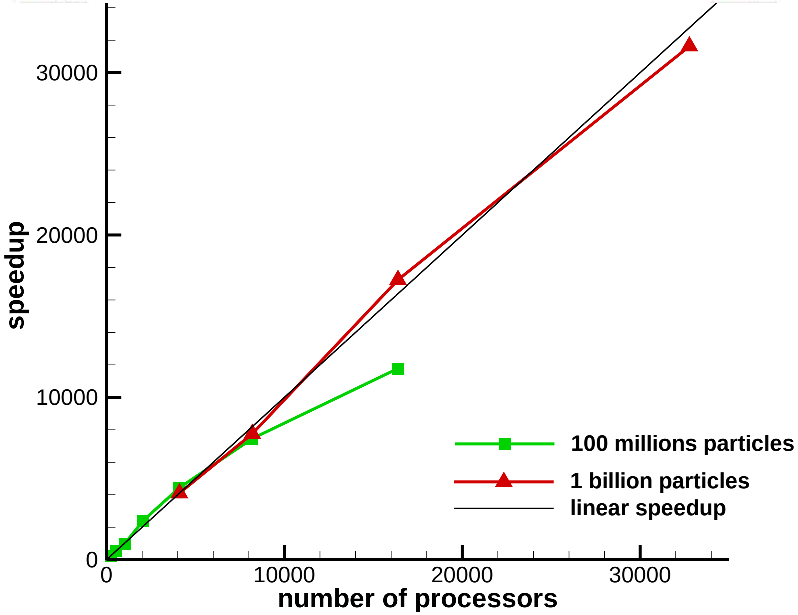




HydrOcean ENSTA Bretagne ECN

SPH-Flow Software

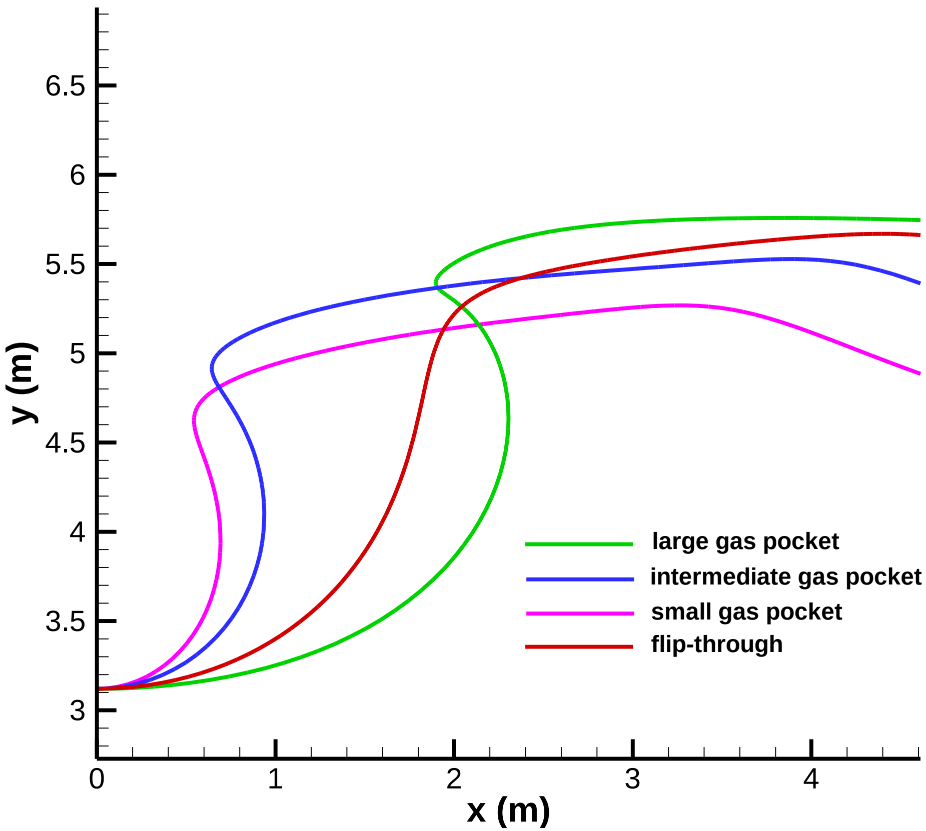
- **Developed by ECN and HydrOcean (9 PhD)**
- **Advanced fluid formulations compared with standard SPH**
  - Riemann solvers for stability
  - Renormalization for accuracy
- **Structural model (PhD supported by GTT)**
  - Elastic model for structure
- **Fluid / Structure interaction**
  - Natural and strong coupling
- **Parallelization**
  - domain decomposition (MPI comm.)
  - Efficient scalability (4000 cores)
  - Up to 1 billion particles



