Experience of Experimental and Analytical Program for Validation of Coupled STH and CFD Codes

Pavel Kudinov, Ignas Mickus, Marti Jeltsov, Kaspar Kööp, Dmitry Grishchenko

Royal Institute of Technology (KTH)

"Remember that all models are wrong;

the practical question is

<u>how wrong</u> *do they have to be*

to ***<u>not be useful</u>****."*

George Edward Pelham Box, (1987)

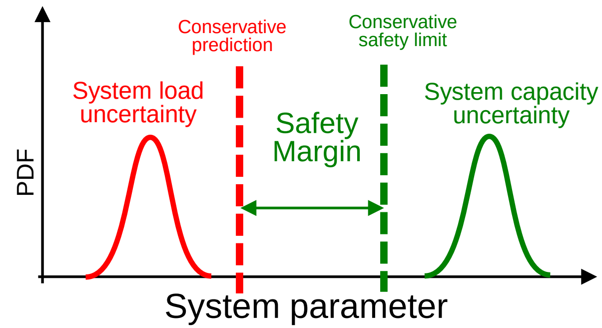
Uncertainty is a source of Risk

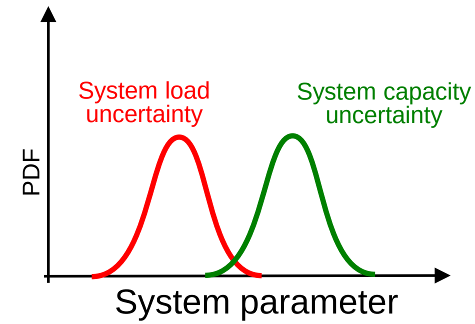
- **Complexity** of the system
  - is a source of **Uncertainty**.
- **Uncertainty**
  - is a source of **Risk**.

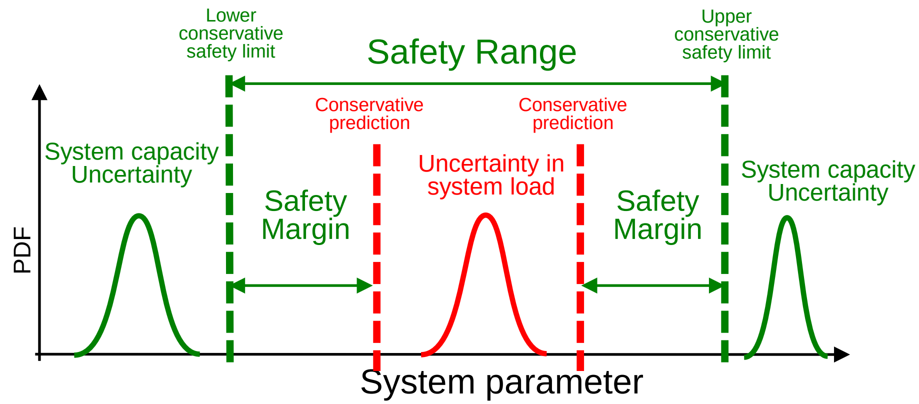
- Passive safety systems performance is affected by:
  - Physical phenomena.
    - Sensitive force balance.
  - Reliability of equipment.

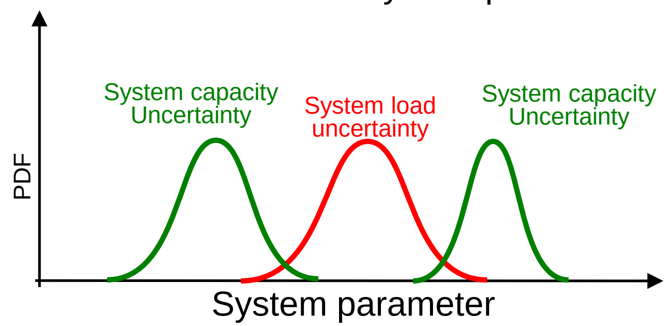
- "Safety range" instead of "safety limit"
  - E.g. failure on both:
    - Insufficient cooling
      - overheating.
    - Excessive cooling
      - coolant freezing.

- Traditional "conservative" approaches often inadequate for
  - Small or negative safety margins.
  - Narrow safety ranges.









Uncertainty types

Uncertainty is important in both

- Phenomena.
  - Predicted by deterministic codes.
- Scenarios.
  - Driven by stochastic failures.

- Epistemic uncertainty
  - lack of knowledge
  - typically: physical parameter
  - can only be described using an interval
- Aleatory uncertainty
  - inherent randomness typically: measured quantity
    - can be described using a probability density function (or a cumulative density function)

- Epistemic and Aleatory uncertainties must be treated separately in the context of Uncertainty Quantification.

V&V and UQ

- Risk assessment require
  - Uncertainty Quantification.

- V&V and UQ provide means to assess
  - Uncertainty
    - in code prediction of the system behavior for intended use, and respective
  - Confidence
    - that **decision** based on simulation is robust
      - Not sensitive to the remaining uncertainty.
        - » **additional data (evidences) and new models**.
    - The evidences can be obtained from both
      - Experiments and
      - Detailed modeling
        - » e.g. LES, DNS.

V&V Main Motivation: New applications

- New designs of liquid metal cooled systems are under development
  - ASTRID, MYRRHA, ALFRED, SEALER, …
- The concepts are not evolutionary.
  - Little, if any, experience of
    - Operation.
    - Licensing.
- Experimental demonstration
  - Scaling of all important phenomena simultaneously in integral tests is generally impossible.
  - Full scale tests are impractical:
    - Design is changing.
- Regulation is changing to reflect the public aversion to risk.
  - Aiming at Practical elimination with regards to large releases.
- Decision making on both “moving targets”:
  - Design and
  - Licensing
- rely on predictive capabilities of the codes.

Regulatory requirements relevant to uncertainty quantification and validation

- Experience of licensing of new nuclear technologies:
- General validation methodology for any code is required
  – E.g. numerical uncertainty and convergence.
- However, no “general” validation of a code or software package
- Validation process to be applied on a specific ‘Safety case’
  – Goal-based rather than rule-based
  – Case specific evidences are required.
    - Driven by properties to be demonstrated
    - Amount of evidence depending on safety properties to be justified
  – Demonstration only related to safety
    - As ordinate and rigorous as possible.
    - Integral effects and potential feedbacks to be adressed as much as possible.
- Very clear success (stopping) criteria:
  – Code X with model Y can demonstrate criterion Z on property A is fullfilled for transients of type B.

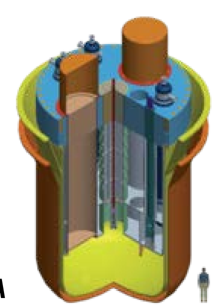
Thermal-hydraulic phenomena in LFRs

- Pool-type LFRs are characterized by
  - multi-dimensional flows,
  - natural circulation
    - sensitive to small changes in the system etc.
- Coupled CFD and STH codes can provide necessary accuracy in resolving both 3D and 1D phenomena.
- Numerical tools for LFR analysis require validation for prediction of design specific phenomena.

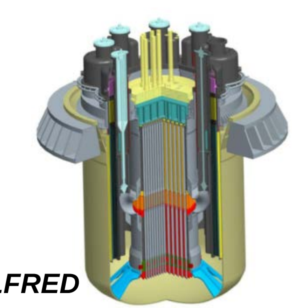
Single phase phenomena	Model type
Free shear	Bulk turbulence
Wall shear	Wall turbulence
Thermal mixing	Momentum convection, bulk turbulence
Thermal stratification	Thermal diffusion
Jet impingement of a surface	Production of turbulence
Thermal inertia of structures	Conjugate heat transfer
Natural circulation	Integrally all model

Multi-phase phenomena	Model type
Gas transport	Interfacial momentum transfer (drag) and buoyancy
Boiling	Irrelevant
Sloshing	ALE, Eulerian+interphase tracking (e.g. VoF, Level Set)
Melting/solidification	

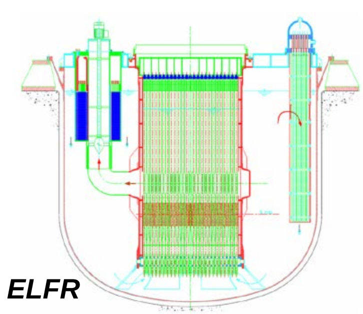
MYRRHA



ALFRED



ELFR



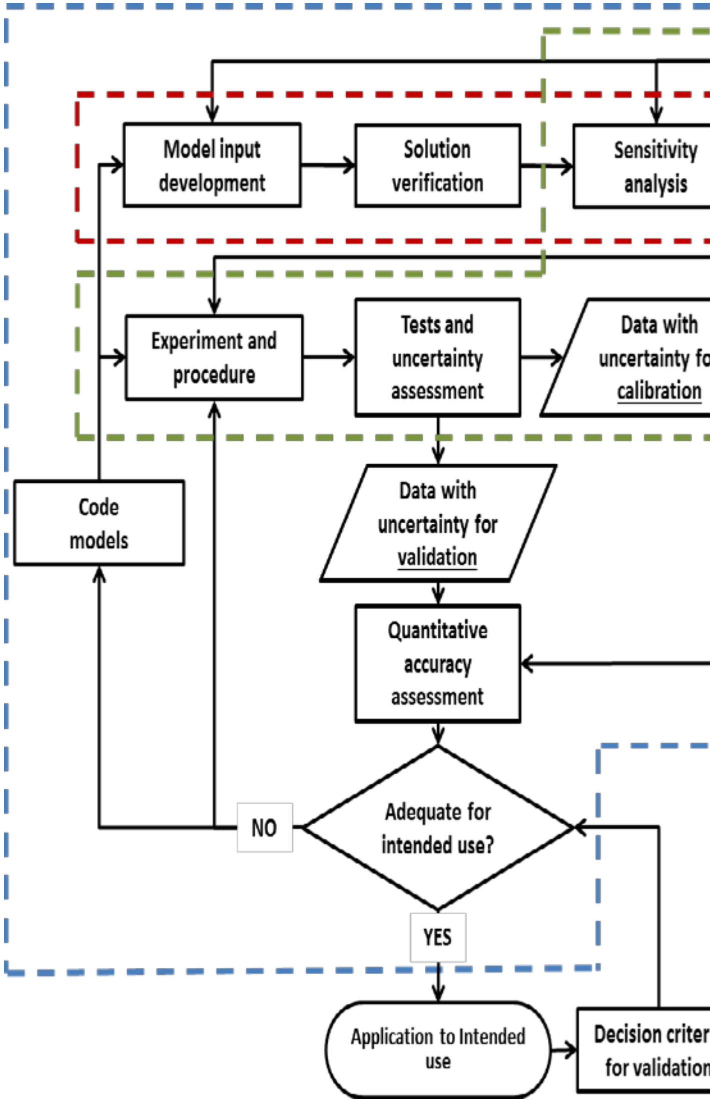
V&V Process

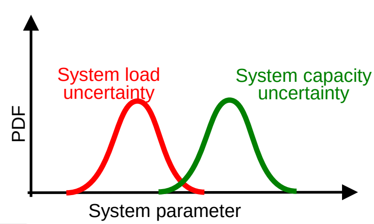
- V&V process Goal:
  - To develop sufficient evidences for robust decision making based on the code prediction.

- Successful V&V process is necessarily:
  - Systematic and complete
    - All uncertainty sources addressed
  - Tightly coupled with application for intended use.
    - Acceptance criteria for intended use (decision).
  - Iterative
    - New data (experimental or risk analysis results) often require changes in
      - Code inputs
      - Models
      - Requirements for new data.
  - Converging:
    - to a robust decision.

Iterative process of Validation

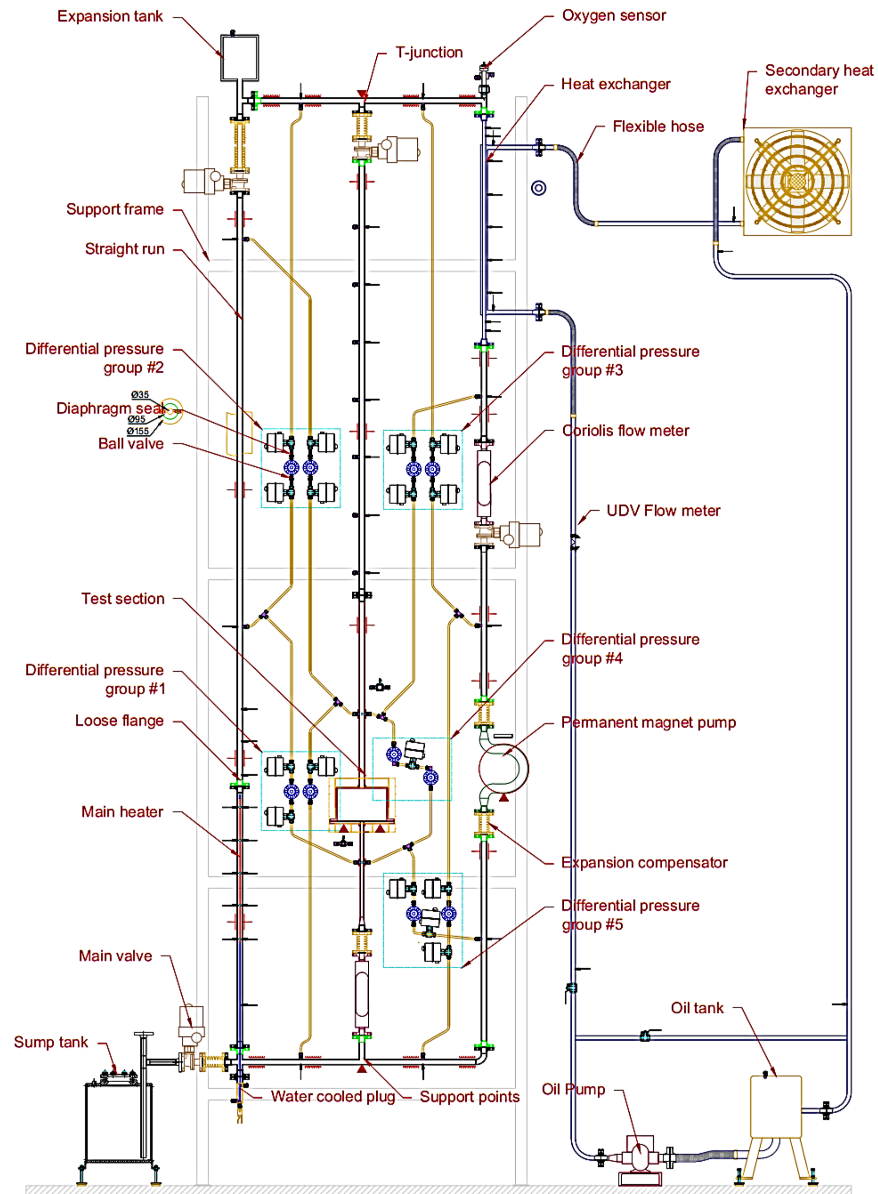
- The process starts with defining
  - the intended use of the model;
  - success criteria for the validation process.
- Verification
  - To demonstrate that numerical uncertainty is not a major contributor.
- Calibration of the code input.
  - to quantify uncertainty in the input parameters that are not measured directly in the experiment.
    - Separate data sets should be used for calibration and validation.
- Validation
  - To determine if model is “adequate” for application to intended use.
- The iterations are needed
  - To reduce the user effect
    - Make final results independent from initial assumptions about uncertain parameters.
  - To identify major sources of uncertainty
    - To reduce them in the next iteration.





