Initial results for modelling the LIVE L3 experiment melt-pool behaviour in transient and quasi steady-state

[1*]Aniket Joshi, [2]Claire Heaney, [2]Liang Yang, [2]Alan Jones, [3]Paul Smith, [4]Ali Tehrani, [2]Christopher Pain

[1]Department of Materials, The Open University, Milton Keynes MK7 6AA, United Kingdom

[2]Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, United Kingdom

[3]Jacobs (UK), Aberdeen AB11 6EQ, United Kingdom

[4]CNE, Imperial College London, London SW7 2AZ, United Kingdom

The Open University

*Contact: aniket.joshi@open.ac.uk

Introduction

Severe accident phenomena

- Focus on pressurized water reactor (PWR) design.
- Melt pool (corium) formed in the lower plenum of the reactor pressure vessel (RPV).
- Corium needs to be retained and cooled, since it is a self-heating substance.
- Numerous experiments performed worldwide. A few of them are:
  - COPRA,
  - **LIVE,**
  - SIMECO.

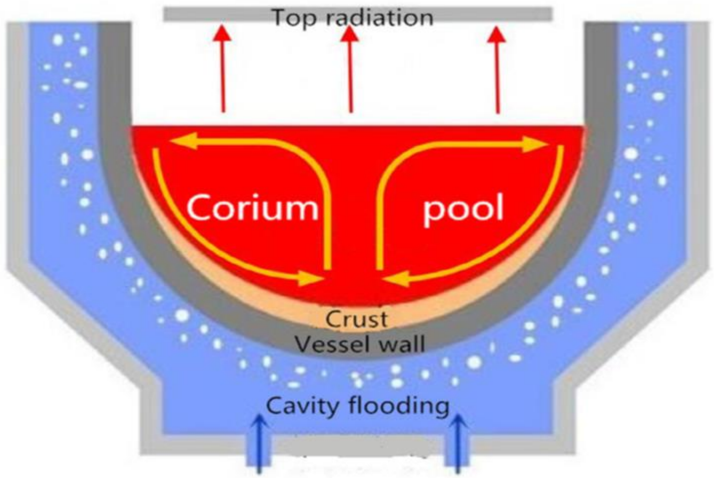


Fig. 1. Schematic of a typical severe accident experiment study [1].

[1] Klein-Heßling, W., et al. "Conclusions on severe accident research priorities." *Annals of Nuclear Energy* 74 (2014): 4-11.

Characteristics of a typical severe accident experiment

- A 2D slice or a 3D hemisphere model of the RPV is considered for experimentation.
- Corium simulant used (usually pre-heated before pouring).
- Volumetric heat generation inside the melt pool to emulate self-heating of corium homogeneously (fig. 2.).
    - Heater grid with independent heating elements preferred for greater control over heating.

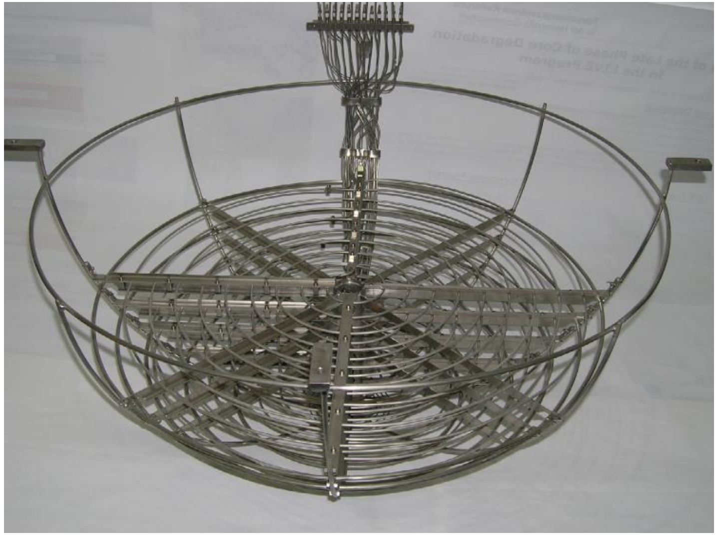


Fig. 2. Volumetric heating system of the LIVE experiments [2].

[2] Gaus-Liu, Xiaoyang, et al. *Test and simulation results of LIVE-L4+ LIVE-L5L*. Vol. 7593. KIT Scientific publishing, 2011.

Introduction

LIVE Experiments (Late In-Vessel Phase Experiments)

- Established within the LACOMERA Project at Karlsruhe Institute of Technology (KIT).
- Uses a 1/5 scaled model of a PWR RPV [2, 3].
- Main objective is to study the core melt phenomena during the late phase of core melt progression.
- Objectives of LIVE L1 and L3 [3]:
    - Investigate melt pool behaviour during air circulation as well as water cooling.
    - Investigate crust formation and its behaviour during flooding.
- Difference between L1 and L3 is in the pouring of the melt simulant into the vessel [3]:
    - L1– melt poured centrally
    - L3– melt poured along the vessel edge
- L3 test parameters [3]:
    - Melt simulant: $NaNO_3$-KNO_3 (20-80 molar ratio)
    - Melt pre-heated to 613K (343℃) before pour

[3] Fluhrer, B., et al. "The LIVE-L1 and LIVE-L3 experiments on melt behaviour in RPV lower head." *FZKA* 7419 (2008): 3-13.

Introduction

LIVE Experiments (Late In-Vessel Phase Experiments)

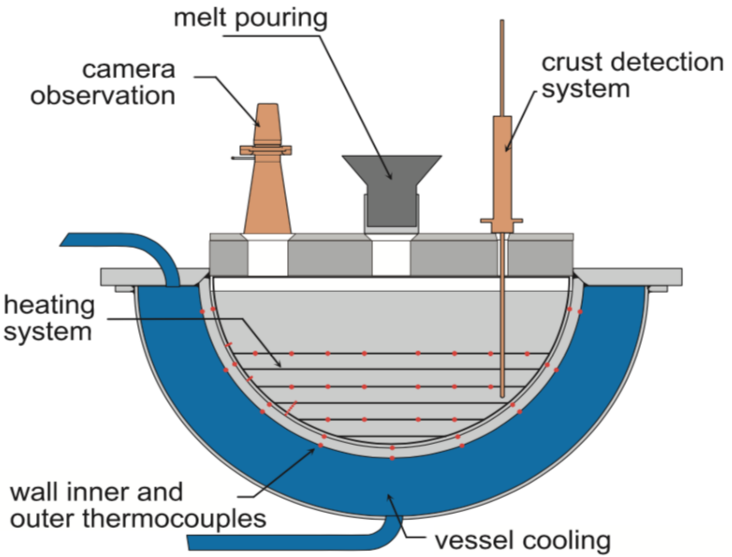


Fig. 3. Generalized schematic of the LIVE suite of experiments [2, 3].