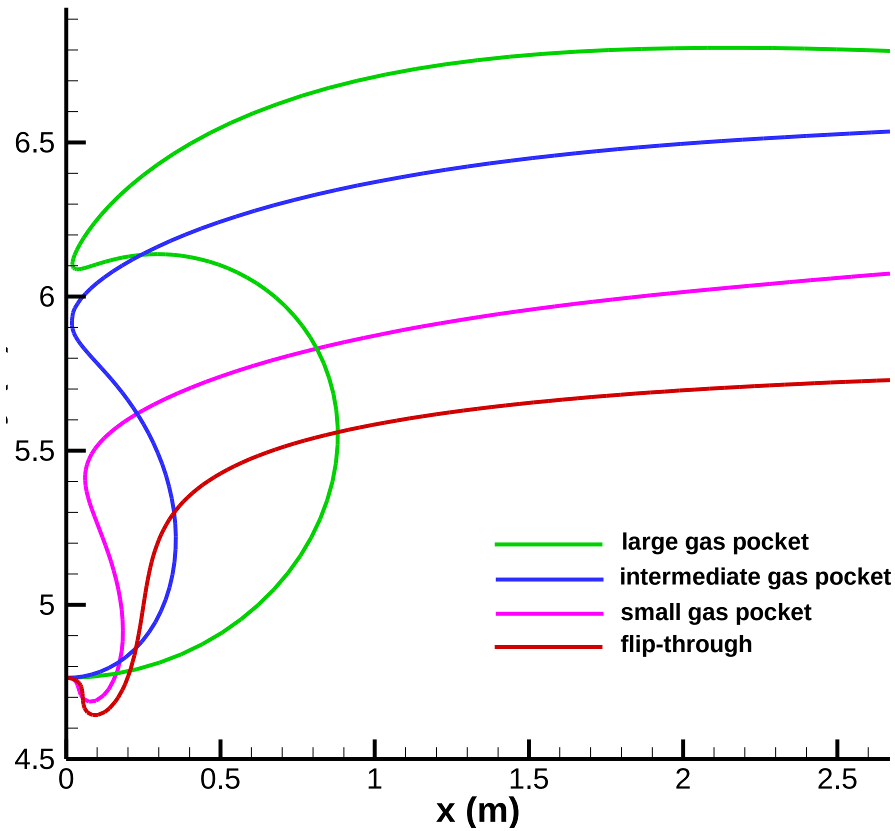
HydrOcean ENSTA Bretagne ECN

Selection of four wave shapes by FSID

- Selected waves at t0

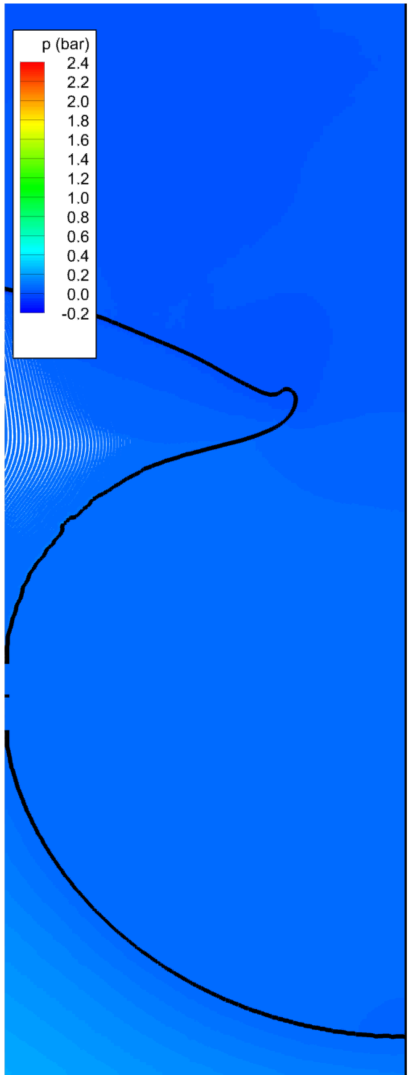


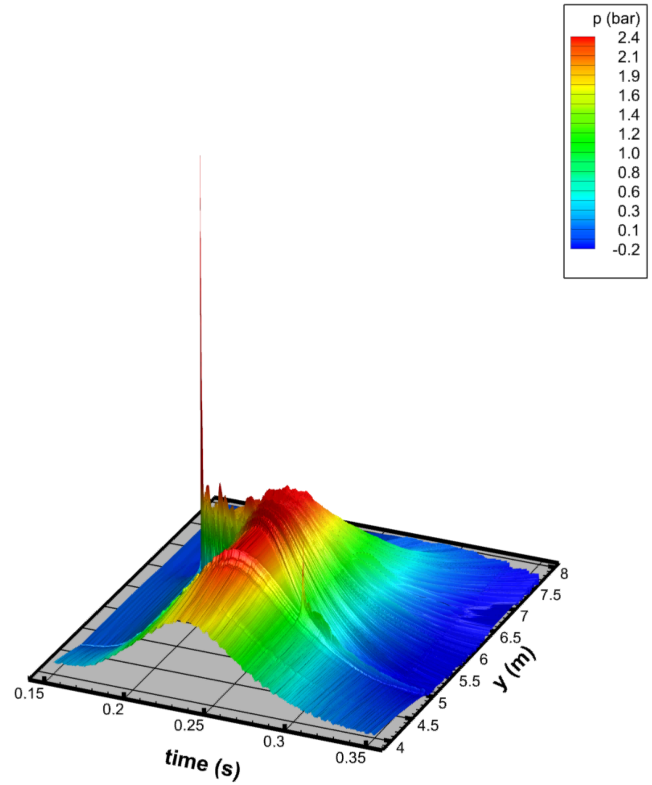
- Selected waves before impact



4 2D simulations of three breaking wave impacts on a flat rigid wall

Large gas-pocket impact

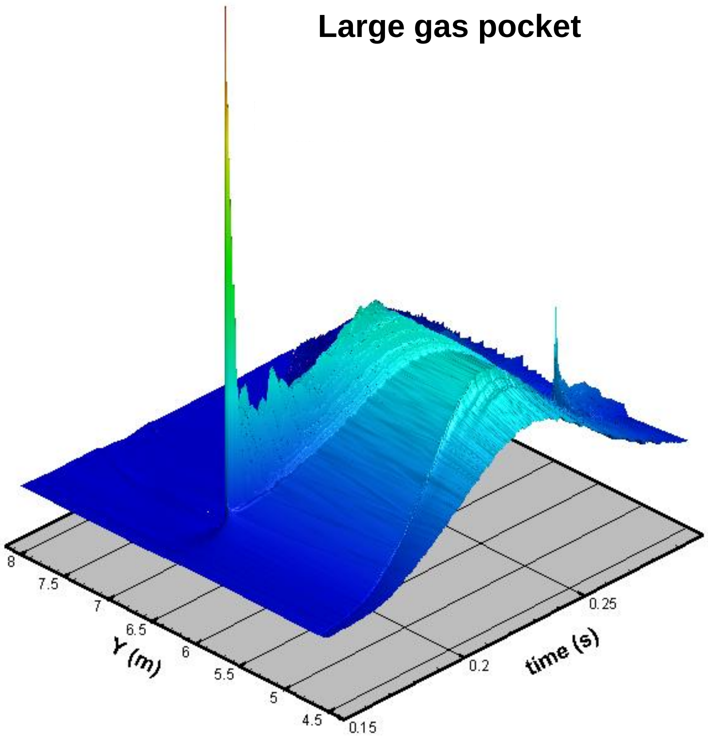




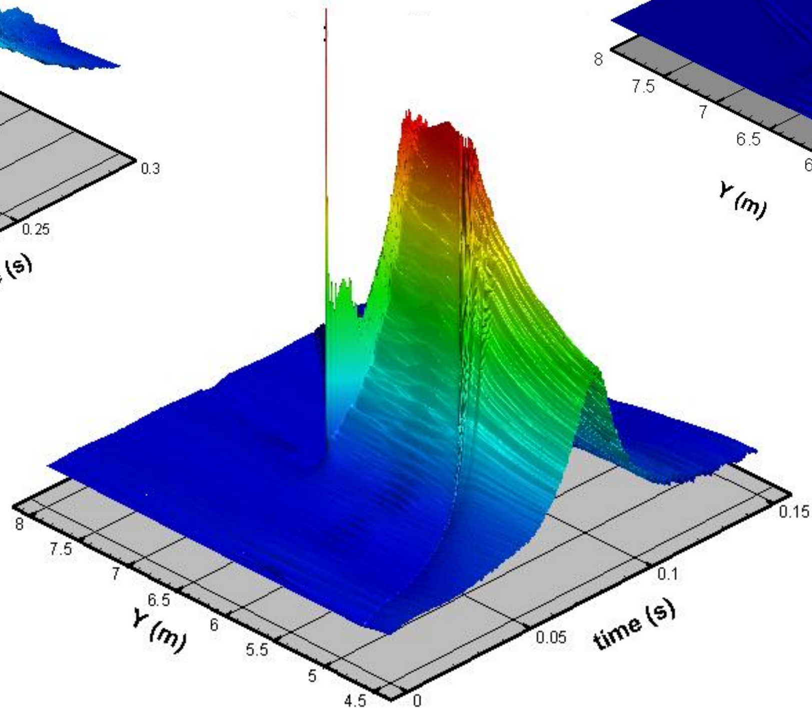
HYDROCEAN

Gas-pocket impacts: Pressure maps

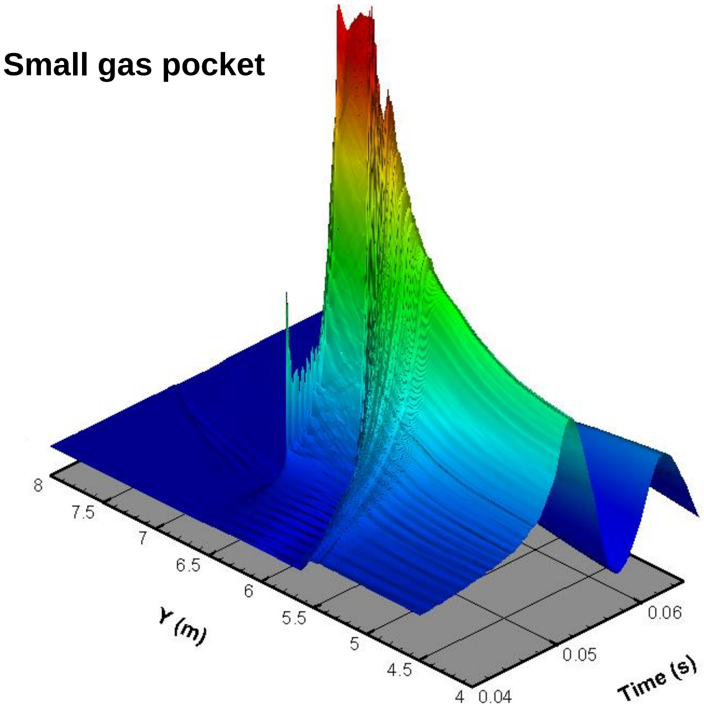
Large gas pocket



Intermediate gas pocket

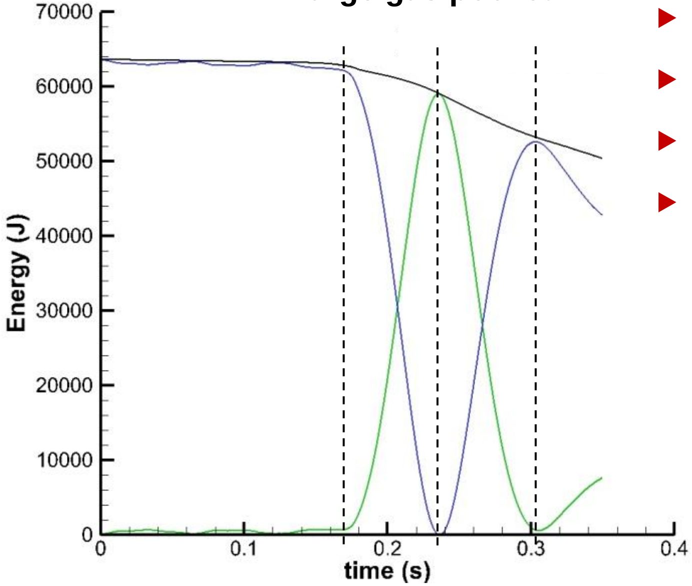


Small gas pocket



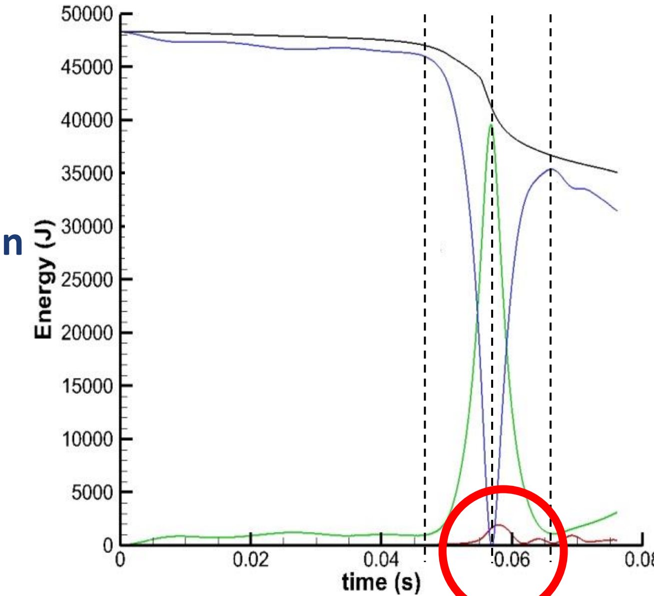
Energy curves: impact phases

Large gas pocket

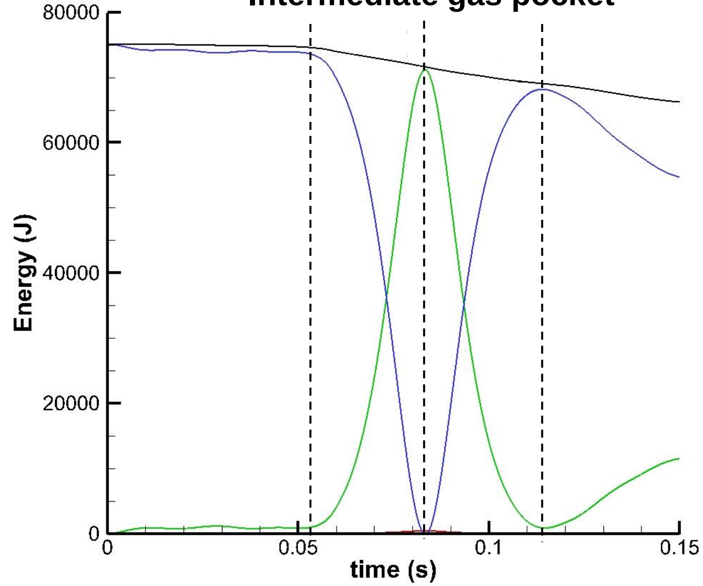


- Wave Propagation
- Gas pocket compression
- Pressure wave
- Gas pocket expansion

Small gas pocket



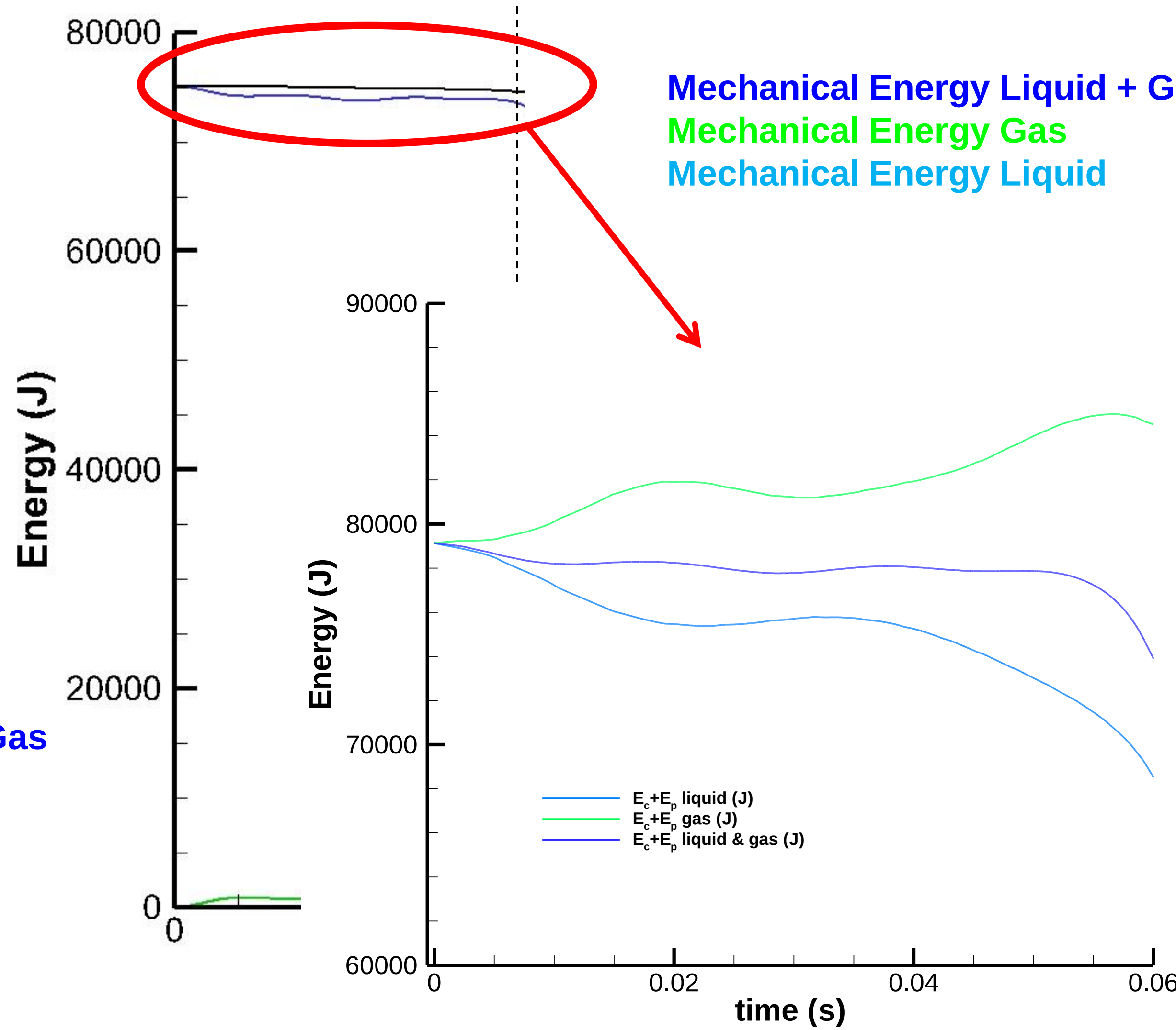
Intermediate gas pocket



Mechanical Energy Liquid + Gas
Internal Energy Gas
Internal Energy Liquid
Total Energy

Gas-pocket impacts: Wave propagation

Energy Transfer from liquid to gas
Incompressible Gas Flow



Mechanical Energy Liquid + Gas
Mechanical Energy Gas
Mechanical Energy Liquid

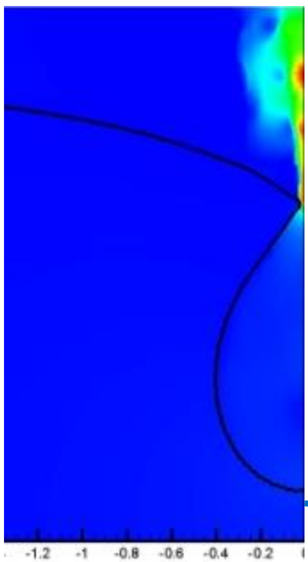
Mechanical Energy Liquid + Gas
Internal Energy Gas
Total Energy

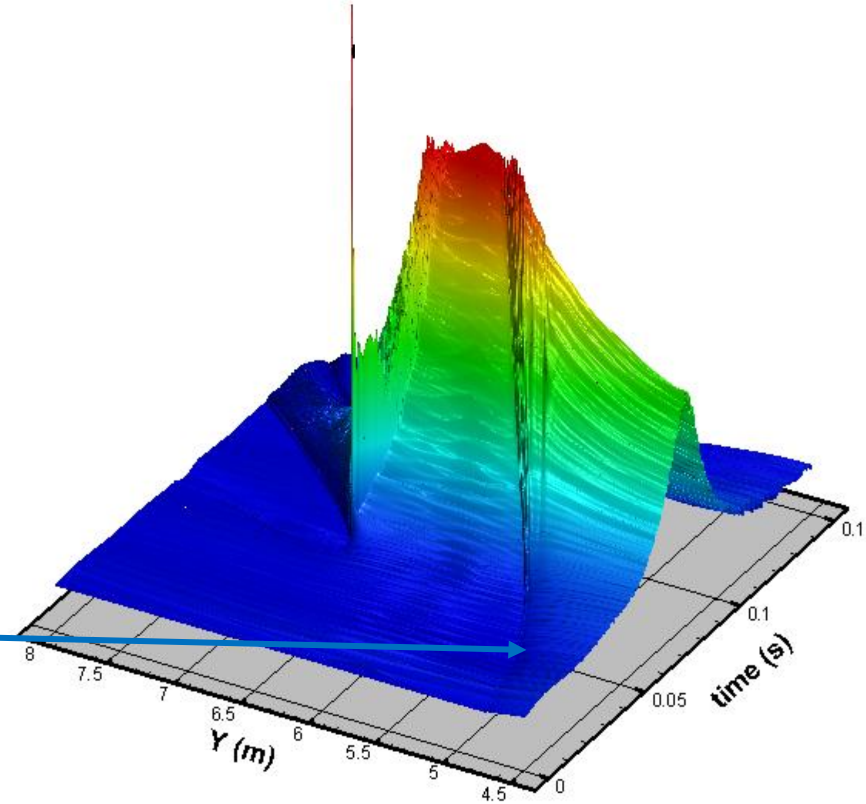
Gas-pocket impacts: impact chart

Energy Transfer from liquid to gas

Incompressible Gas Flow

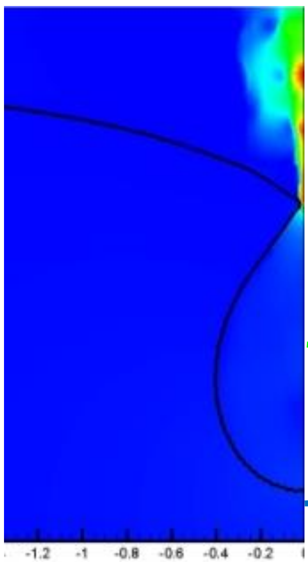
Building Jet (ELP2)

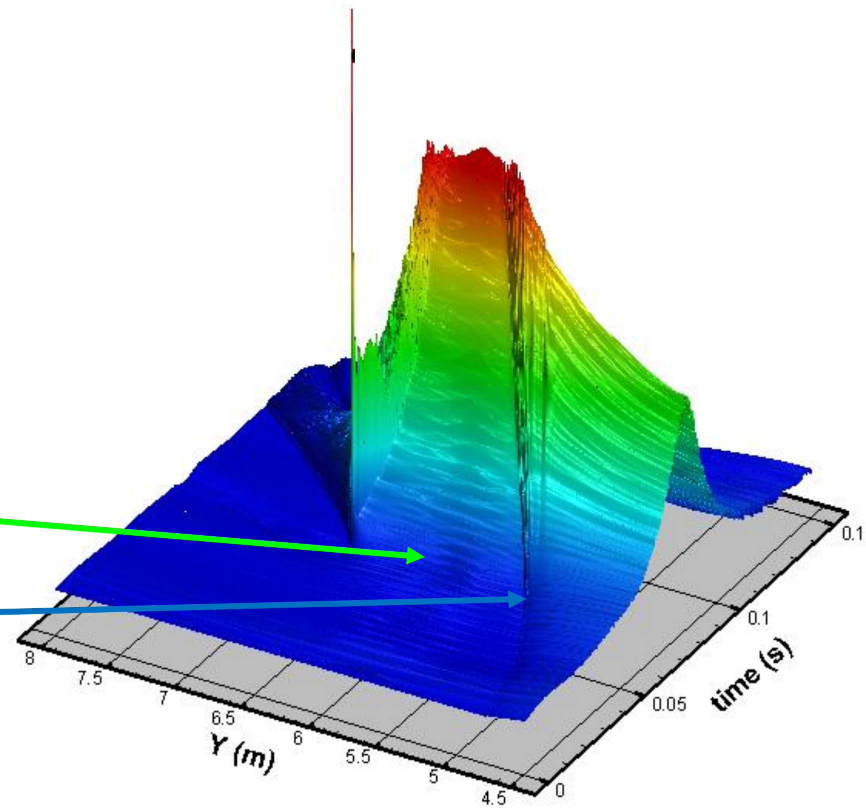




Gas-pocket impacts: impact chart

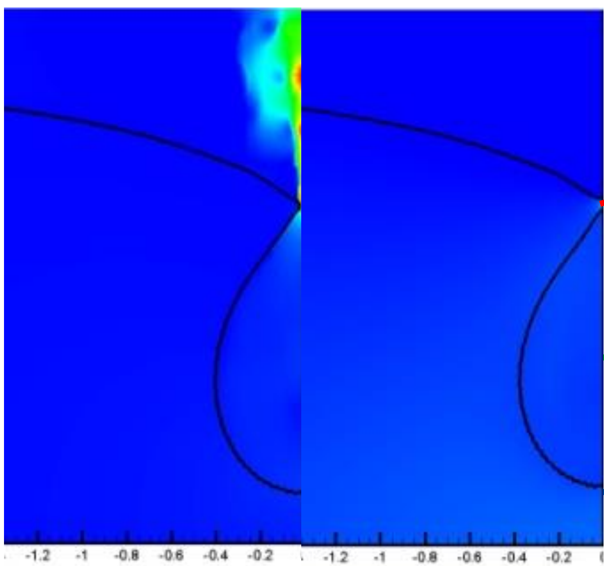
Transfer of energy from liquid to gas (Density Ratio influence)	
Incompressible Gas Flow	Compressed Gas (ELP3)
Building Jet (ELP2)	

