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)

Thermo-mechanical:
Sizing, justification

Thermo-hydraulic:
Exchange performance, headers

General design

Qualification:
DIADEMO CHEOPS

SGHE for ASTRID

Module / core manufacturing
CEA / Industrial

Materials characterization
Materials compatibility
Standard & rules
Inspection
Instrumentation
Na constraint
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

![Diagram](image)
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

1. Identify the predominant physical phenomena
2. Modelling
3. Validation tests
4. Analysis of results & Corrections
5. Model development

\[
\begin{align*}
\frac{3a_2}{dt} + n_1 \bar{R}_u \bar{a}_g &= n_2 (P_2 - P_1) \\
\frac{\partial(a_0 \rho_g)}{\partial t} + \nabla \cdot (a_0 \rho_g \bar{u}_g) &= 0 \\
\frac{\partial(a_0 \rho_p \bar{p}_g)}{\partial t} + \nabla \cdot (a_0 \rho_p \bar{u}_g \bar{u}_g + a_0 \rho_p \bar{u}_g) &= -\bar{R}_u \bar{a}_g - \lambda (\bar{u}_g - \bar{u}_l) \\
\frac{\partial(a_0 \rho_p \bar{p}_g)}{\partial t} + \nabla \cdot (a_0 \rho_p \bar{u}_g \bar{u}_g) &= \bar{R}_u \bar{R}_u - \lambda (\bar{u}_g - \bar{u}_l) \\
\frac{\partial (a_0 \rho_p \bar{p}_g)}{\partial t} + \nabla \cdot (a_0 \rho_p \bar{u}_g \bar{u}_g + a_0 \rho_p \bar{u}_g) &= \bar{R}_u \bar{R}_u - \lambda (\bar{u}_g - \bar{u}_l) \\
\end{align*}
\]
Predominant physical phenomena

- Inhomogeneity of the velocity between two phases

\[ P_a = 20 \text{ bar}, \quad d_N = 0,7 \text{ mm}, \quad x = 14 \text{ mm} \]

(Le Romancer 1991)

\[ P_a = 7 \text{ bar}, \quad d_N = 1,0 \text{ mm} \]

(Vivaldi et al., 2013)
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:

\[ R(t) = \Delta P_{12} \]
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].

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

\[
\begin{align*}
\frac{\partial \alpha_g}{\partial t} + \bar{u}_i \nabla \alpha_g &= 0 \\
\frac{\partial (\alpha_g \rho_g)}{\partial t} + \text{div}(\alpha_g \rho_g \bar{u}_g) &= 0 \\
\frac{\partial (\alpha_g \rho_g \bar{u}_g)}{\partial t} + \text{div}(\alpha_g \rho_g \bar{u}_g \otimes \bar{u}_g + \alpha_g \bar{P}_g) &= P_i \bar{u}_i \nabla \alpha_g + \bar{F}_D + \bar{F}_v \\
\frac{\partial (\alpha_g \rho_g E_g)}{\partial t} + \text{div}(\bar{u}_g (\alpha_g \rho_g E_g + \alpha_g \bar{P}_g)) &= P_i \bar{u}_i \nabla \alpha_g + u_i \bar{F}_D + \bar{u}_g \bar{F}_v \\
\frac{\partial (\alpha_i \rho_i)}{\partial t} + \text{div}(\alpha_i \rho_i \bar{u}_i) &= 0 \\
\frac{\partial (\alpha_i \rho_i \bar{u}_i)}{\partial t} + \text{div}(\alpha_i \rho_i \bar{u}_i \otimes \bar{u}_i + \alpha_i \bar{P}_i) &= P_i \bar{u}_i \nabla \alpha_i - \bar{F}_D + \bar{F}_v \\
\frac{\partial (\alpha_i \rho_i E_i)}{\partial t} + \text{div}(\bar{u}_i (\alpha_i \rho_i E_i + \alpha_i \bar{P}_i)) &= P_i \bar{u}_i \nabla \alpha_i - \bar{u}_i \bar{F}_D + \bar{u}_i \bar{F}_v
\end{align*}
\]

- Numerical scheme:
  - Rusanov solver
  - MUSCL-Hancock

\[\begin{align*}
\alpha & : \text{volume fraction} \\
\rho & : \text{density (kg/m}^3\text{)} \\
u & : \text{velocity (m/s)} \\
P & : \text{pressure (Pa)} \\
E & : \text{total energy (J/kg)} \\
F_D & : \text{drag force (N/m}^3\text{)} \\
F_v & : \text{viscous diffusion (N/m}^3\text{)} \\
g, l, I & : \text{gas, liquid, interface}
\]
Multiphase model

- Limit the non-physical effects of the fictitious phase in the pure phase
  - Shock tube air-sodium
    - Initial conditions
      \[
P: \text{pressure } \text{Pa} ; \quad \rho: \text{density } \frac{\text{kg}}{\text{m}^3} ; \quad u: \text{velocity } \text{m/s}
\]

  - Left chamber
    - \( P_1 = 180; \rho_1 = 856; u_1 = 0; \alpha_1 = 10^{-6} \)
    - \( P_2 = 180; \rho_2 = 84; u_2 = 0; \alpha_2 = 0.999999 \)

