Thin metallic layer thermal-hydraulics modelling - selected aspects of the issue

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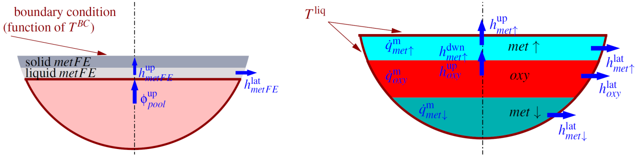
Specific topic issues - REMINDER

The specific topic issues are defined in two points:

1. the study of phase change that a metallic layer can undergo according to the modification of the top boundary condition (e.g. water injection can solidify this steel layer) and
2. the study of the thermohydraulic behavior of a liquid layer when its thickness is decreased (Rayleigh-Benard convection cells are periodically destroyed in such a way that the lateral heat transfer efficiency is reduced).



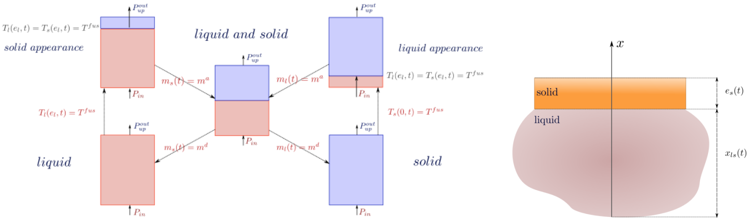
Corium molten material possible configuration. Formation of the liquid metal layer due to the ablation of steel structures (RPV internals and vessel walls).

Issue I. Phase change in the metallic layer - work goal

The goal of the work

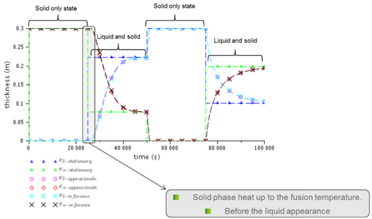
is to propose a complete transient model for the upper steel layer, which can be later on implemented in PROCOR platform and MAAP or MELCOR severe accident integral codes.

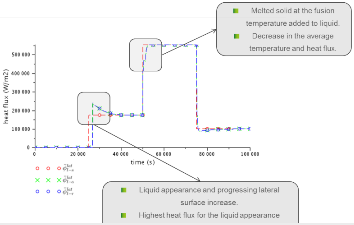
The approach to the problem is through the development of the “reference” solution scheme for the 0D liquid - 1D solid problem. In this step the analysis and comparison of different 0D liquid - 0D solid approximations with respect to the “reference” model are performed.



The system states and 1D pool definition for the problem.

Issue I. Phase change in the metallic layer - calculations





The proposed models were done in JAVA language and the special care was taken for the treatment of the phase appearance (ex. the energy while phase appearance was fully transfered into the melting/solidification process).
The models for the solidification/fusion are

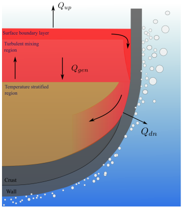
1. the reference,
2. quadratic profile and
3. stationary conduction model.

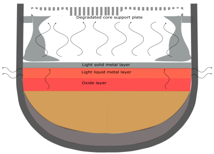
The cases calculated involved various phase changes and the reactor case, where the top boundary condition was taken as cooled by water.

The melt retention in the RPV

IVMR strategy:

The In Vessel Melt Retention strategy is a severe accident management strategy that incorporates the external vessel flooding to remove the heat from the in-vessel molten pool material. For this method, the heat is transferred from the molten pool to the external environment (atmosphere or coolant) through the vessel wall. This impacts highly the structure of the vessel due to high temperature and interaction between corium and steel walls (ablation).





Heat transfer during IVMR strategy.
Focusing effect.

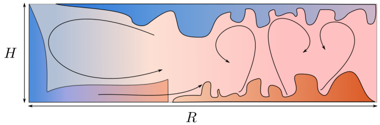
At present:

- RPV integrity preservation, the study of the heat transfer at each side of the vessel walls needs to be performed.
- for the existing reactor design, the concept was considered feasible for the small power reactors
- strategy is already adopted for the **VVER 440 type 213** based on thorough research work for the **Finnish Loviisa NPP and Hungarian Paks NPP** [2].
- interesting from the safety point of view and there is a suggestion that it could be adopted for the high power reactors with power of about 1000 MW or more (H2020).