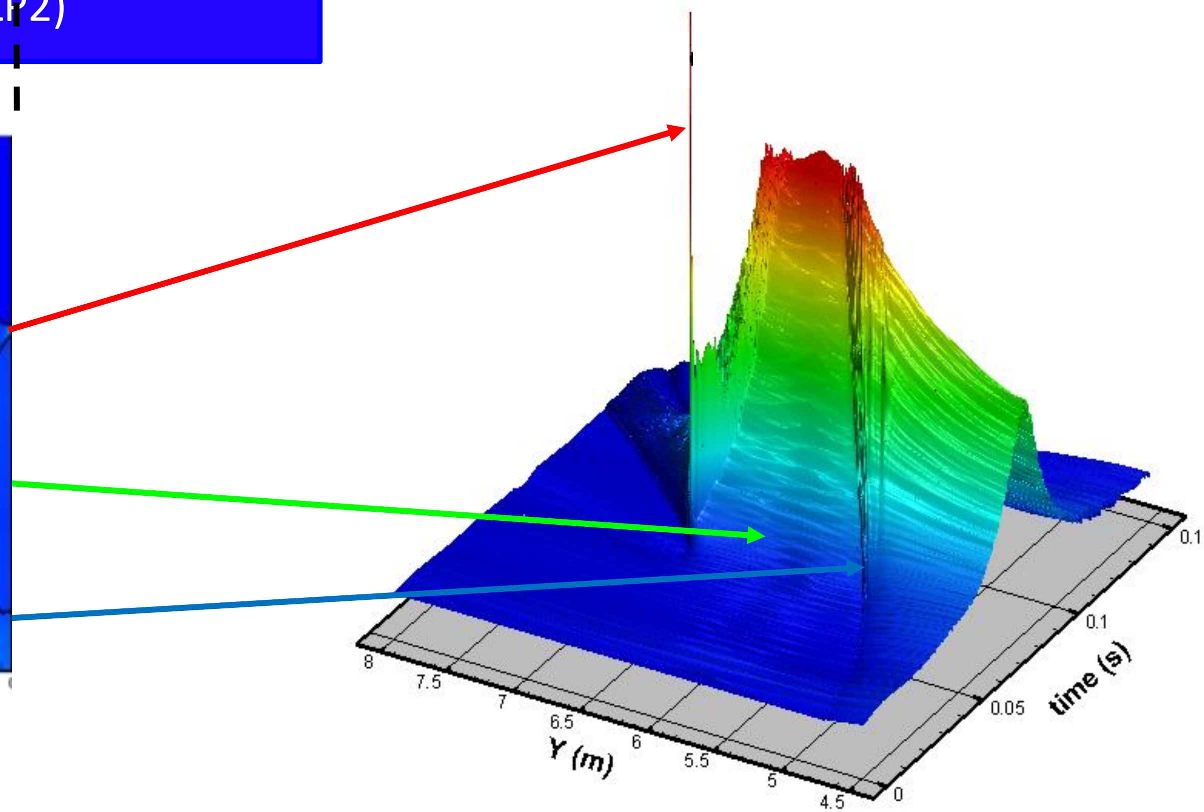




Gas-pocket impacts: impact chart

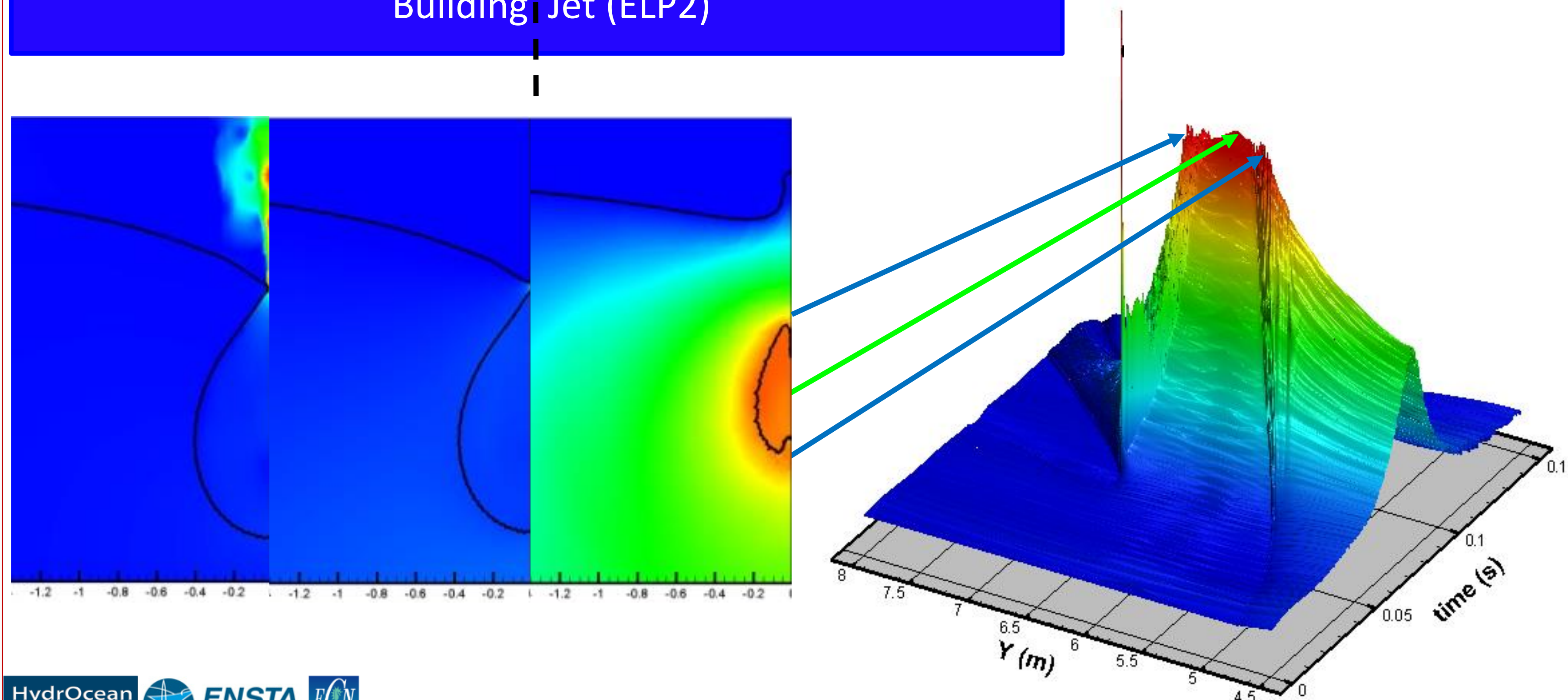
Transfer of energy from liquid to gas (Density Ratio influence)		Direct Impact (ELP1)
Incompressible Gas Flow	Compressed Gas (ELP3)	
Building Jet (ELP2)		



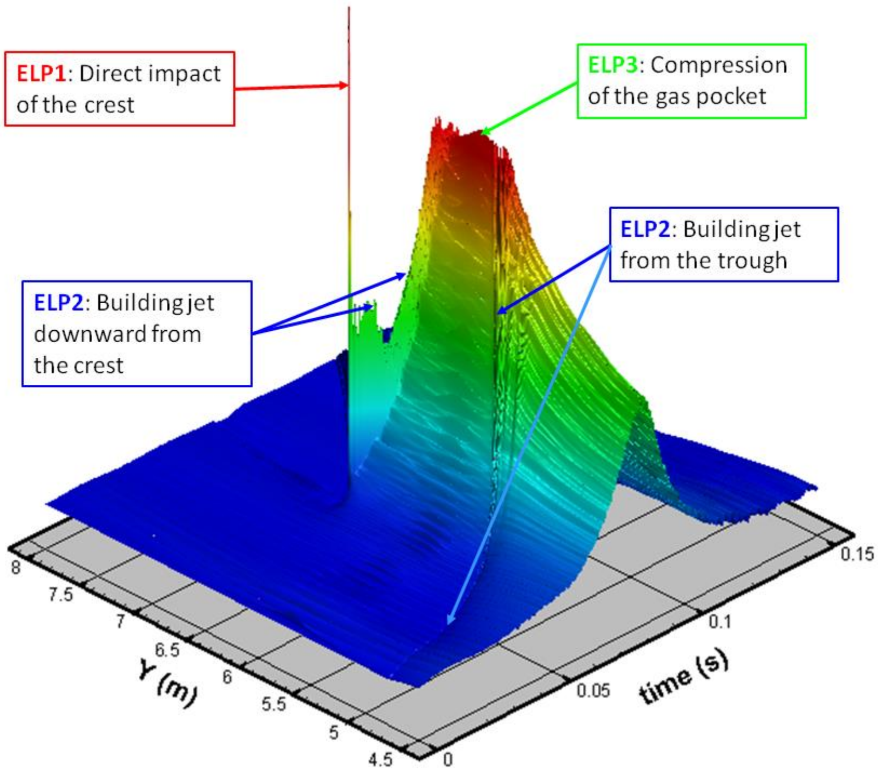


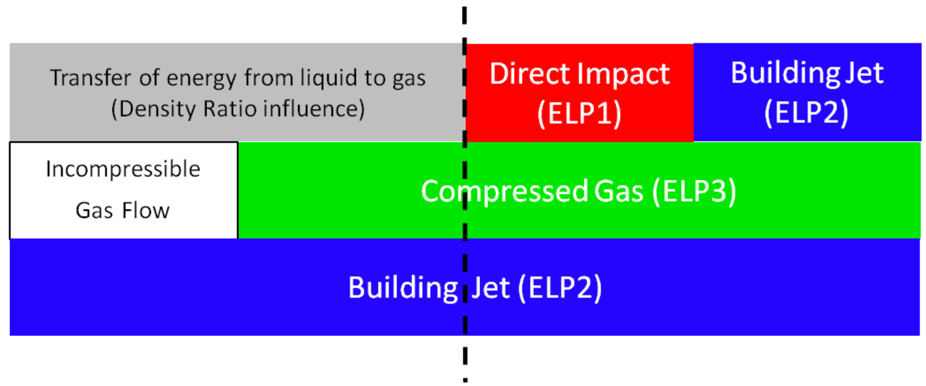
Gas-pocket impacts: impact chart

Transfer of energy from liquid to gas (Density Ratio influence)		Direct Impact (ELP1)	Building Jet (ELP2)
Incompressible Gas Flow	Compressed Gas (ELP3)		
Building Jet (ELP2)			

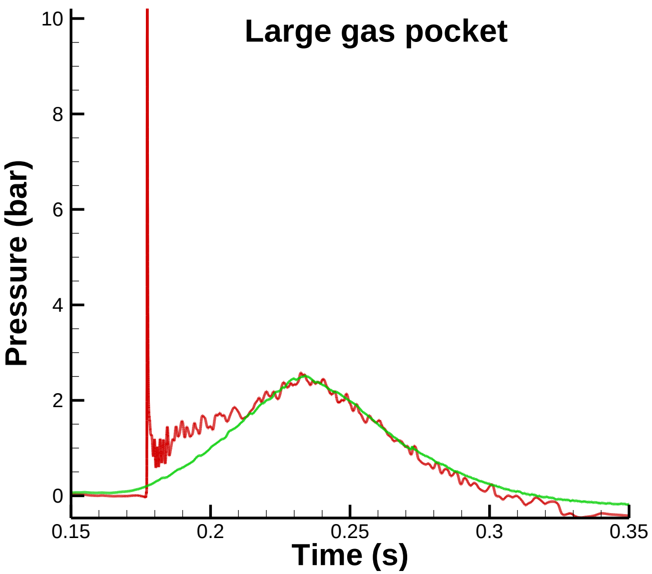


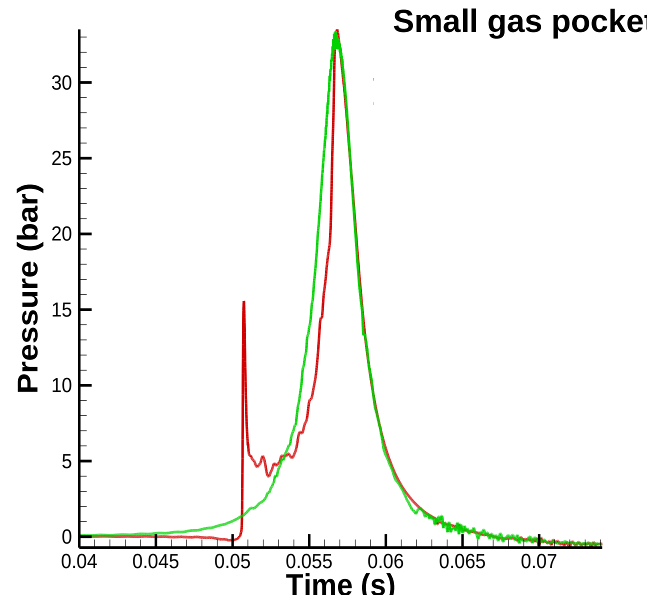
Elementary Loading Processes (ELPs)

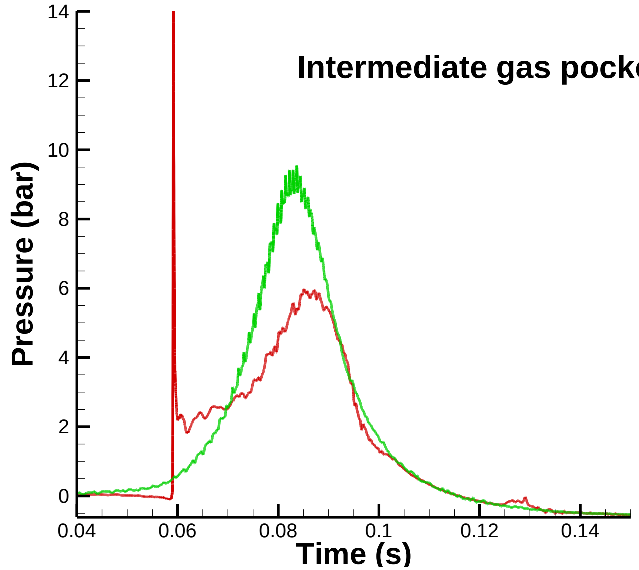




Gas-pocket impacts: Characteristic pressures



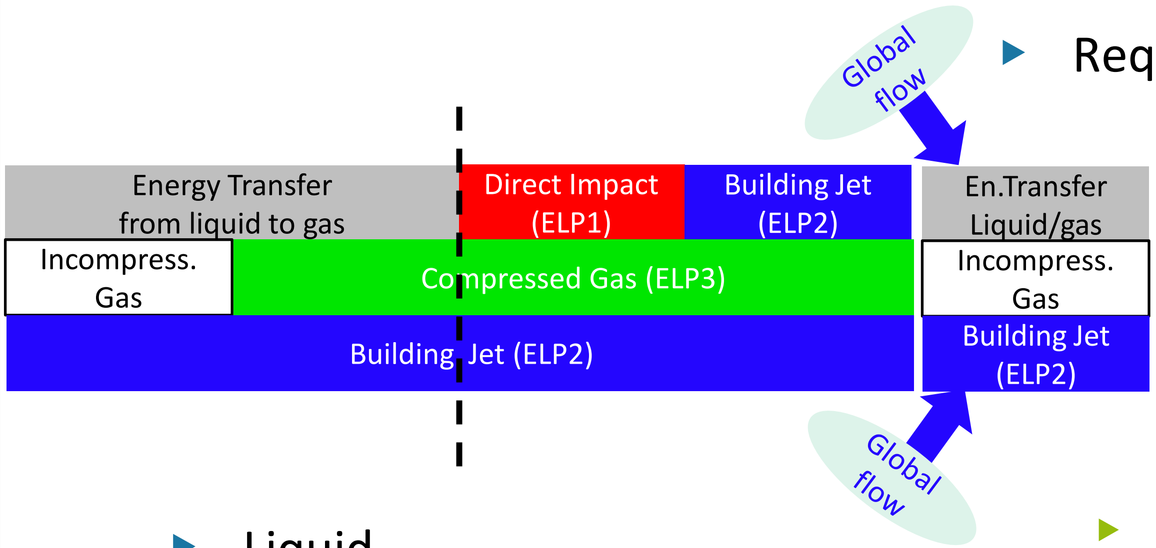




Pressure signal at crest level
Pressure signal in gas pocket

5 Scaling principle

Complete Froude scaling for a gas-pocket impact



Scale 1

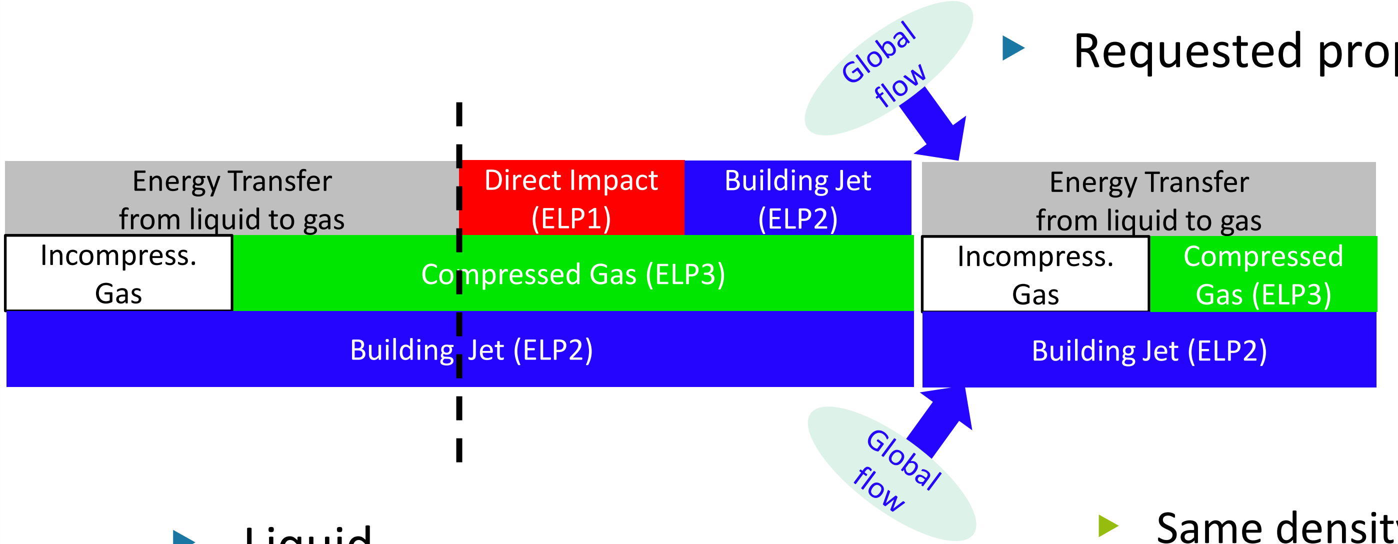
- Liquid
  - $(\rho_l)_1$
  - $(c_{liq})_1$
- Gas
  - $(\rho_{gas})_1$
  - $(c_{gas})_1$

