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Fuel coolant interaction modelling in sodium cooled fast reactors

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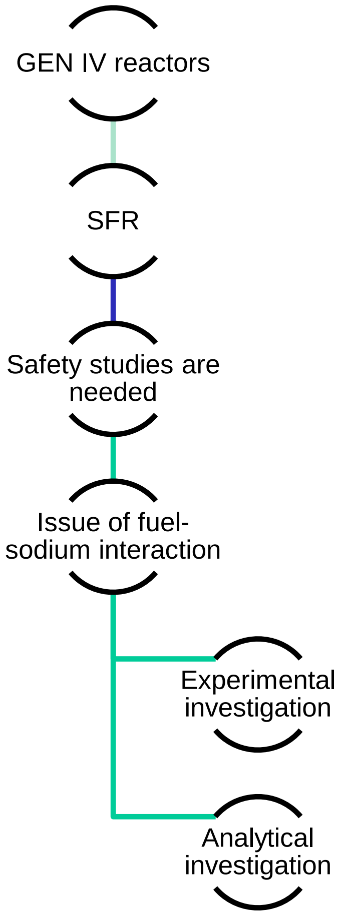
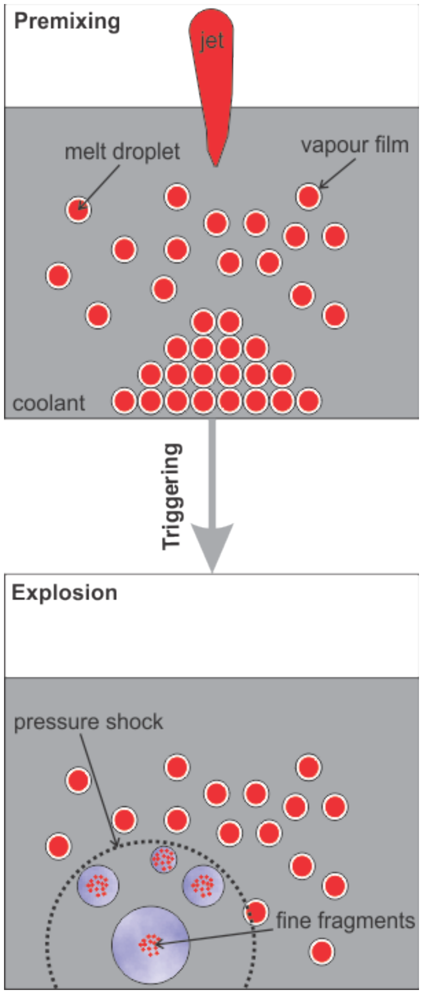
Outline