Thin metallic layer modelling

In this part of work the focus is on the **liquid phase of the metallic layer** during the severe accident course:

- studies investigate the heat transfer regimes in the metallic layer - the time delay of the convection establishment and description of the thermalhydraulics in the metallic layer.
- the goal is to propose **the simplified realistic model**, that could be incorporated to the PROCOR platform.

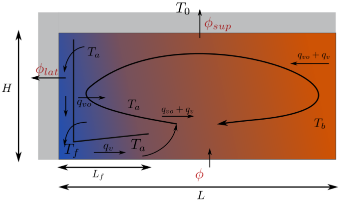


The problem analyses will be performed in several steps:

- Using the **nondimensional analysis** of the conservation equations and boundary conditions, the dominance and time span of the heat transfer regimes will be deduced,
- **a stability analysis** will be done in order to estimate the surface deformation on the steel layer at the free surface boundary,
- will use BALI metal experiment data and perform CFD calculations in order to build simplified model [15].

Issue II. Thermohydraulic behavior of a liquid layer- reduction of the conservativeness

The present model in the PROCOR code is treating the metallic layer in the fluid form as a 0D object. The parameters like *temperature, mass and other physical properties* are calculated for the whole phase. To determine those unknown the closure correlations are needed, which are not developed for every real problem.
The consequence of such treatment is the **high lateral heat flux** to the vessel walls, calculated by the code for the decreasing height of the metallic layer, as a possible moment for the focusing effect (FE) appearance.



Schematic representation of flow structure in metallic layer based on the BALI metal experiment.

Issue II. Thermohydraulic behavior of a liquid layer - reduction of conservativeness cd.

The decrease of the level of the conservativeness through:

- introduction of the delay time for the effective lateral heat flux flow, while the layer formation,

$$\frac{dh}{dt} = \frac{\bar{h} - h}{\tau}$$

- and, the introduction of the correct convection heat transfer correlations adequate for the metallic layer formation and stationary state.
  - present used correlations lead to the overestimation of the focusing effect for thin layers,
  - the reason for the lower impact of the FE while the steel/metallic layer appearance is the breaking of the convection cells.

Teoretyczne i numeryczne modelowanie wymiany ciepła w warstwie metalicznej:

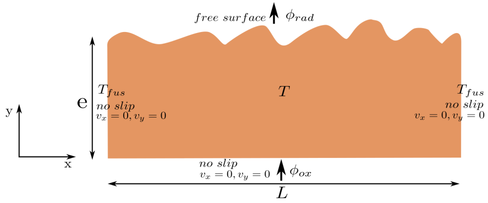
- Celem modelowania wymiany ciepła w warstwie metalicznej w warunkach ciężkiej awarii dla reaktorów energetycznych dużej mocy jest wyznaczenie bardziej szczegółowego i bliższego rzeczywistości strumienia ciepła przekazywanego do zbiornika ciśnieniowego reaktora.
- Wartość strumienia ciepła, powodująca obciążenie cieplne i odkształcenia mechaniczne stalowej ściany zbiornika, wpływa znacząco na czas rozerwania i uwolnienia promieniotwórczych pierwiastków do obudowy bezpieczeństwa.
- Dotychczasowe konserwatywne podejście do modelowania wartości strumienia ciepła, powoduje konserwatywne wartości limitów bezpieczeństwa i odbiega od obserwacji oraz porównania z wynikami eksperymentów (SET - Separate Effect Tests).
- Dlatego w pracy tej przeanalizowana jest wymiana ciepła w warstwie metalu dla określonych warunków brzegowych poprzez prowadzenie analizy perturbacji oraz modelowanie komputerowe za pomocą kodu Fluent eksperymentu BALI przeprowadzonego w ośrodku badawczym CEA.