Scale 1:λ

- Requested properties for CFS
- Same density ratio: $DR_{1/\lambda}=DR_1$
  - $(\rho_g)_{1/\lambda}/(\rho_l)_{1/\lambda}= (\rho_g)_1/(\rho_l)_1$

Complete Froude scaling for a gas-pocket impact

- **Scale 1**
- **Scale 1:λ**
  - Requested properties for CFS

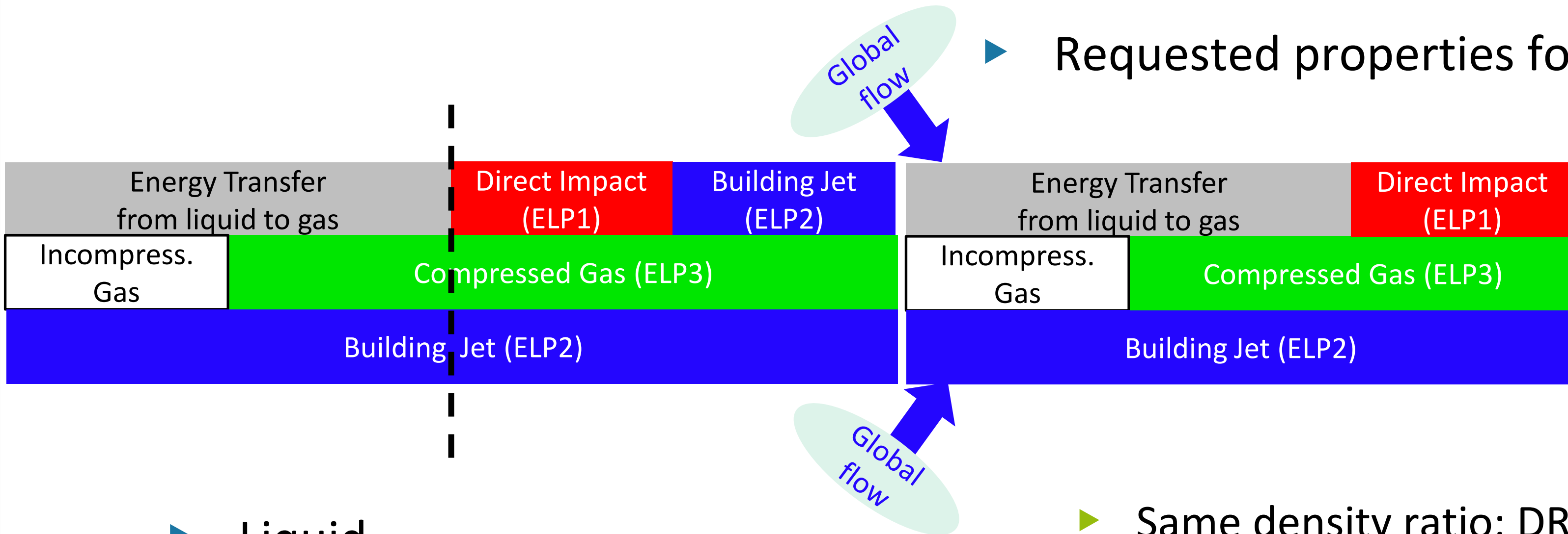


- Liquid
  - $(\rho_l)_1$
  - $(c_{liq})_1$
- Gas
  - $(\rho_{gas})_1$
  - $(c_{gas})_1$

- Same density ratio: $DR_{1/\lambda}=DR_1$
  - $(\rho_g)_{1/\lambda}/(\rho_l)_{1/\lambda}= (\rho_g)_1/(\rho_l)_1$
- Mach similarity into the gas
  - $(c_g)_{1/\lambda} = (c_g)_1/\sqrt{\lambda}$

Complete Froude scaling for a gas-pocket impact

- **Scale 1**
- **Scale 1:λ**
  - Requested properties for CFS



- Liquid
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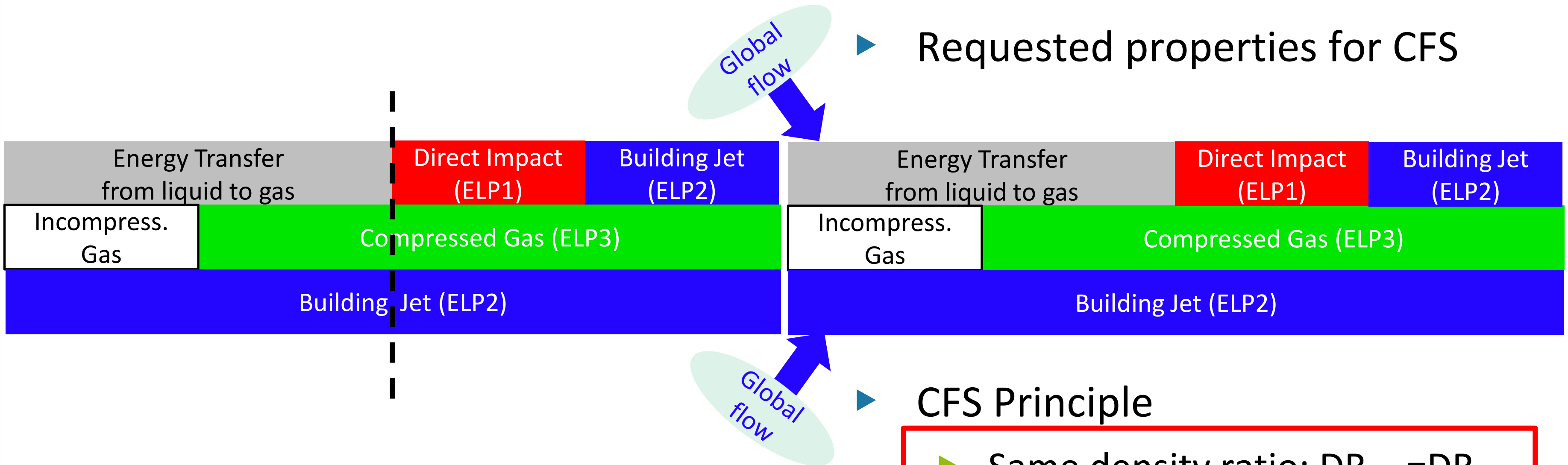
Complete Froude scaling for a gas-pocket impact

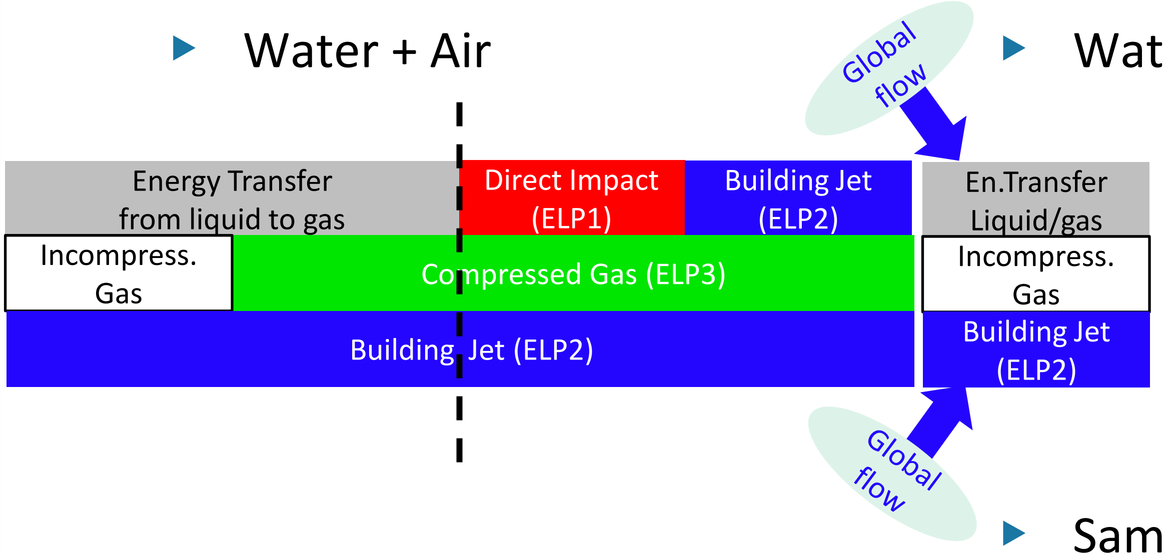
- **Scale 1**
- **Scale 1:λ**
  - Requested properties for CFS



  - CFS Principle
    - Same density ratio: $DR_{1/\lambda}=DR_1$
      - $(\rho_g)_{1/\lambda}/(\rho_l)_{1/\lambda}=(\rho_g)_1/(\rho_l)_1$
    - Mach similarity into the gas
      - $(c_g)_{1/\lambda}=(c_g)_1/\sqrt{\lambda}$
    - Mach similarity into the liquid
      - $(c_l)_{1/\lambda}=(c_l)_1/\sqrt{\lambda}$

Partial Froude scaling for a gas-pocket impact

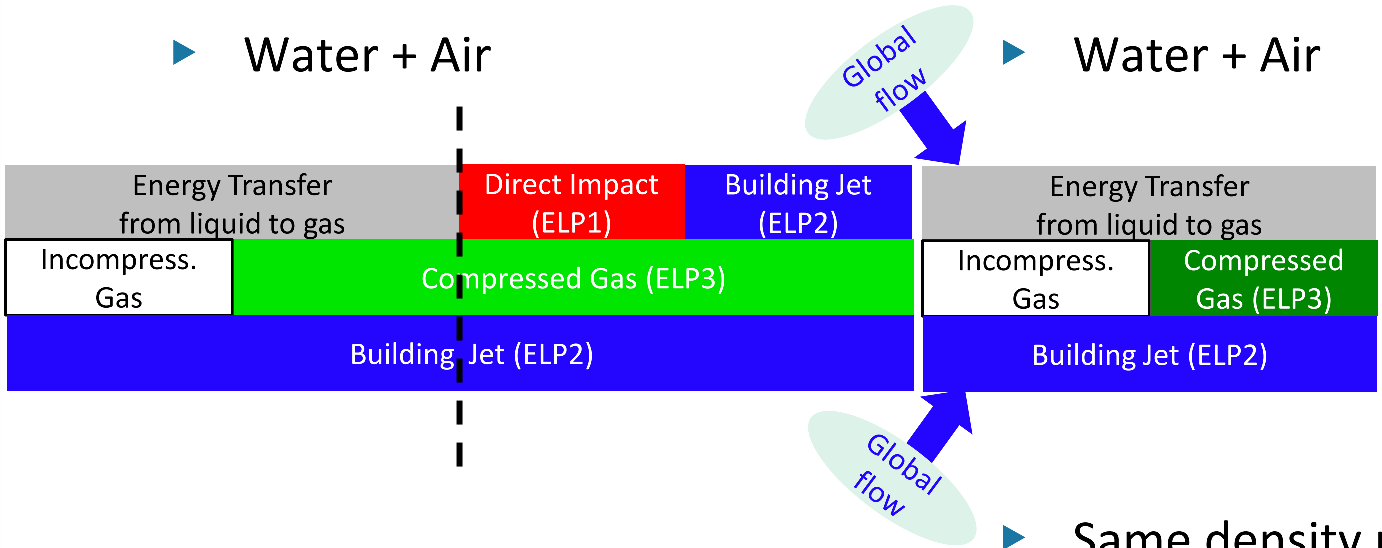
- **Scale 1**
  - Water + Air
- **Scale 1:6**
  - Water + Air



- Same density ratio: OK

Partial Froude scaling for a gas-pocket impact

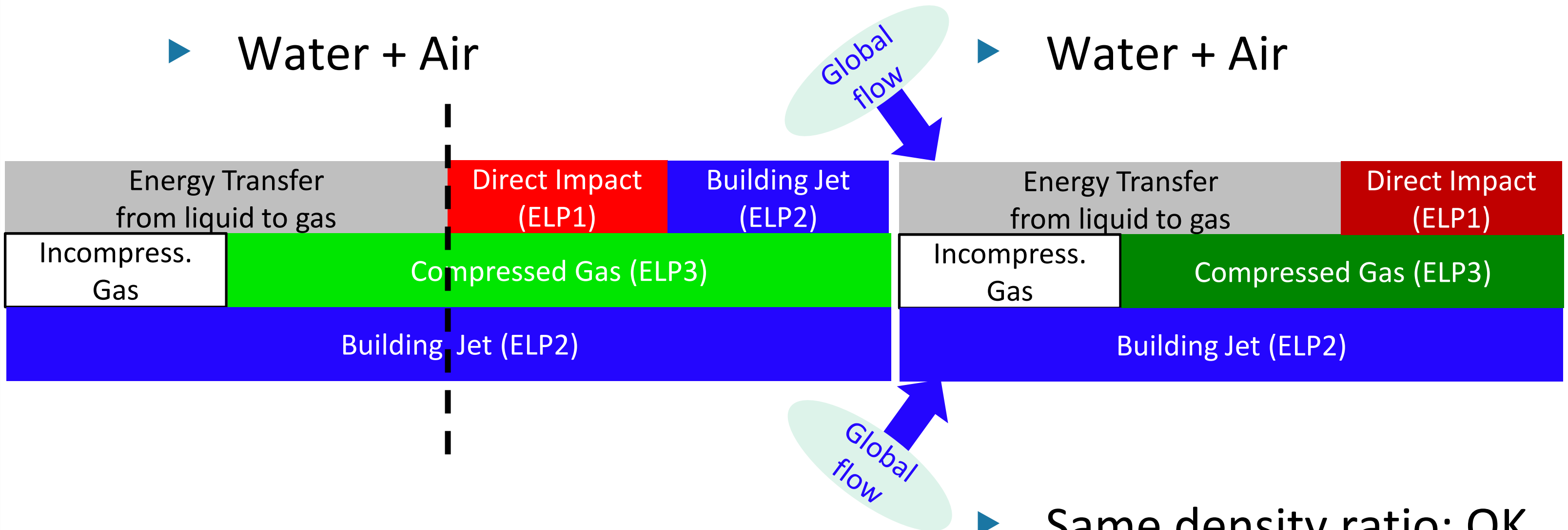
- **Scale 1**
  - Water + Air
- **Scale 1:λ**
  - Water + Air