Fig. 4. Scaled RPV experimental vessel [2, 3].

[3] Fluhrer, B., et al. "The LIVE-L1 and LIVE-L3 experiments on melt behaviour in RPV lower head." *FZKA* 7419 (2008): 3-13.

Introduction

LIVE L3– Experimental stages [3]

Cooling medium	Heating power (kW)	Action	Time (s)
Air	–	Melt poured	0
Air	18	–	131
Air	14	–	371
Air	12	–	2,591
Air	10	–	3,671
Water	10	Water supplied	7,200
Water	7	–	83,100
–	0	End of experiment	102,900

[3] Fluhrer, B., et al. "The LIVE-L1 and LIVE-L3 experiments on melt behaviour in RPV lower head." *FZKA* 7419 (2008): 3-13.

Methodology

LIVE L3– Boundary conditions

- Top and bottom boundary conditions need to be defined [4].
- Numerous heat transfer processes condensed into the top and bottom boundary condition of the vessel.
- Aim of the study:
  - To establish robustness of IC-FERST in analysing transient and quasi steady-state of LIVE L3.
- Transient state observed during melt pour.
- Quasi steady-state observed during [3]:
  - Constant heating phases of air cooling (after ~ 1000s),
  - All water cooling phases.

[4] Zhang, Y. P., et al. "A simple novel and fast computational model for the LIVE-L4." *Progress in Nuclear Energy* 68 (2013): 20-30.

Methodology

LIVE L3– Top Boundary Condition

- Direct temperature readings of LIVE L3 not provided.
- LIVE L4 has an observed temperature of 67.5℃.
- Top boundary condition (BC) taken as 100℃.
    - A conservative estimate since the heating power of L3 is marginally lower than that of L4.
- Fig. 5. illustrates the schematic of top lid of the LIVE experiments.

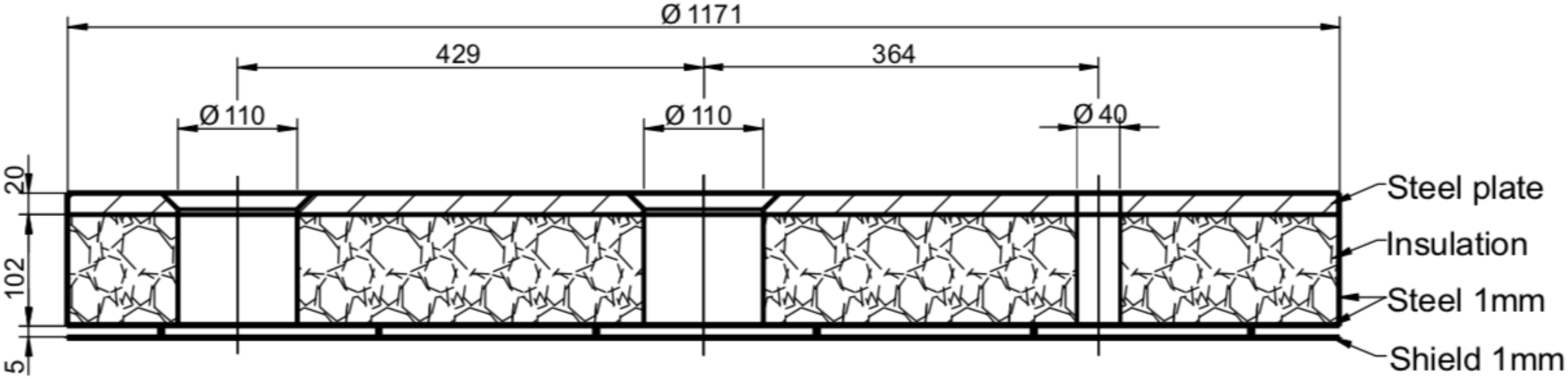


Fig. 5. Top lid schematic of the experimental vessel in the LIVE suite of experiments [3]

LIVE L3– Bottom Boundary Condition

- Different cooling media used on the vessel which, by the process of conduction and convection, absorb the heat from the melt simulant.
- Simplifications used in study:
    - Given inner wall temperatures of vessel, these were extrapolated and used to set a Robin boundary condition.
- Python script used that interpolates temperatures for the bottom boundary on the basis of distance to the nearest sensors.

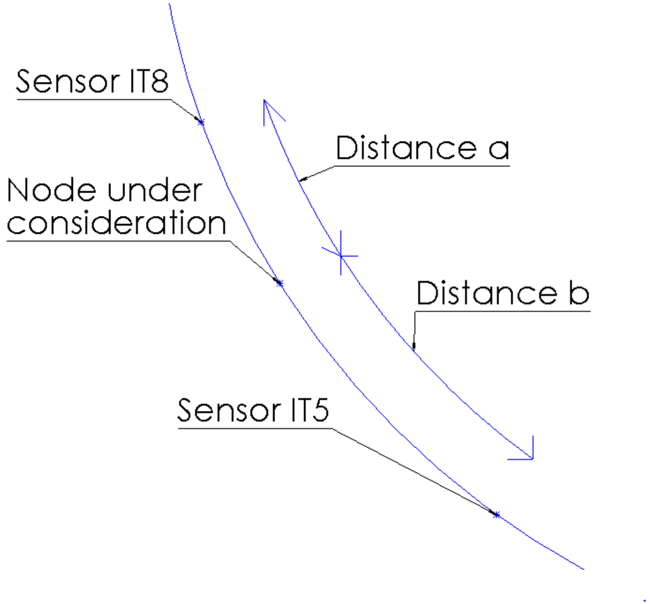


Fig. 6. Illustrating the interpolation of temperature to set bottom boundary condition.