Analiza stabilności:

- Równania hydrodynamiki pomimo swojego skomplikowania pozwalają na rozwiązania stacjonarne.
- Te rozwiązania są możliwe dla zakresu parametrów opisujących przepływ.
- Poza wartościami w przedziale rozwiązanie równań jest niestabilne - mała wartość perturbacji wprowadzona do systemu fizycznego powowduje wytrącenie ze stanu równowagi (stanu stacjonarnego).
- Jest to interesujące ponieważ pozwala na określenie wartości np. poprzez liczby podobieństwa (bezwymiarowe) innych parametrów charakterystycznych, które będą opisywały powstawanie niestabilności przepływu (prędkość, strumień ciepła etc.)

Zagadnienie II. Cieplno-przepływowe zachowanie ciekłej warstwy - rozwiązanie problemu

$$
\begin{aligned}
t &= t_0 t^*,\\
x &= L x^*,\\
y &= e y^*,\\
v_x &= v_0 v_x^*,\\
v_y &= v_0 v_y^*,\\
p &= p_{ref} + p_0 p^*,\\
T &= T_0 + \Delta T T^*,
\end{aligned}
$$



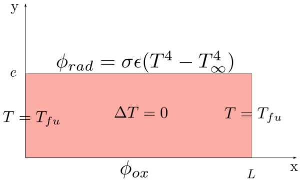
$$\boxed{\Gamma \frac{\partial v_x^*}{\partial x^*} + \frac{\partial v_y^*}{\partial y^*} = 0} \tag{1}$$

$$\boxed{St \begin{bmatrix} \frac{\partial v_x^*}{\partial t^*} \\ \frac{\partial v_y^*}{\partial t^*} \end{bmatrix} + \begin{bmatrix} v_y^* \frac{\partial v_x^*}{\partial y^*} \\ v_y^* \frac{\partial v_y^*}{\partial y^*} \end{bmatrix} = Eu \frac{\partial p^*}{\partial y^*} + Ri T^* + \frac{1}{Re} \frac{\partial^2 v_y^*}{\partial y^{*2}}} \tag{2}$$

$$\boxed{\frac{\partial T^*}{\partial t^*} + \frac{1}{St} \frac{\partial v_y^* T^*}{\partial y^*} = \frac{1}{StPe} \left(\frac{\partial^2 T^*}{\partial y^{*2}} \right).} \tag{3}$$

Metallic layer temperature distribution and Computational Fluid Dynamics simulation

Derivation of the temperature distribution for the metallic layer is based on derivation found in [10].



The layer of liquid metal is at the initial state in no motion, with heating from below and maintained value of the temperature gradient across the layer. For this layer the governing equation is:

$$\nabla^2 T = 0. \tag{4}$$

System is defined by governing equation and 4 boundary conditions:

$$y = \begin{cases} \Delta T(x,y) = 0 \\ \lambda \frac{\partial T(x,0)}{\partial y} = \phi_{ox} \\ -\lambda \frac{\partial T(x,e)}{\partial y} = \sigma\epsilon(T^4 - T^4_\infty) \\ T(0,y) = T_{fus} \\ T(L,y) = T_{fus} \end{cases} \tag{5}$$

Metallic layer temperature distribution and Computational Fluid Dynamics simulation cd.

The idea is to derive the form of the $T(x,y)$ through the solution of the Laplace equation:

$$\begin{cases} f''(x) - kf(x) = 0 \\ g''(y) + kg(y) = 0 \end{cases} \tag{7}$$

The $f(x)$ function takes form:

$$f_k(x) = \sqrt{\frac{2}{L}} sin \omega_k x \tag{8}$$

The equation for the $g(y)$ function:

$$g''(y) - \omega_k^2 g(y) = 0 \tag{9}$$

$$g(y) = \alpha_k e^{\omega_k y} + \beta_k e^{-\omega_k y} \tag{10}$$

$$A_k = \phi_{ox} \frac{\sqrt{2L}}{\pi k} [-(-1)^k + 1] \tag{11}$$

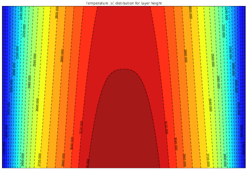
$$B_k = \frac{h}{\lambda} (T_{fus} - T_\infty) \frac{\sqrt{2L}}{\pi k} [-(-1)^k + 1] \tag{12}$$