- Same density ratio: OK
- Gas compressibility bias
  - Gas is much too stiff

Partial Froude scaling for a gas-pocket impact

- **Scale 1**
  - Water + Air
- **Scale 1:λ**
  - Water + Air



- Same density ratio: OK
- Gas compressibility bias
  - Gas is much too stiff
- Liquid compressibility bias
  - Liquid is much too stiff

Partial Froude scaling for a gas-pocket impact

- **Scale 1**
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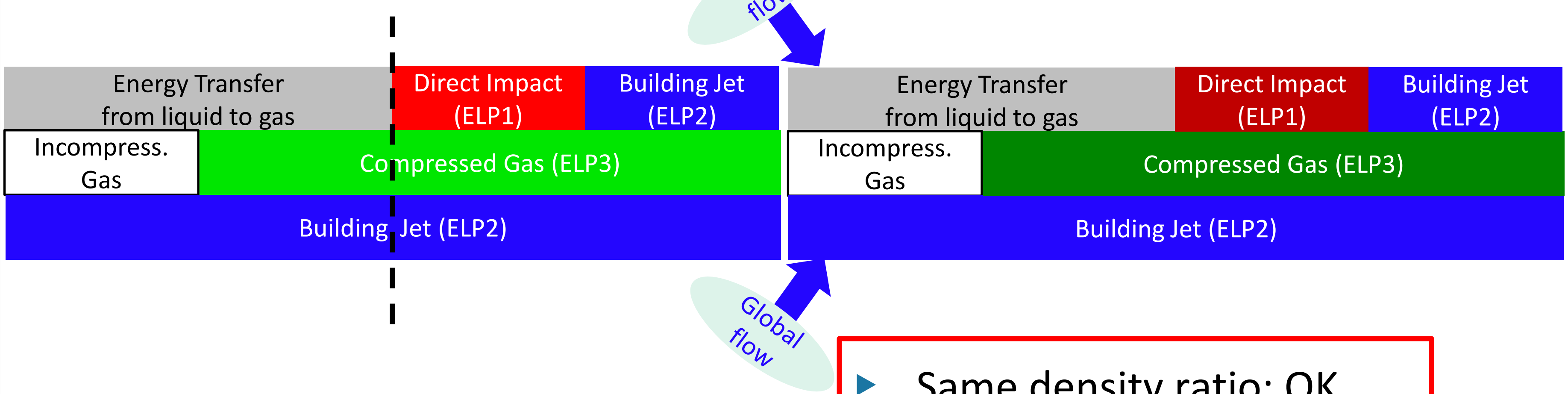
- **Scale 1:λ**
  - Water + Air



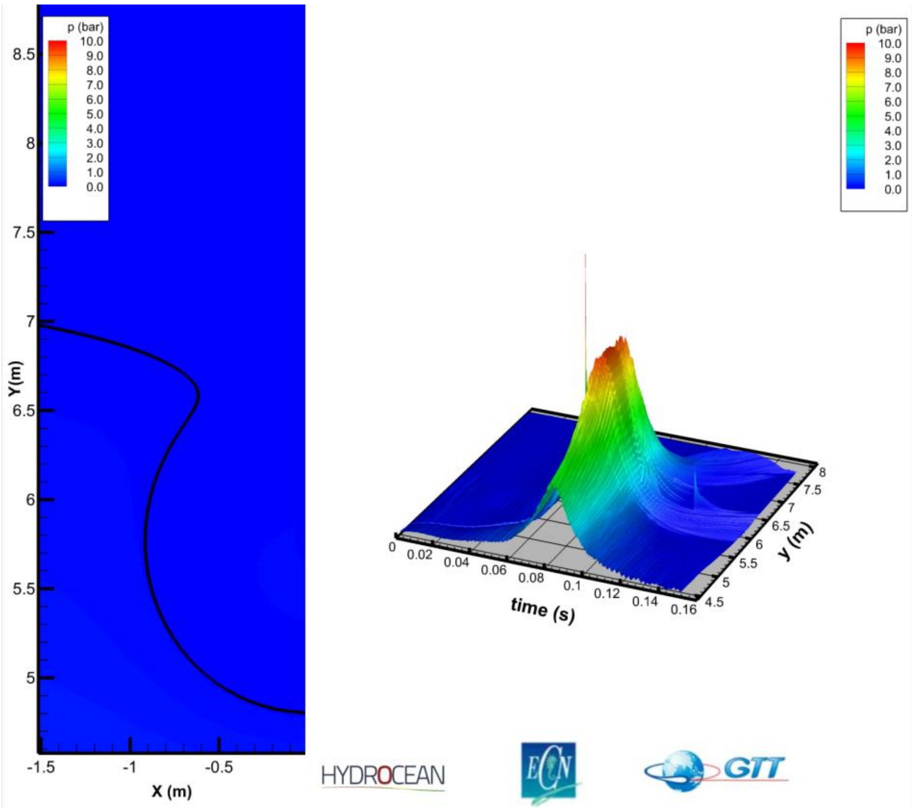
- Same density ratio: OK
- Gas compressibility bias
  - Gas is much too stiff
- Liquid compressibility bias
  - Liquid is much too stiff

6 2D simulations of three breaking wave impacts on a flat rigid wall: Comparison scale 1 and scale 1:6

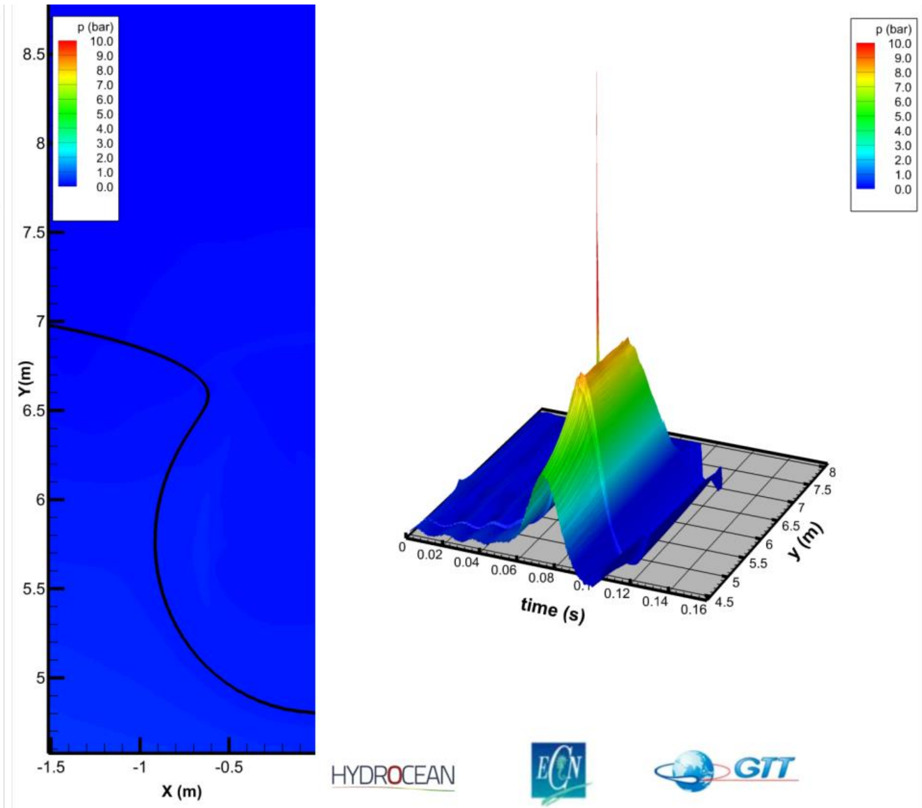
Intermediate gas-pocket impacts

Start/Stop

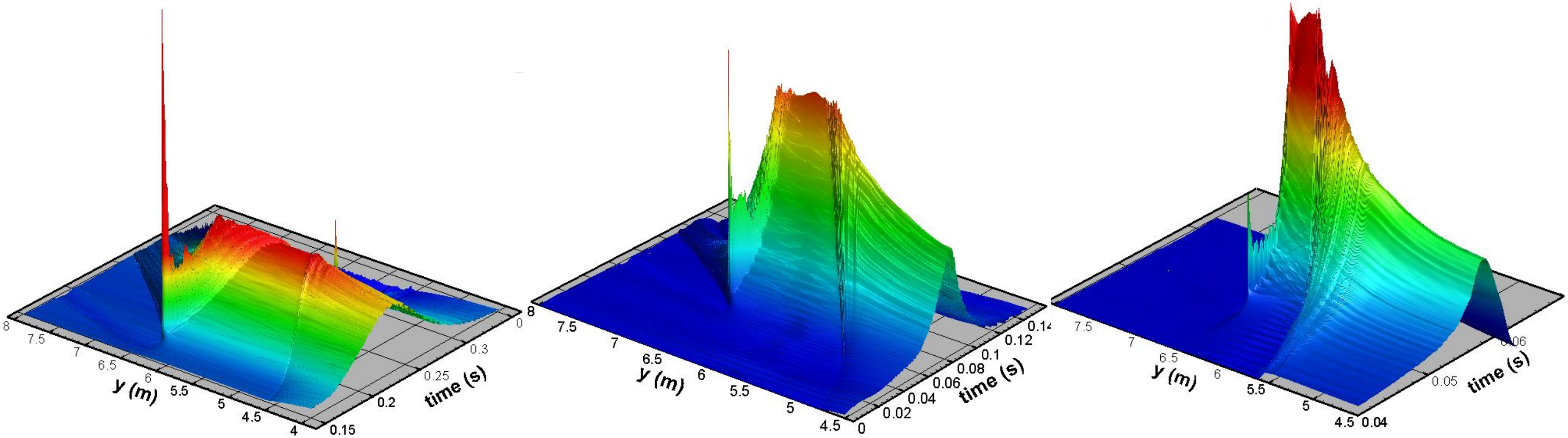
- **Scale 1**



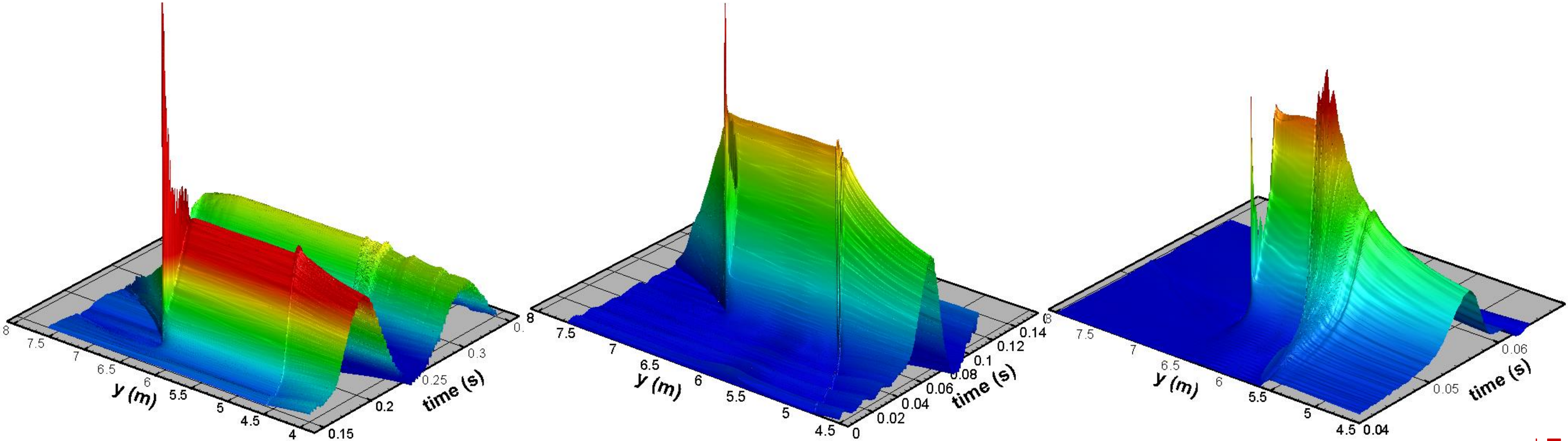
- **Scale 1:6**



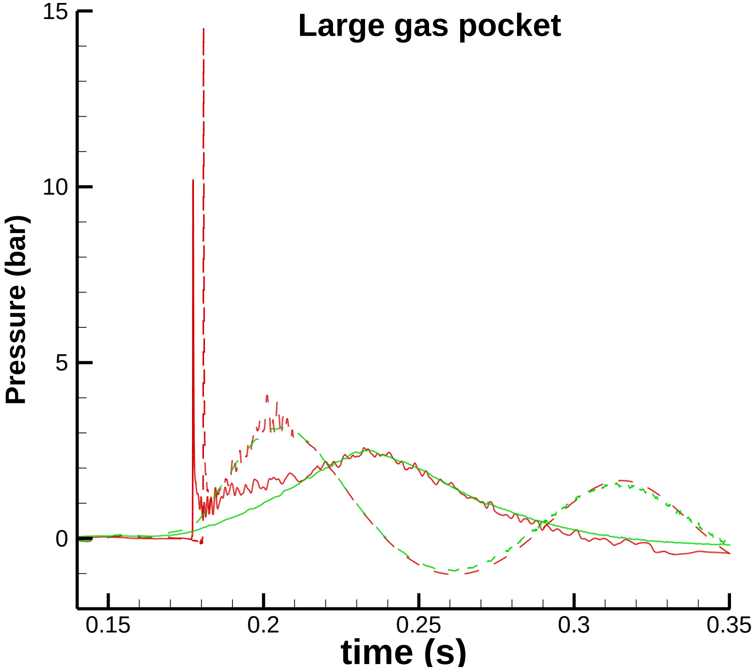
Gas-pocket impacts: Pressure maps

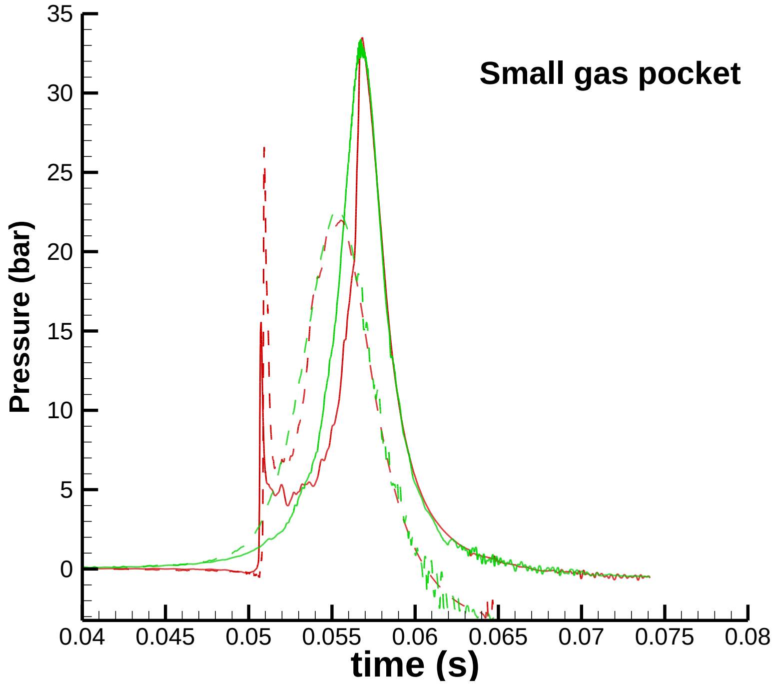


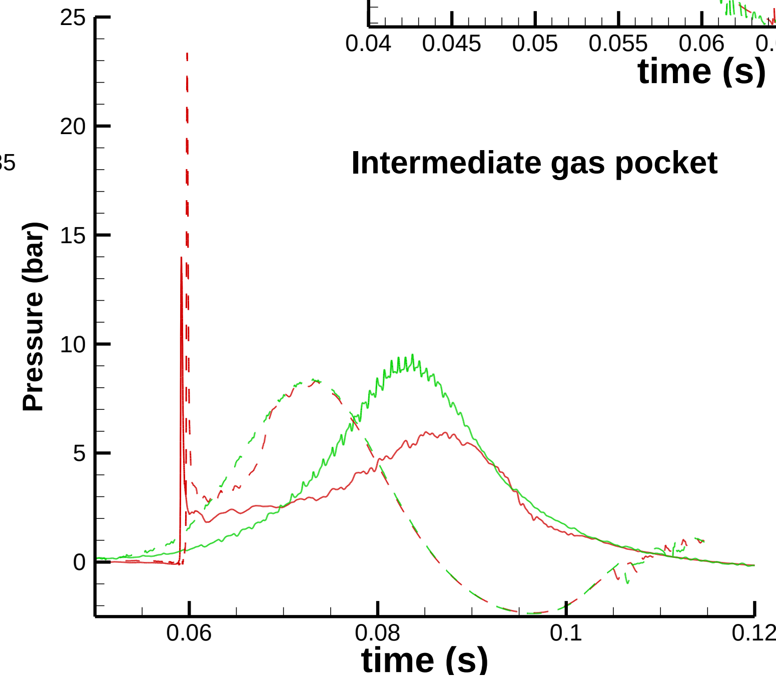
Large gas pocket | **Intermediate gas pocket** | **Small gas pocket**