Methodology

LIVE L3– Bottom Boundary Condition

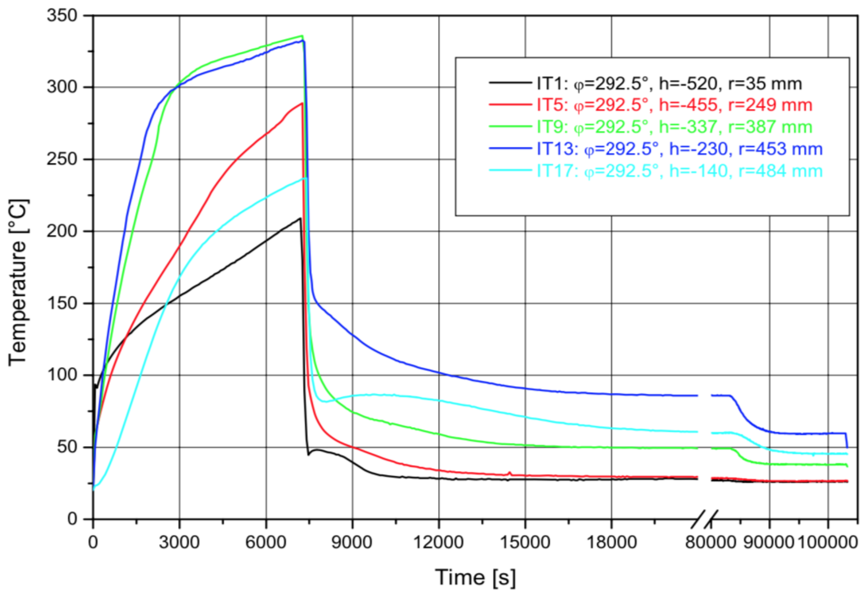


Fig. 7. Inner wall temperatures of the LIVE L3 test [3].

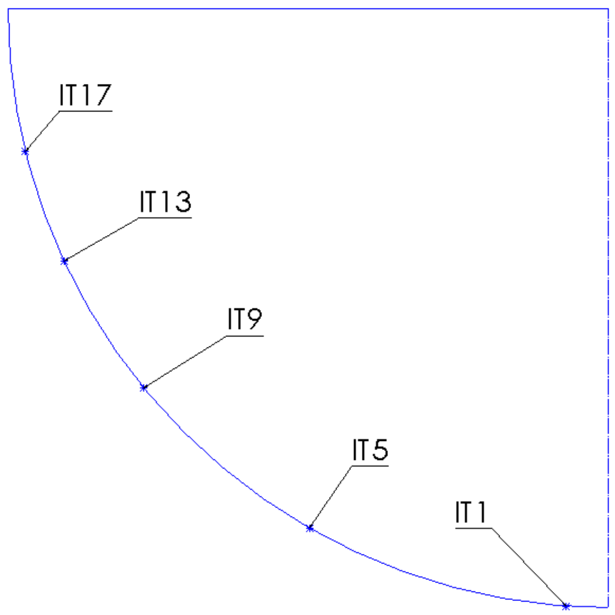


Fig. 8. Approximate position of inner wall temperature sensors.

About IC-FERST

- IC-FERST, a Fluidity dependent package, used.
- Initially developed for numerical modelling porous media flows and subsequently extended to model flows in reactors and multiphase flows such as droplet formation.
- Uses unstructured meshing along with Control Finite Element Volume Method (CVFEM) [5].
    - CVFEM guarantees local mass conservation and can be high-order accurate.
- Continuity equations are embedded in the pressure equation [5]. This enforces:
    - Mass conservation,
    - Exact force balance.
- Velocity and pressure spatially discretized using the $P_1DG\text{-}P_1$ scheme (DG = Discontinuous Galerkin).
    - This translates to first order polynomial discretization for both, with the velocity field using first-order discontinuous galerkin discretization across elements [5].

[5] Gomes, J. L. M. A., et al. "A force-balanced control volume finite element method for multi-phase porous media flow modelling." *International Journal for Numerical Methods in Fluids* 83.5 (2017): 431-445.

Methodology

About IC-FERST

- Mesh adapted to following fields:
    - Galerkin projection,
    - Temperature.
- Metric advection used.
    - Metric advection refers to the process where the field that is being advected by a known velocity field (such as the galerkin projection field) is advected forward in time at the same rate [6].
    - Advected metric provides an estimate of future mesh requirements and be superimposed with the current metric in IC-FERST [6].
    - Superimposing aids in smooth transition of mesh anisotropy when high gradation is required [6].
    - Diffusive scheme (first-order upwind) used in the analysis.

[6] Wilson, Cian. "Modelling multiple-material flows on adaptive unstructured meshes." (2009).

