SECURITY STUDY OF SODIUM-GAS HEAT EXCHANGERS IN FRAME OF SODIUM-COOLED FAST REACTORS

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Meet the presenter

Ms. Fang Chen is a third year PhD student at CEA Cadarache in the "Service de Technologie des Composants et des Procédés (STCP) " in the "Laboratoire de Traitement et des Risques Sodium (LTPS)."

Her PhD research aims at providing a numerical tool that enables users to describe the structure of the jet (bubble distribution, Mach disk, *etc*.) as a function of the flow rate of the gas leak. The developed compressible multiphase flow model is implemented in CANOP that enables users to generate the Adaptive Mesh Refinement and to calculate in parallel.

Ms. Chen is one of the three students who won the Elevator Pitch Challenge (EPiC) contest at the GIF Symposium meeting in Paris in October 2018, and as a result has been awarded the opportunity to give this presentation.

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Outline

- Context & Objective
  - ASTRID Project
  - SGHE design
  - Objective of present work
- Development
  - Predominant physical phenomena
  - Multiphase model
  - Numerical tool
- Results
  - Validation
  - Under-expanded gas jets
- Conclusion & Perspectives

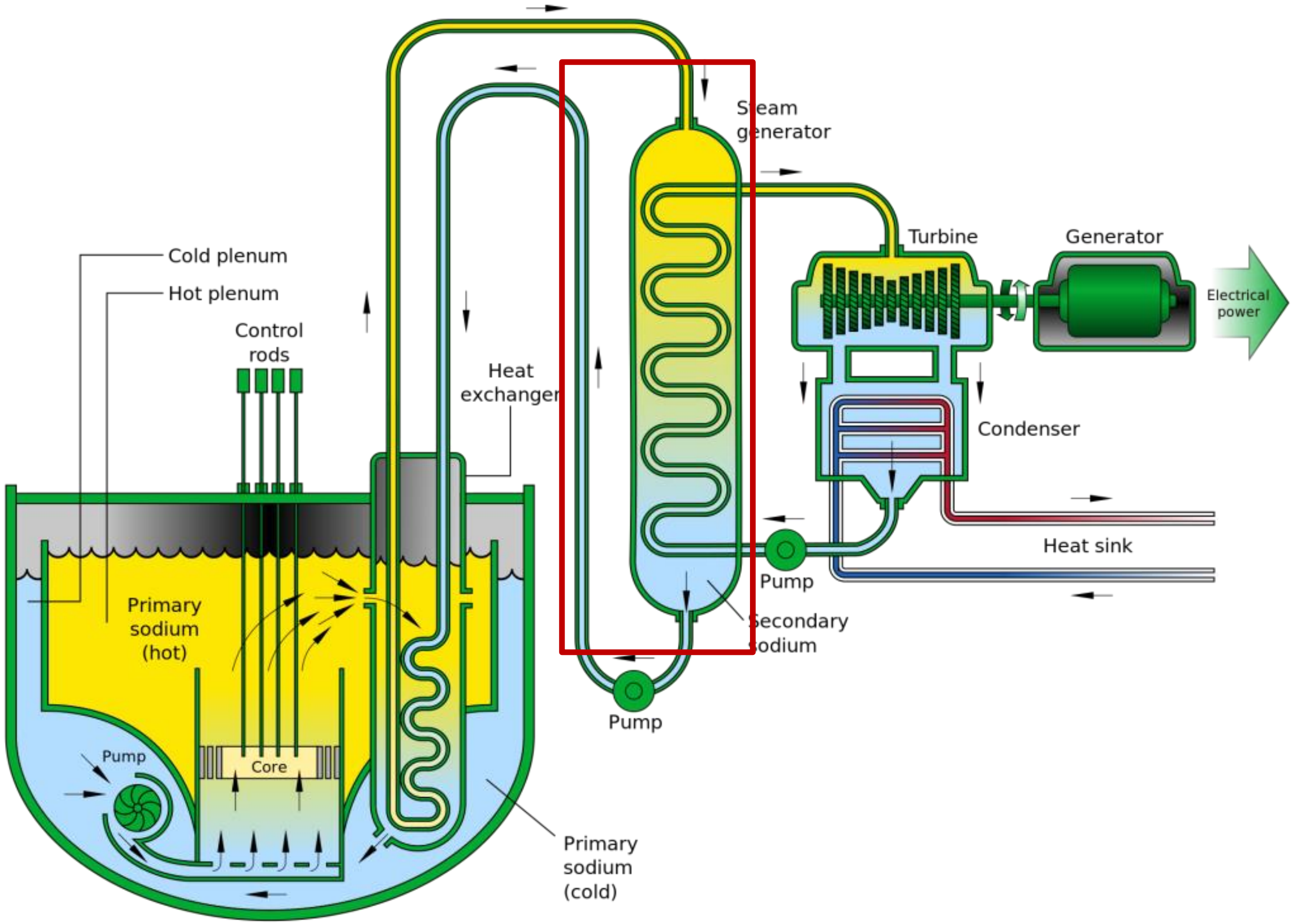
ASTRID Project

(Advanced Sodium Technological Reactor for Industrial Demonstration)

- Safety objective: Sodium Water Reaction prevention

Main favorable features of SFR

- The whole primary circuit (not pressurized) is contained in the main vessel;
- Large boiling margin of sodium;
- High thermal inertia in case of loss of main heat sink;
- Power control by single rod position, no xenon effect, no need of soluble neutron poison;
- Collective dose on a pool type SFR is very low compared to PWR;
- The intermediate system provides an extra containment between the primary circuit and the environment.



ASTRID Project

(Advanced Sodium Technological Reactor for Industrial Demonstration)

- Two Power Conversion Systems (PCS) studied in parallel:

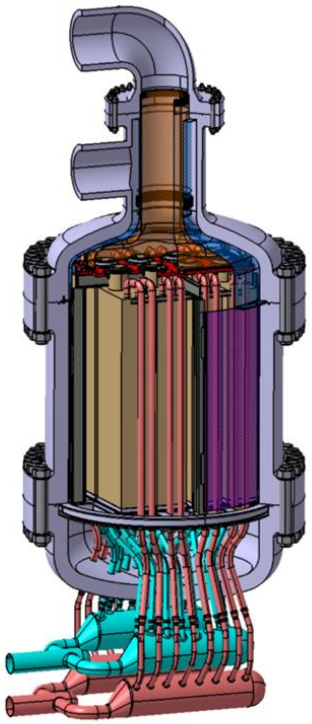
Water Steam PCS with Helicoidal SG

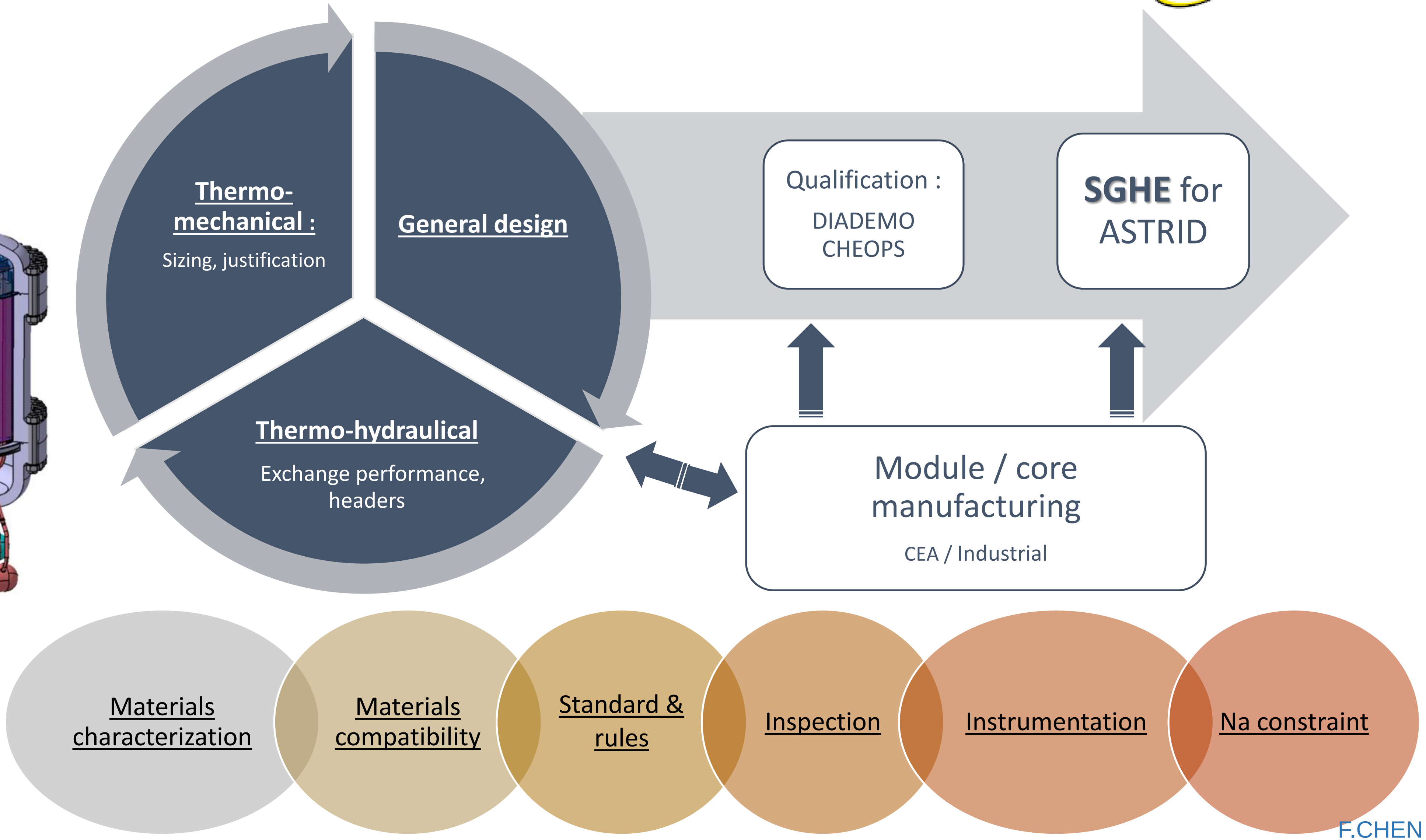
- Maintain a system competence, back up solution if Gas PCS is a dead end.
- *Dependent on industrials partner of ASTRID*
  CEA R&D (material, SWR modelling, transfer Tritium evaluation)

Gas PCS with SGHE

- Sustained level of studied to increase the maturity level of gas PCS and to better assess the risk and cost / advantages
- CEA R&D (**SGHE Development**, operation, safety, transfer Tritium evaluation)

SGHE design
(Sodium Gas Heat Exchangers)



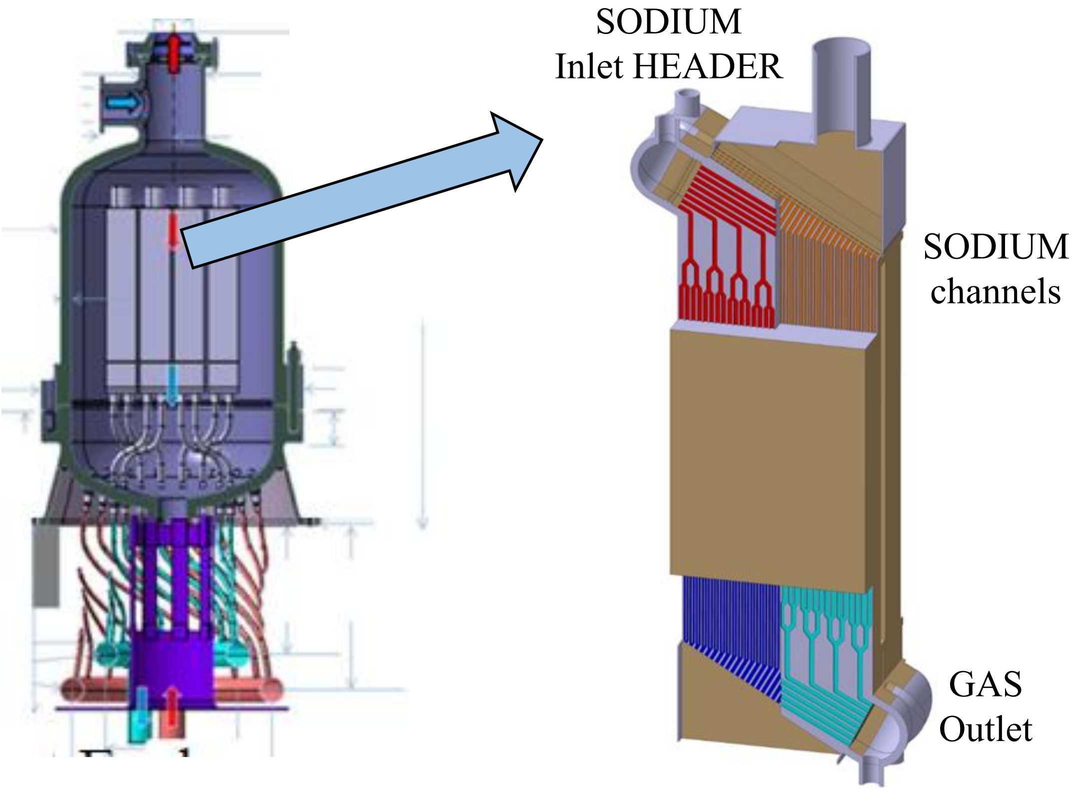


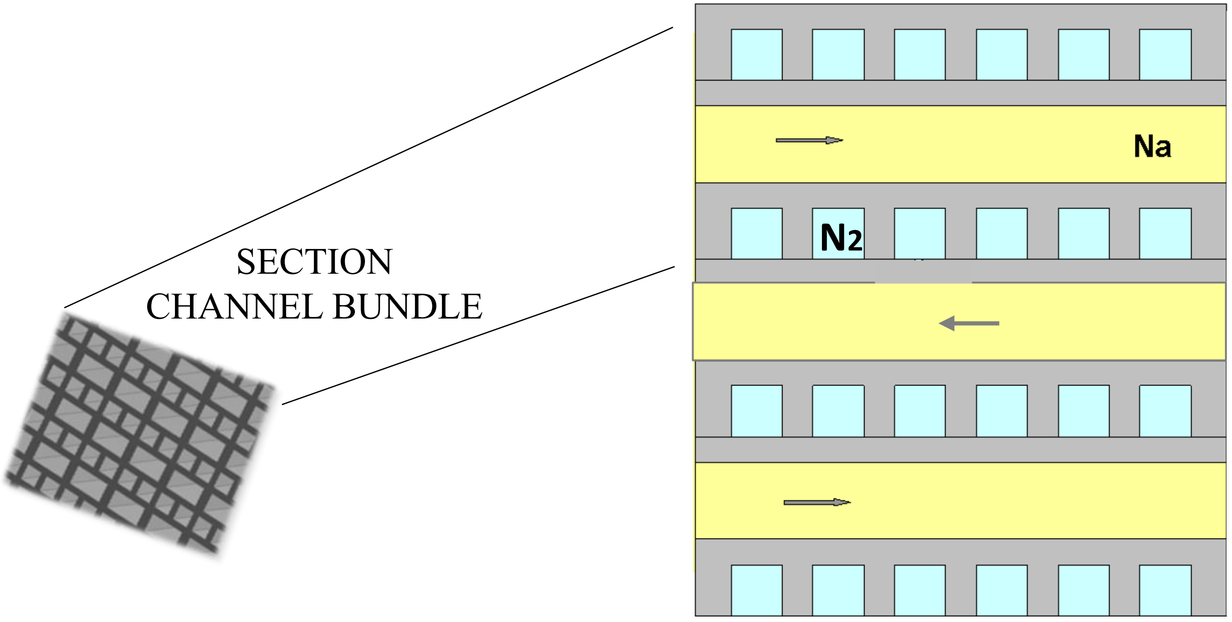
SGHE design

(Sodium Gas Heat Exchangers)