Characteristic pressures



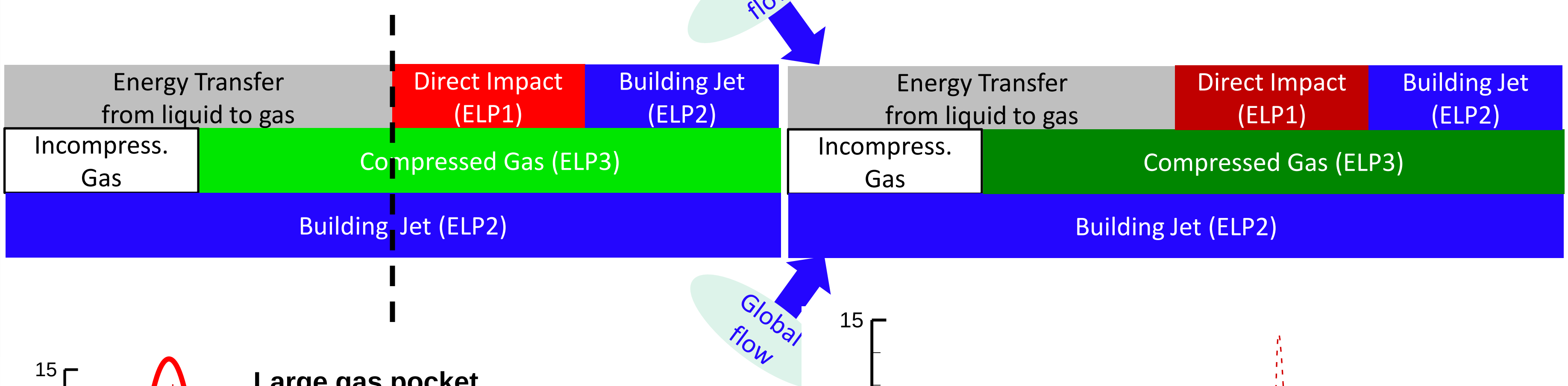


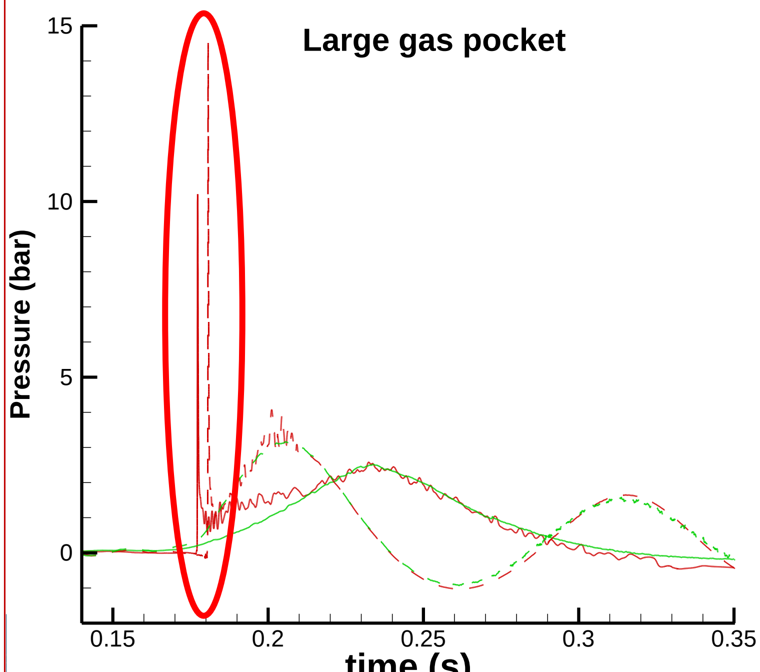


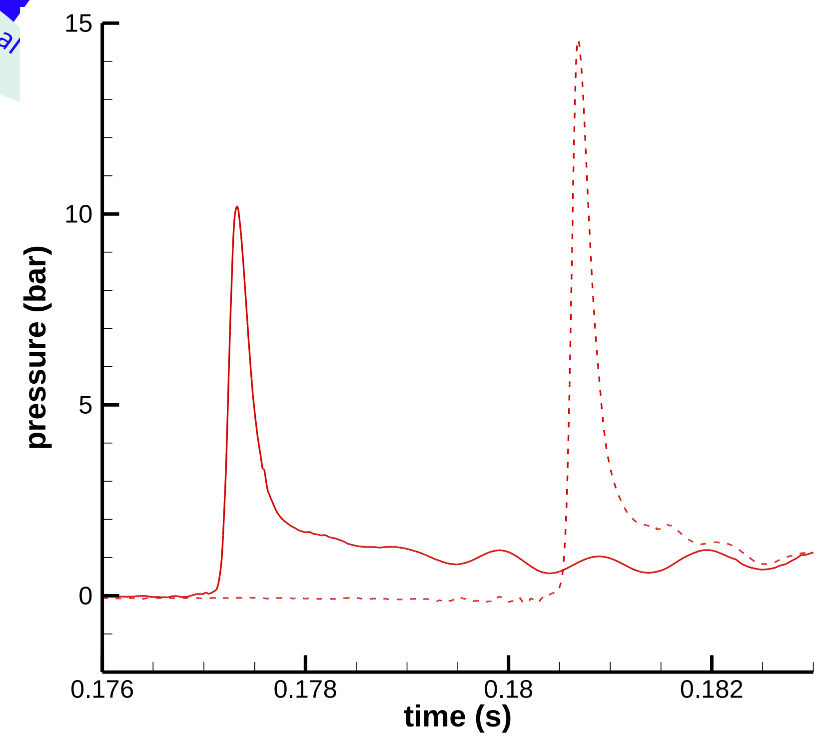
Pressure at crest	**@ scale 1**
Pressure at crest	@ scale 1:6
Pressure in gas pocket	**@ scale 1**
Pressure in gas pocket	@ scale 1:6

Partial Froude scaling for a gas-pocket impact

- **Scale 1**
- **Scale 1:6**



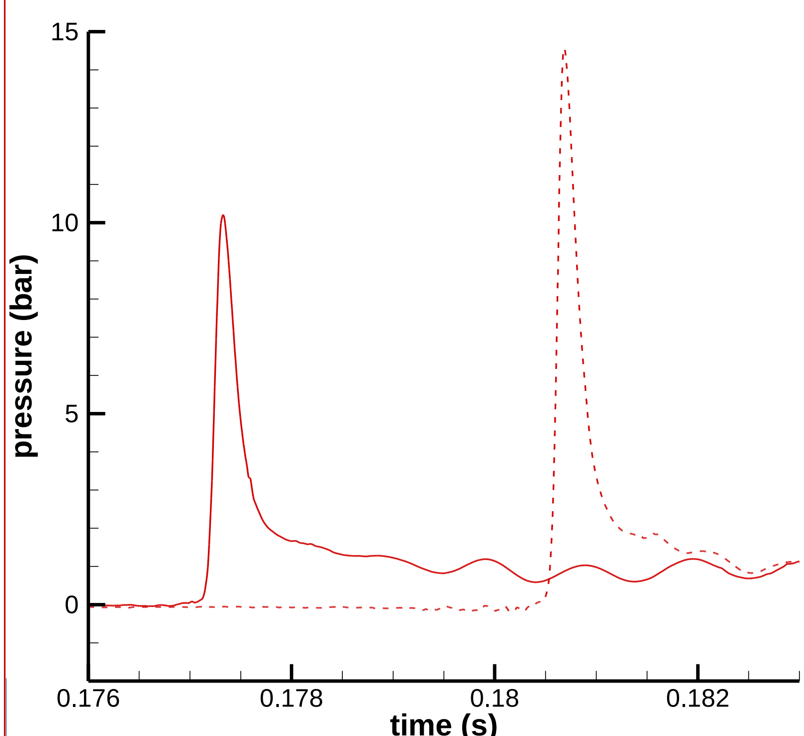




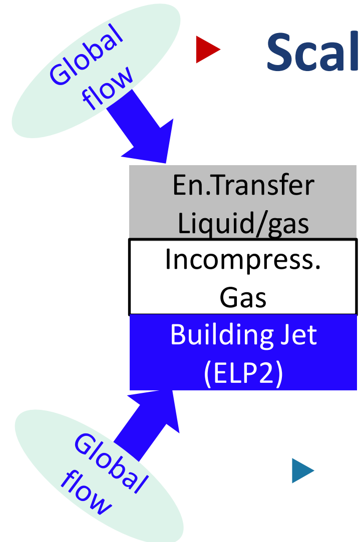
Complete Froude scaling for a gas-pocket impact

- **Scale 1**

En.Transfer Liquid/gas
Incompress. Gas
Building Jet (ELP2)



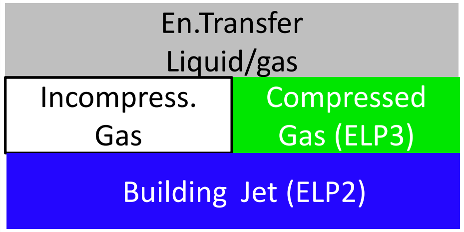
- **Scale 1:6**

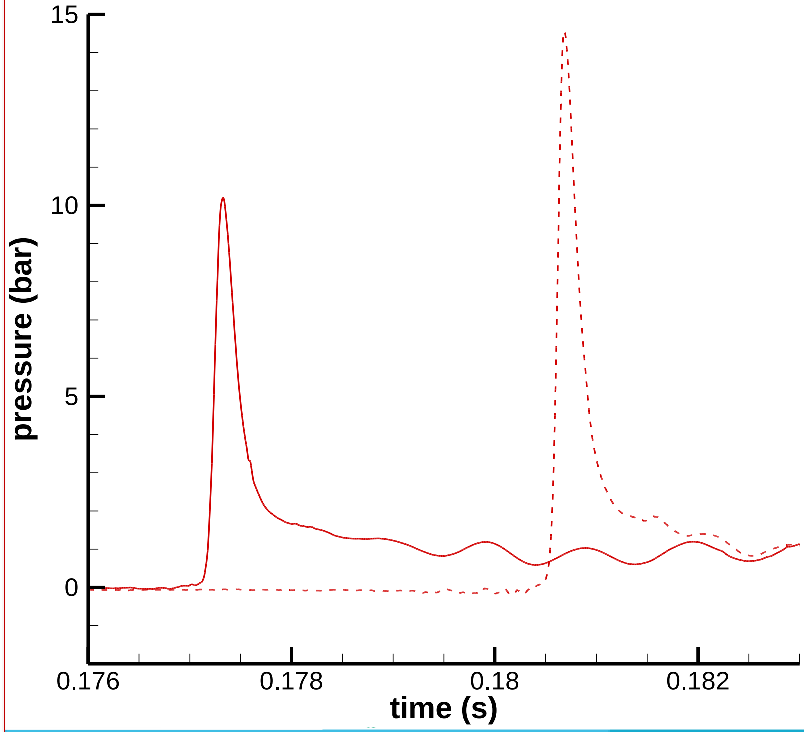


- Same Density Ratio:
  - Propagation phase is similar at both scales

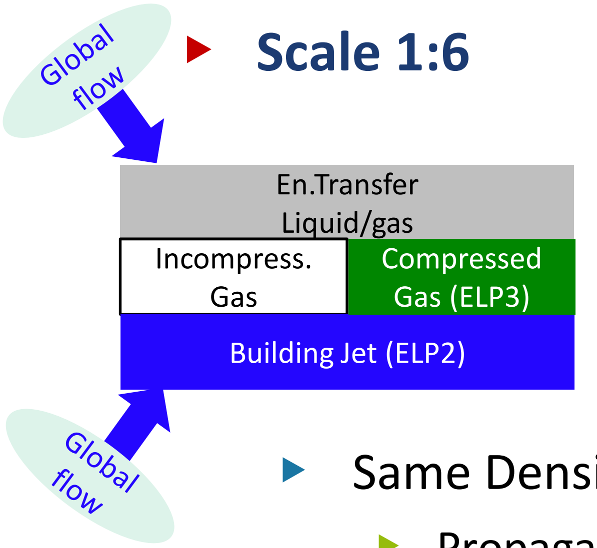
Complete Froude scaling for a gas-pocket impact

- **Scale 1**





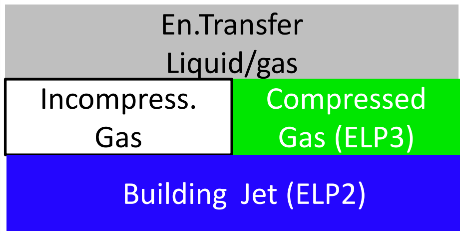
- **Scale 1:6**

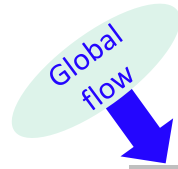


- Same Density Ratio:
  - Propagation phase is similar at both scales
- Gas compressibility bias
  - Stronger gas flow

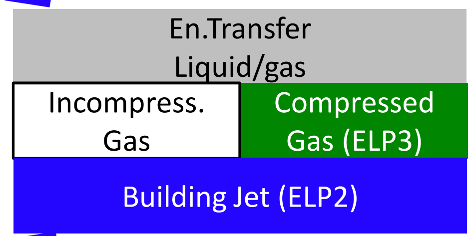
Complete Froude scaling for a gas-pocket impact