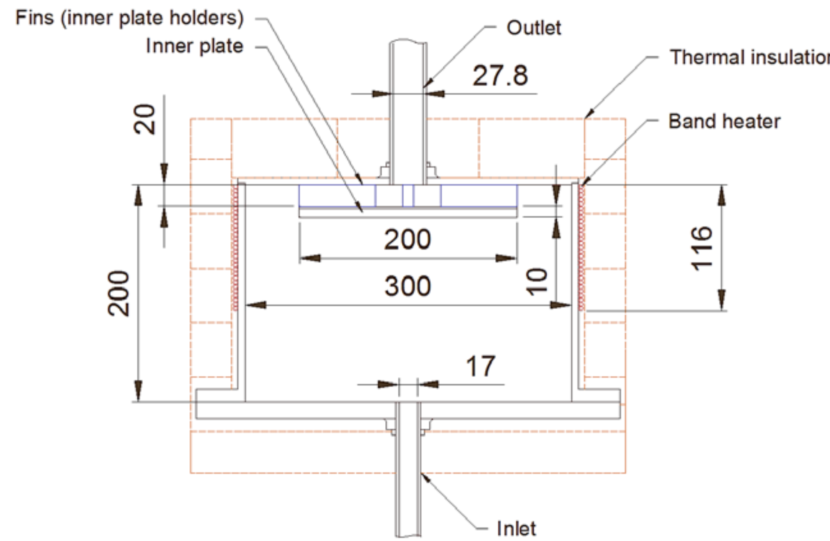
TALL-3D Facility

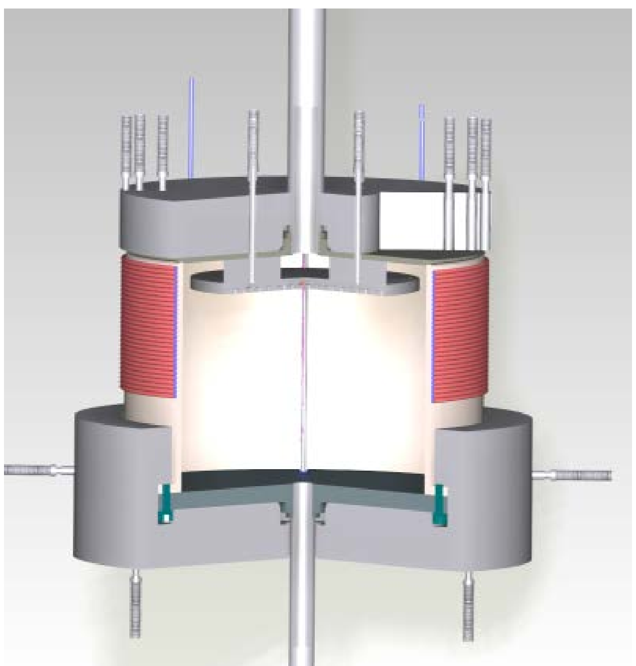
- Designed for validation of standalone and coupled STH and CFD codes
  - Divided into sections with measurements of boundary conditions for each section
- 3 vertical legs (5.83 m):
  - Main Heater (MH) leg (left)
  - 3D leg (middle)
  - HX leg (right)
- 2 electrical heaters:
  - Rod-type MH 21 kW (max)
  - Rope-type 3D heater 15 kW (max)
- Counter-current HX
- Instrumentation for:
  - In-flow LBE temperature (214 TCs)
  - LBE mass flow rate
  - Differential pressure

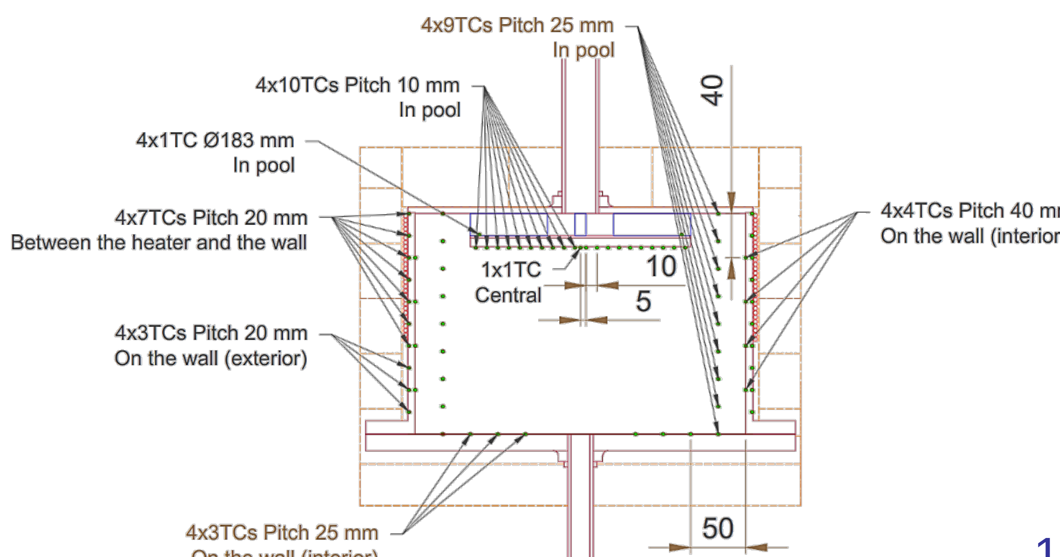


TALL-3D test section

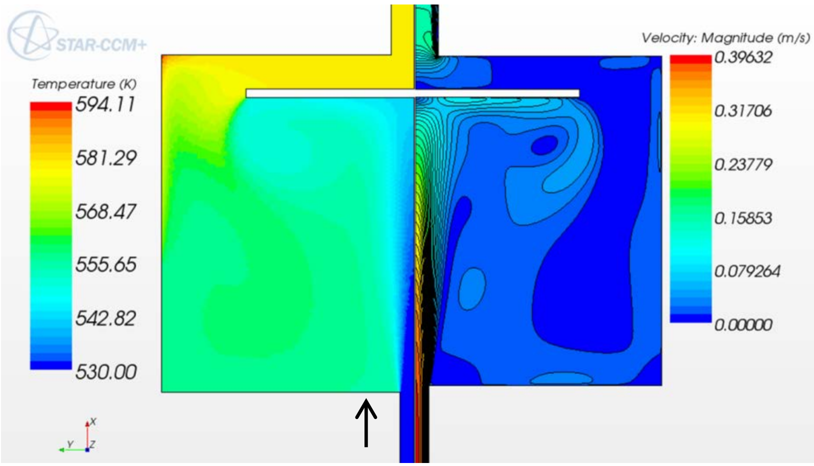
- **Designed to introduce transient 3D effects into the system**
- **The dimensions are selected to have jet mixing the pool at high flow rate (forced convection) and allow development of thermal stratification at low flow rates (natural circulation)**



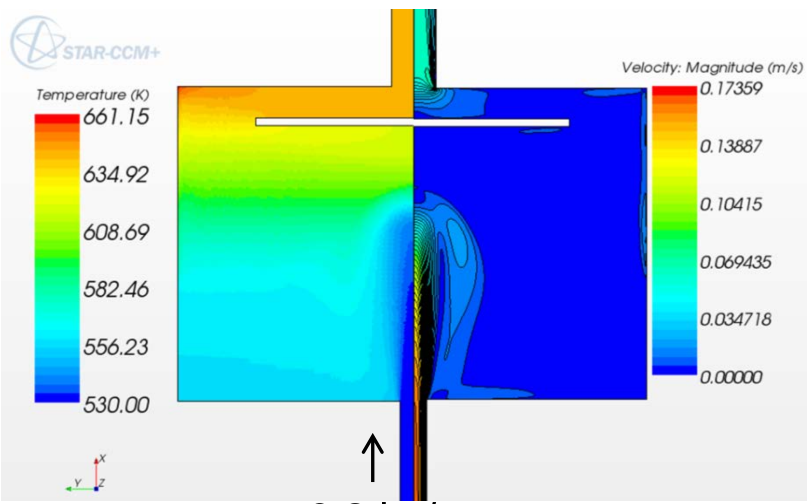




TALL-3D test section: Pre-test simulations



0.7 kg/s



0.3 kg/s

- CFD pre-test analysis
  - Star-CCM+,
  - 2D axisymmetric (only fluid region),
  - Steady,
  - RANS.
- Full mixing at $\dot{m} > 1.0\ kg/s$
  - jet penetrates the stratified layer and mixes the pool
- Partial mixing at $\dot{m} \approx 0.7\ kg/s$
  - Jet penetrates the stratified layer in the middle of the pool, but has not enough momentum to penetrate the buoyant wall jet at the heated wall
- Thermal stratification at $\dot{m} < 0.3\ kg/s$
  - jet is too “weak” to break the stratified layer

TH phenomena in TALL-3D

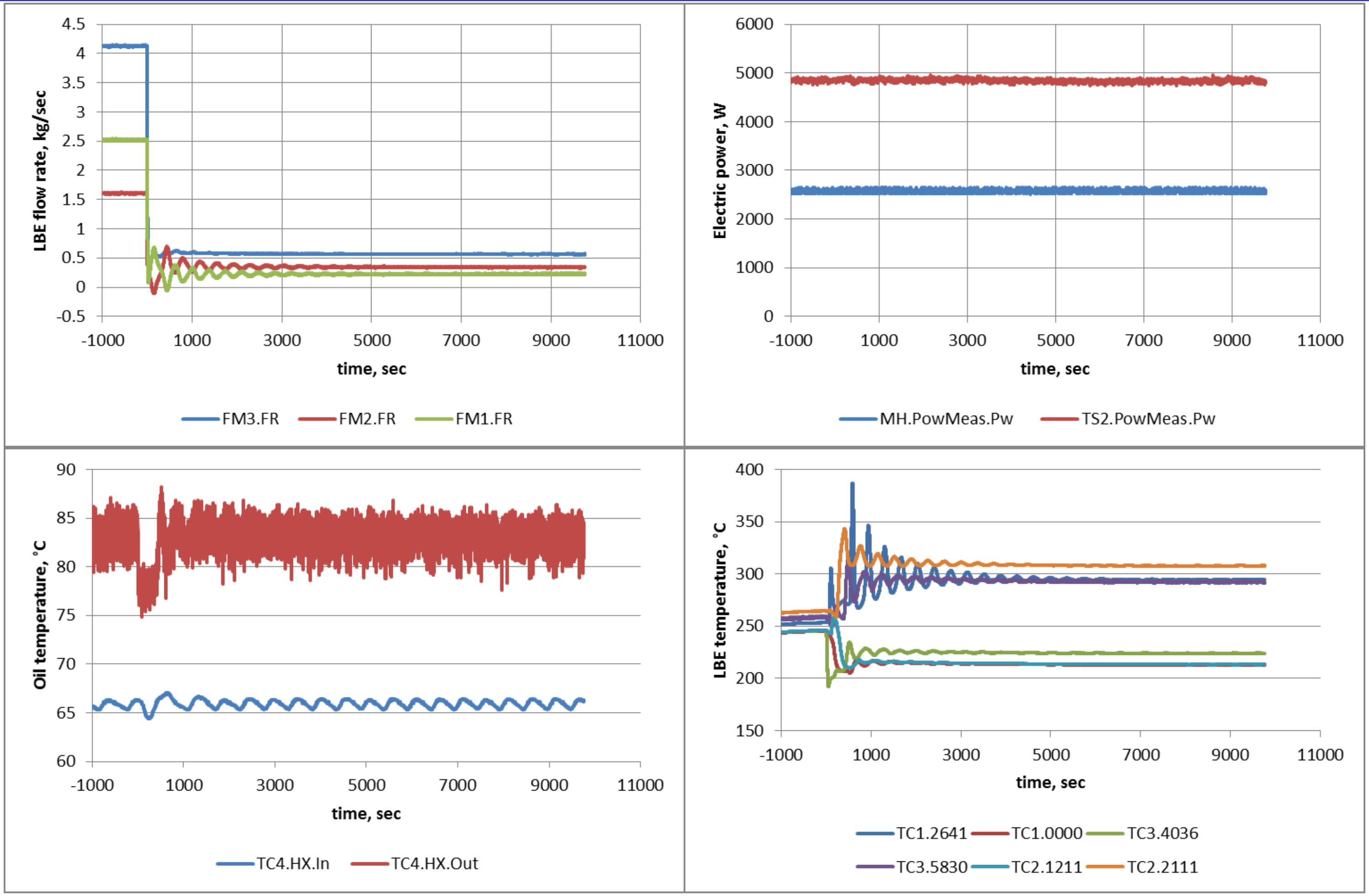
Phenomenon	Description	Regime	Experiments
Free jet flow	Thermal mixing and stratification in the test section are governed by the jet dynamics. A necessary condition for CFD validation, then, is that the codes accurately simulate free jets in a pool-like geometry in steady state conditions, both in forced and in natural circulation. Measurements: Temperature measurements on the inner circular plate are the validation data for this phenomenon.	Re, Ri	N01, F01, T01
Jet impingement on a surface	It is a key factor to produce the recirculation patterns inside the test section. The design simulations show that the jet will not reach the disk in natural circulation conditions therefore this validation can only be performed against steady state, forced circulation experiments. Measurements: Minimum mass flow rate for the jet to reach the disk measured by a Coriolis FM is used in validation metric.	Re	F01, T01
Jet induced circulation in the pool	Circulation in the pool is produced by the diversion of the inlet jet due to the circular inner plate. Validation data can be therefore obtained in forced or fast natural circulation experiments. Measurements: As the circulation drives mixing, validation data for this phenomenon is the temperature field in the test section.	Re	F01, T01
Thermal stratification	The codes' capability to capture transient development of stratification after switching on the heater can be assessed against temperature data obtained in forced (at small flow rates to prevent jet reaching the plate to enhance mixing) or natural circulation thermal transients in the loop. Measurements: Inner pool thermocouples.	Gr, Re	F01, N01, T01
Mixing	The codes' capability to capture thermal mixing can be assessed against temperature data obtained in steady state forced circulation experiments. Measurements: Inner pool thermocouples.		F01, T01
Thermal inertia of the structure	Heat transfer between LBE and heater/ambient is dependent on the thermal conductivity and capacity of the wall materials. Thermal inertia is important in transients where the temperature changes on either side of the walls, e.g. heater is switched on/off. Measurements: Temperature at the outer and inner side of the wall is measured in order to validate thermal conductivity model.	Re	T01
Thermal conduction through the plate	Fluid temperatures below and above the circular plate can be different resulting in heat transfer through the plate. The circular plate is made of conductive material and the temperature gradient through that material is therefore a subject to validation. Measurements: Thermocouples at the bottom and top of the plate.	Re	F01, N01, T01
Turbulence	Turbulence modeling is regarded as the one of the major contributors to uncertainty in the CFD M&S. TALL-3D provides integral data for turbulence studies. Turbulence produced in the wall boundary and jet shear layers is responsible for the flow energy loss in the test section. Measurements: Pressure loss over the test section is considered in validation metric.		F01, N01, T01