Methodology

Mesh adaptivity algorithm

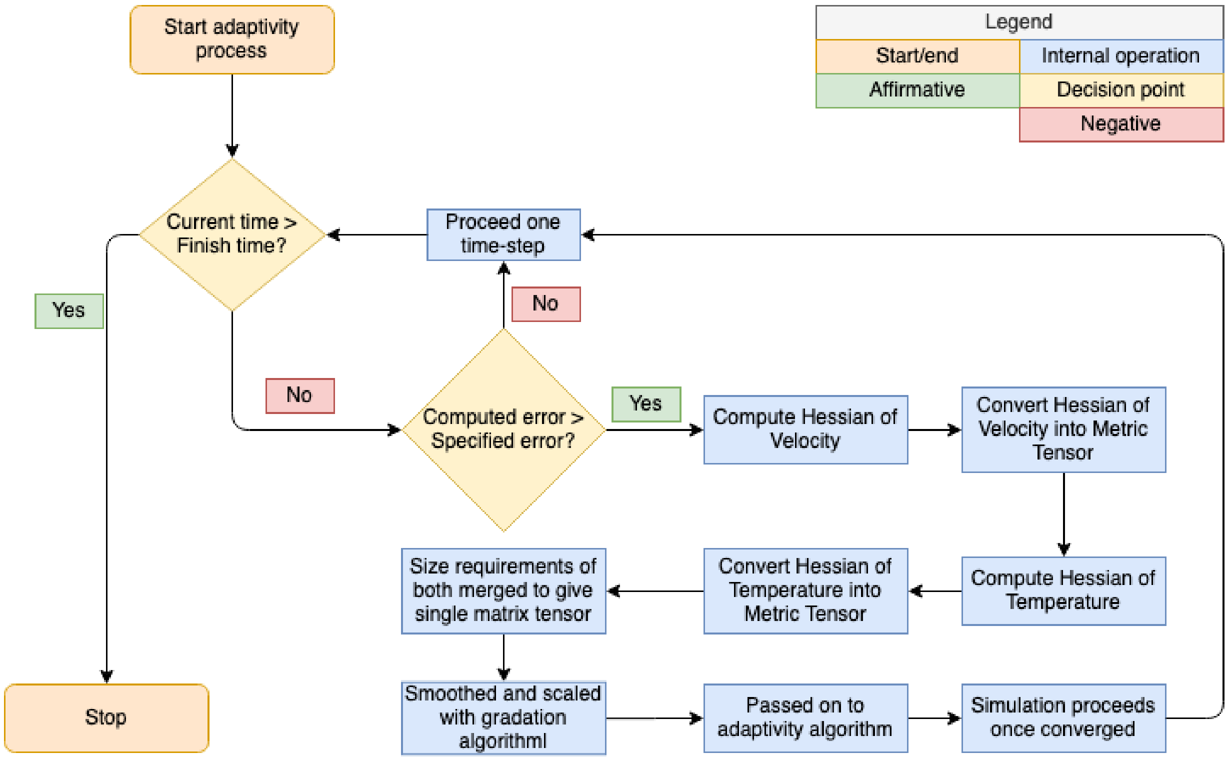


Fig. 9. Mesh adaptivity algorithm in IC-FERST

Results

Analytical solution

- Only used as a guideline to evaluate general melt pool behaviour.
- Consider the following heat balance:
  - $\rho V C_p \frac{DT}{Dt} = Heat\ source\ - hA(T - T_{wall}),$
  - First term represents internal energy while the last term represents the bottom convection behaviour.
- Illustrating for typical values used in the L3 experiment:
  - $1862 \cdot 0.119 \cdot 1369\ \frac{DT}{Dt} = 18000\ - (70 \cdot 0.9\ (T - 373)).$

Results

Analytical solution– 14 kW phase

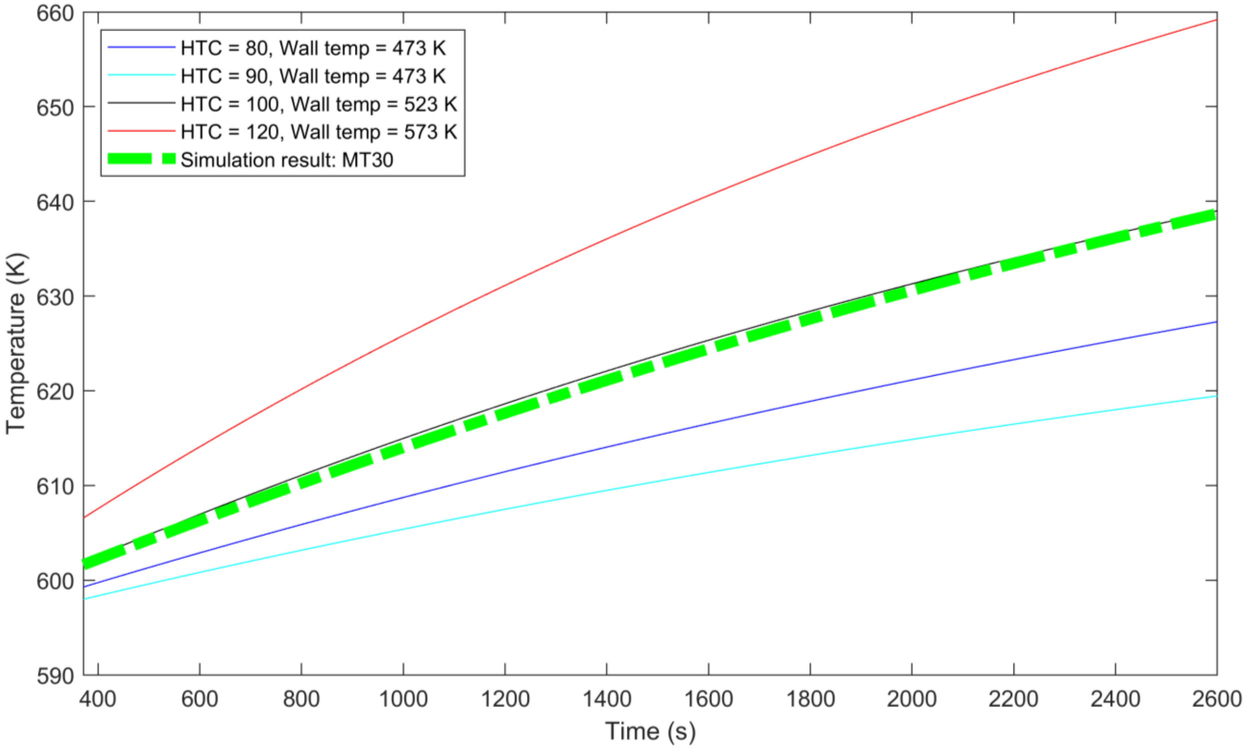


Fig. 10. Comparing with analytical solution– MT30 sensor in the 14kW phase.