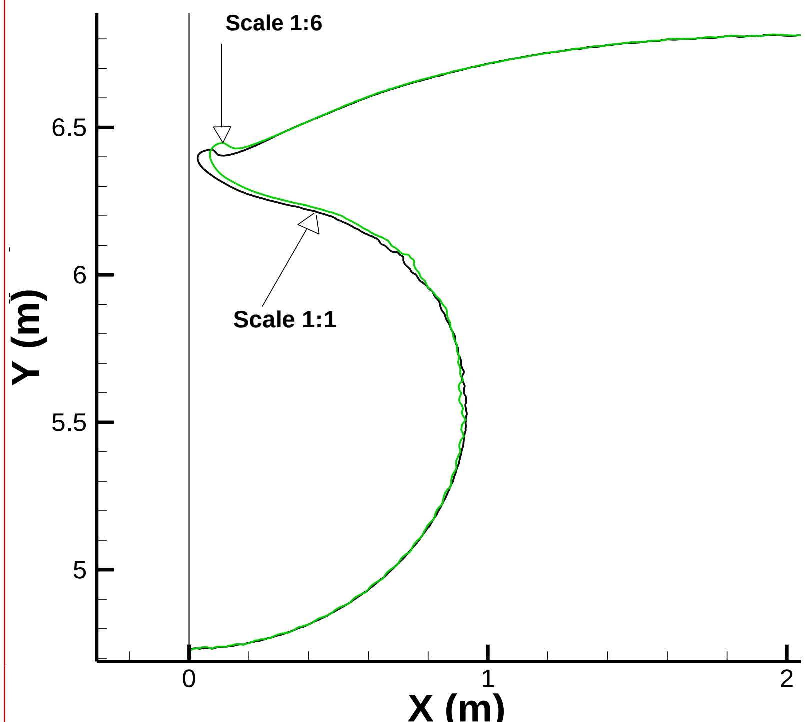
- **Scale 1**





- **Scale 1:6**





- Same Density Ratio:
  - Propagation phase is similar at both scales
- Gas compressibility bias
  - Stronger gas flow
  - Wave shape is modified

Complete Froude scaling for a gas-pocket impact

- **Scale 1**

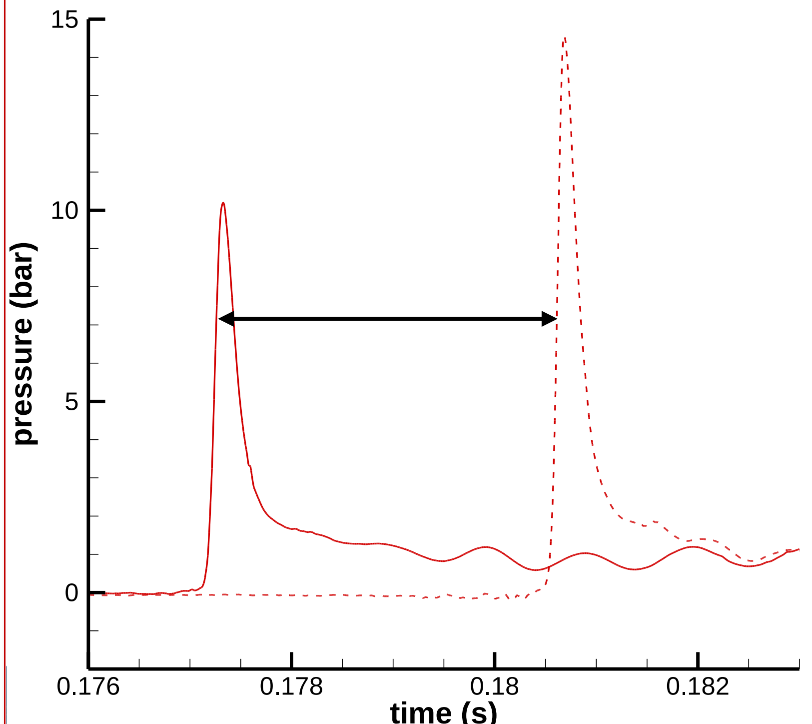
En.Transfer Liquid/gas
Incompress. Gas | Compressed Gas (ELP3)
Building Jet (ELP2)

- **Scale 1:6**

Global flow

En.Transfer Liquid/gas
Incompress. Gas | Compressed Gas (ELP3)
Building Jet (ELP2)

Global flow

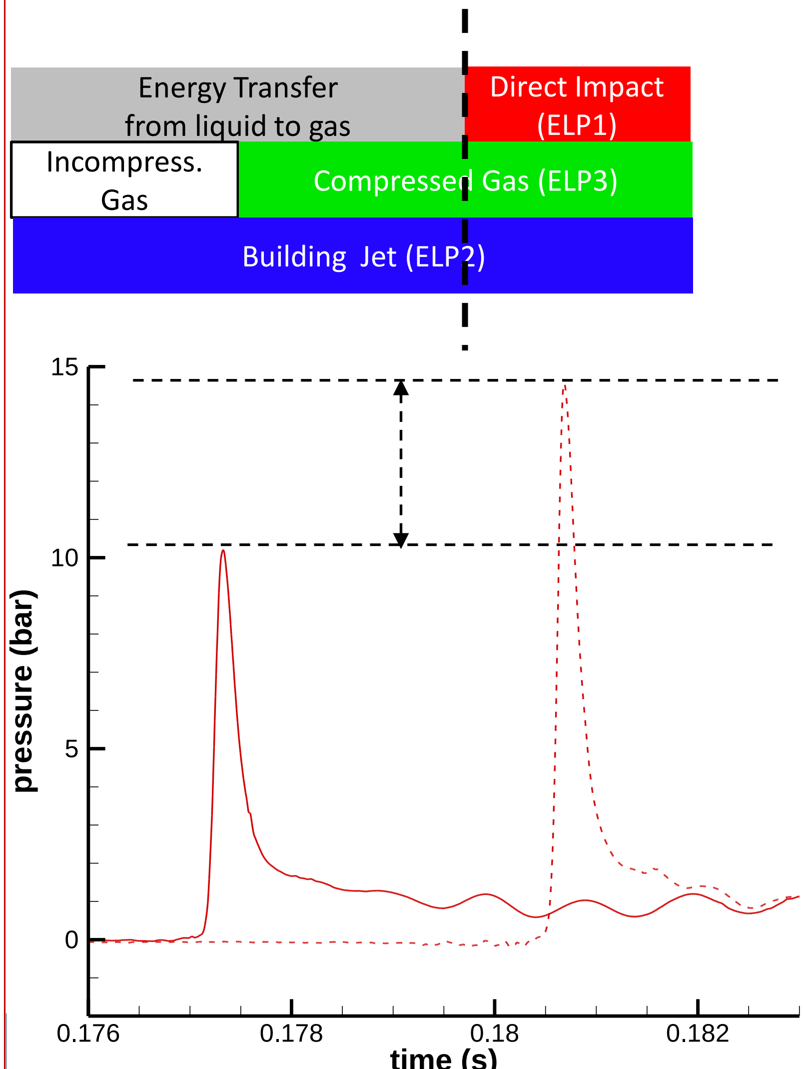


Mitigation

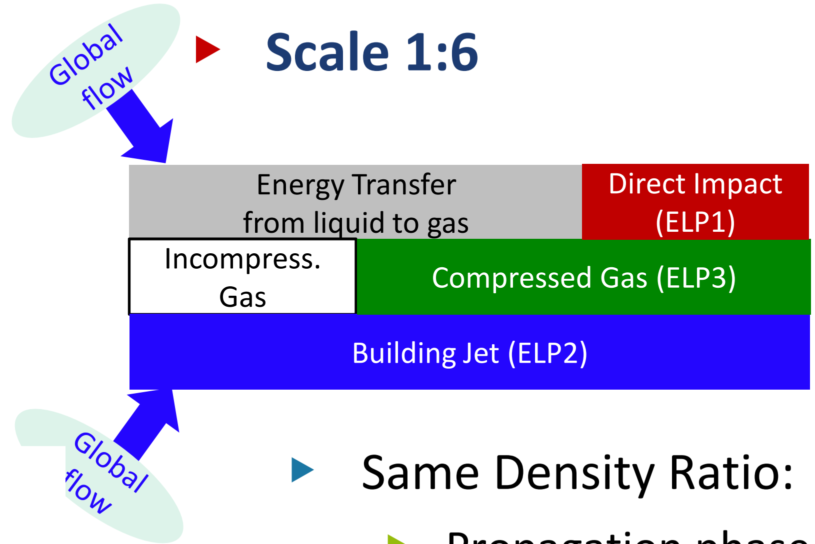
- Same Density Ratio:
  - Propagation phase is similar at both scales
- Gas compressibility bias
  - Stronger gas flow
  - Wave shape is modified
  - Crest is delayed

Complete Froude scaling for a gas-pocket impact

- **Scale 1**



- **Scale 1:6**



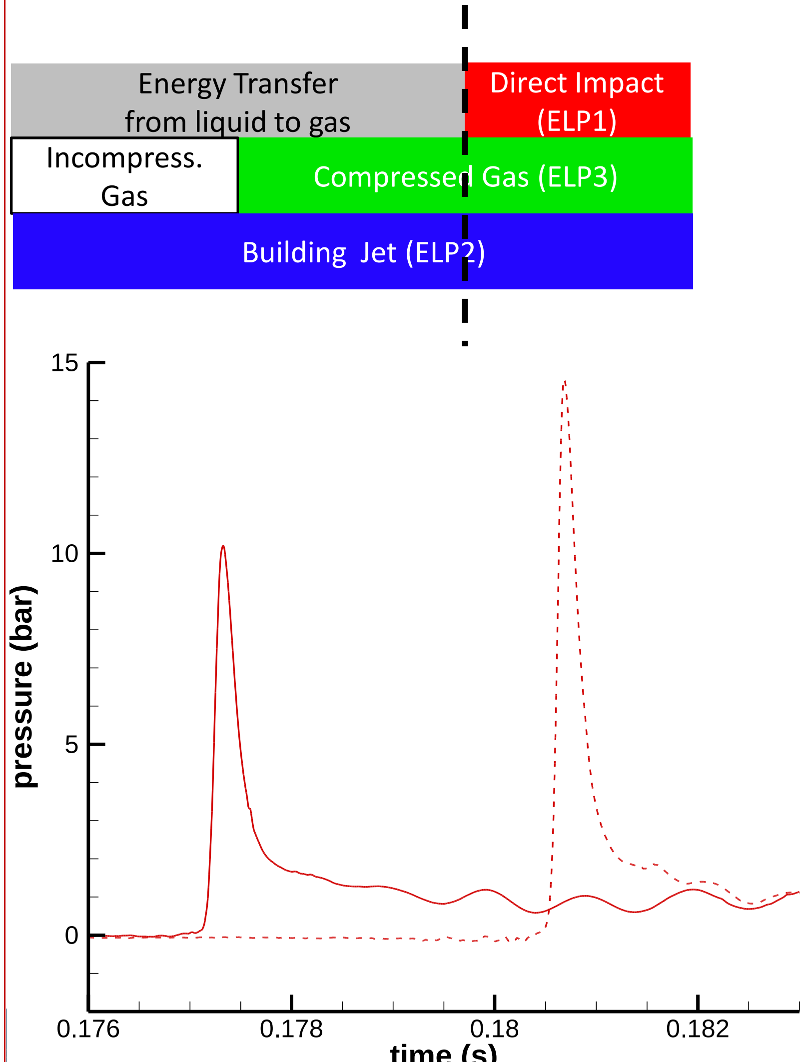
- Same Density Ratio:
  - Propagation phase is similar at both scales
- Gas compressibility bias
  - Stronger gas flow
  - Wave shape is modified
  - Crest is delayed
- Liquid compressibility

Mitigation

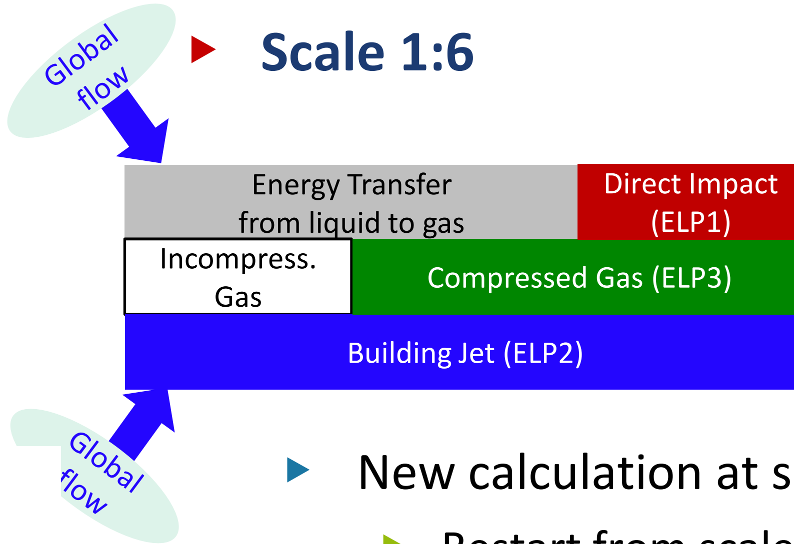
?

Complete Froude scaling for a gas-pocket impact

- **Scale 1**



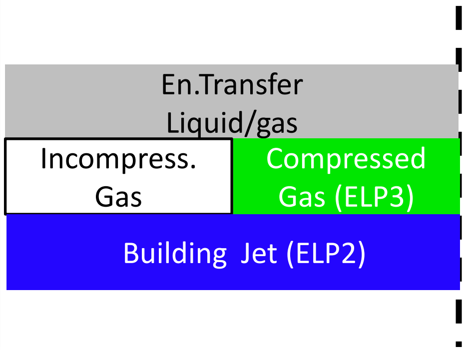
- **Scale 1:6**

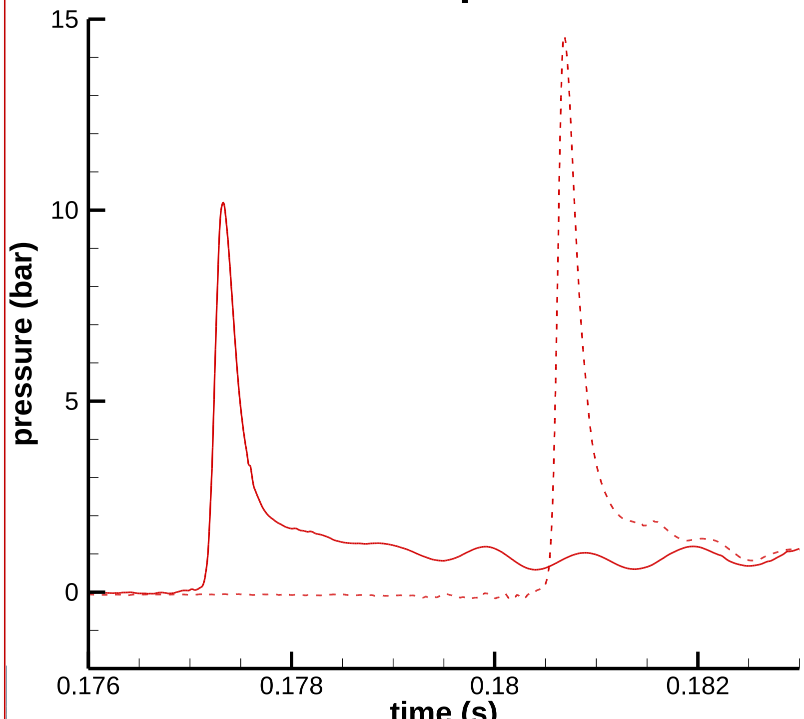


- New calculation at scale 1:6
  - Restart from scale 1 just before the impact

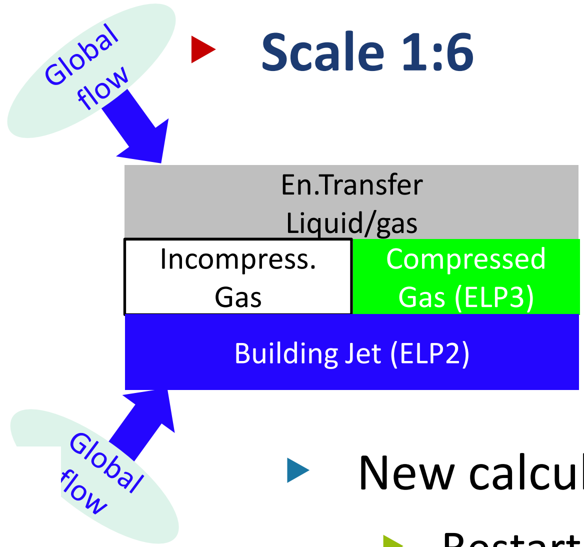
Complete Froude scaling for a gas-pocket impact