- A 40 kW was tested in CEA (Plancq et al., 2018)
- ~37.5 % of efficiency
- Bundle of plates in compression: limits the tensile solicitations of isthmuses,
- High compactness,

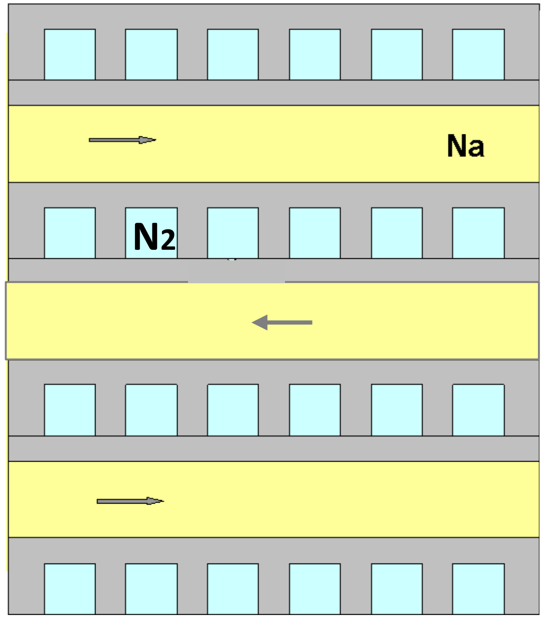
- Minimize pressure drop on the gas side, vessel acting as header,
- Limitation of loads due to thermal expansion of structures,
- Module access is allowed for the maintenance and ISIR,
- Module structure temperature driven by Na : absence of gas header improves thermomechanical behavior (transitory).



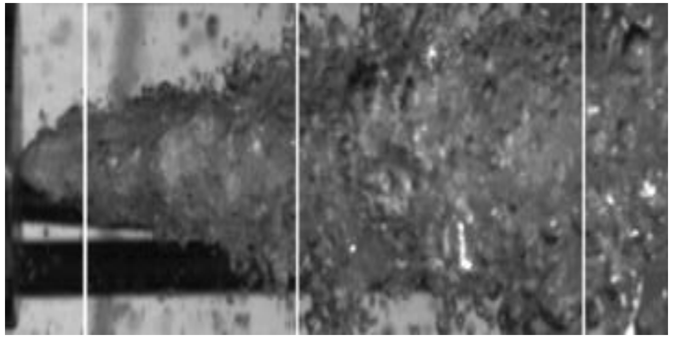


Objective of present work

- Pressure difference between the secondary & tertiary loop:
  - 180 bar in gas loop,
  - 5 bar in sodium loop.
- Accident scenario (wall crack): gas leak into sodium, under-expanded gas jet.
- Safety analysis: acoustic detection of gas leak

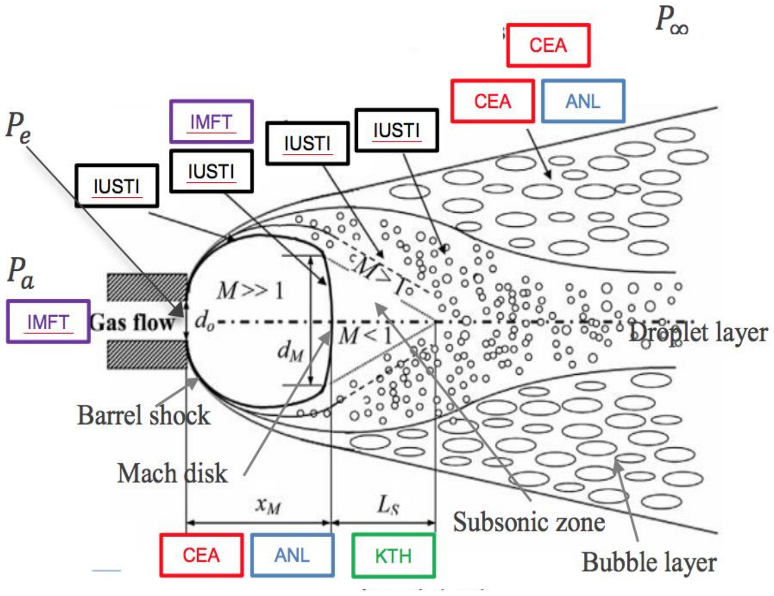


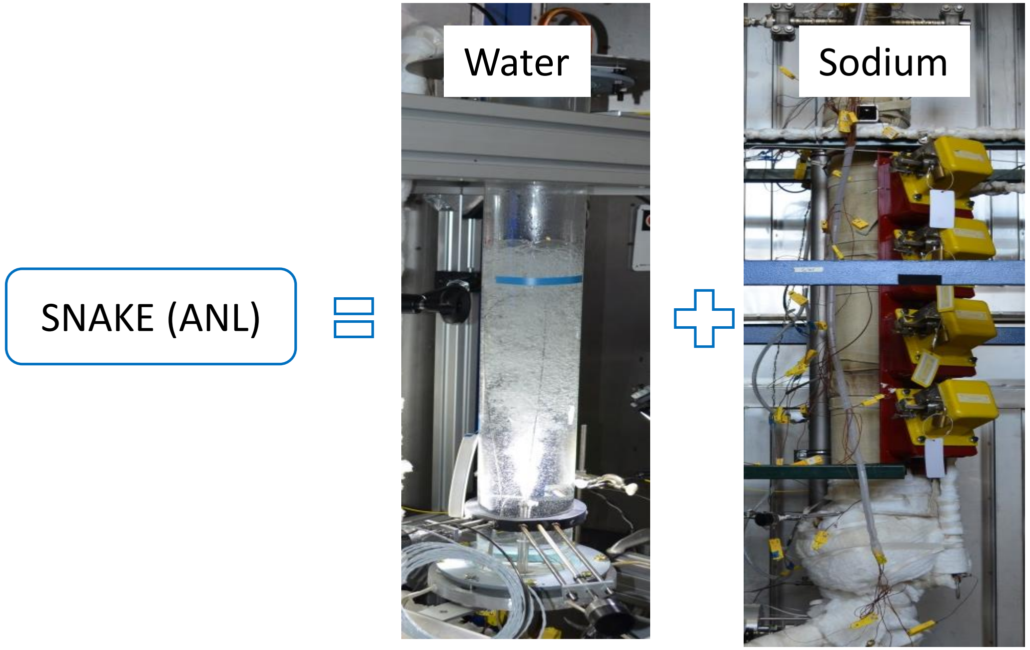
Bubble distribution + Mach disk = Acoustic detections of gas leak



Objective of present work

- Organization:
  - Viscous Nozzle flow : IMFT
  - Compressible flow (Barrel shock, Mach disk) : IMFT, CEA, IUSTI, ANL
  - Acoustic for leak noise detection : CEA, KTH
  - Liquid droplets behavior in supersonic flow: IUSTI
  - Bubble distribution : ANL and CEA (IKHAR)
- Objective: provide a numerical tool to find the structure of under-expanded gas jet as a function of the flow rate of the gas leak

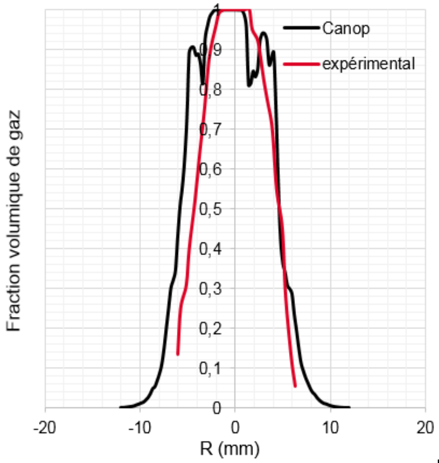


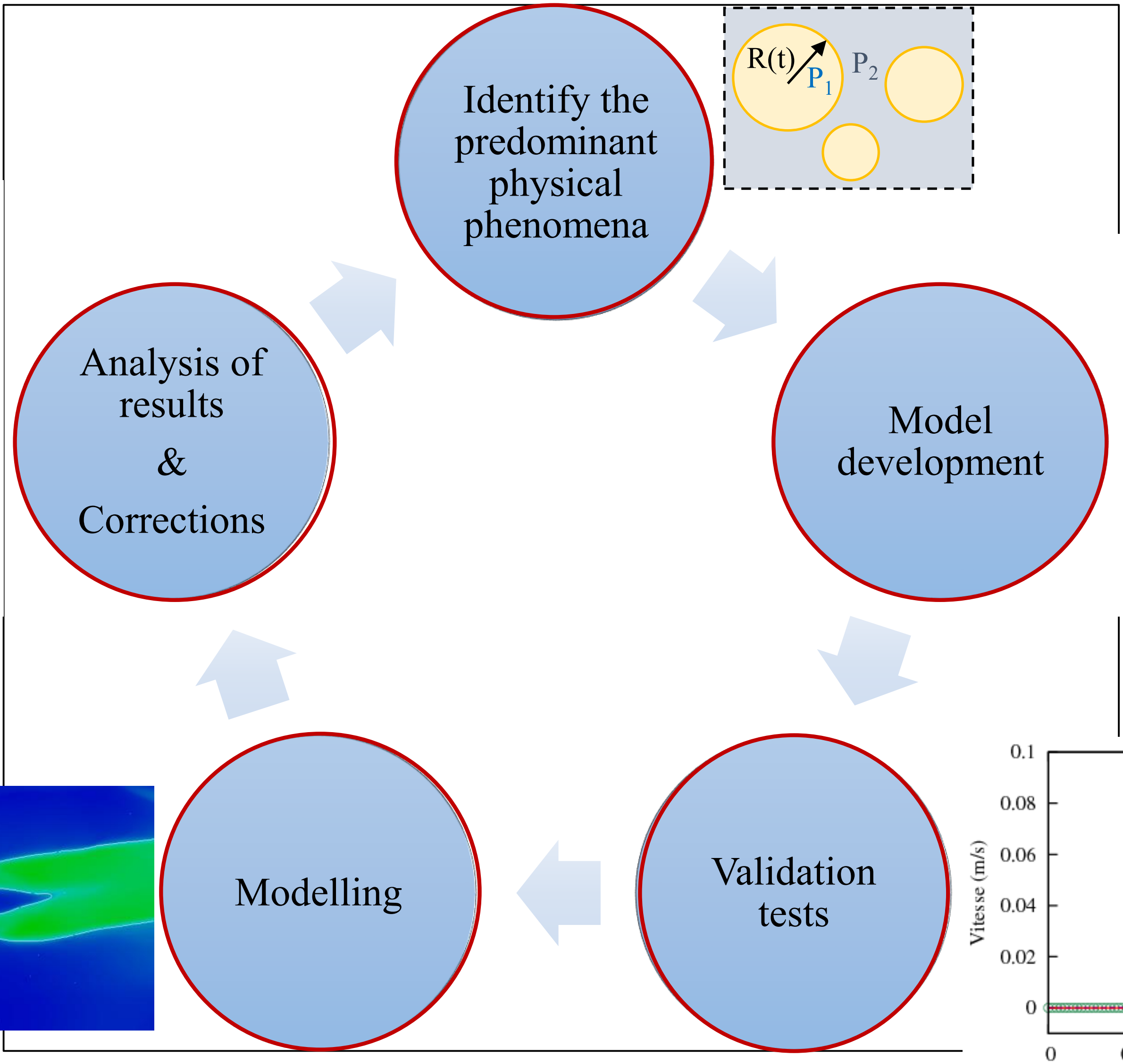


Development

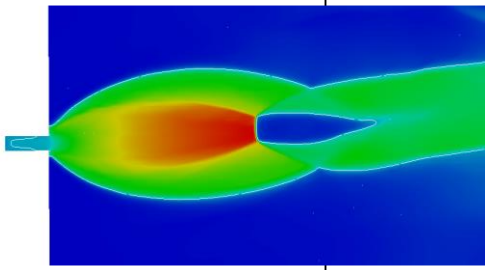
- Predominant physical phenomena
- Multiphase model
- Numerical tool