- Introduction
- Premixing phase
- Explosion phase
- Conclusions



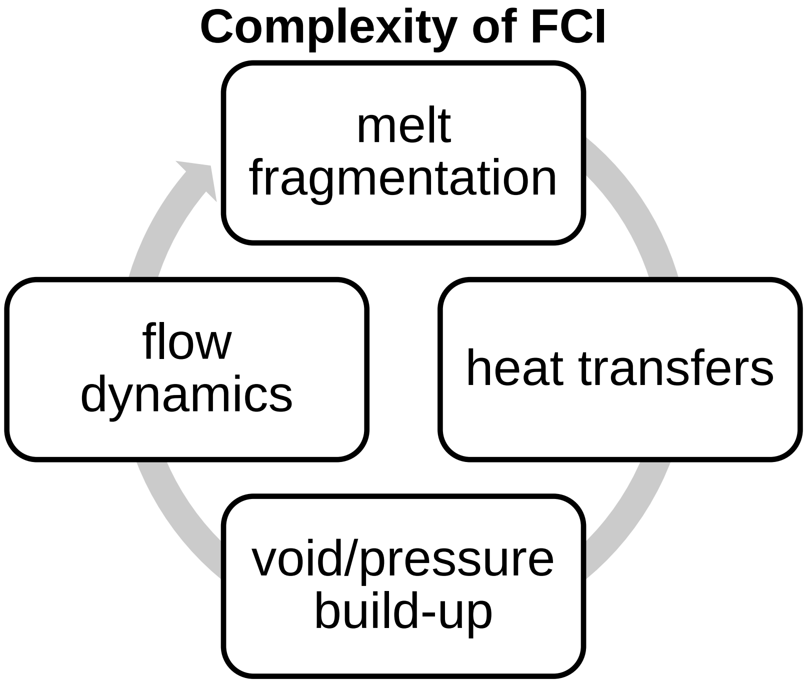
Introduction

- Four major accident scenarios are relevant for SFR
  - Unprotected Loss of Flow (ULOF)
  - Total Instantaneous Blockage (TIB)
  - Unprotected Transient Over Power (UTOP)
  - Unprotected Loss of Heat Sink (ULOHS)
- Fuel-sodium interaction issues
  - Debris coolability
  - Vapour explosion, may occur during core melt accident when rapid and intense heat transfer follows interaction between molten material and coolant. Strength depends on
    - melt mass, void, melt solidification



Introduction

- Capabilities of FCI codes to cover fuel-water interaction in reactor cases were demonstrated in the frame of
  - OECD SERENA
  - EU SARNET
- Applicability of the premixing and explosion models in the MC3D code (IRSN, France) to cover fuel-sodium interaction is currently under examination



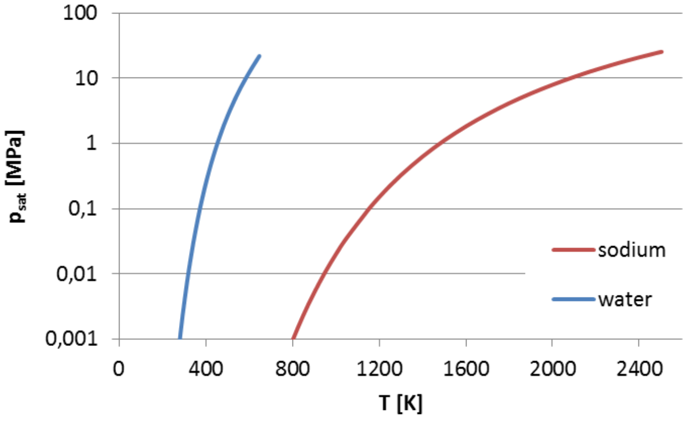
Premixing

- Premixing phase is important
  - To determine initial conditions of a possible vapour explosion
  - Drives formation of debris bed on the core catcher and thus potential coolability of corium
- Key processes
  - Melt fragmentation
  - Heat transfer
  - Void build-up

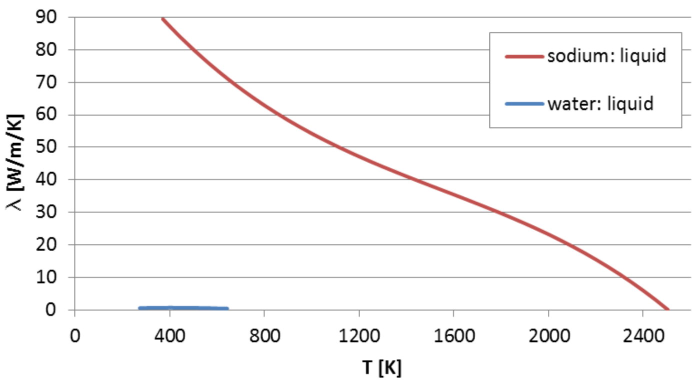
Premixing: melt fragmentation

- Reality
  - Melt fragments due to various instabilities created at melt-coolant contact
  - Different melt scales are often intermixed
  - Feedback effect of vaporization
    - water: mainly in film boiling conditions
    - sodium: also important effect of transition and nucleate boiling