NB! In initial or final steady states belonging to transient tests, Reynolds number is between 3,600 and 58,000.
Lower and higher Reynolds values occur during flow oscillations and in the dedicated test for different steady states.

Design of the test matrix

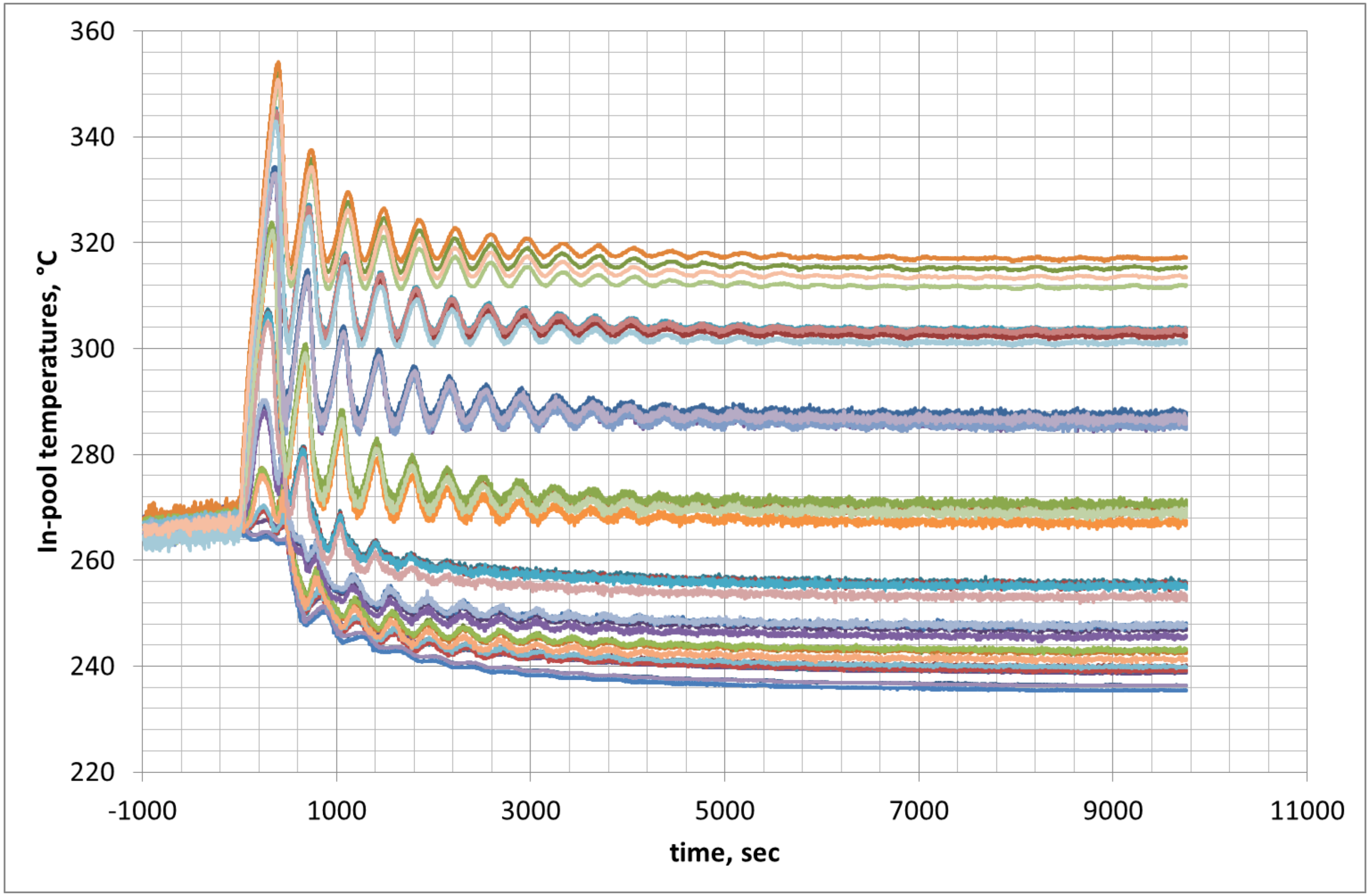
- Commissioning tests:
  - Actual vs intended performance of the experimental setup:
    - Equipment
    - Physical phenomena
- Quantification of measurement uncertainties:
  - Tests for quantification and reduction of experimental uncertainty, e.g. measurement offsets for actual physical channels.
- Code input calibration tests:
  - Test for calibration of model input parameters and quantification of their uncertainty.
- Code validation tests:
  - Separate effect tests.
  - Integral effect tests.
  - Benchmark tests.
  - Repeatability: quantification of experimental aleatory uncertainty.

TG03.S301: S3_FN_11_11



- T02.10 test transient data
  - T01.10 simulation results illustrate the case where, despite the presence of minor 3D effect influence, the stand-alone STH simulation can correctly predict complex transient behavior of the TALL-3D facility.

TG03.S301: S3_FN_11_11



- Transition from mixing to stratification in the 3D pool during the transient.

Background: APROS system thermal hydraulic

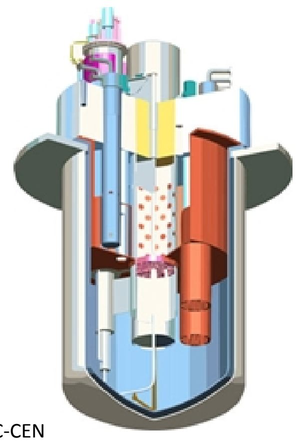
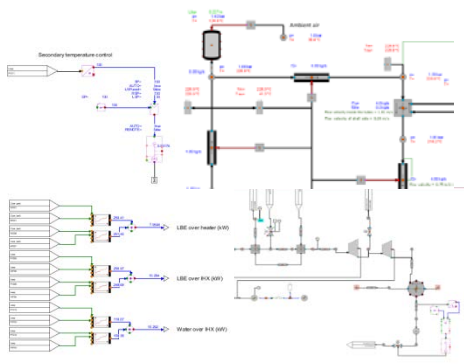
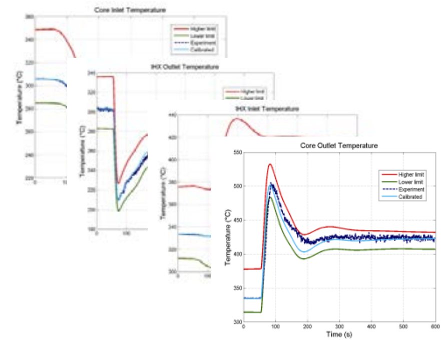


Image: SKC-CEN

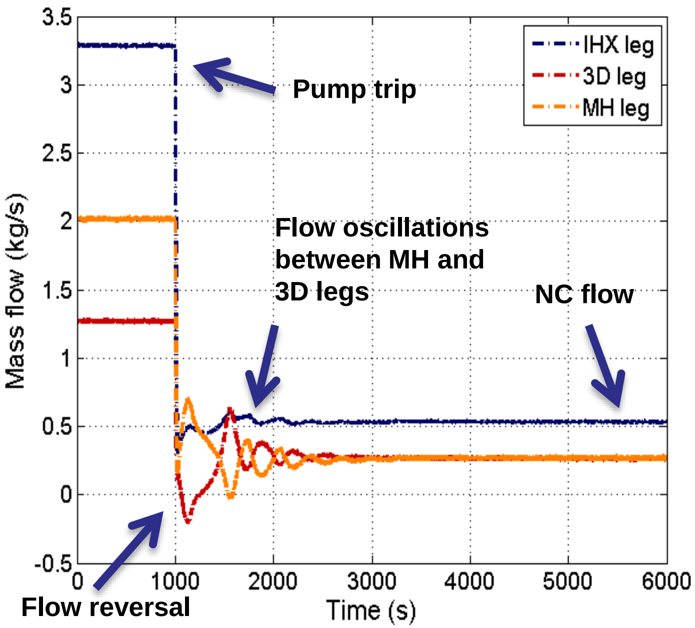


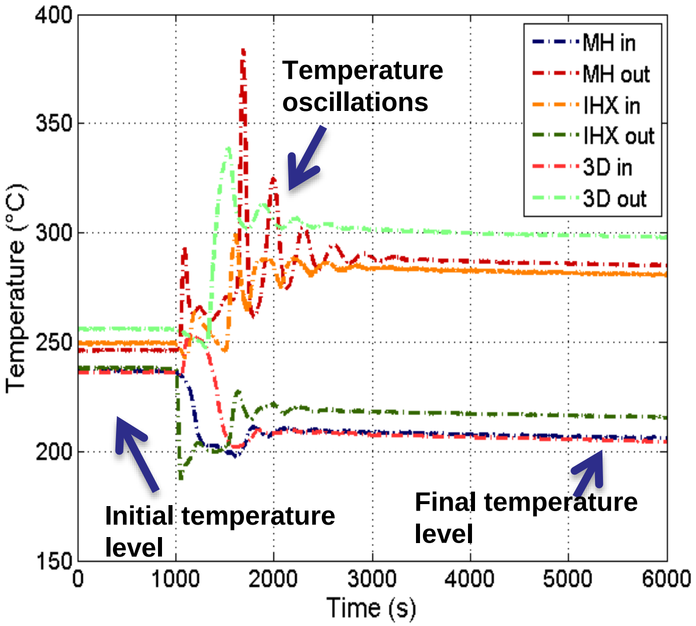


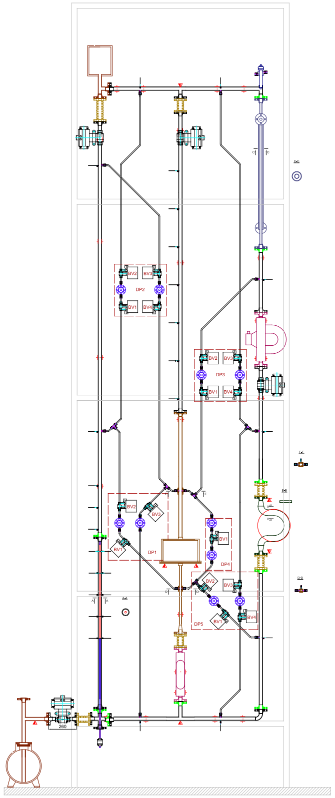
Technology Concept → **Process** Model → **Performance** Indicators

- APROS is a computer code which combines STH with 1D/3D core neutronics and full automation system modelling
  - Developed by VTT and Fortum (Finland)
  - Validation of APROS has been limited to light water cooled systems
    - test facilities and reactors
  - APROS LBE + argon cooling fluid simulation capabilities were implemented in APROS homogeneous flow model
- Envisioned as a concept evaluation tool
- APROS LBE simulation capabilities require validation against experimental data