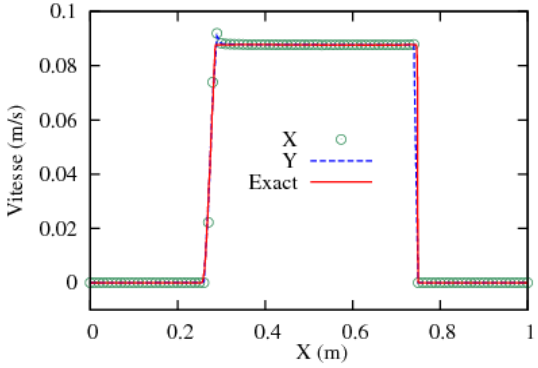
Development process





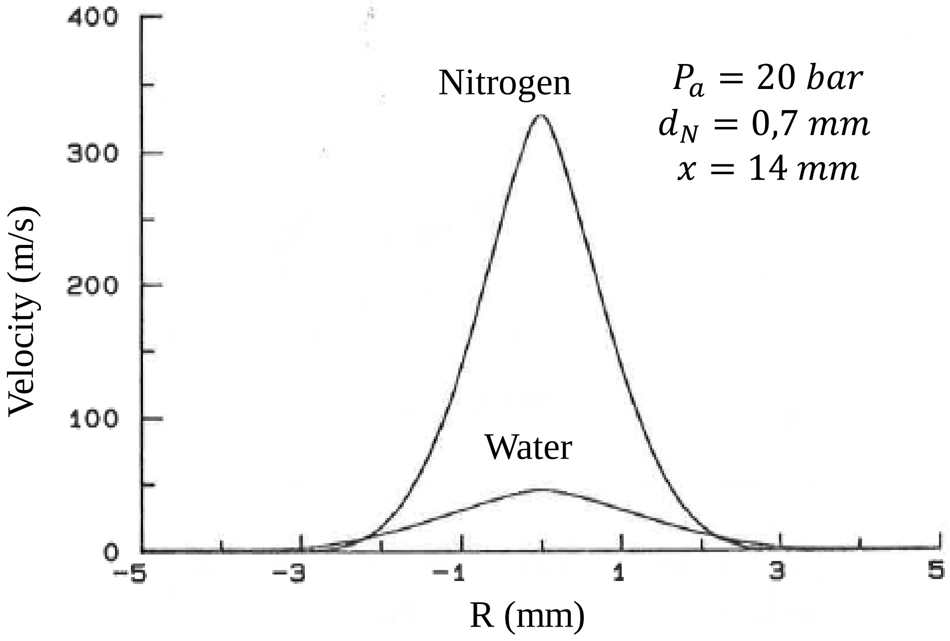
$$\frac{\partial \alpha_g}{\partial t} + u_I \vec{\nabla} \alpha_g = \mu (P_g - P_l)$$
$$\frac{\partial (\alpha_g \rho_g)}{\partial t} + div(\alpha_g \rho_g \vec{u_g}) = 0$$
$$\frac{\partial (\alpha_g \rho_g \vec{u_g})}{\partial t} + div(\alpha_g \rho_g \vec{u_g} \otimes \vec{u_g} + \alpha_g P_g) = P_I \vec{\nabla} \alpha_g - \lambda(\vec{u_g} - \vec{u_l})$$
$$\frac{\partial (\alpha_g \rho_g E_g)}{\partial t} + div(\vec{u_g}(\alpha_g \rho_g E_g + \alpha_g P_g)) = P_I u_I \vec{\nabla} \alpha_g - \lambda u_I (\vec{u_l} - \vec{u_g})$$
$$\frac{\partial (\alpha_l \rho_l)}{\partial t} + div(\alpha_l \rho_l \vec{u_l}) = 0$$
$$\frac{\partial (\alpha_l \rho_l \vec{u_l})}{\partial t} + div(\alpha_l \rho_l \vec{u_l} \otimes \vec{u_l} + \alpha_l P_l) = P_I \vec{\nabla} \alpha_l + \lambda(\vec{u_g} - \vec{u_l})$$
$$\frac{\partial (\alpha_l \rho_l E_l)}{\partial t} + div(\vec{u_l}(\alpha_l \rho_l E_l + \alpha_l P_l)) = P_I u_I \vec{\nabla} \alpha_l + \lambda u_I (\vec{u_l} - \vec{u_g})$$



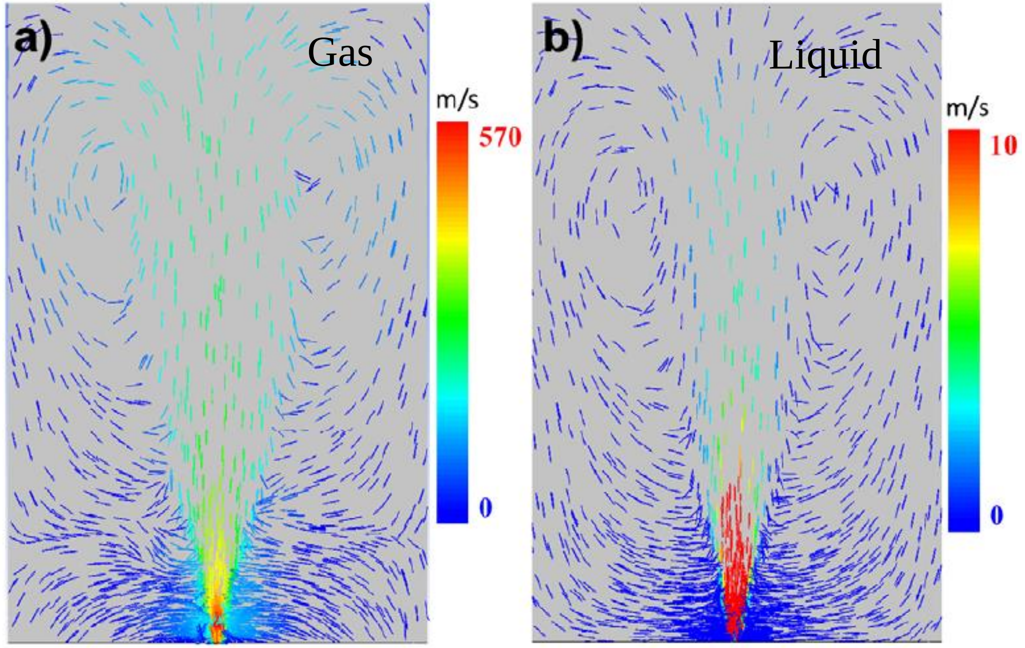


Predominant physical phenomena

- Inhomogeneity of the velocity between two phases



$P_a = 20\ bar,\ d_N = 0{,}7\ mm, x = 14\ mm$
(Le Romancer 1991)

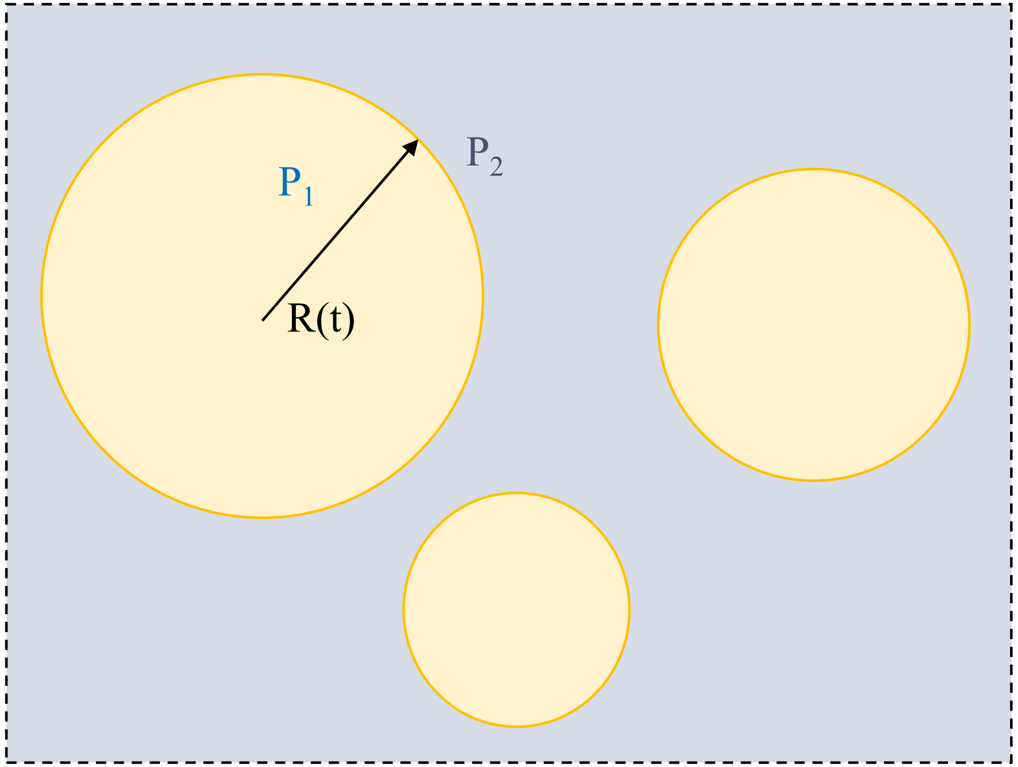


$P_a = 7\ bar,\ d_N = 1{,}0\ mm$
(Vivaldi et al., 2013)

Model = Two velocities / Drag force + Others ?

Predominant physical phenomena

- Inhomogeneity of the pressure of two phases



A flow with dispersed phases (bubbles & droplets)

Track the evolution of the bubble size:

Rayleigh-Plesset Equation:

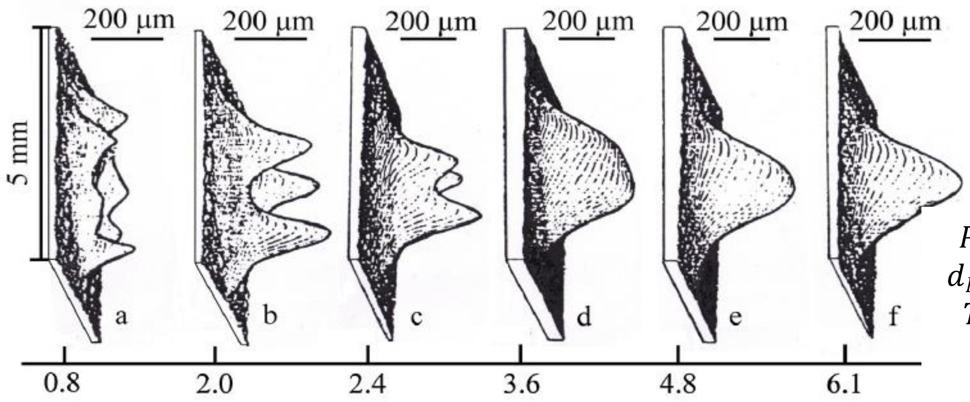
$$R(t) = \Delta P_{12}$$

Model = Two velocities / Drag force + Two pressures + Others ?

Predominant physical phenomena

- Viscous diffusion
  - Effects at the nozzle & the curvature of the incident shock wave
  - Taylor-Görtler instability affects the jet structure downstream of flow

Modelling of the under-expanded jets obtained with the AVBP code. The results colored by the mass flow rate [Chen et al., 2018].



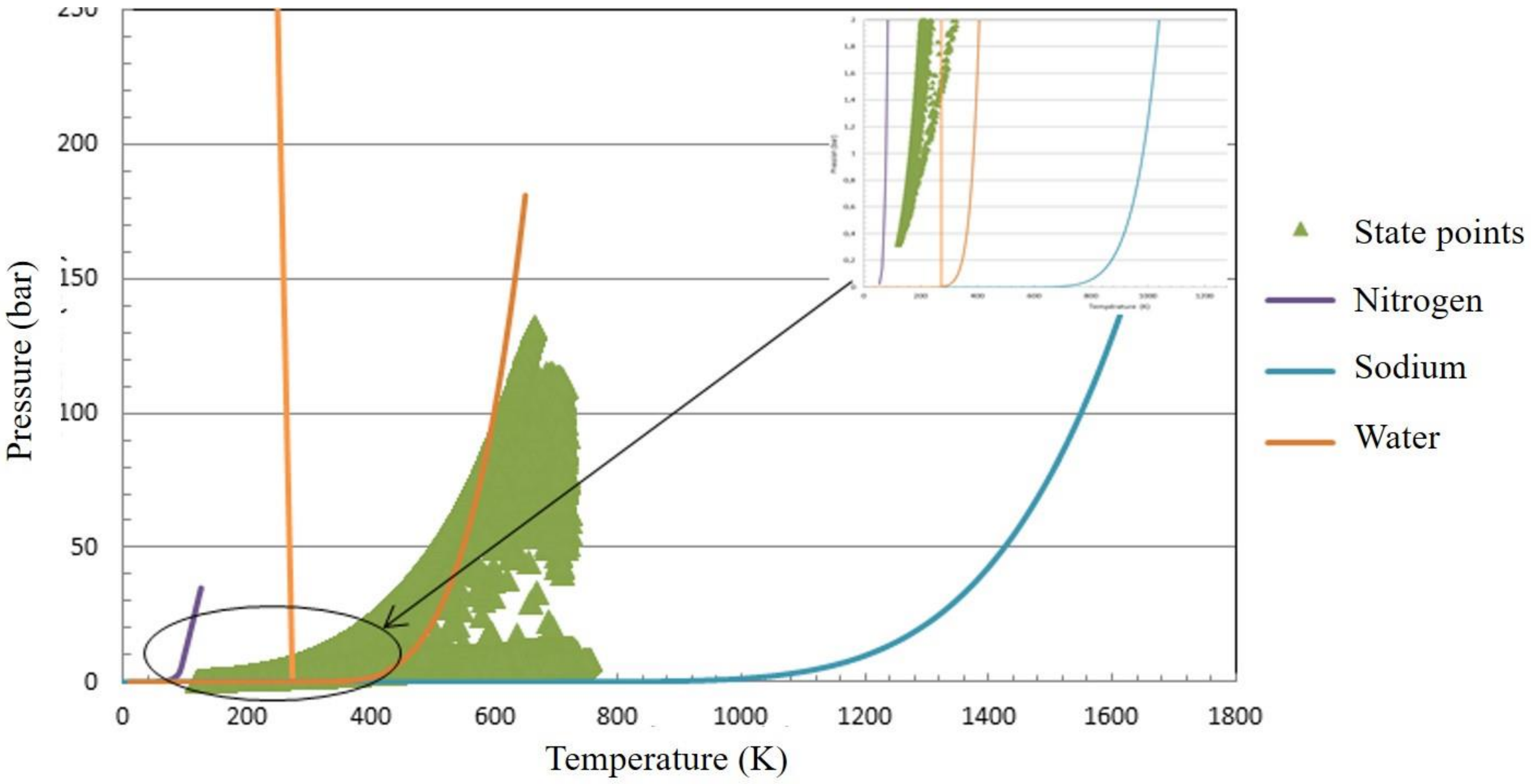
$P_a = 30\ bar$
$d_N = 0{,}7\ mm$
$T_a = 773\ K$
$x/\ x_{DM}$

The impacts produced by the under-expanded nitrogen jets in sodium hydroxide [Lécume et al., 1989].