Vapour pressure

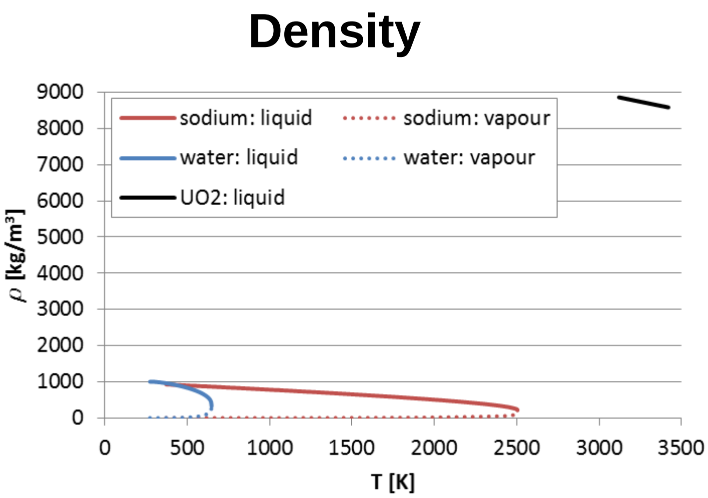


Thermal conductivity



Premixing: melt fragmentation

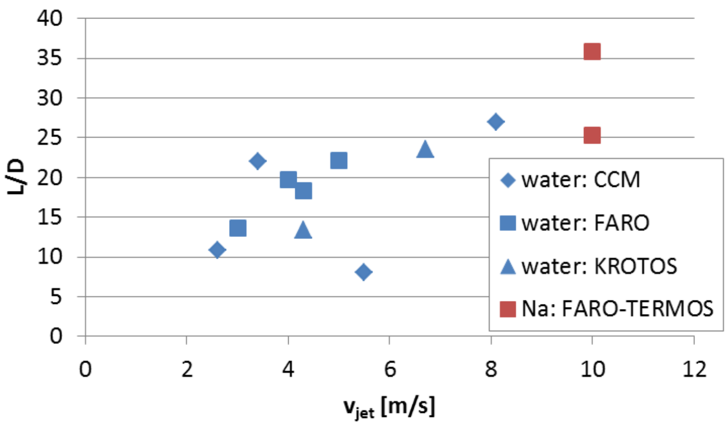
- Modelling
  - Dominating role of Kelvin-Helmholtz mechanisms
    - consensus obtained during the OECD SERENA project for vertical jets
    - differences of water and sodium density are not sufficiently important to anticipate differences in fragmentation rate
  - Concept of primary and secondary fragmentation
  - Local and global models
    - at sub-cooled conditions a quasi liquid-liquid behaviour with small impact of boiling may be expected
    - around saturation conditions a strong impact of boiling



Premixing: melt fragmentation

- Experiments with sodium
  - Two different behaviours might be anticipated
    - quasi liquid/liquid behaviour with small impact of boiling
    - strong impact of boiling process as it is known that transition boiling (and also nucleate) is a quite dynamic process
  - Experiments with sodium all show a turbulent behaviour, attributed to transition boiling, accompanied by pressure events
  - Thermal effects on fragmentation rate should then be studied with more precision

Jet break-up length



Premixing: heat transfer

Film boiling → Transition boiling → Nucleate boiling → Convection

Film boiling

- Saturated conditions
- Sub-cooled conditions

Transition boiling

- Interpolation between minimal and maximal heat fluxes

Nucleate boiling

Convection

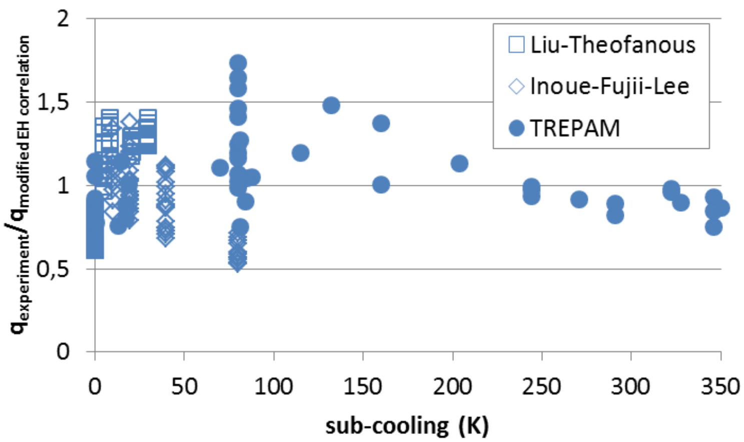
Radiative

- Emissivity of water ~0.9
- Emissivity of sodium ~0.05

Premixing: heat transfer

- Film boiling heat transfer in water is well characterized
- Theoretical background of Epstein-Hauser (EH) correlation makes it the preferred choice for the characterization of film boiling heat transfer in FCI codes
- EH based approach
  - Reasonably describes experiments with water
  - On theoretical level the approach could be also applicable for sodium, however applicability shall be demonstrated with experiments