Example of Experimental Data

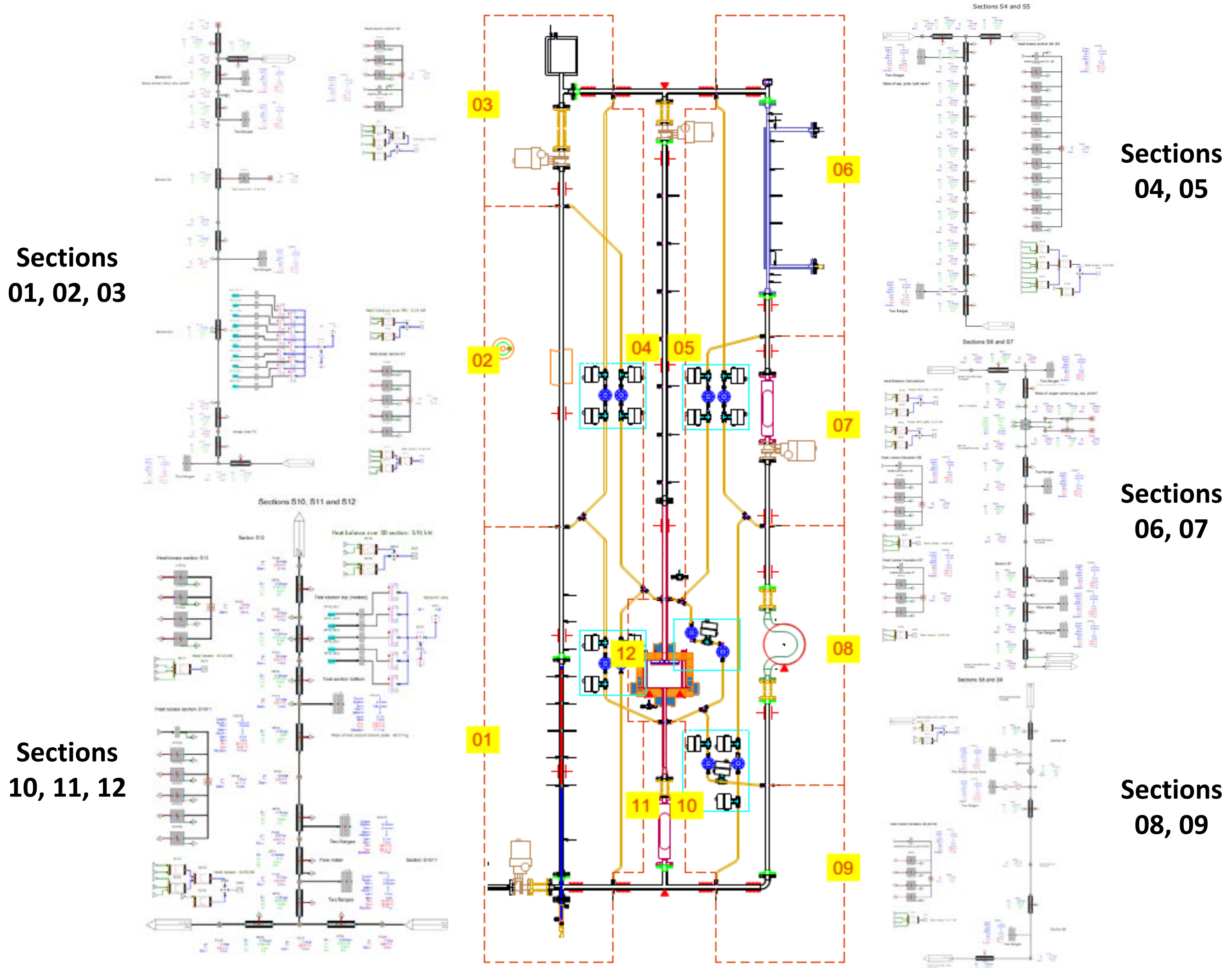






- Data from T01 and T02 experiment series was used in this work
- The series was focused on transients from forced circulation to natural circulation with all facility legs open
  - Modelling of onset and stability of natural circulation essential for LFR design and safety analysis
  - Mutual feedback between thermal and flow phenomena provides significant modelling challenge
- Competing flow paths between MH and 3D legs result in complex transient behavior – mass flow and temperature oscillations
- Mixing/stratification in 3D test section (3D flow phenomena)

TALL-3D Facility APROS Model

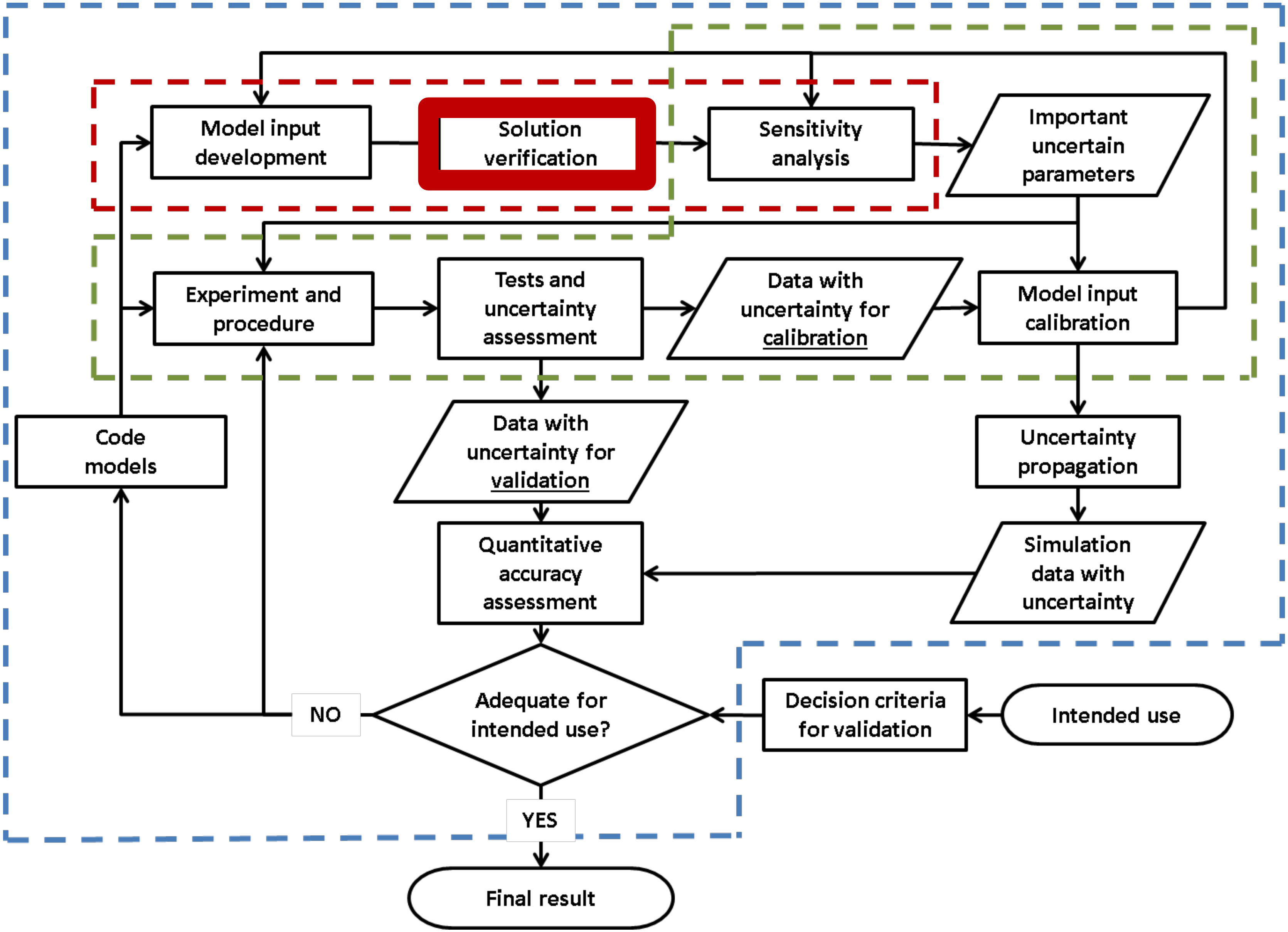


- Model is subdivided according to the sections in TALL-3D
  - For which BCs can be provided separately

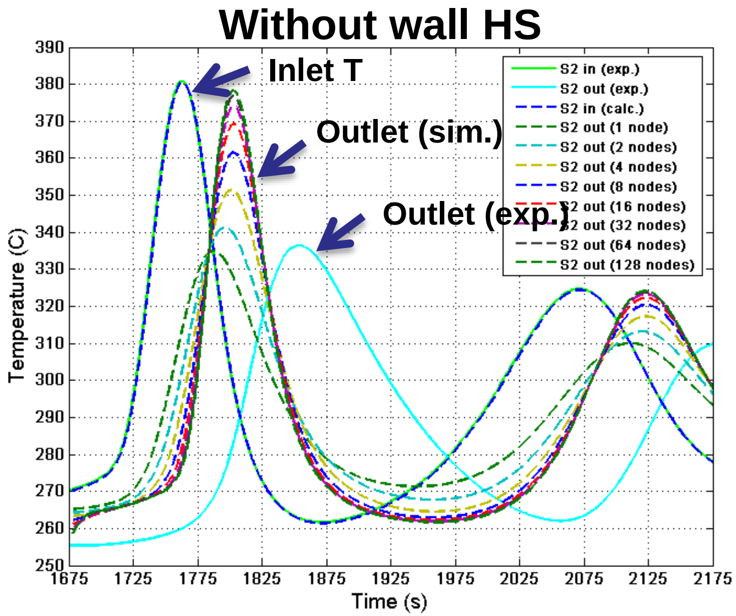
Input Uncertainty

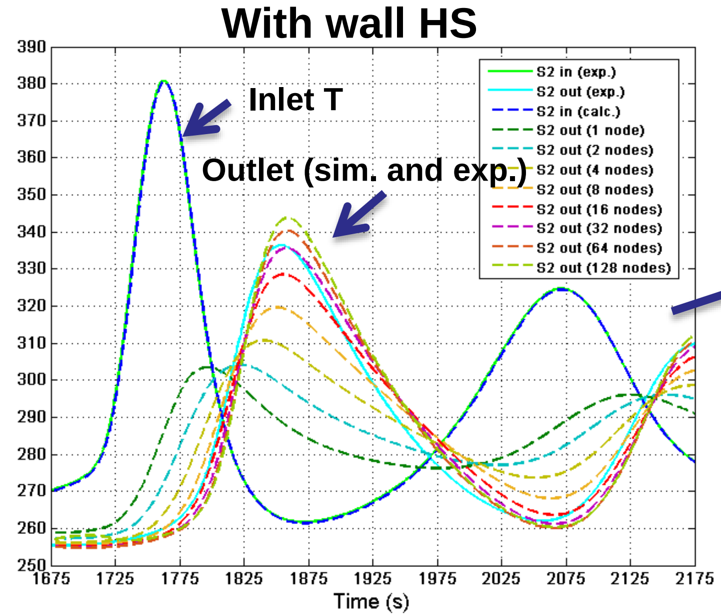
- **Geometry**
  - General layout from CAD drawings, uncertainty negligible.
  - Uncertainty introduced by modelling complex geometry objects (e.g. valves with actuators, flow meters, …) as 1D heat structures:
    - Introduction of ”effective heat capacity” and ”effective heat loss”
- **Materials**
  - Steel, insulation, secondary coolant specifications are provided by manufacturers with estimates of uncertainty (5%).
  - Use of pre-heaters in the facility constitutes a small gap (~1 mm) between the piping outer wall and insulation.
    - This gap is resolved by special ”gap” material for which the properties are varied from air to steel in sensitivity study.
- **Initial and Boundary conditions**
  - Powers of the heaters, secondary side parameters, ambient air temperature, expansion tank pressure and temperature.
- **Constitutive model parameters**
  - Wall surface roughness and flow loss coefficients.

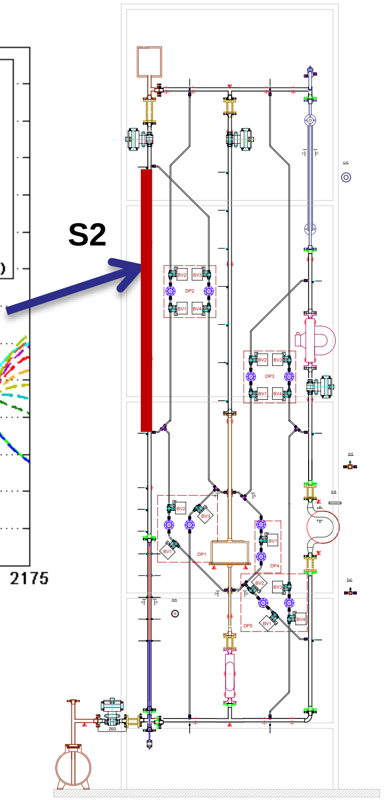
Approach to Validation



Grid Convergence Study

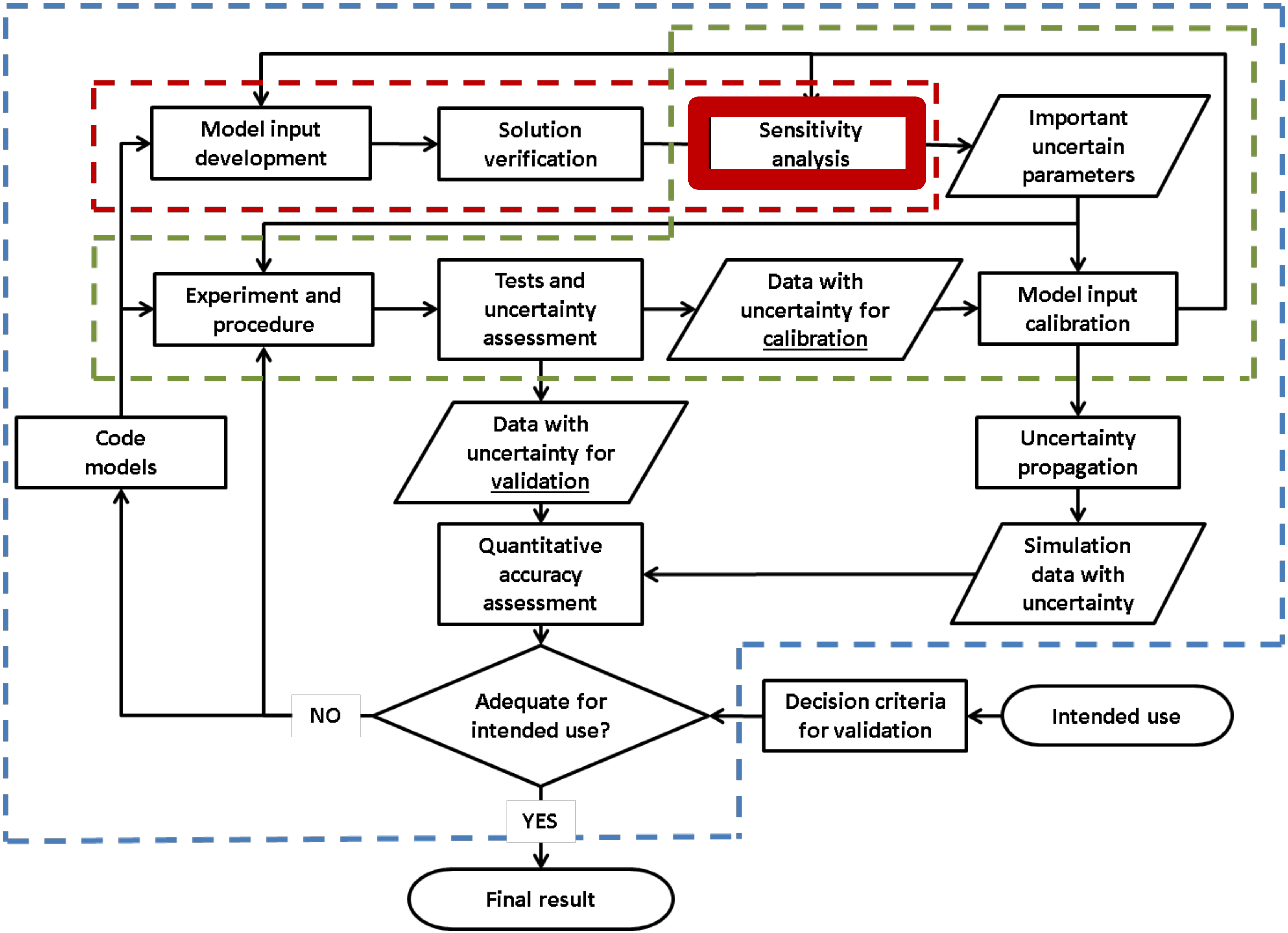






- **Propagation of temperature through a pipe with/without thermal inertia and heat losses**
- **5 cm/node adequate to reproduce typical case of experimental temperature peak propagation**
  - **Facility <u>section</u> 2 (2.35 m insulated pipe)**
  - **Experimental temperature and mass flow BCs**
  - **Node size 235-1.8 cm (1-128 nodes)**
  - **Diffusion of outlet *T* peak even with 1.8 cm nodes (2.2 °C) without wall HS**
  - **T_{128}-T_{64} = 1.4 °C**
  - **Very small node size unaffordable computationally for multiple code executions**
  - **Node size 3.7 (64) – 7.3 (32) cm shows numerical effects combined with wall HS modelling of similar magnitude as in the experiment**