Results

Flow Profiles

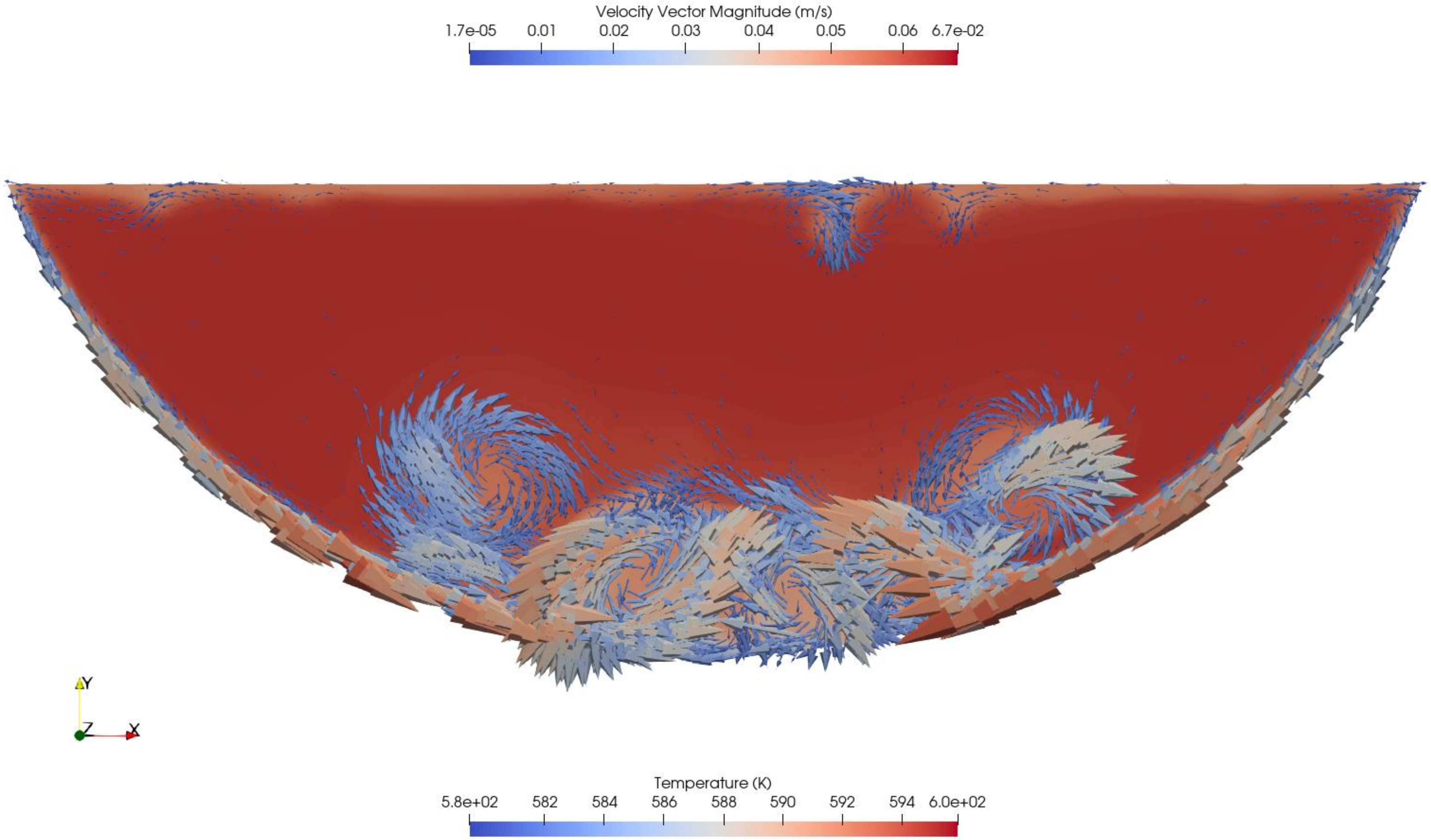


Fig. 11. Temperature field with superimposed velocity vectors at t = 171s.

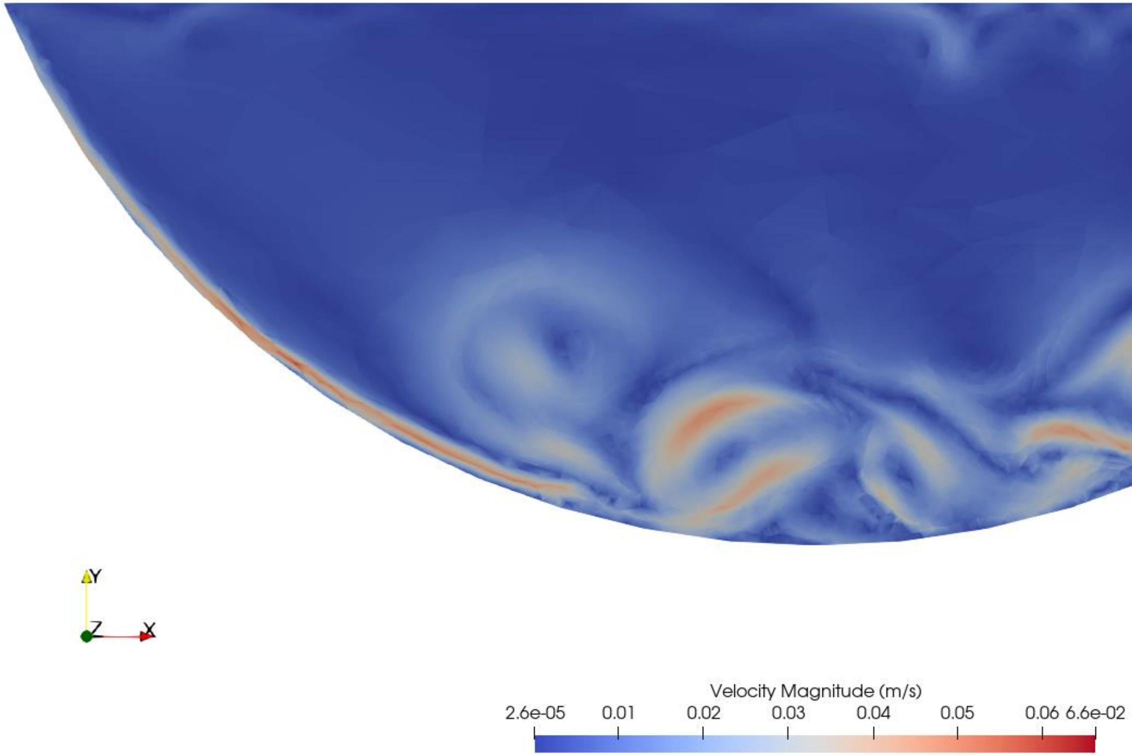


Fig. 12. Velocity field at t = 171s.