Modified EH correlation vs. experimental data

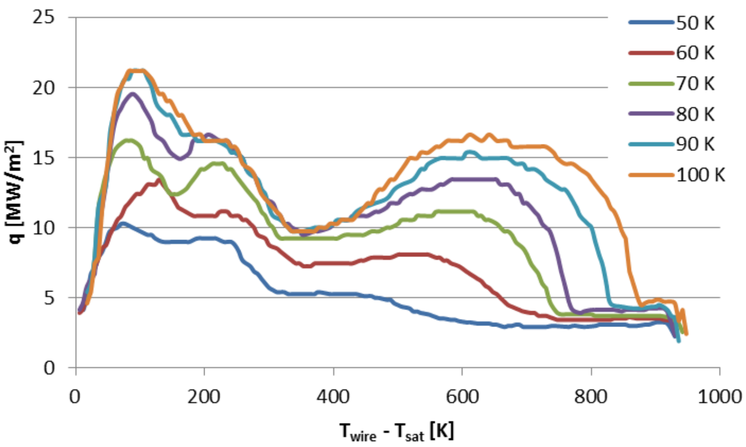


Premixing: heat transfer

- In some experiments with sub-cooled water and the surface temperature above the homogeneous nucleation temperature the heat transfer was higher than typically observed in film boiling regime

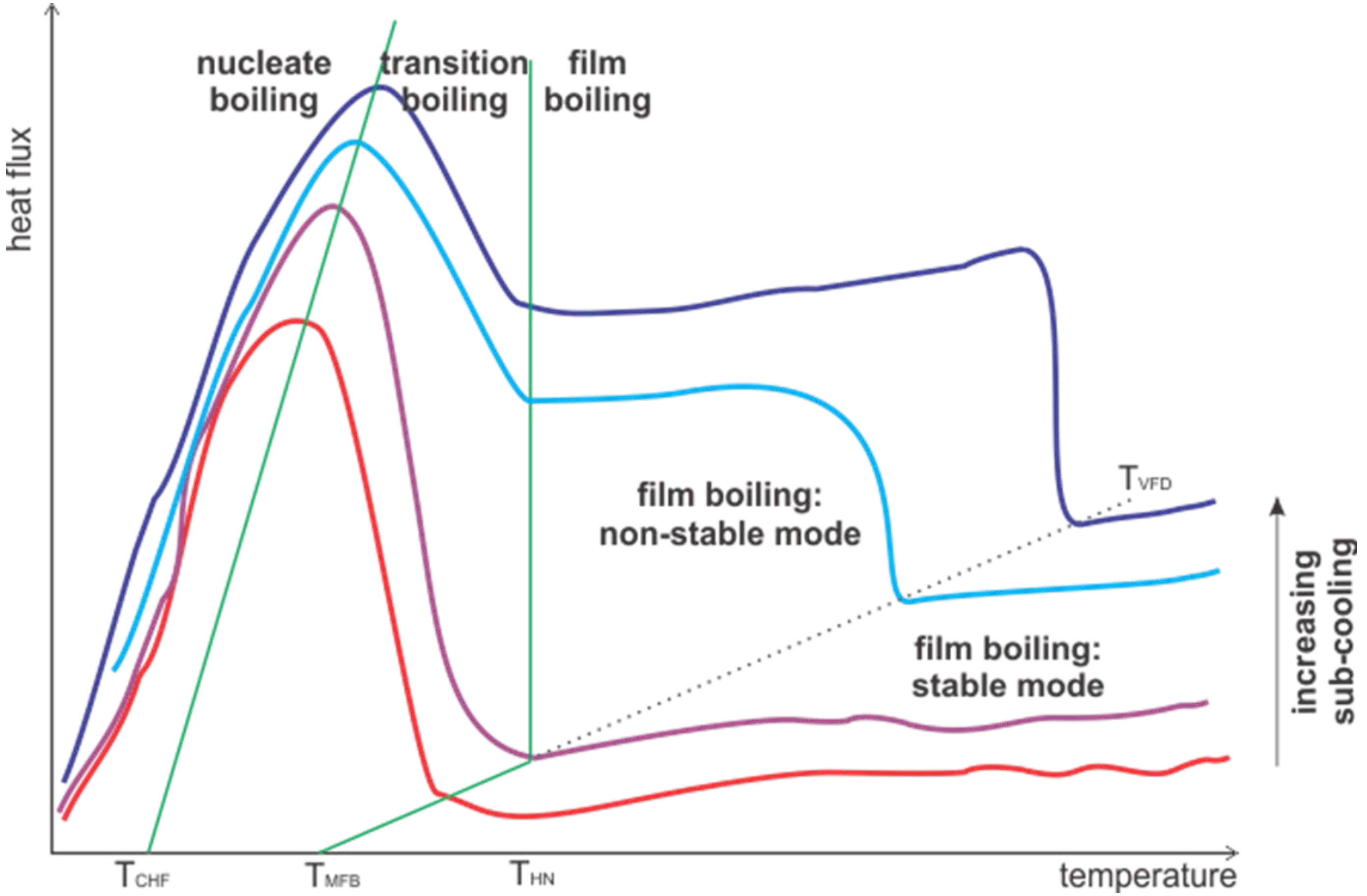
- Existence of such conditions during FCI in sodium shall be experimentally investigated because the expected sub-cooling in SFR is in range of few hundreds K