Model = Two velocities / Drag force + Two pressures + Viscous diffusion + Others ?

Predominant physical phenomena

- No chemical reactions (concluded from the experiments in ANL)
- No phase change [Chen et al., 2016] (technical note not published)



Multiphase model

- Baer-Nunziato + Drag force + Viscous diffusion + Others ?

$$\frac{\partial \alpha_g}{\partial t} + \vec{u_I}\vec{\nabla}\alpha_g = 0$$

$$\frac{\partial(\alpha_g\rho_g)}{\partial t} + div(\alpha_g\rho_g\vec{u_g}) = 0$$

$$\frac{\partial(\alpha_g\rho_g\vec{u_g})}{\partial t} + div(\alpha_g\rho_g\vec{u_g}\otimes\vec{u_g} + \alpha_g\overline{\overline{P_g}}) = P_I\vec{\nabla}\alpha_g \boxed{+\vec{F_D}} \boxed{+\vec{F_v}}$$

$$\frac{\partial(\alpha_g\rho_g E_g)}{\partial t} + div(\vec{u_g}(\alpha_g\rho_g E_g + \alpha_g\overline{\overline{P_g}})) = P_I\vec{u_I}\vec{\nabla}\alpha_g \boxed{+\vec{u_I}\vec{F_D}} \boxed{+\vec{u_g}\vec{F_v}}$$

$$\frac{\partial(\alpha_l\rho_l)}{\partial t} + div(\alpha_l\rho_l\vec{u_l}) = 0$$

$$\frac{\partial(\alpha_l\rho_l\vec{u_l})}{\partial t} + div(\alpha_l\rho_l\vec{u_l}\otimes\vec{u_l} + \alpha_l\overline{\overline{P_l}}) = P_I\vec{\nabla}\alpha_l \boxed{-\vec{F_D}} \boxed{+\vec{F_v}}$$

$$\frac{\partial(\alpha_l\rho_l E_l)}{\partial t} + div(\vec{u_l}(\alpha_l\rho_l E_l + \alpha_l\overline{\overline{P_l}})) = P_I\vec{u_I}\vec{\nabla}\alpha_l \boxed{-\vec{u_I}\vec{F_D}} \boxed{+\vec{u_l}\vec{F_v}}$$

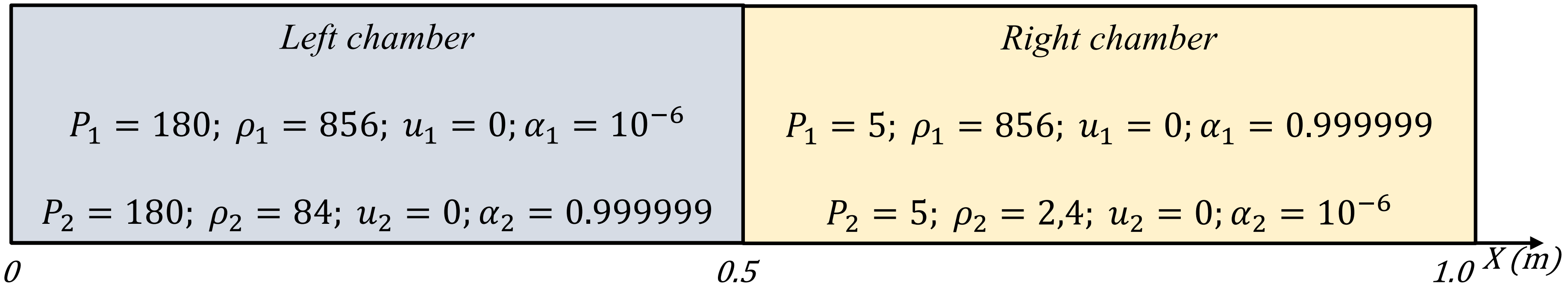
α	:	volume fraction
ρ	:	density (kg/m^3)
u	:	velocity (m/s)
P	:	pressure (Pa)
E	:	total energy (J/kg)
F_D	:	drag force (N/m^3)
F_v	:	viscous diffusion (N/m^3)
g, l, I	:	gas, liquid, interface

- Numerical scheme:
  - Rusanov solver
  - MUSCL-Hancock

Multiphase model

- Limit the non-physical effects of the fictitious phase in the pure phase
  - Shock tube air-sodium
    - Initial conditions

$$P\text{: pressure Pa ; } \quad \rho\text{: density } \frac{kg}{m^3}\text{ ; } \quad u\text{: velocity m/s}$$

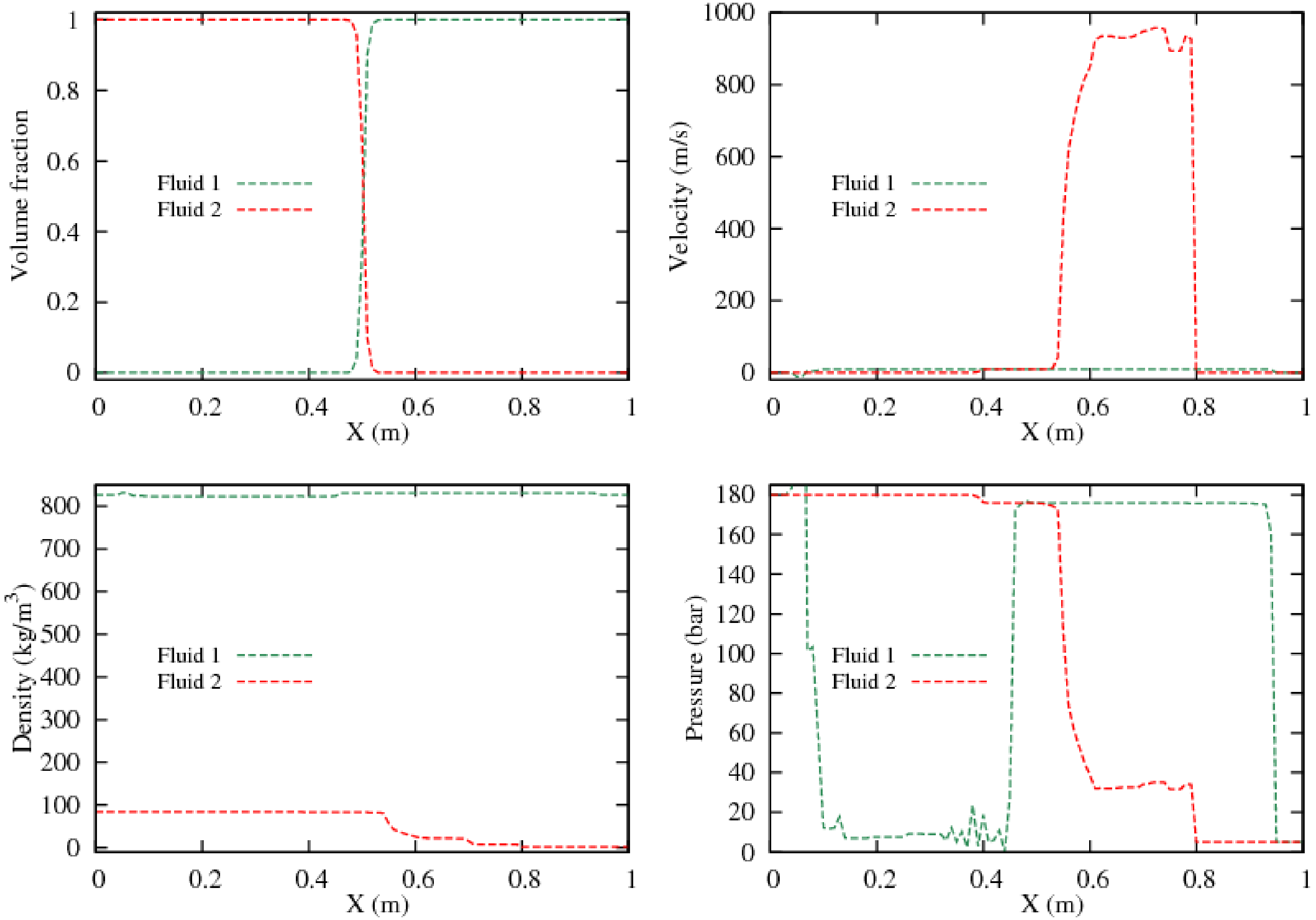


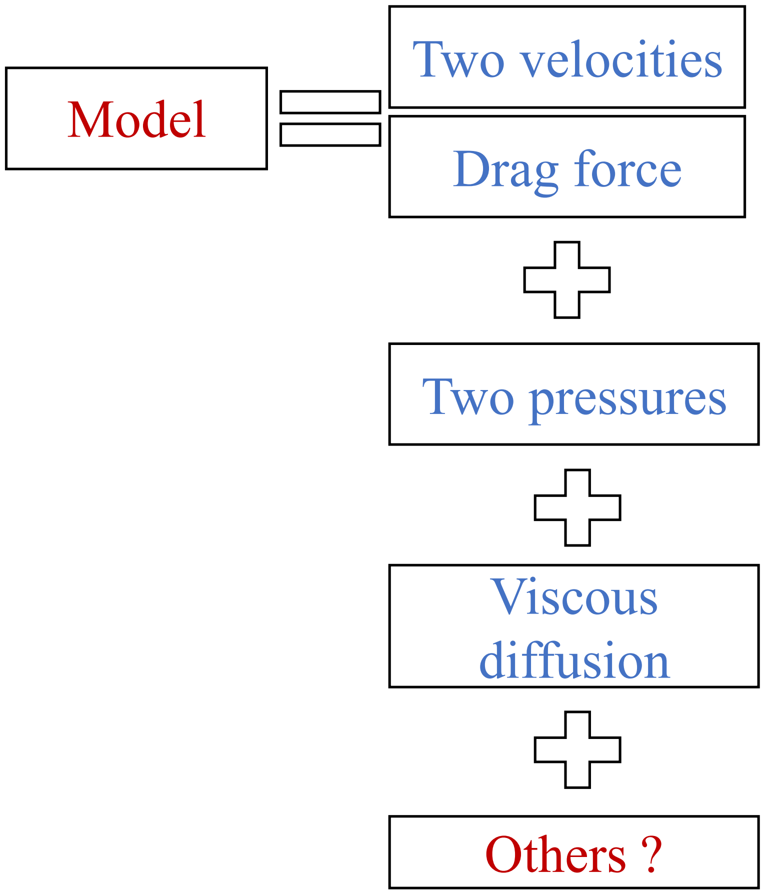
- Parameters of EOS (Albert-Nobel-Stiffened-Gas)

	γ	π (Pa)	q (J/kg)	b (m^3/kg)
Fluid 1	1.19	$7.03*10^8$	-1177788	$6.61*10^{-4}$
Fluid 2	1.4	0	0	0

Multiphase model

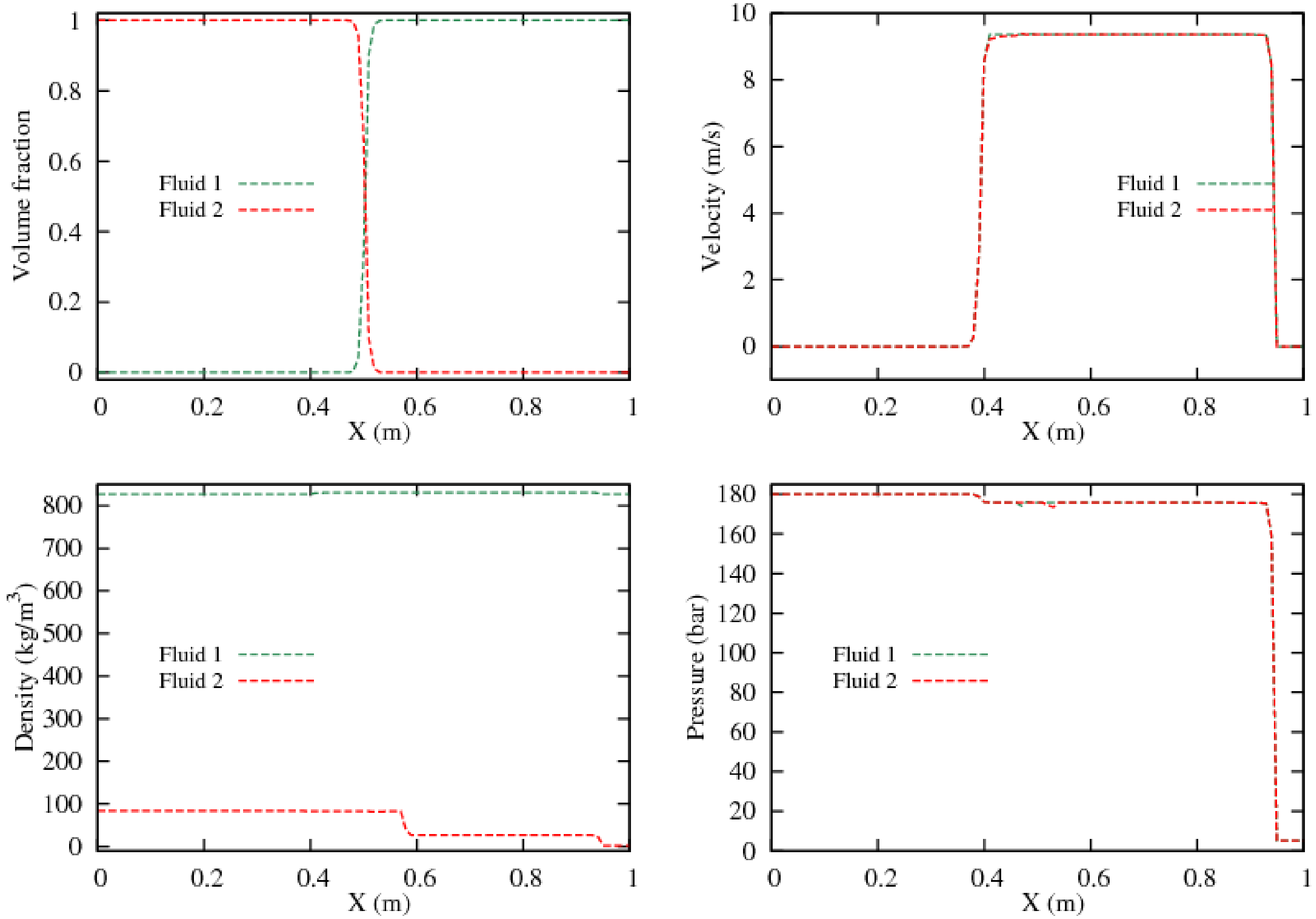
- Limit the non-physical effects of the fictitious phase in the pure phase
  - Results