Approach to Validation



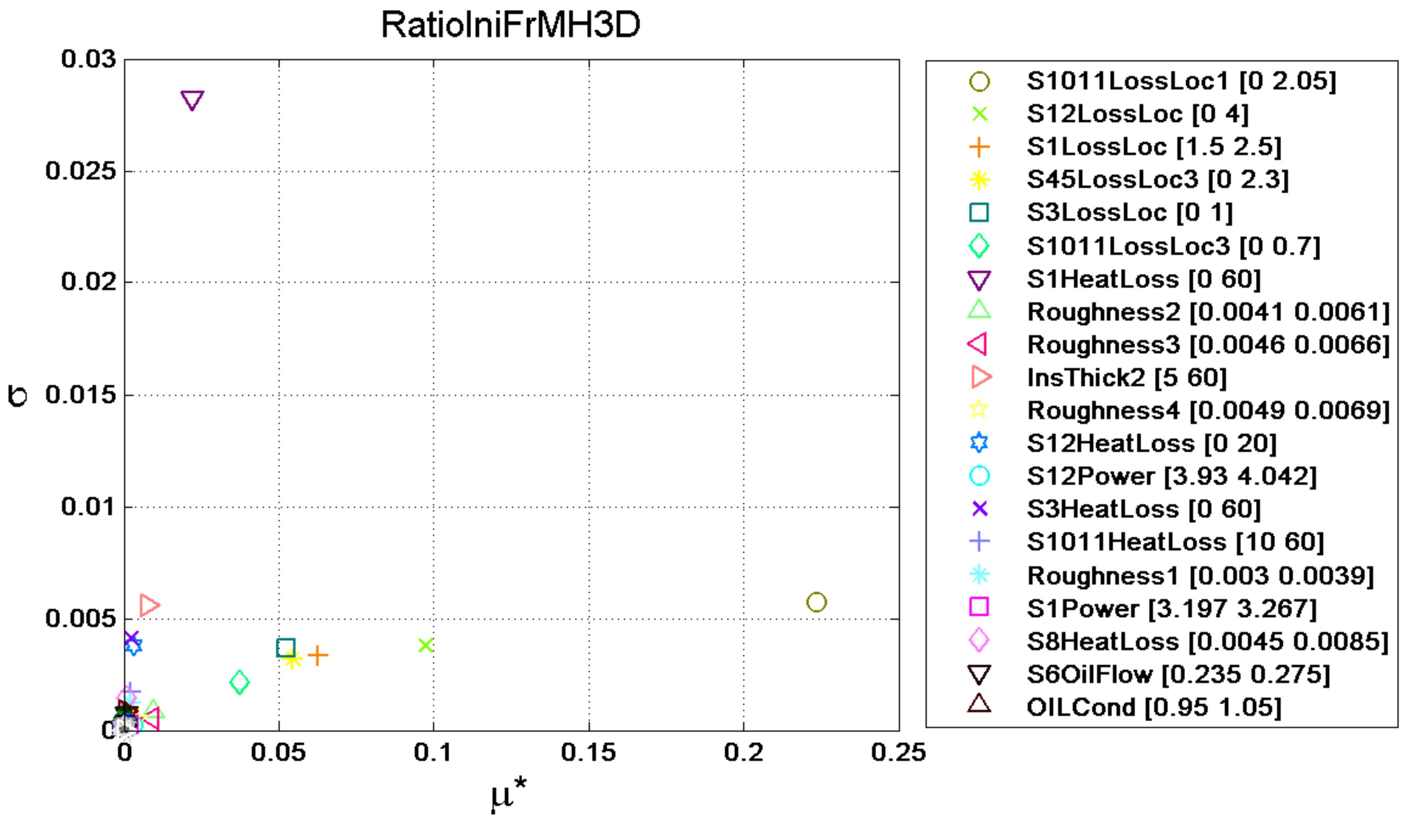
Process of Sensitivity Analysis

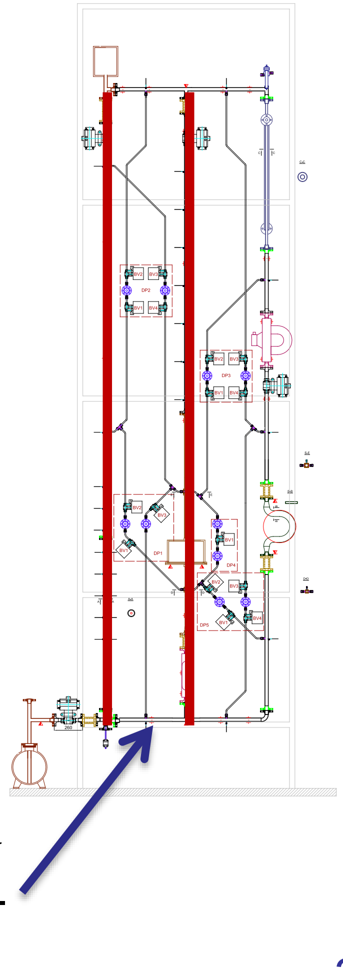
- SA results depend on selected ranges
  - Large effort is required to obtain data for the ranges
    - Variation of parameters for each model section independently (total 58 parameters)

- A process is necessary to minimize efforts and reduce the user influence on the results
  - Initial (conservative) guess.
  - Iterative refinement of the ranges for the most influential parameters
  - Stopping criteria:
    - No further qualitative change in SA result
    - Further refinement needs calibration data

Selected Results of Sensitivity Analysis

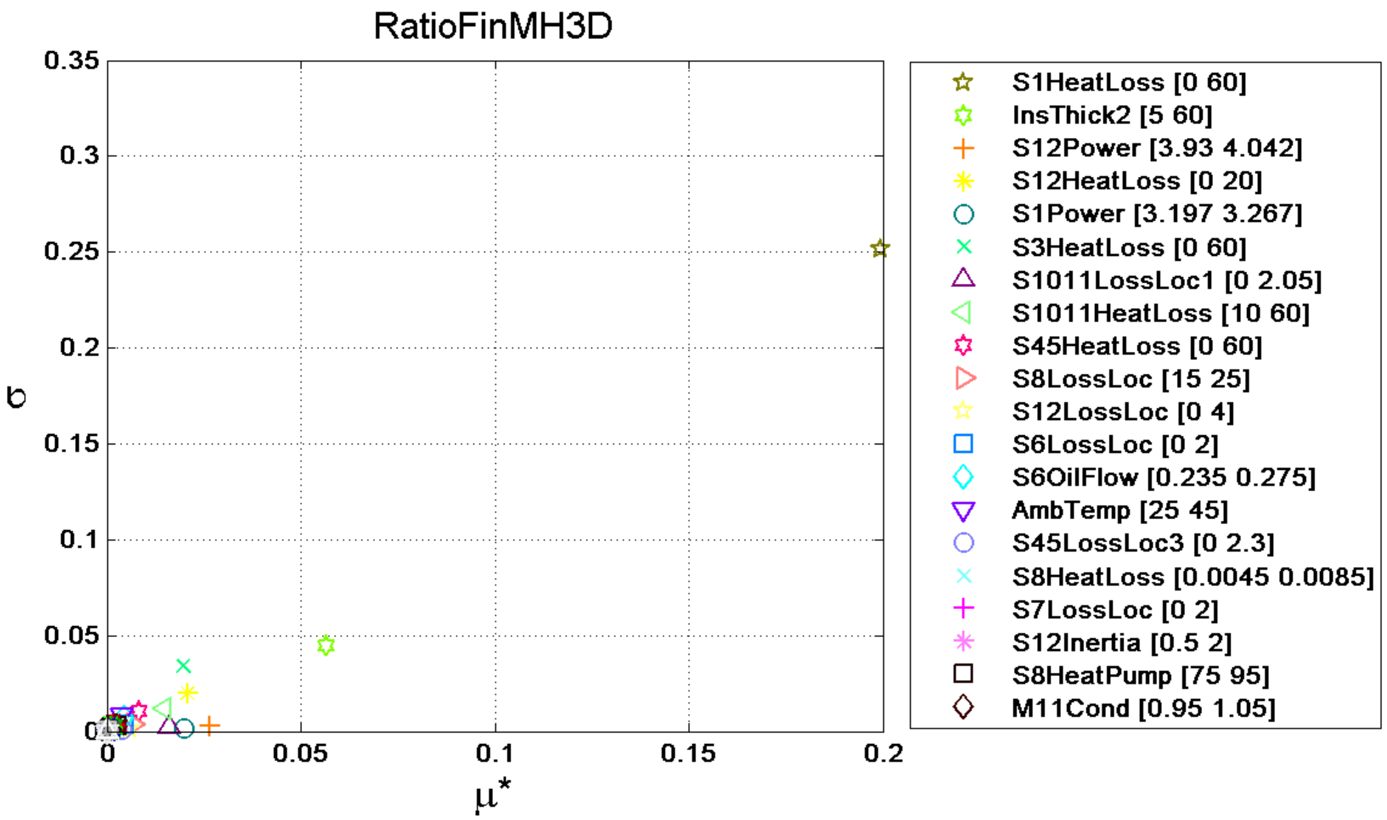
- Initial mass flow rate distribution between MH and 3D legs
  - mostly influenced by local loss coefficients

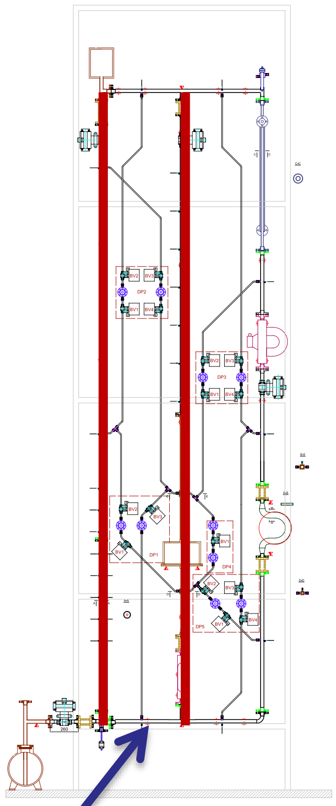




Selected Results of Sensitivity Analysis

- Final mass flow rate distribution between MH and 3D legs
  - mostly influenced by heat losses and powers of the MH and 3D heater





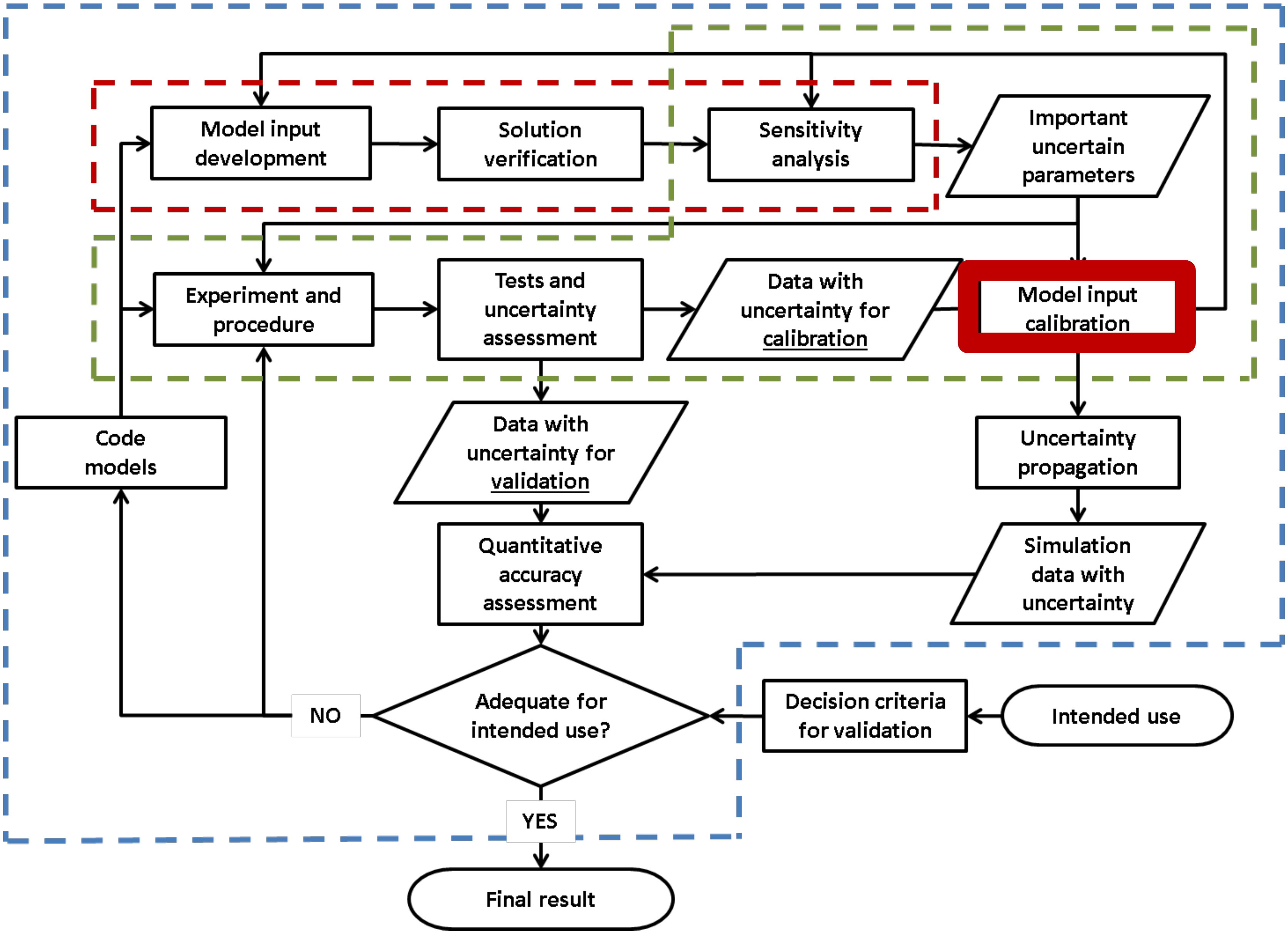
$$\frac{MH}{3D}$$

Sensitivity Analysis: Summary

- Uncertainty is important in:
  - Hydraulic losses
  - Thermal losses
  - Thermal inertia
  - Secondary coolant mass flow rate