Heat flux in sub-cooled conditions



Extracted from reference:
H. Honda, H. Takamatsu, H. Yamashiro, Heat-transfer characteristics during rapid quenching of a thin wire in water, Heat Transfer - Japanese Research, 21(8) (1992) 773-791.

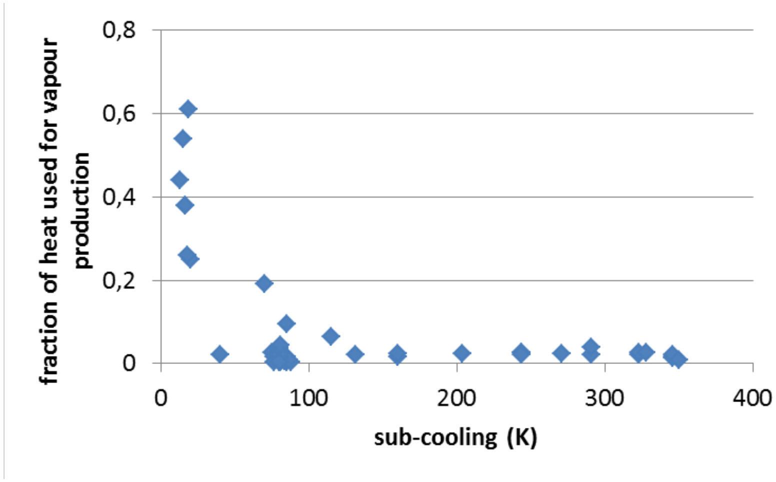
Premixing: heat transfer



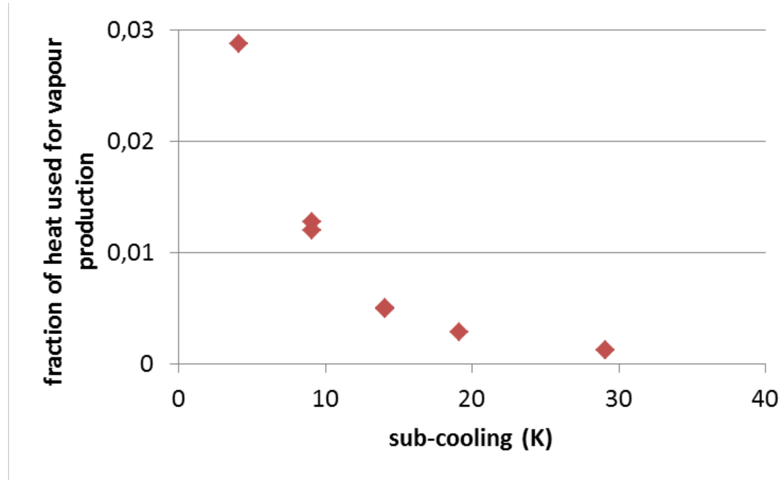
Premixing: void build-up

Water: fraction of heat used for vaporization in TREPAM forced convection experiments