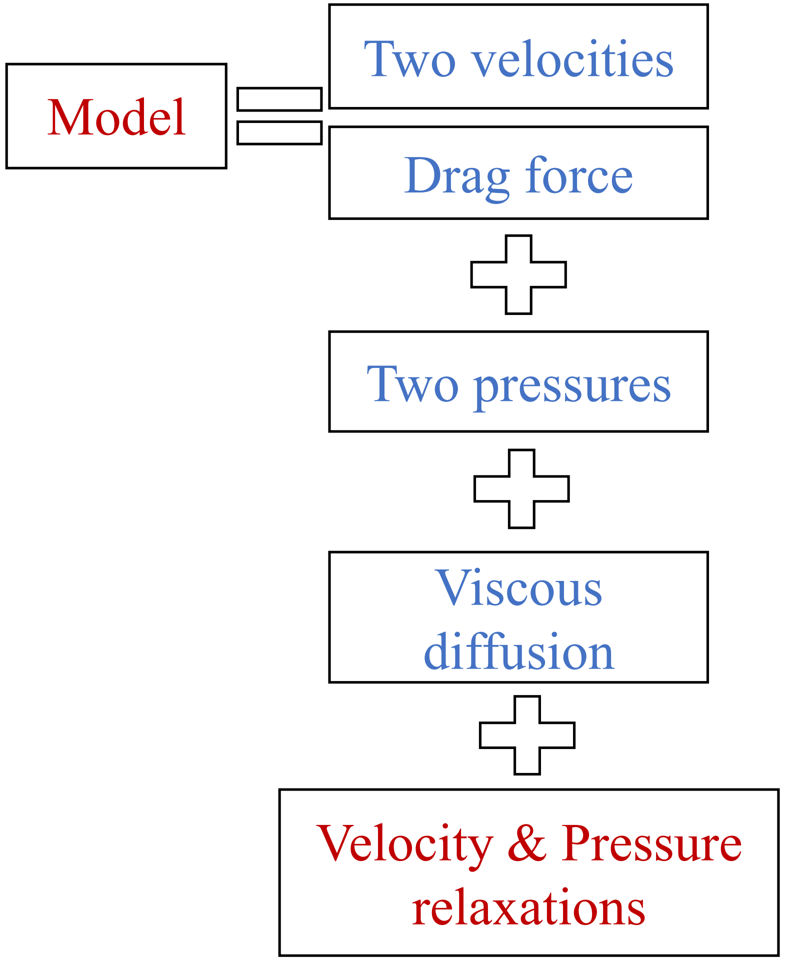




Multiphase model

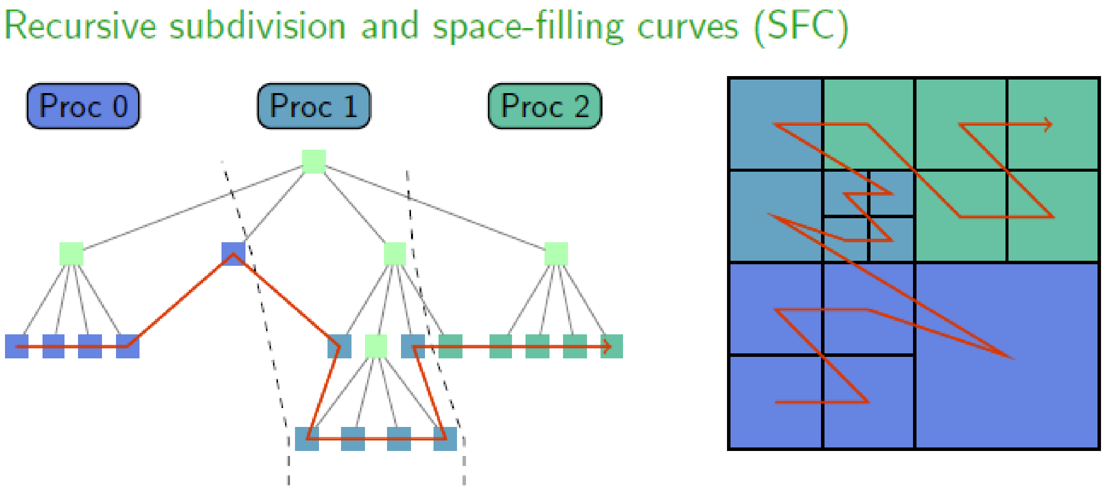
- Limit the non-physical effects of the fictitious phase in the pure phase
  - Corrected results



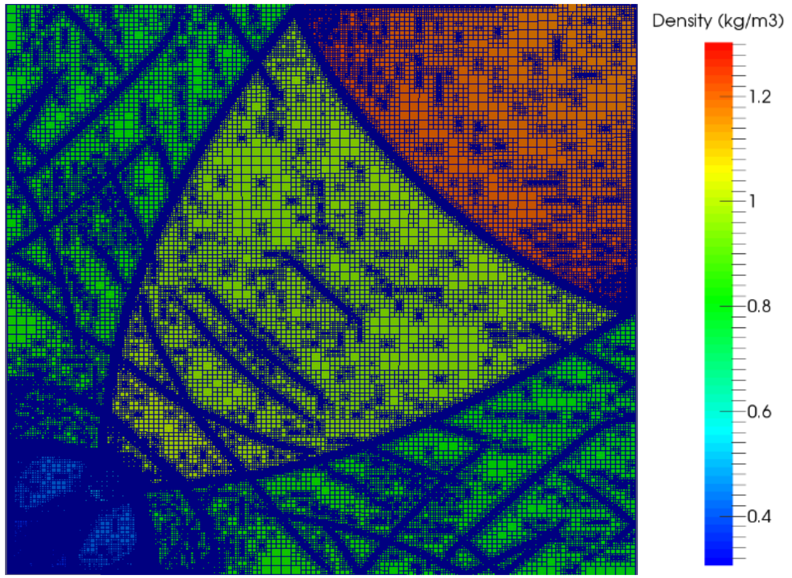


Numerical tool - CANOP

- Two layers in CANOP:
  - Low-level layer:
    - ➢ cell-based Adaptive Mesh Refinement (P4est library),
    - ➢ efficient parallel computation.



- ▸ 1:1 relation between leaves and elements → efficient encoding
- ▸ Map a 1D curve into 2D or 3D space → total ordering
- ▸ Recursive self-similar structure → scale-free
- ▸ Tree leaf traversal → cache-efficient



An AMR example controlled by the gradient of density.

  - High-level layer, for implementing numerical schemes:
    - ➢ Finite volume method,
    - ➢ PDF problems in Fluid Dynamics (for astrophysics, multiphase flows, *etc*).

Numerical tool - CANOP

- General sketch of CANOP framework

Common functions

Time iteration
Mesh adaptation
Connectivity
Geometry
Quadrant management

Branches in CANOP

Scalar advection
Monophasic Euler equation
3 eqs two-fluid flow [Drui et al., 2016]
Superbifluid (7 eqs)
…

Functions defined by user

User data
Numerical schemes
AMR indicator
Initial conditions
Boundary conditions
Modelling geometry

Tasks sent to machines in IDRIS

Results

- Model validation
- Under-expanded gas jets

Calculation strategy

Validation of convective part

- Two-phase shock tube tests: analytical cases of the literature

Validation of source terms

- Viscous diffusion: Poiseuille flow
- Momentum exchange: mixing layer between two fluids

Modelling of under-expanded gas jets

- Comparison between the numerical results & experiments
- Under-expanded gas jets in SGHE channel

Model validation

- Convective part
  - Initial conditions

P: pressure Pa ; ρ: density $\frac{kg}{m^3}$; u: velocity m/s

Left chamber

$P_1 = 1;\ \rho_1 = 1;\ u_1 = 0; \alpha_1 = 0.7$

$P_2 = 0.3;\ \rho_2 = 0.2;\ u_2 = 0; \alpha_2 = 0.3$

Right chamber

$P_1 = 1;\ \rho_1 = 1;\ u_1 = 0; \alpha_1 = 0.3$

$P_2 = 1;\ \rho_2 = 1;\ u_2 = 0; \alpha_2 = 0.7$

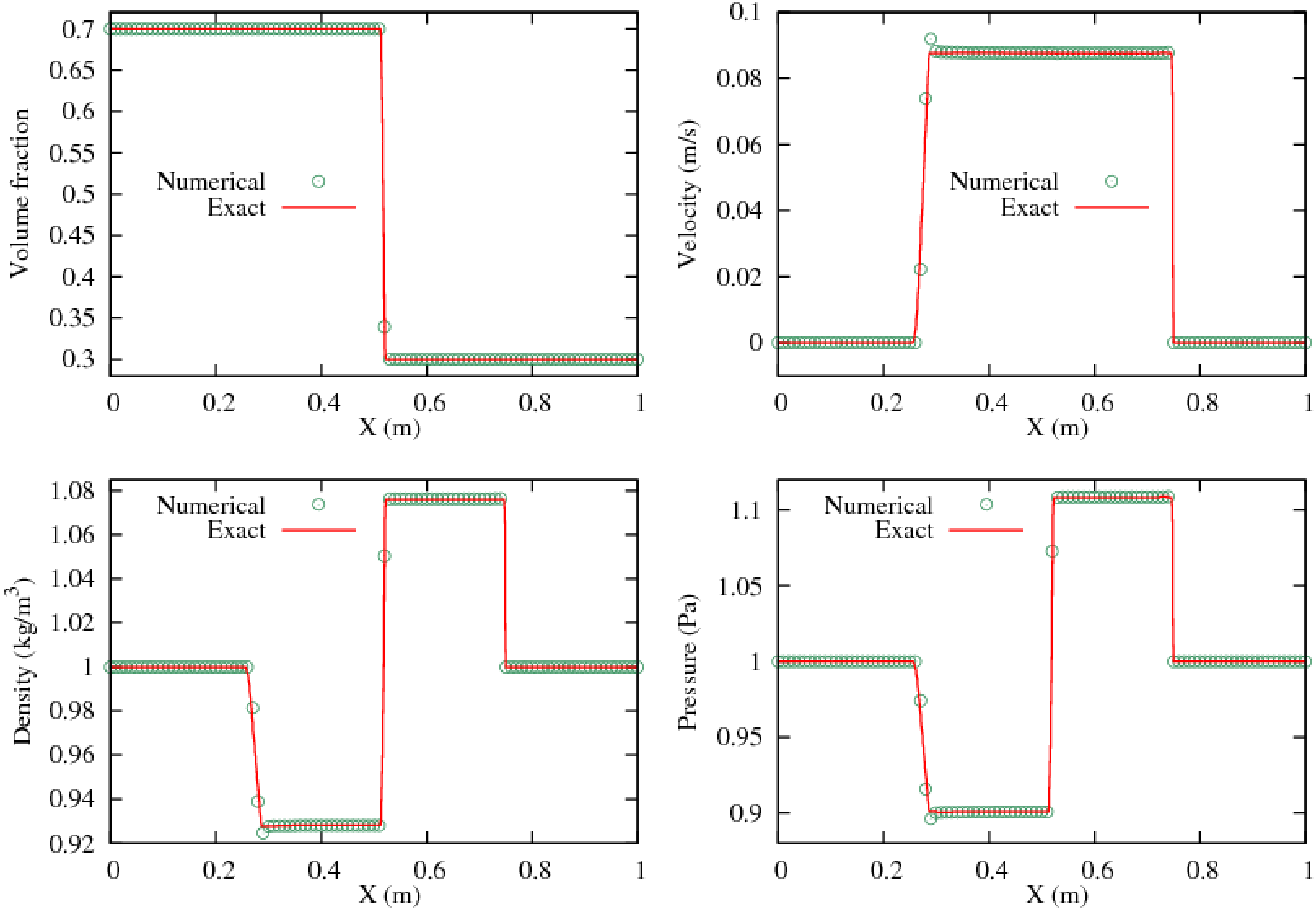
X (m): *0* — *0.5* — *1.0*

  - EOS parameters for two fluids (Albert-Nobel-Stiffened-Gas)

	γ	$\pi\ (Pa)$	***q (J/kg)***	***b*** (m^3/kg)
Fluid 1	1.4	0	0	0
Fluid 2	1.4	0	0	0