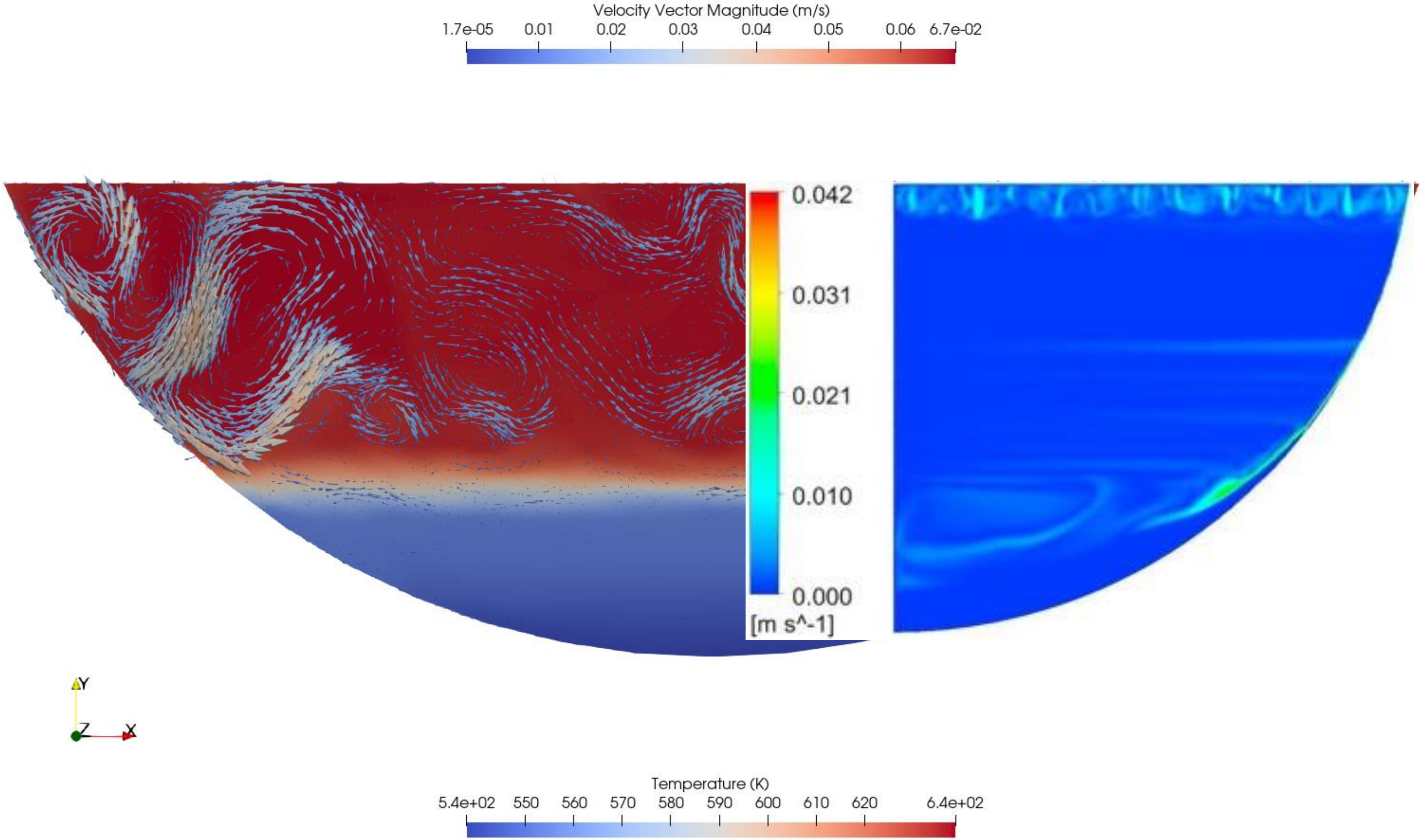


Fig. 13. Temperature field with superimposed velocity vectors at quasi steady-state, along with the velocity field in steady-state simulation from the COPRA (water-cooled) experiment [7].

Results

Temperature comparison

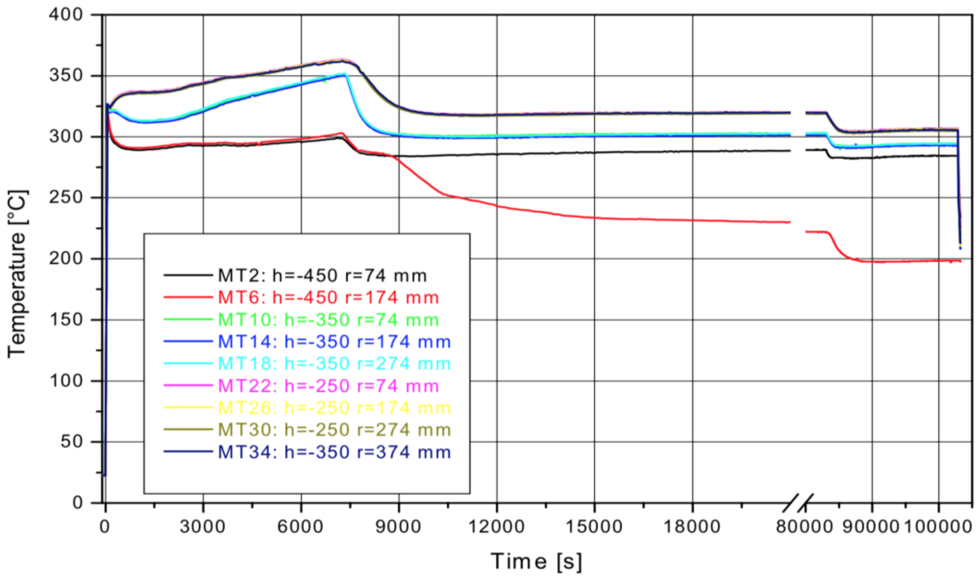


Fig. 14. Melt pool temperatures from the L3 experiment [3].