Sodium: fraction of heat used for vaporization in Farehat et al pool boiling experiments



Reference:
G. Berthoud, Use of the TREPAM hot wire quenching test results for modelling heat transfer between fuel and coolant in FCI codes, Nucl Eng Des, 239(12) (2009) 2908-2915.



Reference:
A. Le Belguet, G. Berthoud, M. Zabiégo, Analysis of film-boiling heat transfer on a high temperature sphere immersed into liquid sodium, 15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-15, (2013).

Premixing: void build-up

- Parametric approach
  - Vaporization vs. heat up
    - 100% of heat for vaporization at saturated conditions
    - 100% of heat for bulk heat up above threshold sub-cooling
  - Bubbles diameter
    - user parameter
- Continuous vapour generation
  - Vaporization vs. heat up
    - net mass of vaporization could be assessed using EH approach
    - bubbles condense in sub-cooled conditions
  - Bubbles diameter
    - size of generated bubbles is same as of droplet

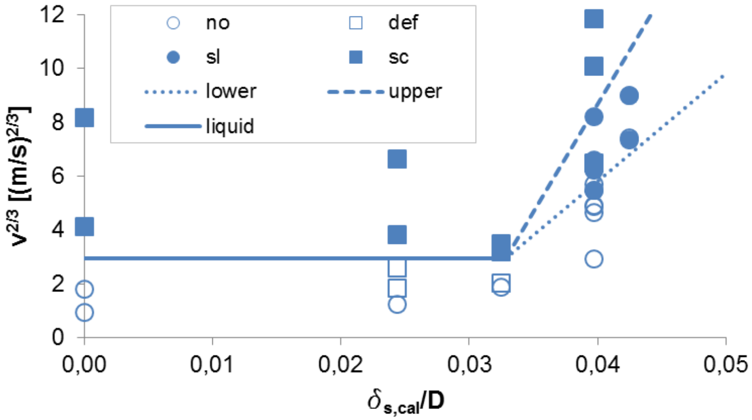
Explosion

- Strength of explosion depends on
  - Ability of melt droplets to fine fragment
  - Presence of void
  - Ability of coolant to evaporate
- Key processes
  - Fine fragmentation
  - Heat transfer
  - Pressurization

Explosion: fine fragmentation

- Hydrodynamic
  - Critical conditions
    - Weber number
    - modified Weber number
  - Fragmentation rate
    - dimensionless break-up time
  - Fragments size
    - user parameter
    - Weber number
- For water hydrodynamic fine fragmentation is considered as dominant
- Importance of thermal fine fragmentation should be examined for sodium.

Critical conditions for liquid and partly solidified droplets in water

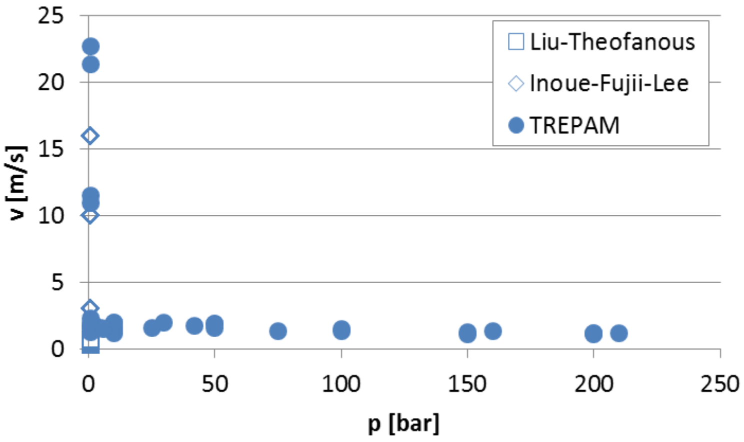


Reference:
M. Uršič, M. Leskovar, M. Burger, M. Buck, Hydrodynamic fine fragmentation of partly solidified melt droplets during a vapour explosion, Int J Heat Mass Tran, 76 (2014) 90-98.