- Uncertainty is less important in:
  - Expansion tank BCs
  - Ambient air temperature
  - Secondary coolant temperature

Approach to Validation



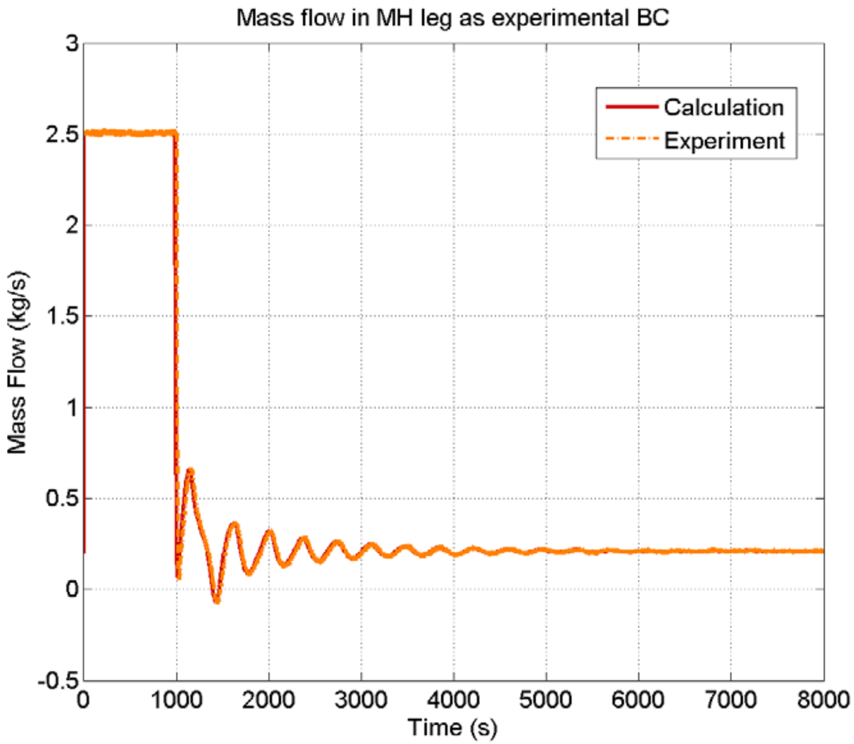
Input Calibration

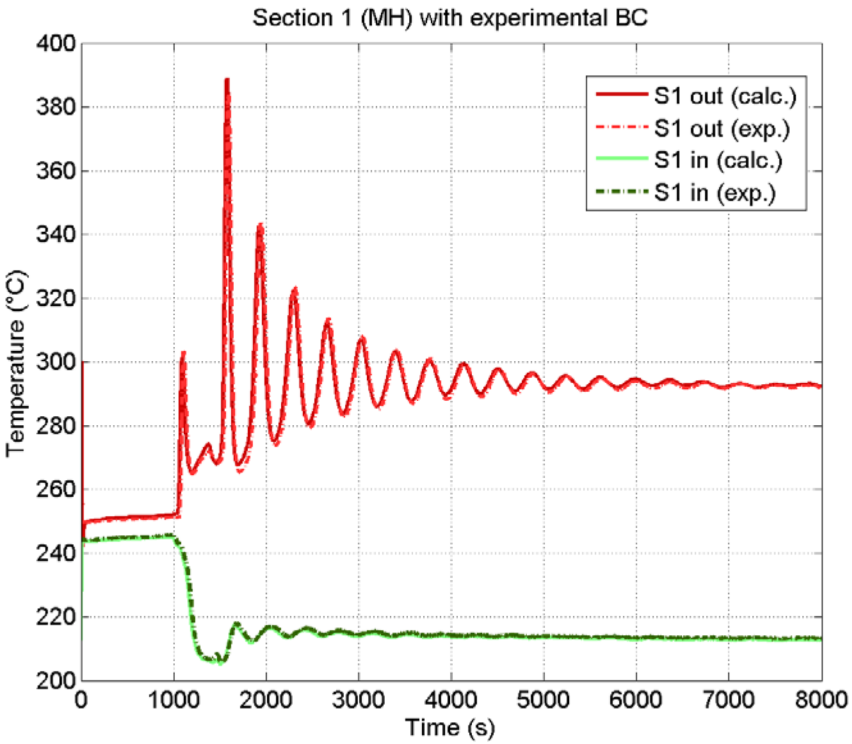
- *Calibration*: the process of adjusting physical modeling parameters in the computational model to improve agreement with experimental data.

- Full separation of input calibration and code validation
  - blind comparison with validation data set

- Calibration data should maximize each separate effect of the Most influential (according to SA) “calibratable” input parameters :
  - Calibration of one parameter at a time
    - ”Section by section” calibration
    - Number of constraints equal to number of parameters being calibrated
  - Transparency.

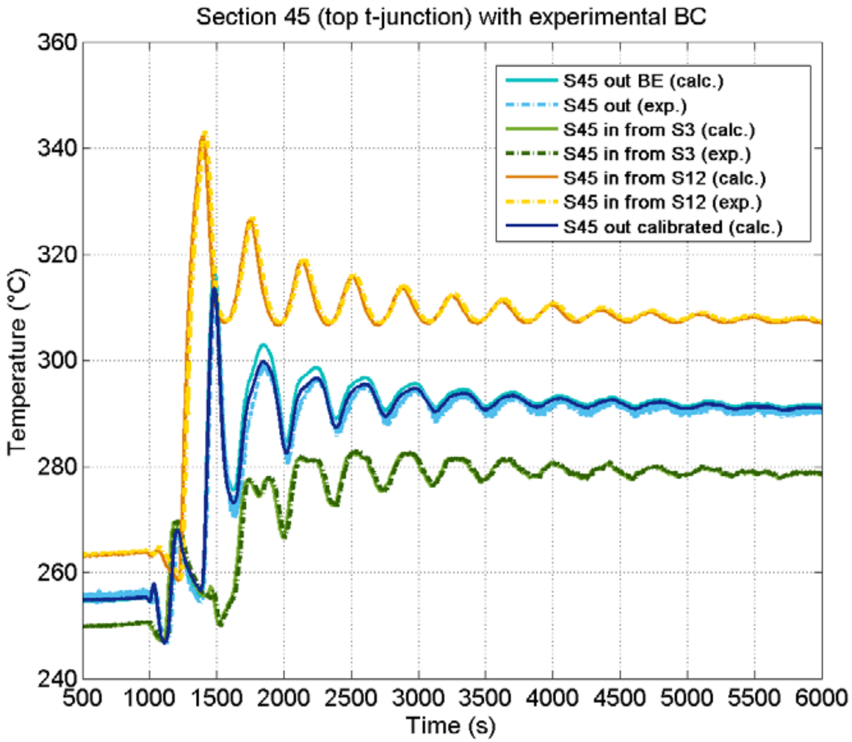
Model Calibration: Thermal Inertia

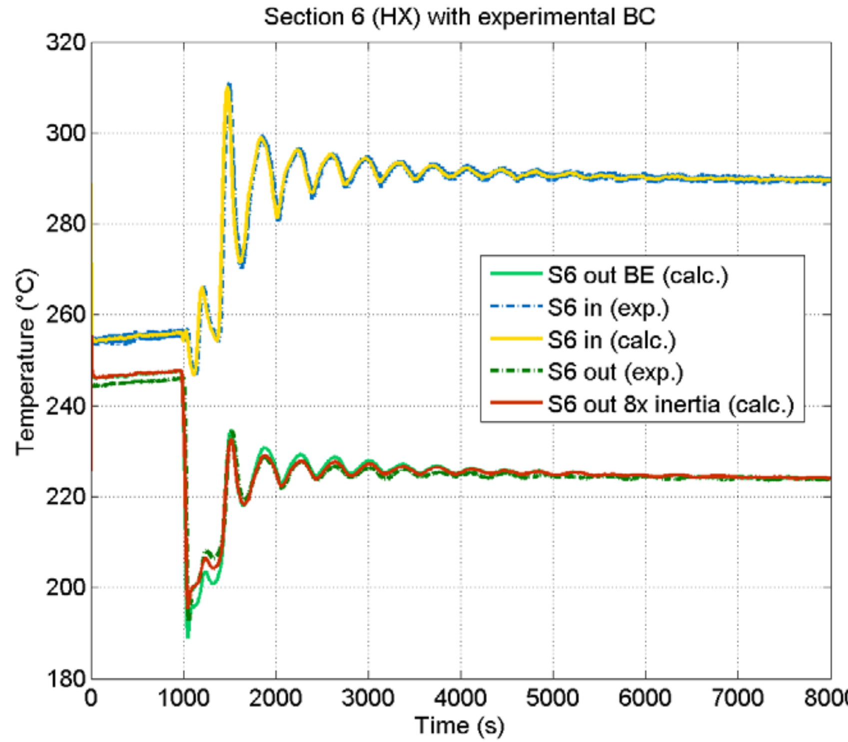




- For loop sections 1, 2 and 9, initial guess value of thermal inertia yielded only minor discrepancies between the calculation and the experiment
- Magnitude of thermal inertia effect may have been over-estimated in the sensitivity analysis

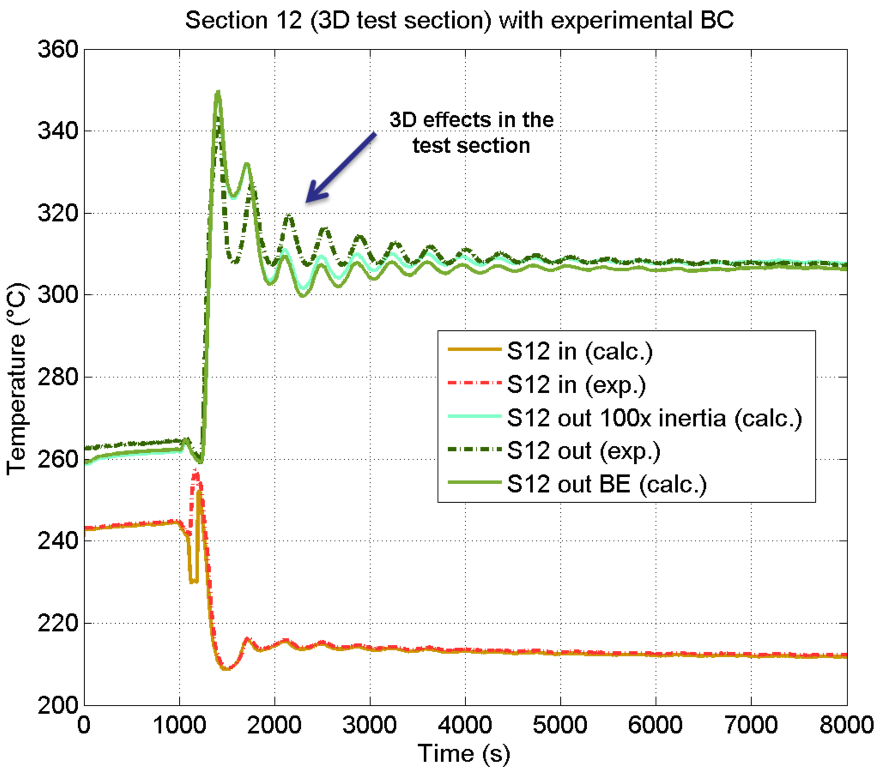
Model Calibration: Thermal Inertia

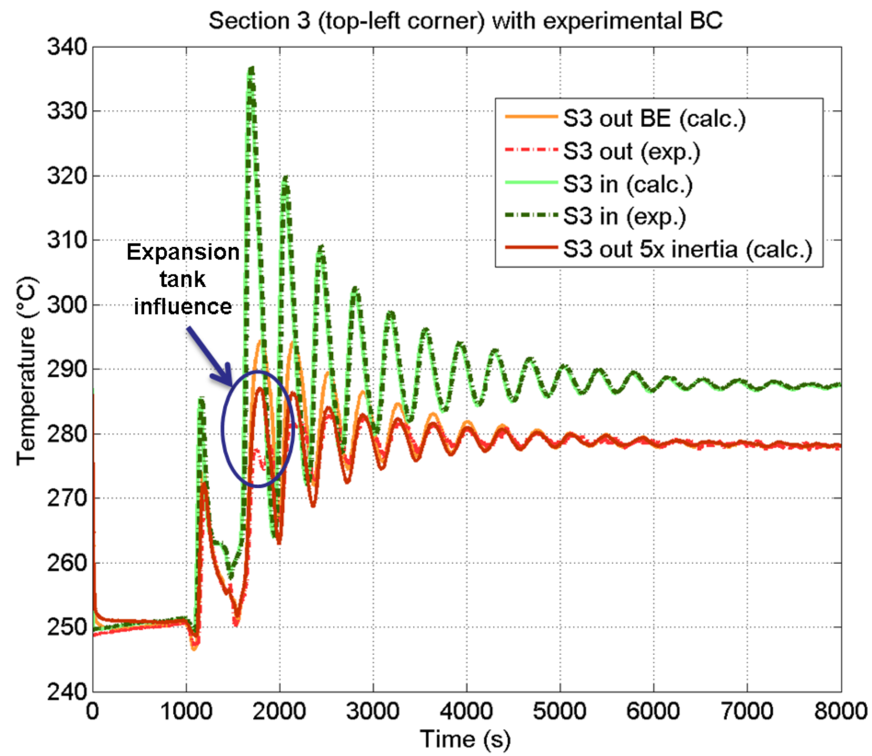




- For sections S3, S45, S6, S7, S8 and S1011 adjustment of specific volumetric heat capacity was necessary to improve the agreement.
- Example above shows section S45 (top t-junction) and S6 (heat exchanger) calibration.
  - The uncertainty coefficient for specific volumetric heat capacity was increased 6 times in S45 and 8 times in S6