- **Scale 1**





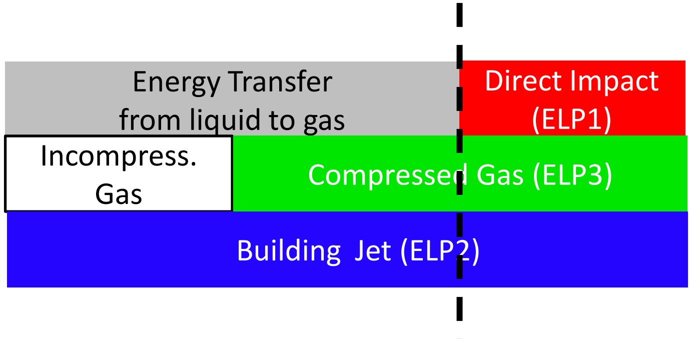
- **Scale 1:6**

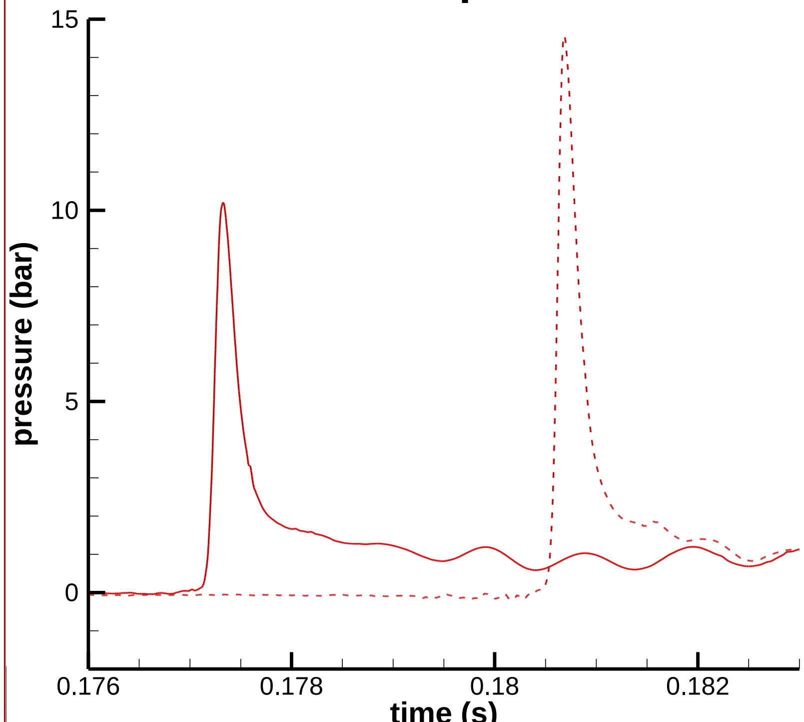


- New calculation at scale 1:6
  - Restart from scale 1 just before the impact
  - Impact calculation with relevantly scaled liquid:
    - $(c_l)_{1/6} = (c_l)_1/\sqrt{6}$

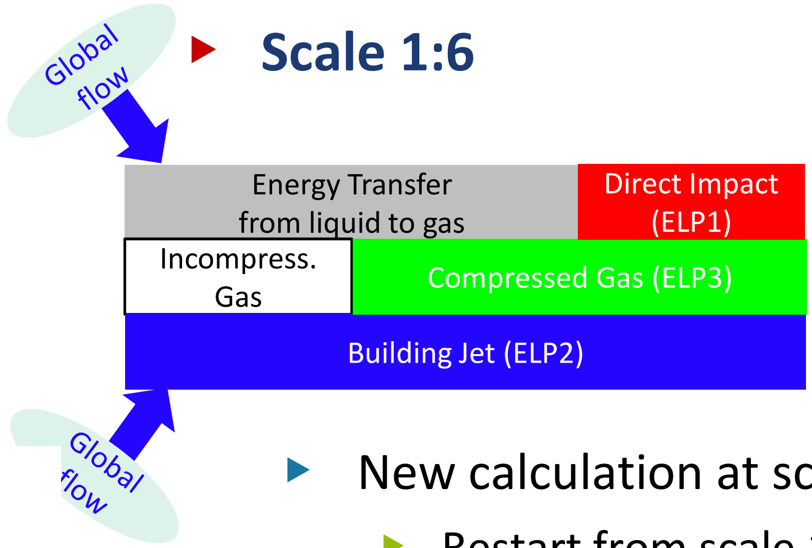
Complete Froude scaling for a gas-pocket impact

- **Scale 1**





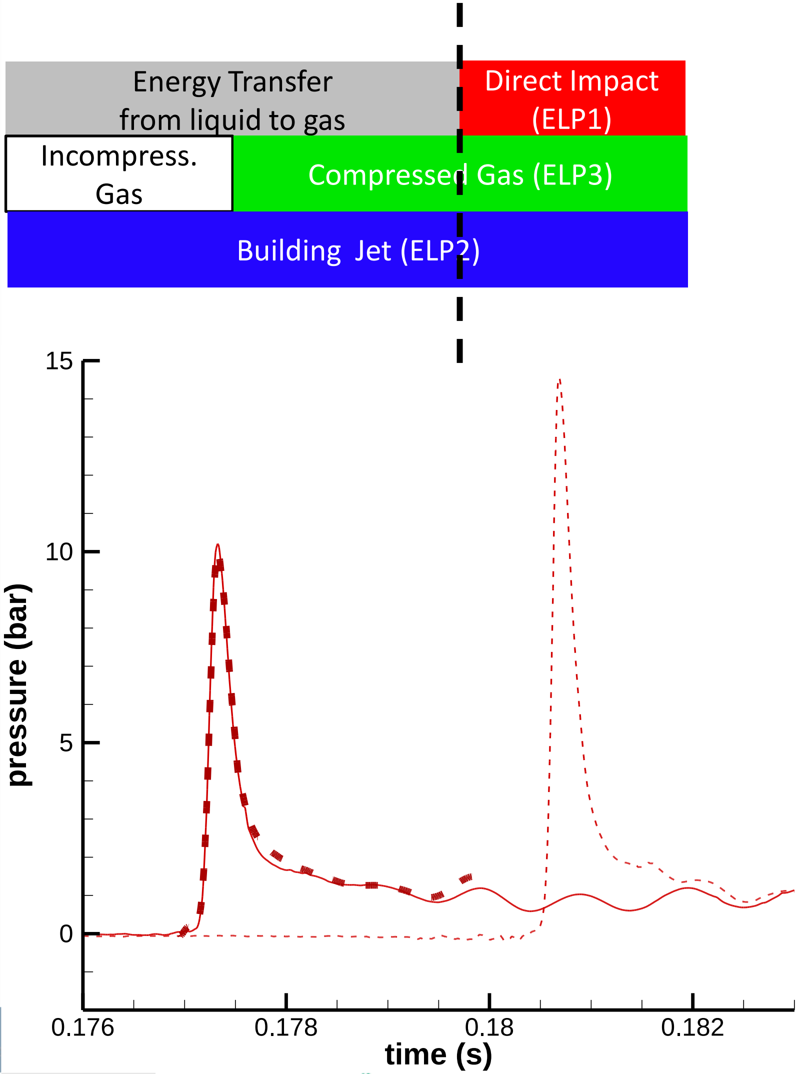
- **Scale 1:6**



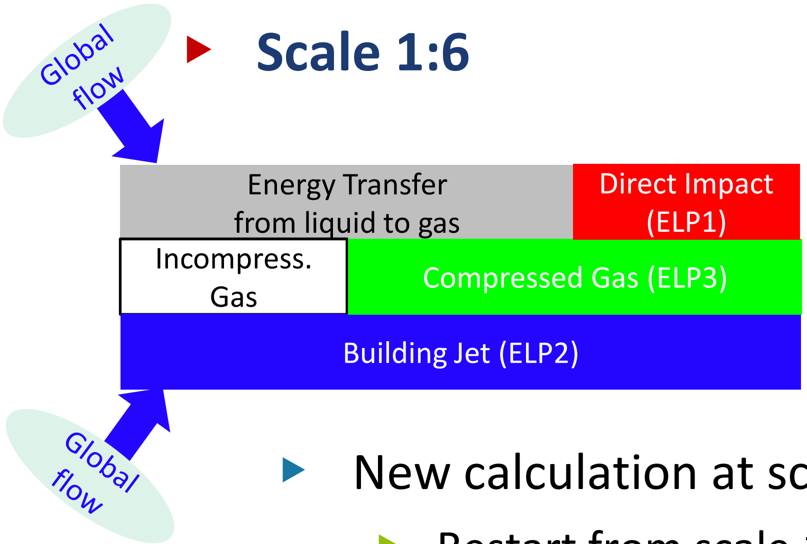
- New calculation at scale 1:6
  - Restart from scale 1 just before the impact
  - Impact calculation with relevantly scaled liquid:
    - $(c_l)_{1/6} = (c_l)_1/\sqrt{6}$

Complete Froude scaling for a gas-pocket impact

- **Scale 1**



- **Scale 1:6**



- New calculation at scale 1:6
  - Restart from scale 1 just before the impact
  - Impact calculation with relevantly scaled liquid:
    - $(c_l)_{1/6} = (c_l)_1/\sqrt{6}$

- CFS conditions during impact

Conclusions

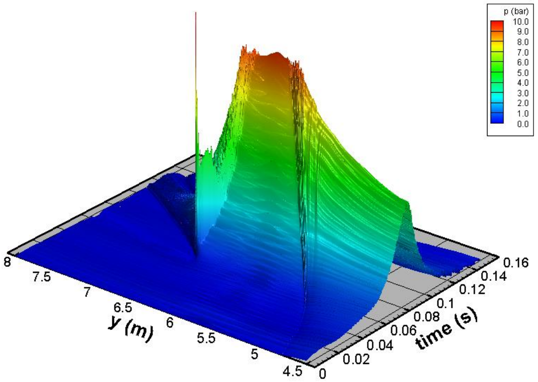
- **Good ability of SPH-Flow to simulate wave impacts**
  - Ability to reproduce accurately typical wave shapes before impact
  - Pressure map very similar to those obtained during sloshing tests
  - Continuum of pressure sensors
  - Need of an important refinement (2 mm between particles) in the impact area
  - Free surface instabilities are not captured (pseudo-convergence)
- **Wave loads**
  - Pressure maps are very similar for the different gas pocket impacts
  - Each typical area of the map is associated to an ELP
  - The three ELPs are involved
  - Max pressure at crest does not depend on the size of the pocket
  - The smaller the pocket the larger the pressure inside

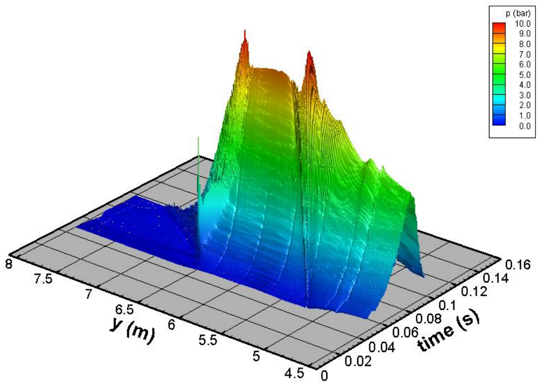
Conclusions

- **Simulations of liquid impacts at two different scales brings insight into the influence of the different biases**
  - According to CFS principle, a liquid impact at scale $1/\lambda$ is Froude-similar to the impact at scale 1 if
    - Inflow conditions are Froude-scaled
    - Density ratio are the same
    - Speed of sounds are Froude-scaled in gas and liquid (Mach similarity)
  - There are always gas and liquid compressibility biases
  - A scaling study is equivalent to a sensitivity study on gas and liquid properties at scale 1
  - The pressure peaks due to crest impacts are always overestimated at model scale
  - Gas pocket pressures is better described by a similarity given by a simple piston model (Genralized Bagnold Model)

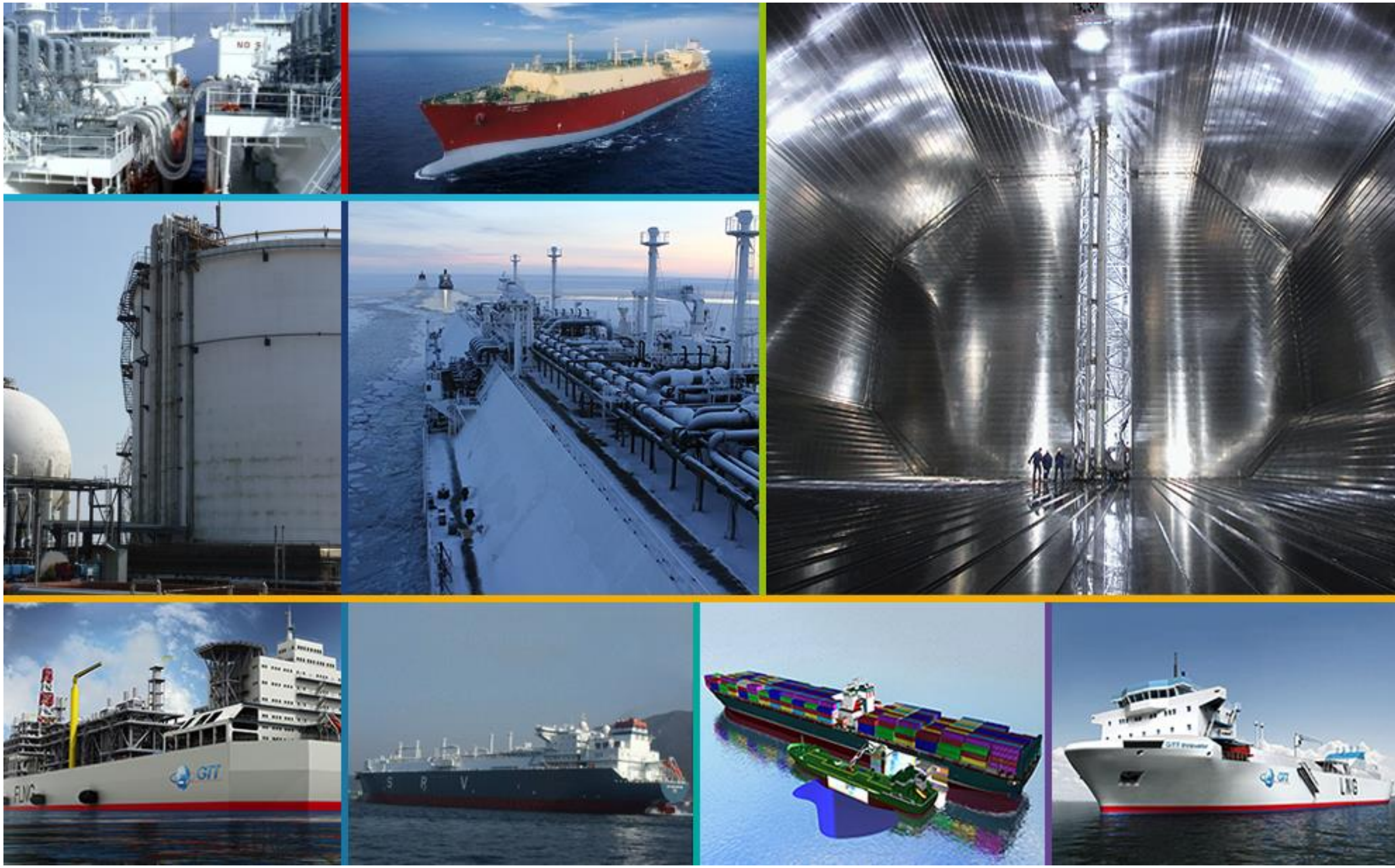
Conclusions

- **Experimental model for sloshing model tests could be improved**
  - For the time being DR is kept the same as both scales but there is a large compressibility bias
  - A better balance between DR bias and compressibility bias is possible with heavier ullage gases
- **Future and on-going work**
  - Influence of hydro-elasticity
  - Influence of phase change
  - Free surface instabilities → variability





Thank you for your attention



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