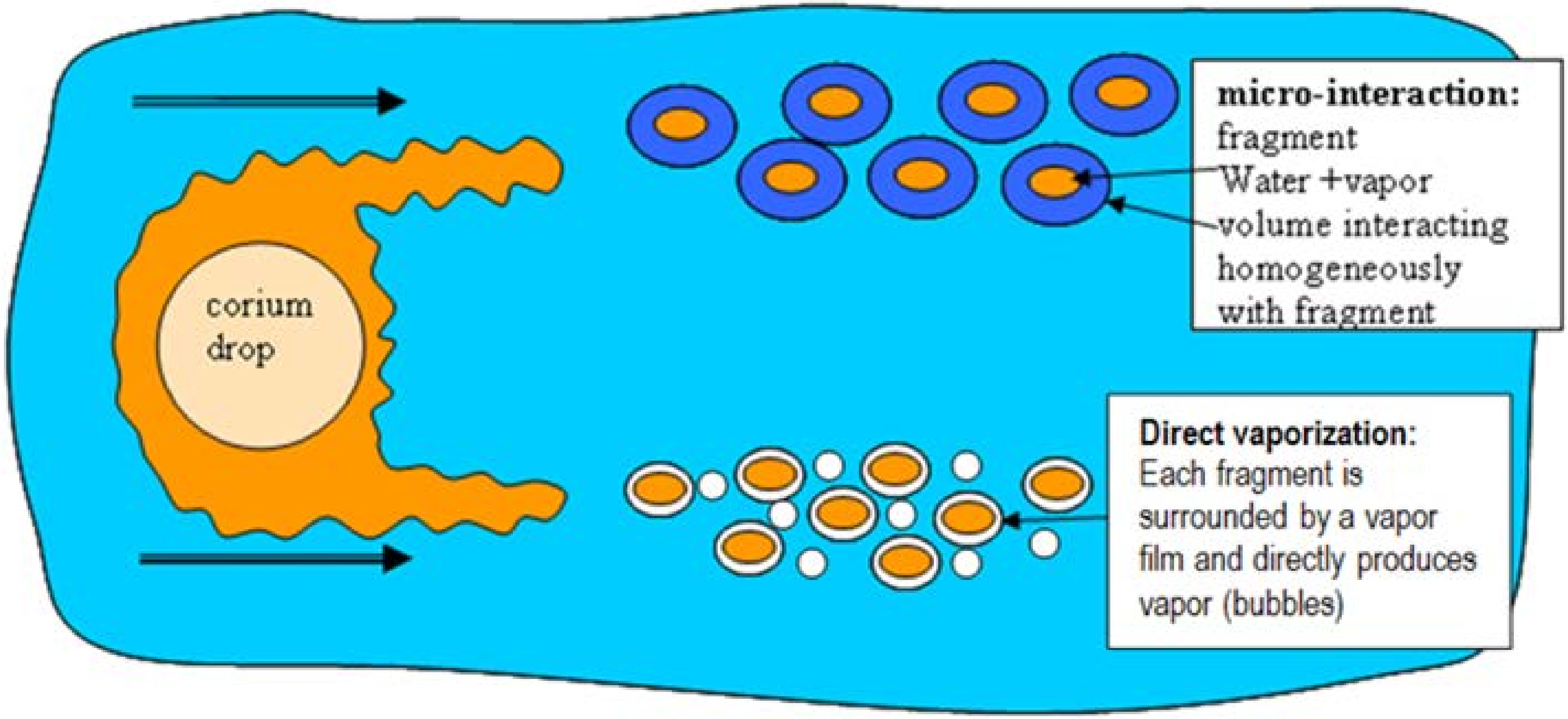
Explosion: heat transfer

- Water
  - Analysis of TREPAM experiments indicates that Epstein-Hauser approach could be sufficient for water
  - Additional experimental data for higher relative velocities needed
- Sodium
  - No experimental data
  - EH approach could be applicable on theoretical level