Model validation

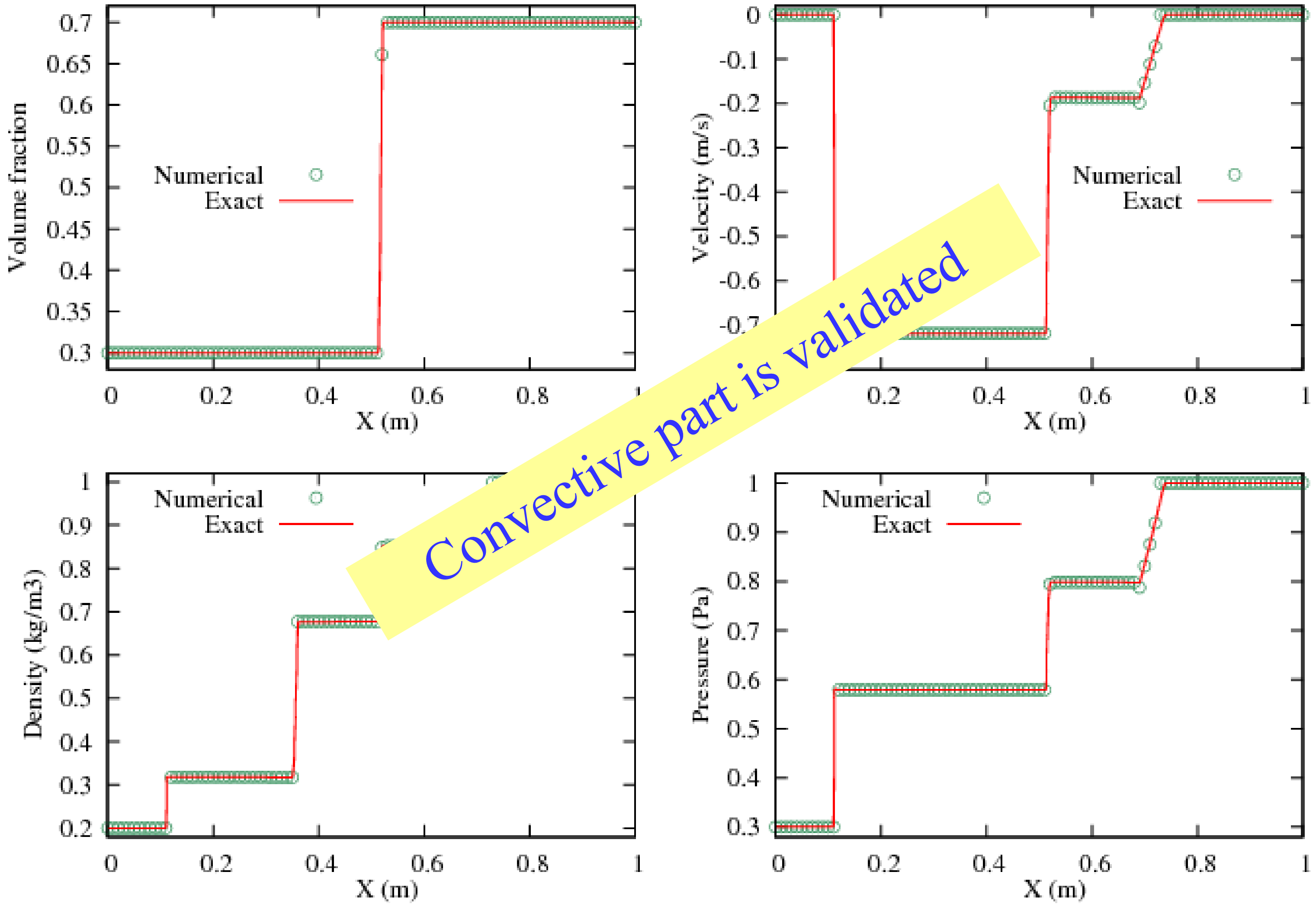
- Convective part
  - Results



Fluid 1

Model validation

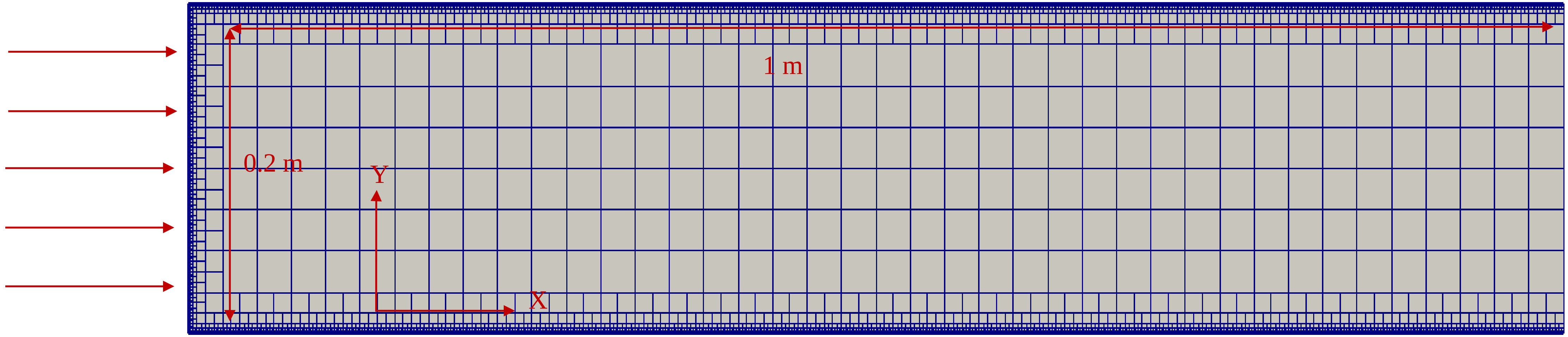
- Convective part
  - Results



Fluid 2

Model validation

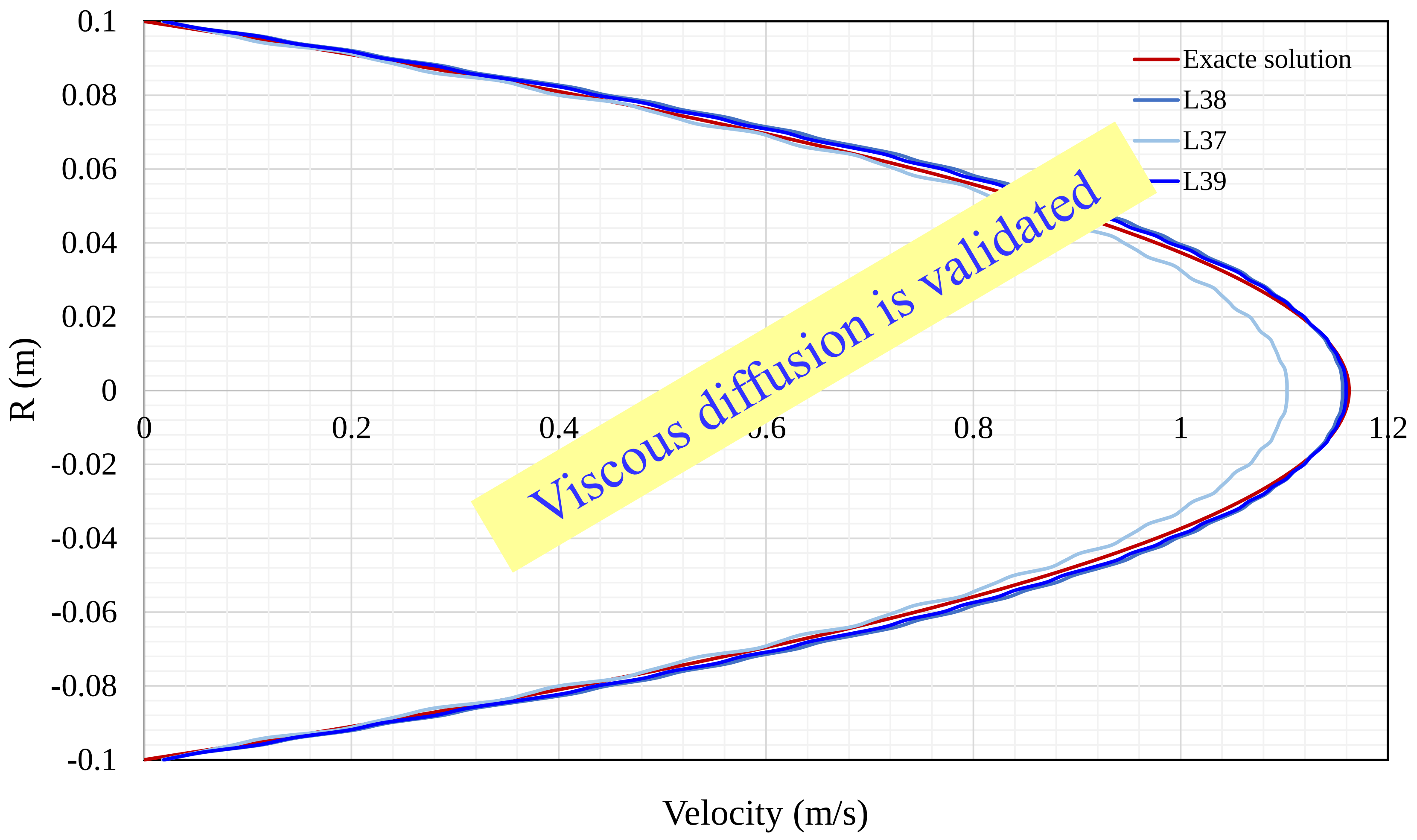
- Viscous diffusion
  - Initial conditions



U	Density	Pressure	Dynamic viscosity	Conductivity	Pr	Mach	Re	Gamma
(m/s)	*(kg/m³)*	*(Pa)*	*(Pa.s)*	*(J/K/m)*	-	-	-	-
1.0	1.0	4.4643	$5*10^{-3}$	6.95	0.72	0.4	200	1.4

Model validation

- Viscous diffusion
  - Results



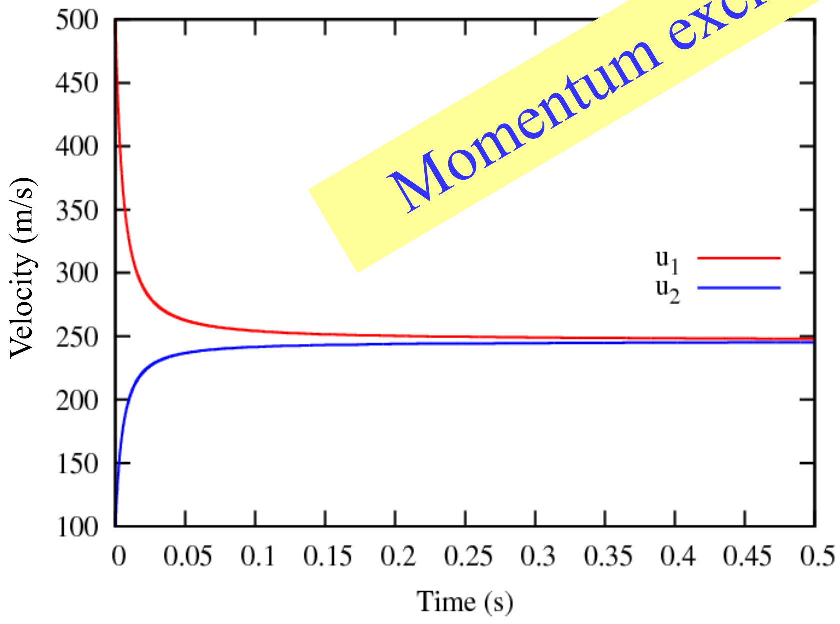
Model validation

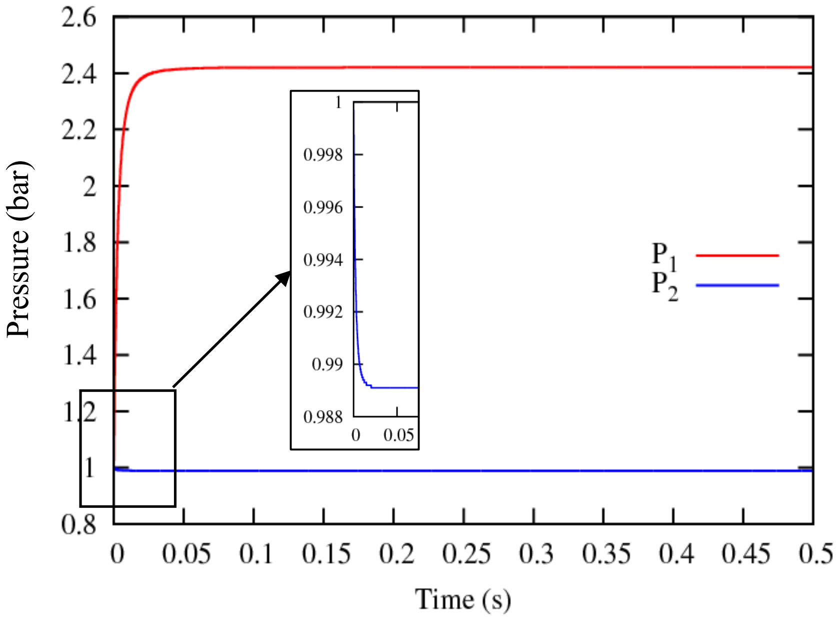
- Momentum exchange
  - Initial conditions

Fluid 1	$\alpha_1 = 0.999999,\ u_1 = 500\, m/s,\ v_1 = 0\, m/s,\ \rho_1 = 1000\ kg/m^3,\ P_1 = 1\, bar,$ $\gamma_1 = 4.4, \quad \pi_1 = 6e8$
Fluid 2	$\alpha_1 = 1e-6,\ u_2 = 100\, m/s,\ v_2 = 0\, m/s,$ … $m^3,\ P_2 = 1\, bar,$ $\gamma_2 = 1.4,$ …