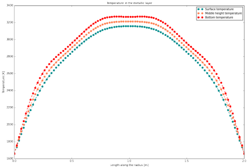
$$\beta_l = \frac{1}{2} \frac{\lambda^2 \omega_l B_l - A_l (\lambda^2 \omega_l e^{\omega_l e} + h)}{(\lambda^3 \omega_l sinh \omega_l e + h\lambda \omega_l cosh \omega_l e)} \tag{13}$$

$$\alpha_l = \frac{1}{2} \frac{A_l (\lambda^2 sinh \omega_l e + h cosh \omega_l e - e^{\omega_l e} - \frac{h}{\lambda^2 \omega_l}) + B_l}{(\lambda^3 \omega_l sinh \omega_l e + h\lambda \omega_l cosh \omega_l e)} \tag{14}$$

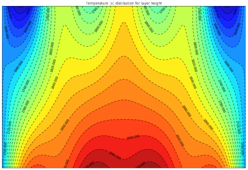
Metallic layer temperature distribution. Results.

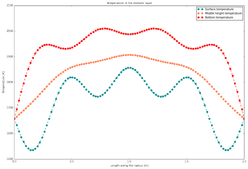
0.05 m metallic layer height





0.3 m metallic layer height

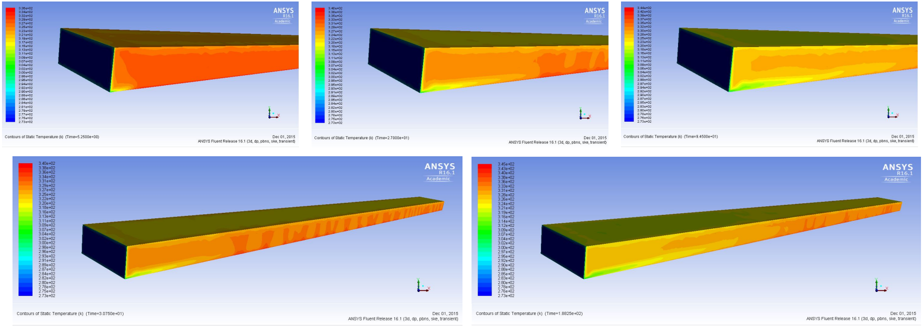




- Data for temperature distribution evaluation:
  1. Domain x length (m): $L = 2.0$
  2. Domain y length (m): $h = 0.05 - 0.4$
  3. Heat flux from the oxide pool $(\frac{W}{m^2})$: $\phi_{ox} = 7700.0$
  4. Metal conductivity $(\frac{W}{mK})$: $\lambda = 35.0$
  5. Infinity temperature (K): $T_{\infty} = 1600.0$
  6. Surface temperature (K): $T_{surf} = 1800.0$
  7. Metal fusion temperature (K): $T_{fus} = 1658.0$
  8. Surface emissivity factor: $\epsilon = 0.8$
- For lower metallic heights - from the temperture distribution function evaluation conduction is dominating.
- High BC impact on the surface temperature of the layer - partial solidification of the layer on top for volumes in contact with lateral boundary.

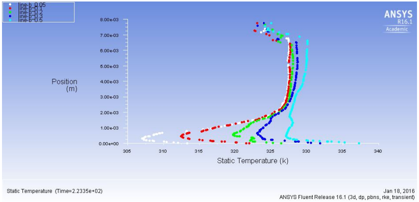
Computational Fluid Dynamics simulation. BALI experiment.

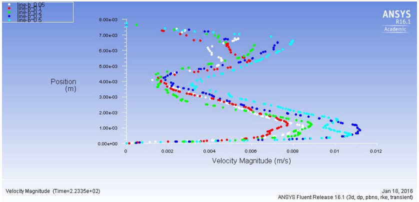
- the BALI experiment aimed to study the focusing-effect phenomenon in full scale and water as simulant fluid,
- different tests have been run for 5 to 40 cm heights of water layer with uniform or non uniform distribution of bottom heat flux.
- cooled on lateral wall with uniform temperature condition (ice crust formation) and on upper boundary with a plastic heat exchanger to simulate radiative heat transfer. [15]



- the heat transfer mechanismis similar to Rayleigh-Bénard convection

Computational Fluid Dynamics simulation. BALI experiment.