Parameters map for different heat transfer experiments performed at conditions relevant for FCI



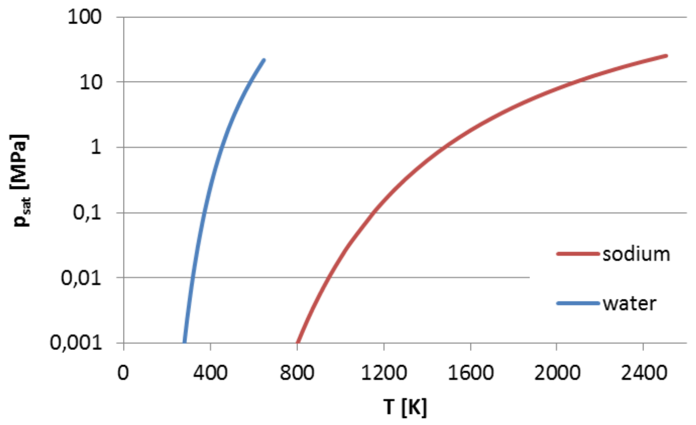
Explosion: pressurization



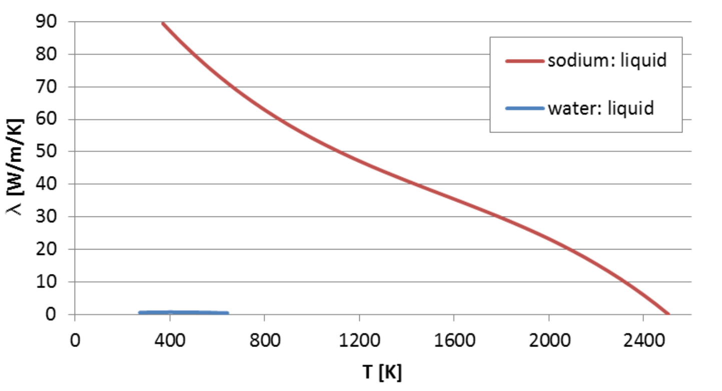
Explosion: pressurization

- Direct boiling
  - Vaporization
    - ability to boil
    - mode of heat transfer at significant velocities and high-pressures
    - fraction of heat used for vaporization at sub-cooled conditions
  - Effect of condensation on heat transfer in sub-cooled conditions
- Micro-interaction
  - Entrainment rate of coolant

Vapour pressure



Thermal conductivity



Conclusions: premixing

- Status
  - Melt fragmentation
    - experimental data and comparable governing sodium and water properties are indicating that similar jet fragmentation mechanisms are acting in water and sodium
    - Kelvin-Helmholtz approach
    - secondary fragmentation is under investigation
  - Heat transfer
    - Epstein-Hauser approach in film boiling
    - interpolation in transition boiling
  - Void build-up
    - parametric dissipation in film boiling
    - continuous vapour generation

- Needs for sodium
  - Melt fragmentation
    - impact of jet diameter, jet velocity and sodium sub-cooling on break-up length and debris size spectrum
    - thermal fragmentation
  - Heat transfer
    - sodium experiments
    - effect of sub-cooling on film boiling regime
    - criteria for temperature range of different regimes
  - Void build-up
    - DNS like for assessing fraction of heat used for vaporization

Conclusions: explosion

- Status
  - Fine fragmentation
    - focus on hydrodynamic fragmentation
    - Weber number for critical conditions and/or fragments size of liquid droplets
    - modified Weber number for critical conditions of partly solidified droplets
  - Heat transfer
    - Epstein-Hauser based approach
  - Pressurization
    - direct boiling
    - micro-interaction

- Needs for sodium
  - Fine fragmentation
    - impact of solidification on droplet fine fragmentation
  - Heat transfer
    - experiments with sodium
  - Pressurization
    - DNS like around fragments