  - Right chamber
    - \( P_1 = 5; \rho_1 = 856; u_1 = 0; \alpha_1 = 0.999999 \)
    - \( P_2 = 5; \rho_2 = 2.4; u_2 = 0; \alpha_2 = 10^{-6} \)

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

<table>
<thead>
<tr>
<th>Fluid</th>
<th>( \gamma )</th>
<th>( \pi (\text{Pa}) )</th>
<th>( q (\text{J/kg}) )</th>
<th>( b (\text{m}^3/\text{kg}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid 1</td>
<td>1.19</td>
<td>7.03*10^8</td>
<td>-1177788</td>
<td>6.61*10^{-4}</td>
</tr>
<tr>
<td>Fluid 2</td>
<td>1.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Multiphase model

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

--- Results

- Model
  - Two velocities
  - Drag force
  - Two pressures
  - Viscous diffusion
  - Others?
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.
  - High-level layer, for implementing numerical schemes:
    - Finite volume method,
    - PDF problems in Fluid Dynamics (for astrophysics, multiphase flows, etc).

Recursive subdivision and space-filling curves (SFC)

- 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.
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

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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

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

\begin{align*}
\text{Left chamber} & : \\
P_1 &= 1; \quad \rho_1 = 1; \quad u_1 = 0; \quad \alpha_1 = 0.7 \\
P_2 &= 0.3; \quad \rho_2 = 0.2; \quad u_2 = 0; \quad \alpha_2 = 0.3 \\
\text{Right chamber} & : \\
P_1 &= 1; \quad \rho_1 = 1; \quad u_1 = 0; \quad \alpha_1 = 0.3 \\
P_2 &= 1; \quad \rho_2 = 1; \quad u_2 = 0; \quad \alpha_2 = 0.7
\end{align*}

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

<table>
<thead>
<tr>
<th></th>
<th>( \gamma )</th>
<th>( \pi \ (\text{Pa}) )</th>
<th>( q \ (\text{J/kg}) )</th>
<th>( b \ (\text{m}^3/\text{kg}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid 1</td>
<td>1.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fluid 2</td>
<td>1.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Model validation

- Convective part
  - Results

Fluid 1

![Graphs showing model validation results for Fluid 1.](image-url)
Model validation

- Convective part
  - Results

Convective part is validated

Fluid 2
Model validation

- Viscous diffusion
  - Initial conditions

<table>
<thead>
<tr>
<th>U</th>
<th>Density (kg/m³)</th>
<th>Pressure (Pa)</th>
<th>Dynamic viscosity (Pa.s)</th>
<th>Conductivity (J/K/m)</th>
<th>Pr</th>
<th>Mach</th>
<th>Re</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>4.4643</td>
<td>5.0 × 10⁻³</td>
<td>6.95</td>
<td>0.72</td>
<td>0.4</td>
<td>200</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Model validation

- Viscous diffusion
  - Results

Viscous diffusion is validated
Model validation

- Momentum exchange
  - Initial conditions

<table>
<thead>
<tr>
<th>Fluid 1</th>
<th>( \alpha_1 = 0.999999 ), ( u_1 = 500 \text{ m/s} ), ( v_1 = 0 \text{ m/s} ), ( \rho_1 = 1000 \text{ kg/m}^3 ), ( P_1 = 1 \text{ bar} ), ( \gamma_1 = 4.4 ), ( \pi_1 = 6e8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid 2</td>
<td>( \alpha_2 = 1e-6 ), ( u_2 = 100 \text{ m/s} ), ( v_2 = 0 \text{ m/s} ), ( \rho_2 = 7 \text{ kg/m}^3 ), ( P_2 = 1 \text{ bar} ), ( \gamma_2 = 1.4 ), ( \pi_2 = 0.0 )</td>
</tr>
</tbody>
</table>

- Results

![Momentum exchange is validated](image)
Under-expanded gas jets

- Comparison with experiments (Colleoc 1990)

### Experimental facility (Colleoc 1990)

- **Nitrogen reservoir**
  - \( P_1 = P_g = 180 \text{ bar} \)
  - \( \rho_g = 0.95 \text{ kg/m}^3 \)
  - \( \rho_l = 856 \text{ kg/m}^3 \)
  - \( u_l = u_g = 0 \text{ m/s} \)
  - \( \alpha_l = 0.9999999 \)
  - \( \alpha_g = 1 \times 10^{-6} \)

- **Jet submerged into water**

- **Nozzle**

- **Nitrogen**
  - \( P = 180 \text{ bar} \)

- **Water**
  - \( P = 1 \text{ bar} \)
Under-expanded gas jets

Comparison with experiments (Colleoc 1990)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Numerical results</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Experiment Image]</td>
<td>![Numerical results Image]</td>
</tr>
<tr>
<td>![Experiment Image]</td>
<td>![Numerical results Image]</td>
</tr>
</tbody>
</table>

Volume fraction of gas

$t = 130 \text{ ms}$

$t = 260 \text{ ms}$
Under-expanded gas jets

- Comparison with experiments (Colleoc 1990)

Profiles of volume fraction

Mach disk

(a) Mono-phasic
(b) Bi-phasic
Under-expanded gas jets

- Gas jets submerged into sodium liquid in SGHE

Hypothesis:

- Uniform size of droplets & bubbles;
- No fragmentation of particles owing 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