Momentum exchange is validated

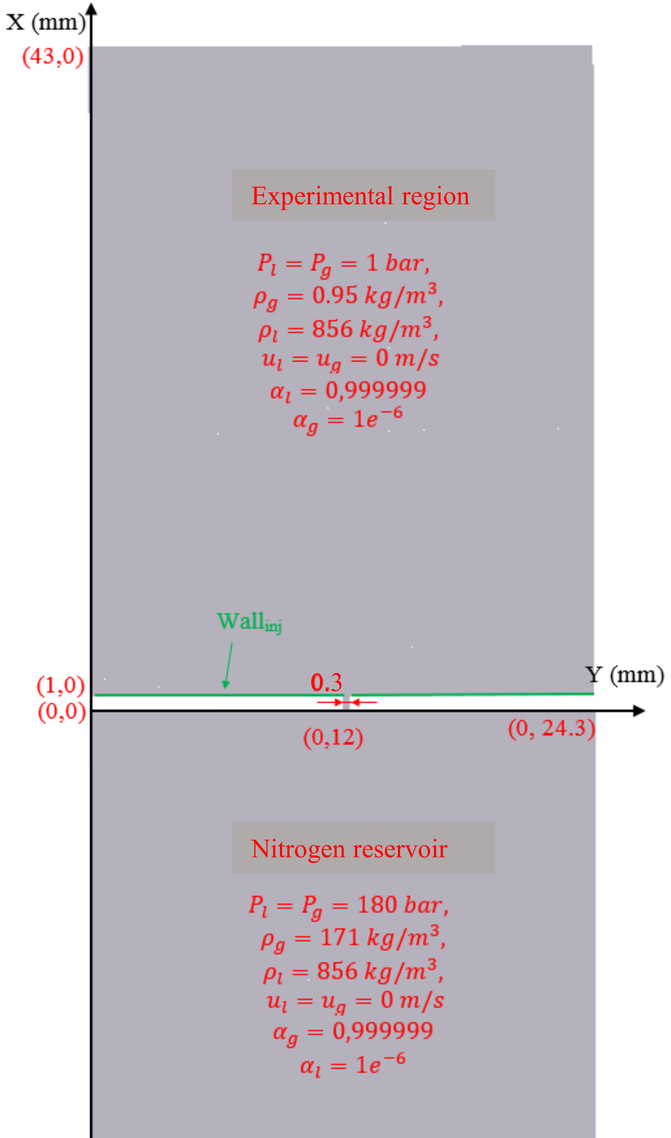
  - Results

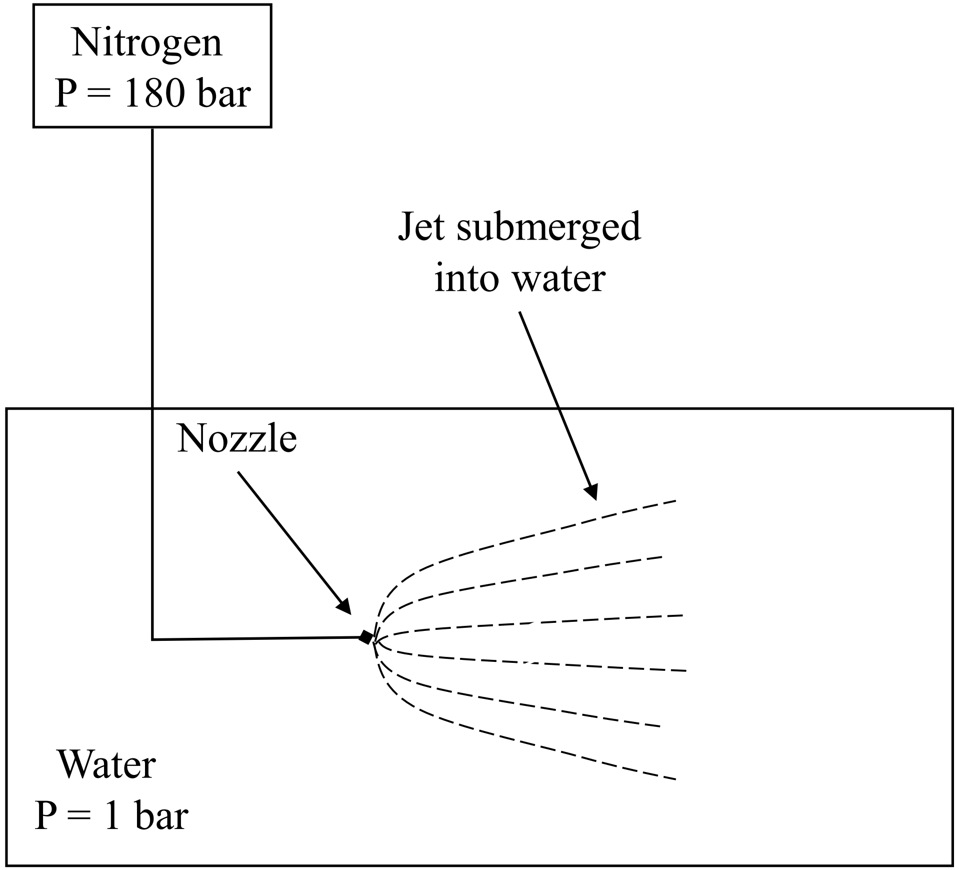




Under-expanded gas jets

- Comparison with experiments (Colleoc 1990)



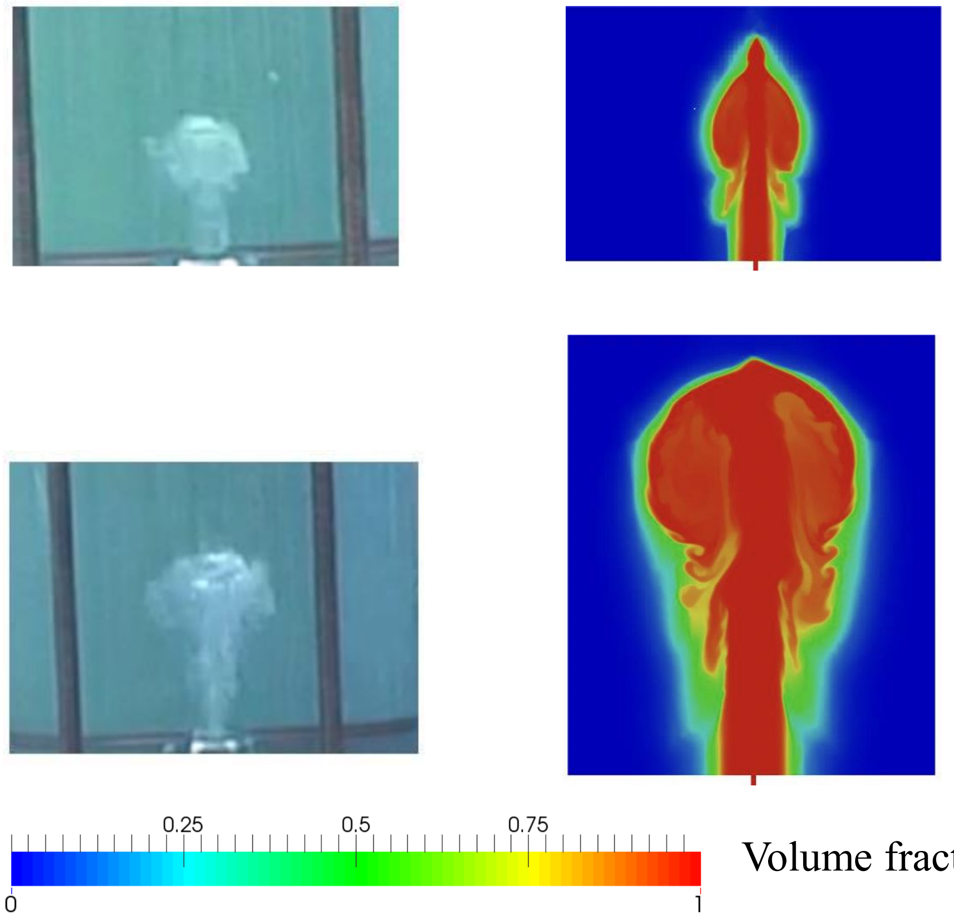


Experimental facility (Colleoc 1990)

Under-expanded gas jets

- Comparison with experiments (Colleoc 1990)