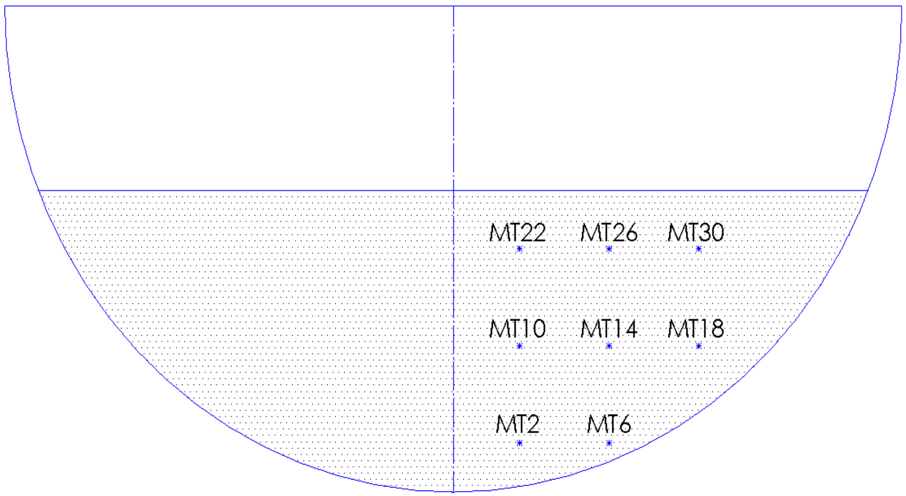


Fig. 15. Melt pool sensor positions

Results

Temperature comparison

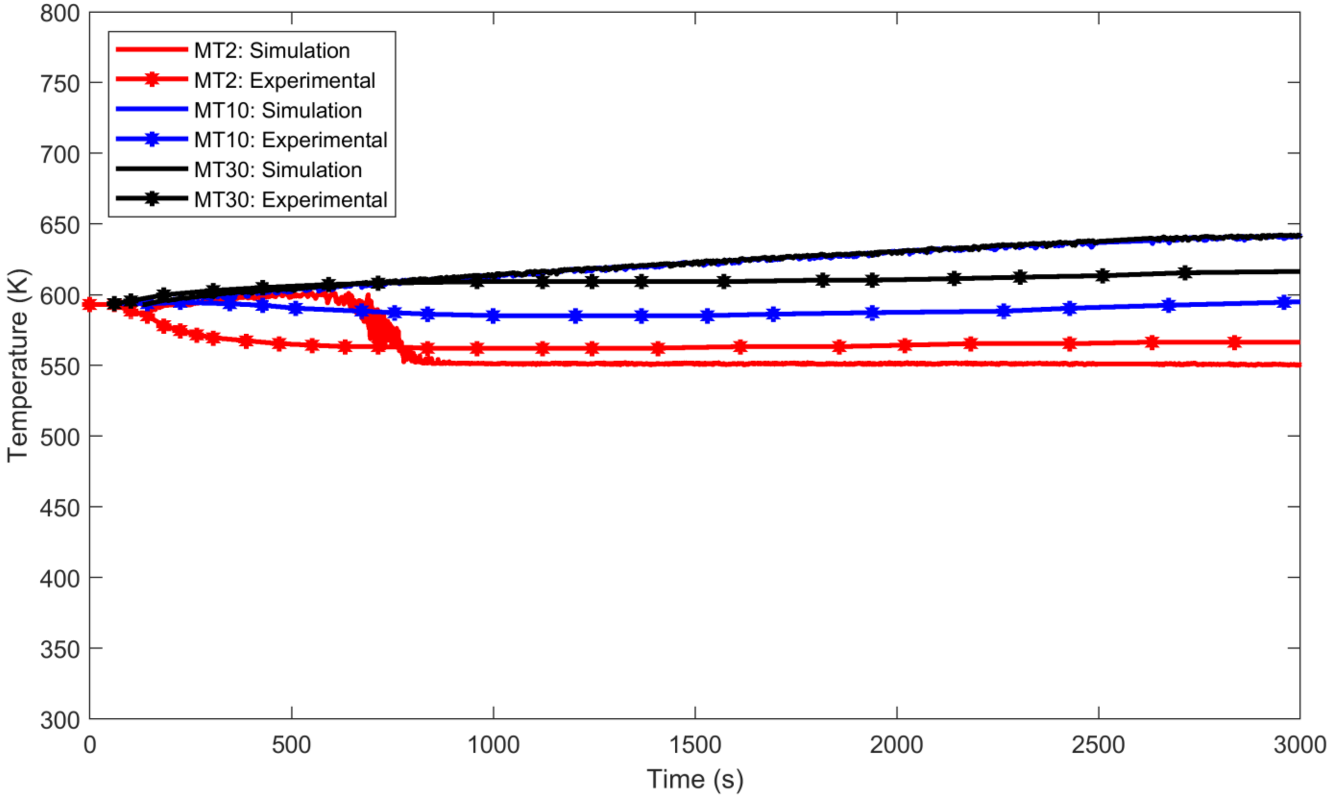
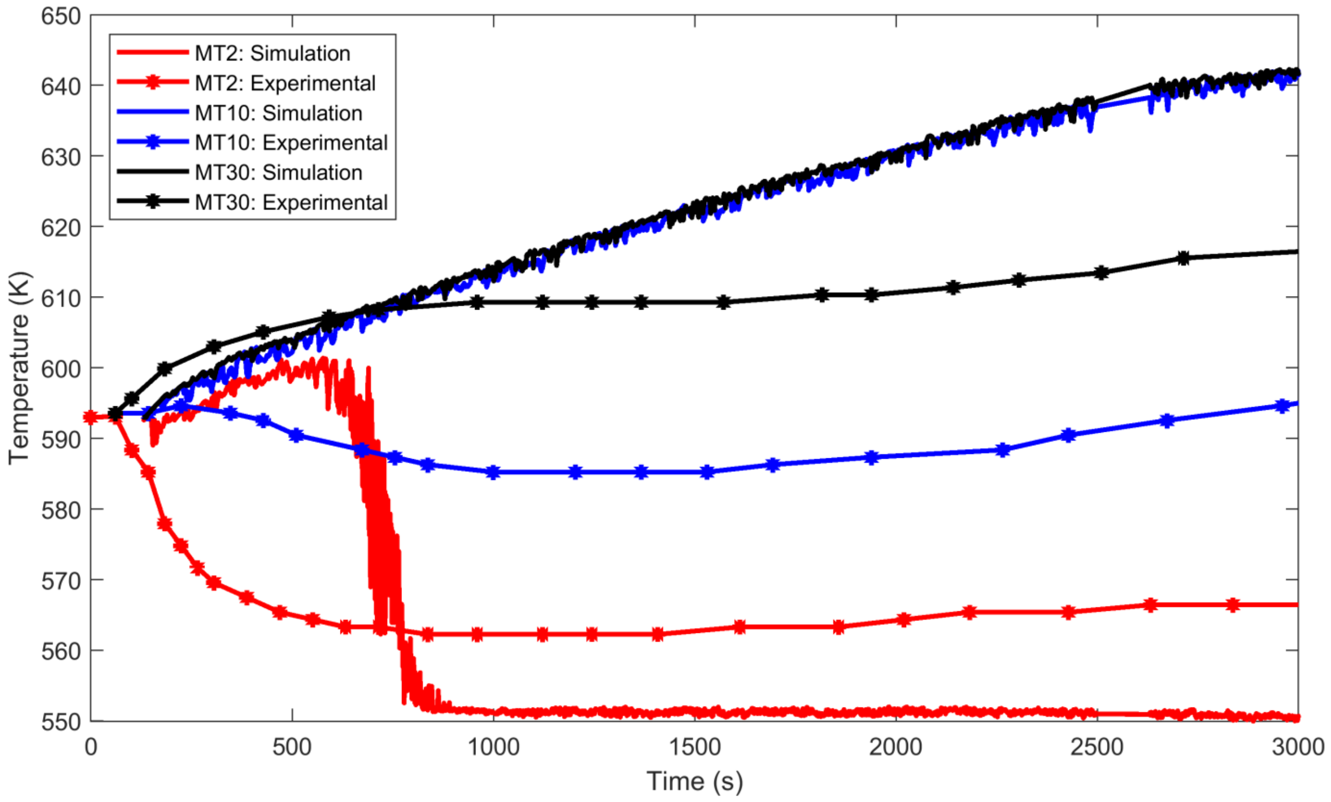