Top BC - uniform temperature: this temperature can be derived using the averaged pool temperature and the Globe-Dropkin heat transfer correlation to compute h_{pool}, constructed using the pool depth as characteristic length L and the average pool properties:

$$Nu_{up} = \frac{(h_{pool} \cdot L)}{\lambda_{pool}} = 0.069 \cdot (Ra_L)^{(\frac{1}{3})} \cdot Pr^{0.074} \tag{15}$$

$$Ra_L = \frac{g\beta}{\nu\alpha} \cdot (T_{pool} - T_i) \cdot L^3 \tag{16}$$

which will be computed using the interface temperature T_i from the previous time step, or using the average temperature difference measured in the experiments: 6.1 $^\circ C$ for case 1 U, 6.9 $^\circ C$ for case 4 U and 5.5 $^\circ C$ for case 7 U. This method yields a uniform temperature, making it impossible to study the temperature profile along the epoxy plate, but should properly reproduce the power split.

Conclusion and summary

- The introduction to the perturbation analysis is done to derive the temperature distribution in the thin metallic layer in the stationary state.
- This gives the possibility to implement the temperature function into the calculation code and derive the lateral fluxes to the PWR vessel walls for the stationary state before the convection cells creation onset.
- introductory BALI metal experiment simulation by the CFD method shows the occurrence of anticipated phenomena - cold tongue, instabilities and non uniform temperature distribution across the domain height.
- to be continued with more specific BC conditions and experimental domain stationary walls (conduction through the domain boundaries needs to be modelled), transition to the full reactor simulations.

Thank you for your attention today.

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Bibliography

- http://cordis.europa.eu
- B. R. Sehgal, Nuclear Safety in Light Water Reactors: Severe Accident Phenomenology, Elsevier, 2012, pp. 550-551
- R. Le Tellier, L. Saas and F. Payot, Phenomenological analyses of corium propagation in LWRs: the PROCOR software platform
- L. Saas, R. Le Tellier, S. Bajard, A Simplified Geometrical Model for Transient Corium Propagation in Core for an LWR with Heavy Reflector, International Congress on Advances in Nuclear Power Plants, 2015
- R. Le Tellier, , L. Saas, S. Bajard, Transient stratification modelling of a corium pool in a LWR vessel lower head, Nuclear Engineering and Design, Volume 287, June 2015, Pages 68–77
- P. Darnowski , E. Skrzypek, P. Mazgaj, K. Swirski, P. Gandrille, Total loss of AC power analysis for EPR reactor, Nuclear Engineering and Design Volume 289, August 2015, Pages 8–18
- S. Globe, D. Dropkin, Natural convection heat transfer in liquids confined by two horizontal plates and heated from below, Journal of heat transfer, vol. 81, pp. 24–28, 1959.
- S.W. Churchill, H.H.S. Chu, Correlating equations of laminar rand turbulent free convection from a vertical plate, International journal of heat and mass transfer, vol. 18, pp. 1323–1329, 1975.

T.C. Chawla, S.H. Chan, Heat transfer from vertical/inclined boundaries of heat-generating boiling pools, Journal of heat transfer, vol. 104, pp. 465–473, 1982.

S. Chandrasekhar , Hydrodynamic and Hydromagnetic Stability, Courier Corporation, 1961

J.M. Bonnet and J.M. Seiler, "Thermohydraulic phenomena in corium pool: the bali experiment," in Proc. of ICONE 7. Tokyo, japan, 1999.

A. Bonelli, O. Mazzantini, M. Sonnenkalb, Station Black-Out Analysis with MELCOR 1.8.6 Code for Atucha 2 Nuclear Power Plant, Science and Technology of Nuclear Installations Volume 2012 (2012)

H. Esmaili, M. Khatib-Rahbar, Analysis of in-vessel retention and ex-vessel fuel coolant interaction for AP1000, Tech. Rep. NUREG/CR-6849 ERI/NRC04-201, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (2004)

D. Skrien, Object-Oriented Design Using Java, Hardcover, January 22, 2008

J.M. Bonnet, C. Villermaux, BALI-metal test reports : focussing effect investigation, July 2001, CEA/Grenoble