Model Calibration: Thermal Inertia

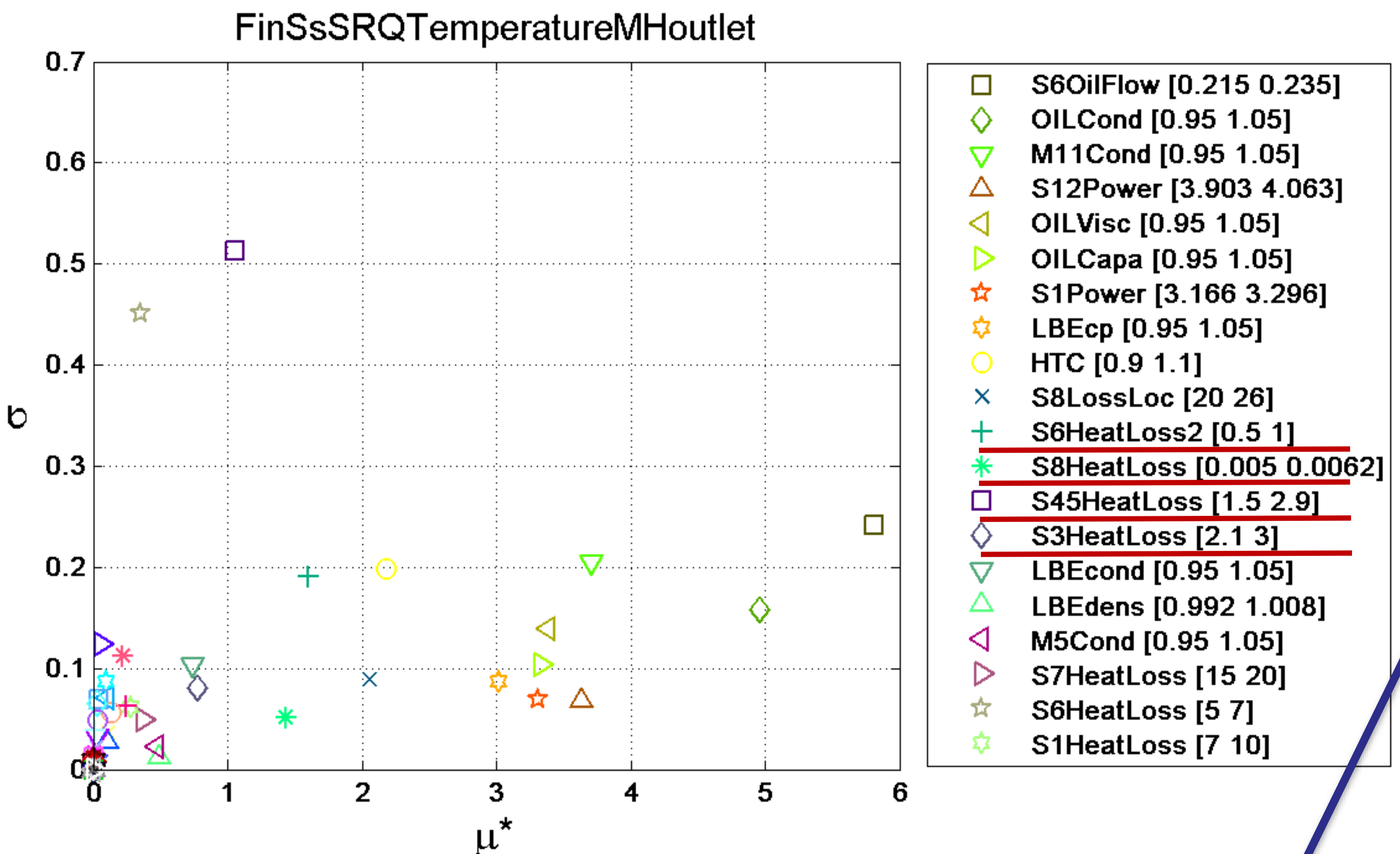


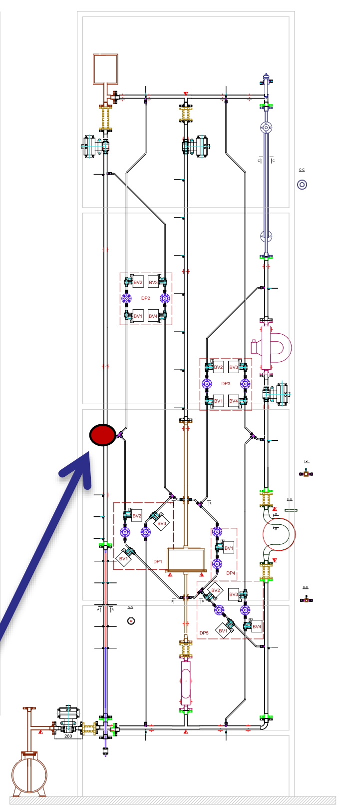


- 1D code can not capture 3D phenomena
- Thermal inertia in section 12 (left) and section 3 (right) could not have been adjusted to properly resolve the whole temperature transient curve
  - Discrepancies in section 3 can be attributed to the local mixing of the colder LBE from the expansion tank
  - Transient mixing/stratification effects in the 3D test section

Post-calibration SA

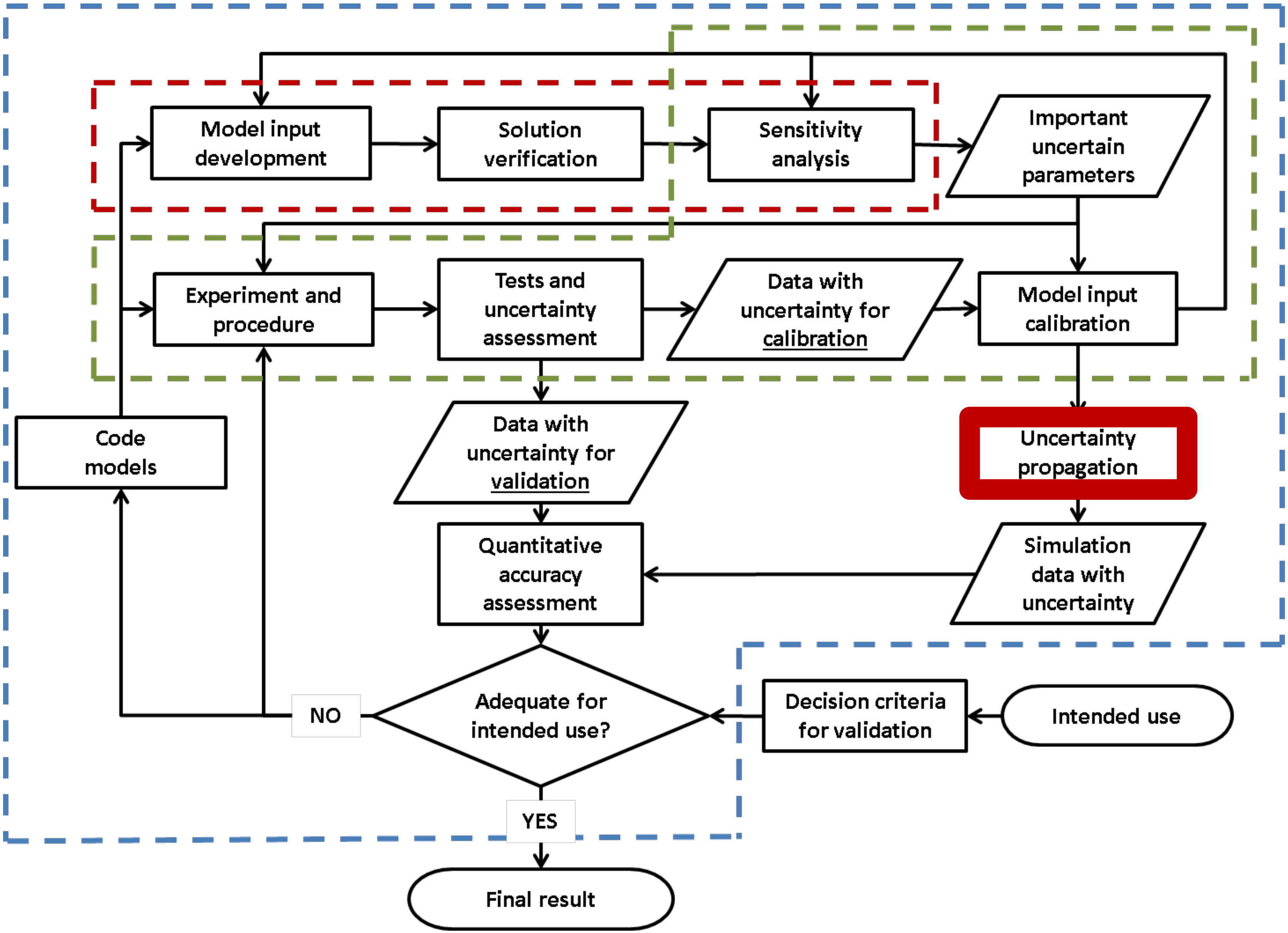
- Effects of calibrated parameters generally decreases.
  - Magnitude is now similar to that of the uncertainty in heater power BCs and LBE properties.
  - Relative importance of material properties and secondary coolant mass flow rate uncertainty has increased.





S2 (MH) outlet

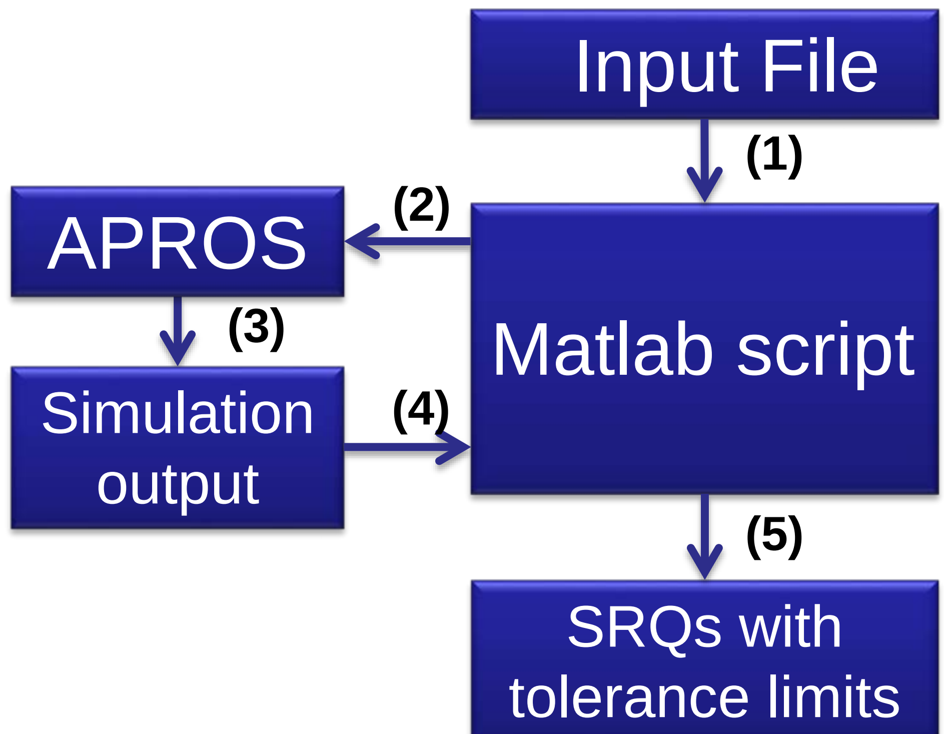
Approach to Validation



Uncertainty Propagation

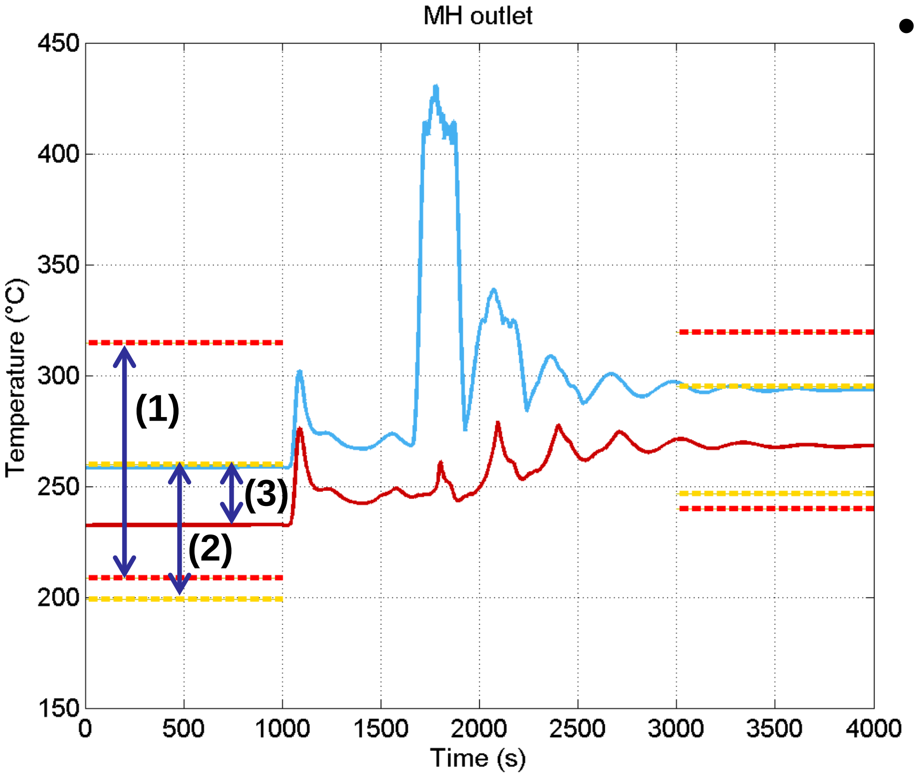
- Uncertainty propagation by input sampling
- Number of code executions according to Wilks
  - $\alpha \geq (1-\gamma)n\gamma^{n-1} + \gamma^{n}$
  - For $\beta = 1 - \alpha = 0.95$ and $\gamma = 0.95 n = 93$
- Output uncertainty quantified by non-parametric tolerance intervals