Fig. 16. Sensor comparison (simulation and experiment)

Results

Temperature comparison



- MT10 and MT30 have almost similar values.
- MT2 temperature initially rises before stabilising.
- Difference in measurements can be attributed to different forms of analyses– the analysis is done in 2D (slice), while the experiment is 3D.

Fig. 17. Sensor comparison (simulation and experiment)– zoomed in

Conclusions and Future work

Conclusions

1. Analysis behaviour compared with analytical solution.
2. Quasi steady-state reached with a maximum error of 7.56% at MT10 sensor.
3. Flow profiles approach those as observed in BALI or COPRA simulations [7].

[7] Luo, Simin, et al. "COPRA experiment and numerical research on the behavior of internally-heated melt pool with eutectic salt." *Applied Thermal Engineering* 140 (2018): 313-324.

Future work

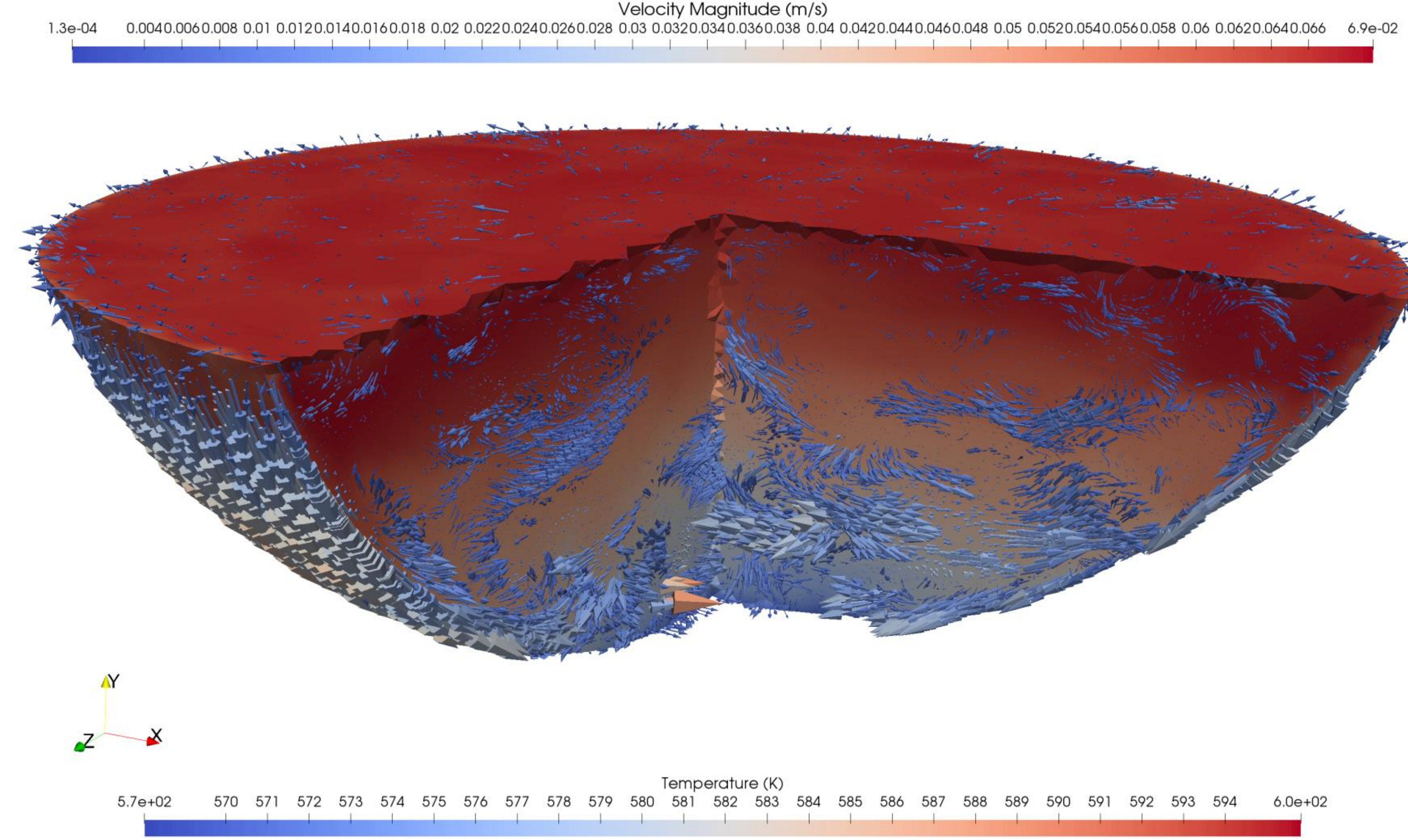


Fig. 18. 3D simulation depicting the temperature field with velocity vectors at t = 200s

Conclusions and Future work

Future work

- Obtain crust material data to emulate proper crust formation.
- Model L1 test the L4/L5 suite of tests to further demonstrate IC-FERST's capability in SA simulations.
- This analysis was done on a 2D slice geometry. This will be further built open as:
  - Full analysis in 3D and perform sensitivity analysis.
  - Use the knowledge gained in 2D slice simulations to analyse the recently published COPRA experiments, where the vessel is a 2D slice.

Thank you