Experiment | Numerical results



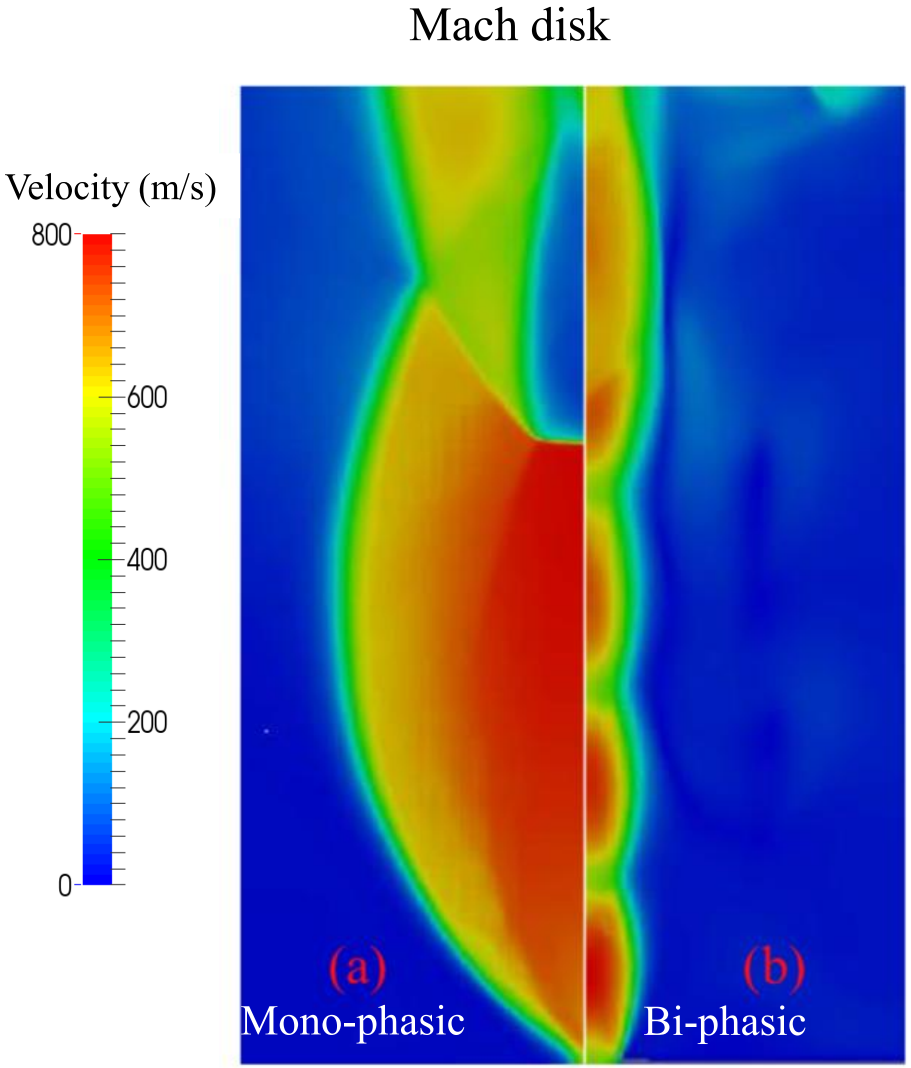
t = 130 ms

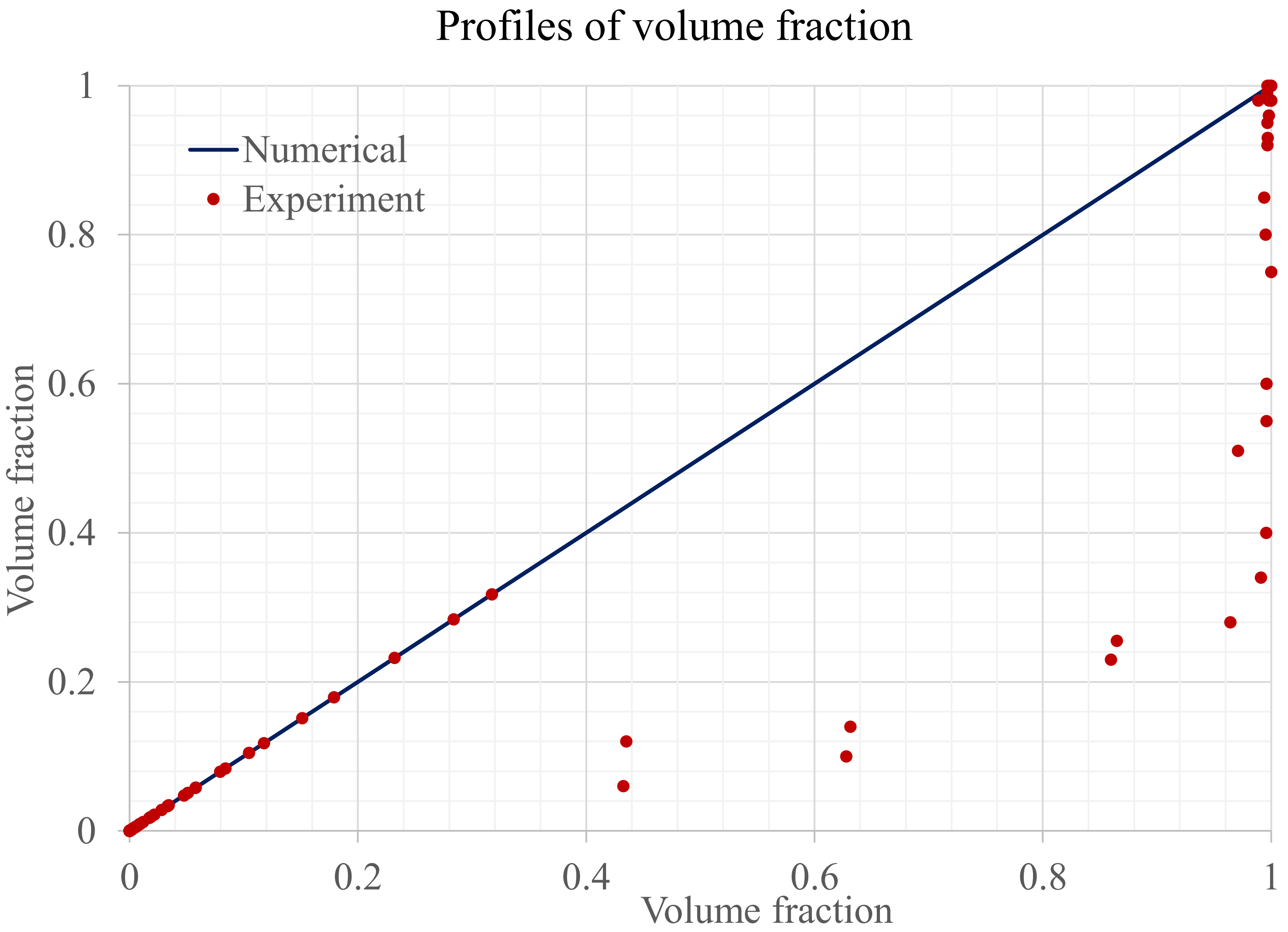
t = 260 ms

Volume fraction of gas

Under-expanded gas jets

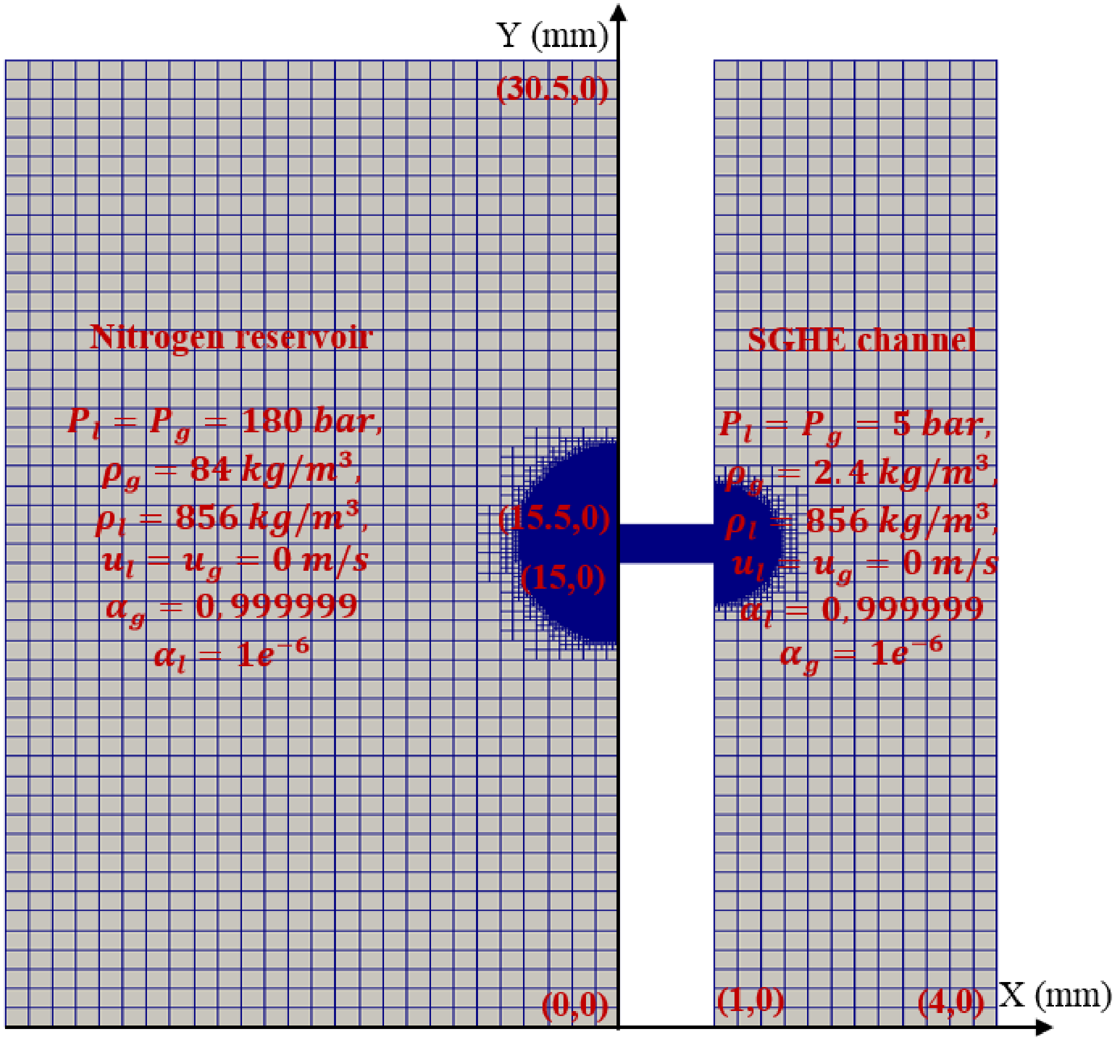
- Comparison with experiments (Colleoc 1990)





Under-expanded gas jets

- Gas jets submerged into sodium liquid in SGHE

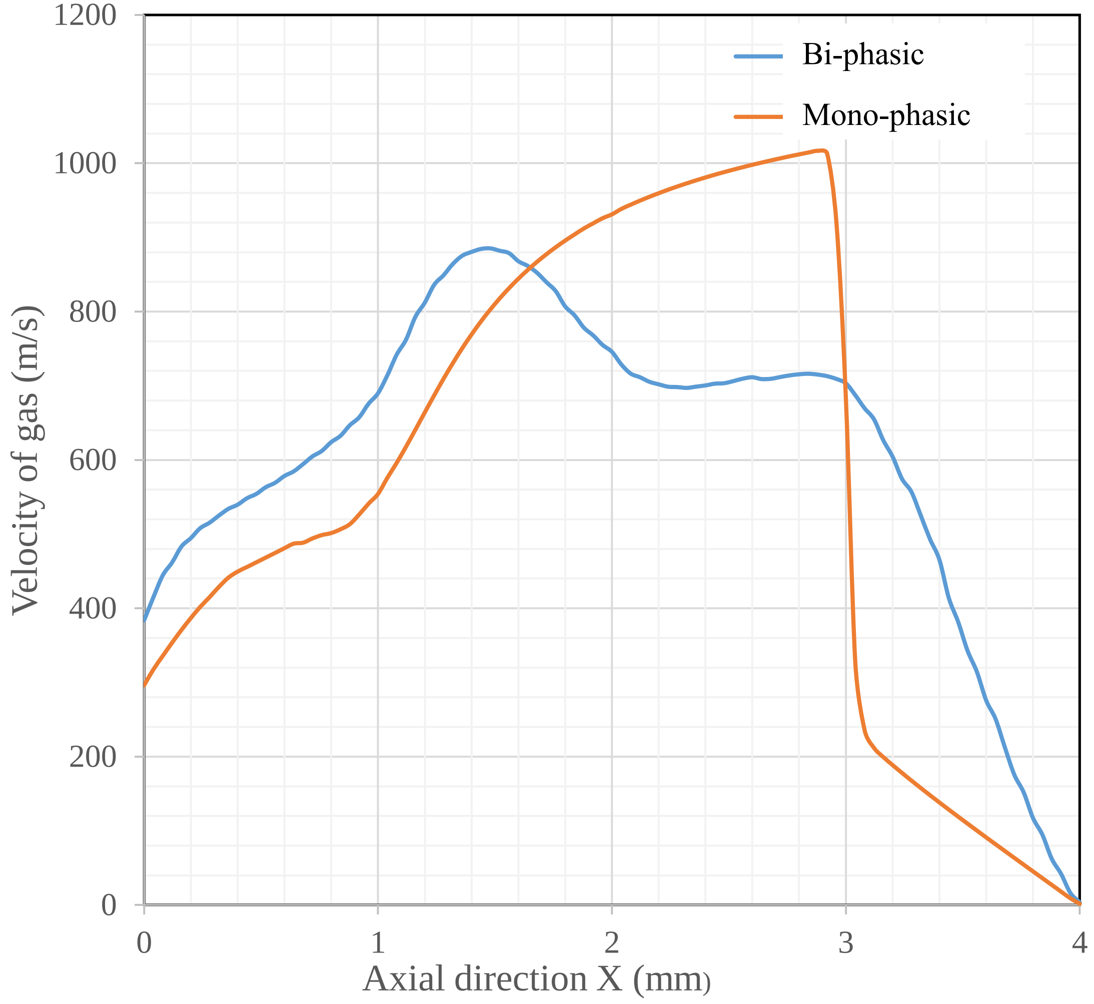


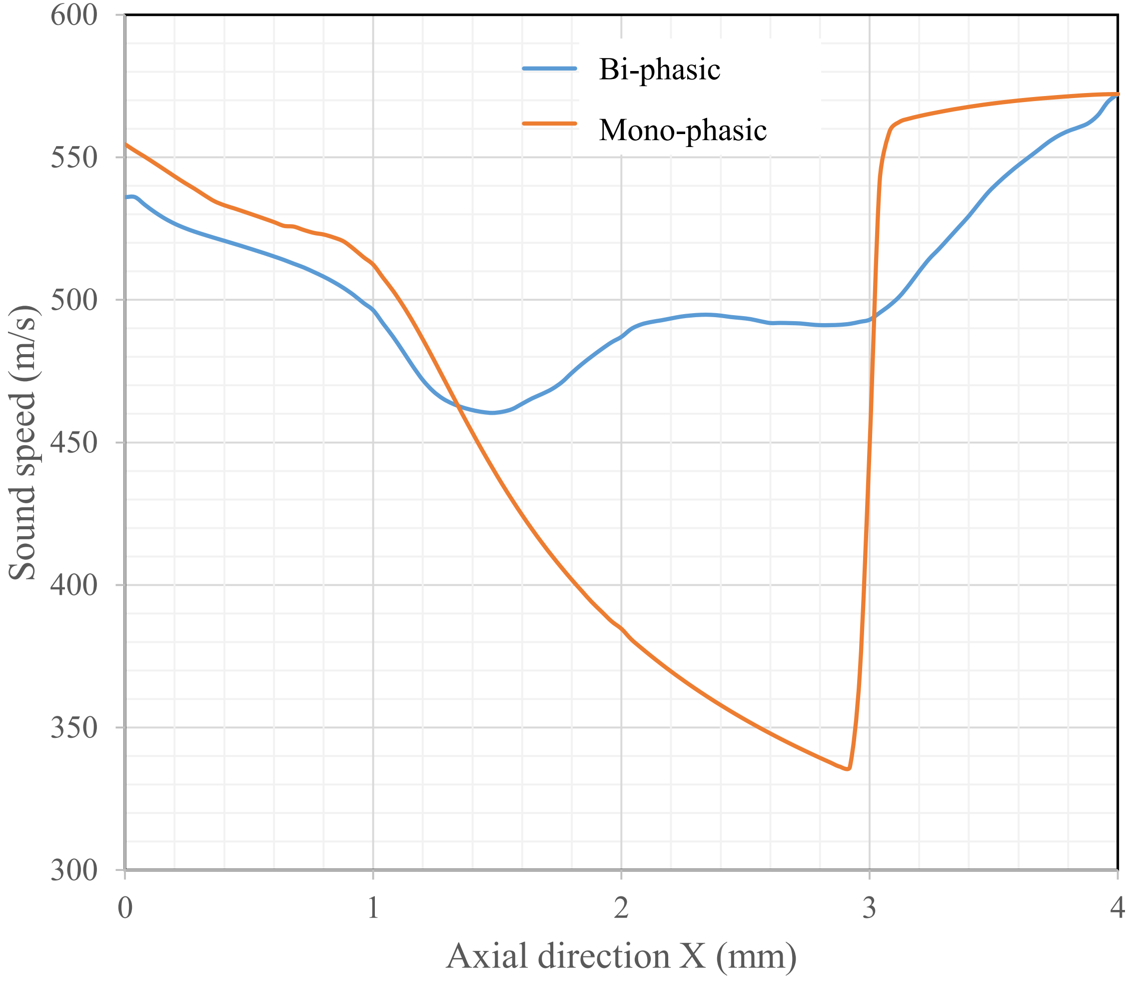
Hypothesis:

- Uniform size of droplets & bubbles;
- No fragmentation of particles owning to the shock waves;
- Homogeneity of interface property;
- No turbulent model.

Under-expanded gas jets

- Gas jets submerged into sodium liquid in SGHE

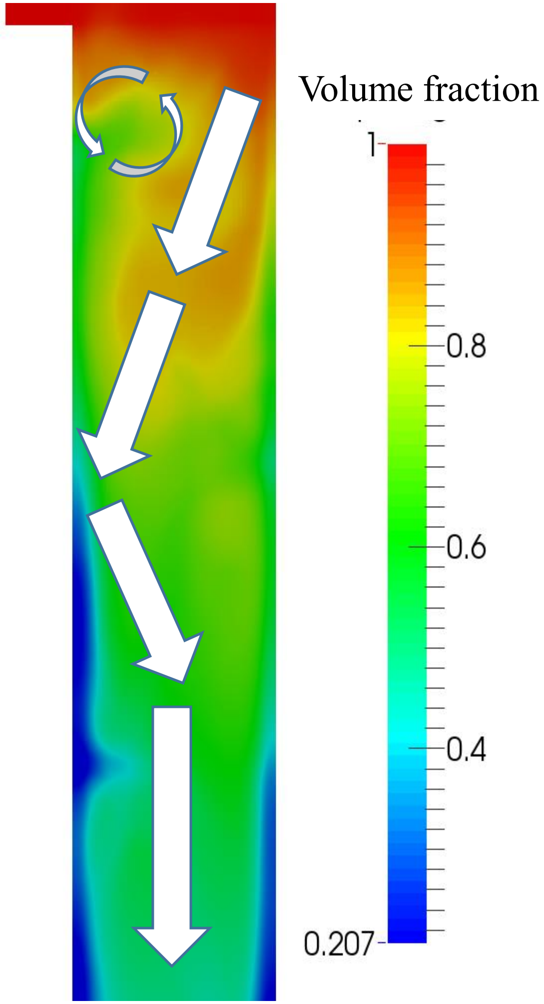




Localization of Mach disk is smoother for a bi-phasic jet in SGHE channel

Under-expanded gas jets

- Gas jets submerged into sodium liquid in SGHE



Bubbles are advected throughout the channel

Provide the bubble distribution for the acoustic method to detect gas leak

Further experimental validation on IKHAR 2 facility in CEA Cadarache

Conclusion & Perspectives

Conclusion & Perspectives

- Conclusion:
  - A bi-phasic flow model integrating main physical phenomena of an under-expanded gas jet is developed;
  - The model is implemented in a numerical tool CANOP, and its capability to reproduce different two phase flow configurations is validated;
  - The results of modelling of under-expanded gas jet in a SGHE channel are promising.

- Perspectives:
  - Improvement of the interface properties (pressure & velocity) in function of different dispersed phases (droplets & bubbles);
  - Take into account the size inhomogeneity of dispersed phases;
  - Experiment IKHAR 2 will be carried out to check the flow behavior in a channel;
  - Experiment of gas jets in a SGHE collector.

Thank you for your attention

Questions?

Upcoming Webinars

29 August 2019	Lead Containing Mainly Isotope ^{208}Pb: New Reflector for Improving Safety of Fast Nuclear Reactors	Dr. Evgeny Kulikov, National Research Nuclear University “MEPhI,” Russia
25 September 2019	Gen-4 Coolants Quality Control	Dr. Christian Latge, CEA, France
23 October 2019	Passive Decay Heat Removal System	Dr. Mitchell Farmer, ANL, USA