1. **Read-in files with APROs attributes and ranges**
2. **Create input samples by Simple or LHS sampling; feed values to APROS and control simulation**
3. **Output files for each simulation run**
4. **Reading and post-processing of output files**
5. **Graphs for selected SRQs with tolerance limits, ranges, validation metric results.**



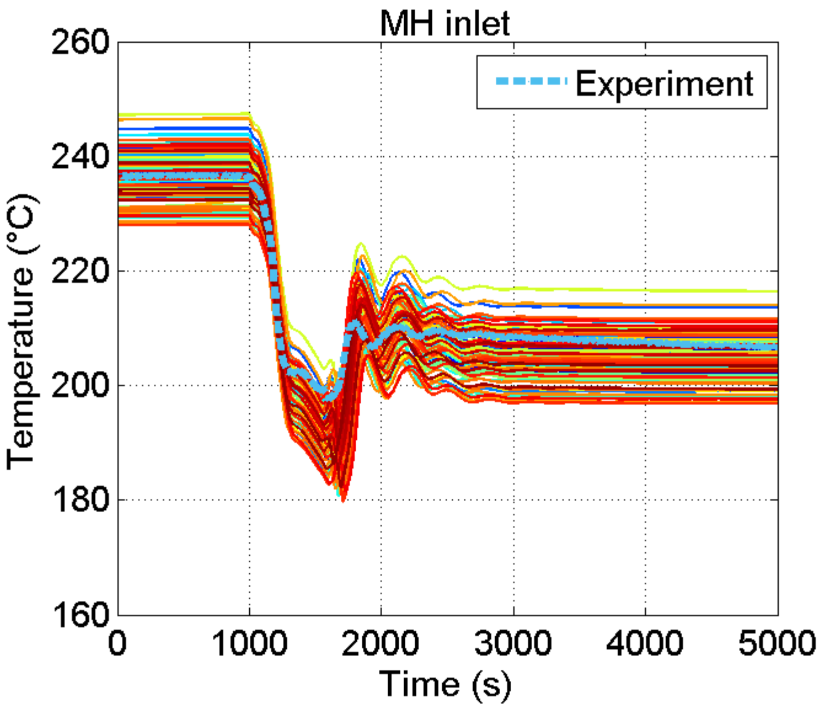
Example of Uncertainty Reduction in SA and Calibration Process

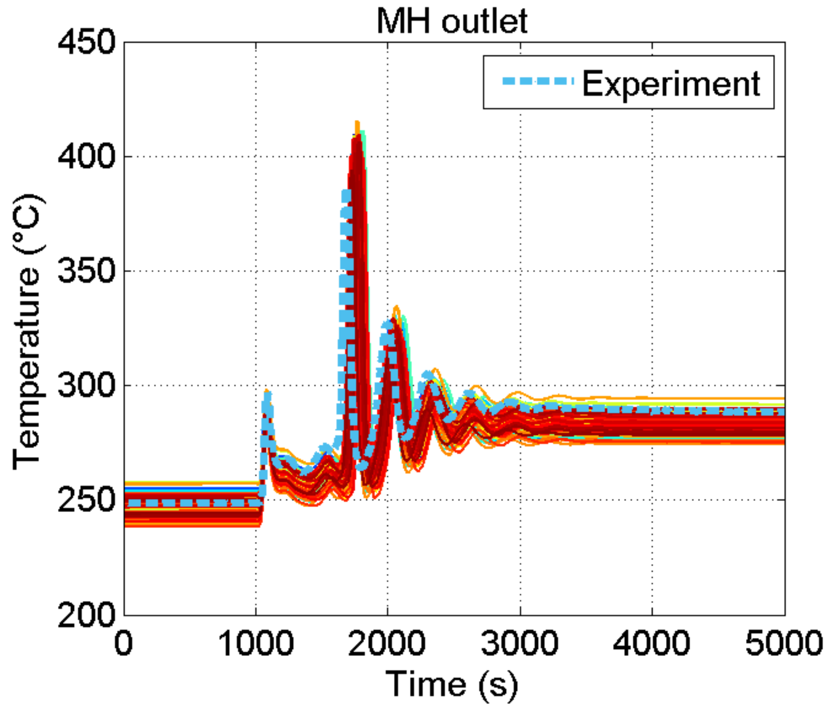
- Evidences (experimental data) are used to bound the assumptions
- Further reduction of uncertainty requires more evidences



- Steady-state simulation output uncertainty ranges
  1. Initial iteration of sensitivity analysis (in red)
     - Range ≈ 106 °C
  2. Final iteration of sensitivity analysis (in orange)
     - Range ≈ 61 °C
  3. Uncertainty propagation after model input calibration (solid curves)
     - Range ≈ 25 °C

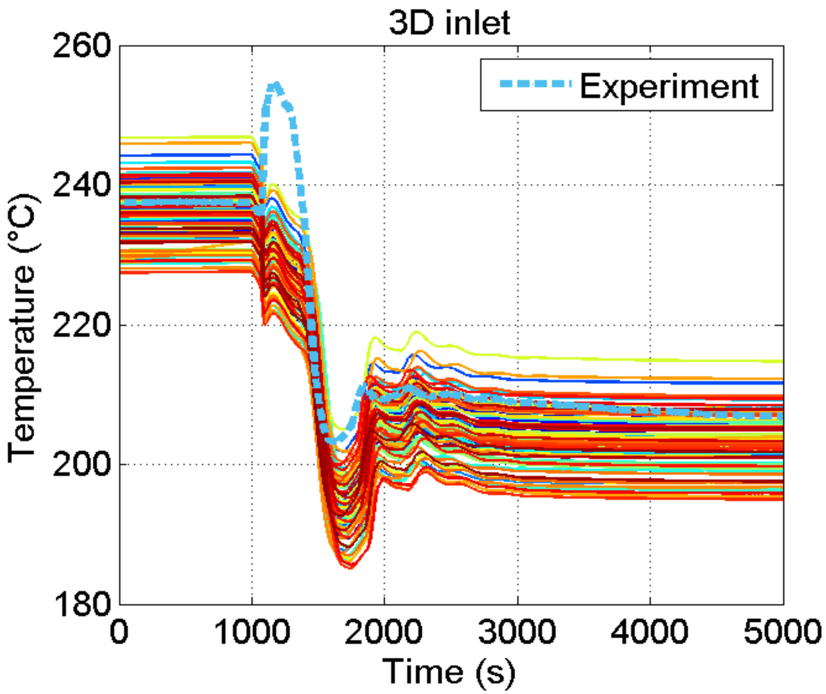
T01.10: MH Section Temperatures

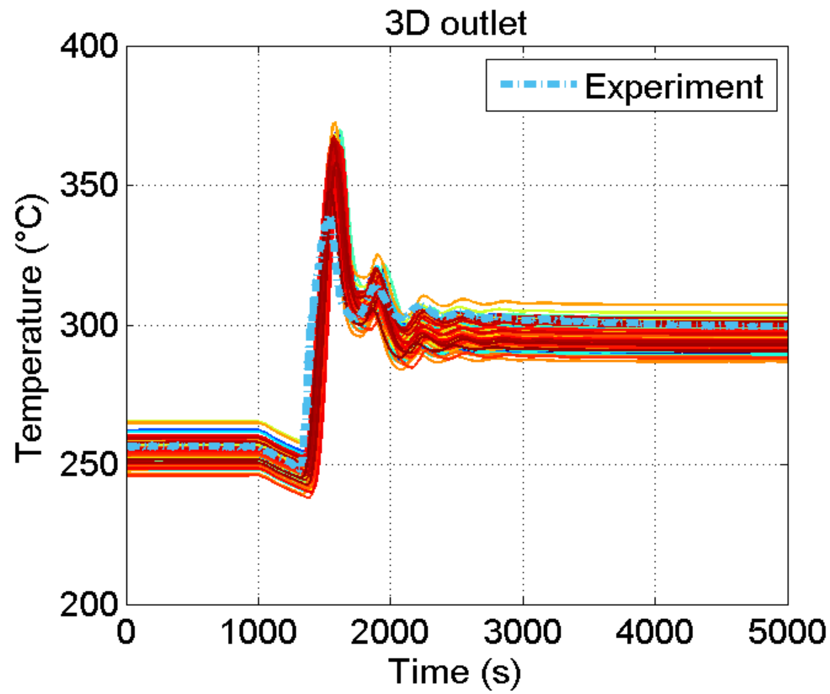




- Effects of 3D phenomena on the integral behavior evident in other SRQs
- For first 100 s good predicted transient progression (1)
- Subsequent temperature peaks shifted to the right (happen later) compared to the experiment (2)
- Slower transient flow dynamics result in higher temperature peaks for MH outlet SRQ
- Average simulation uncertainty range
  - 20 °C for MH inlet SRQ
  - 25 °C for MH outlet SRQ (result affected by overlapping curves in transient)
    - ~20 °C in steady states

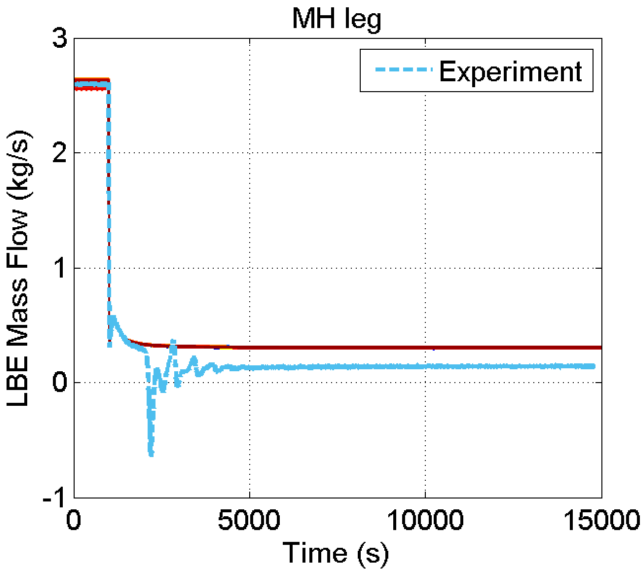
T01.10: 3D Test Section Temperatures

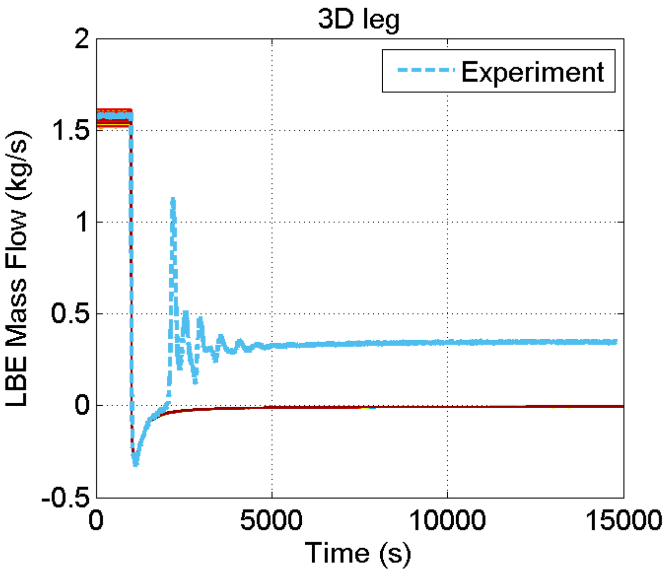


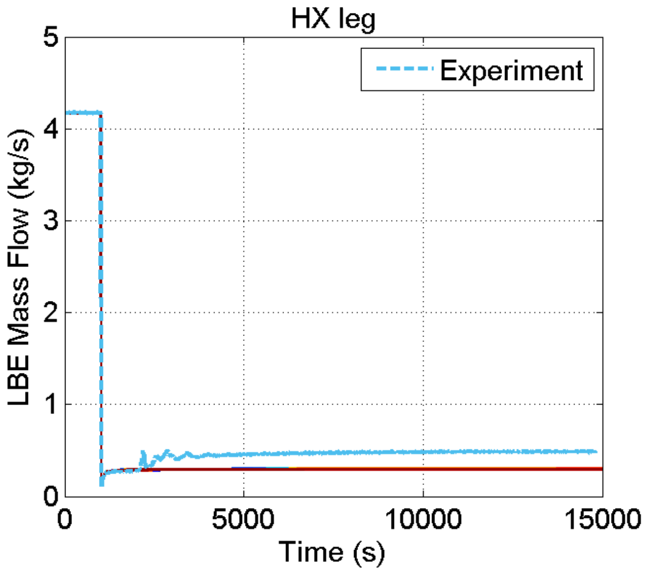


- 3D effects evident in experimental temperature curves
- Re-distribution of the hotter LBE to lower elevations in the facility (seen in left figure)
- Transition between mixing and stratification
  - Lower transient peak temperature in experiment compared to simulation
- Average simulation uncertainty range
  - 20 °C for 3D inlet SRQ
  - 22 °C for 3D outlet SRQ

T02.06: LBE Mass Flow Rates

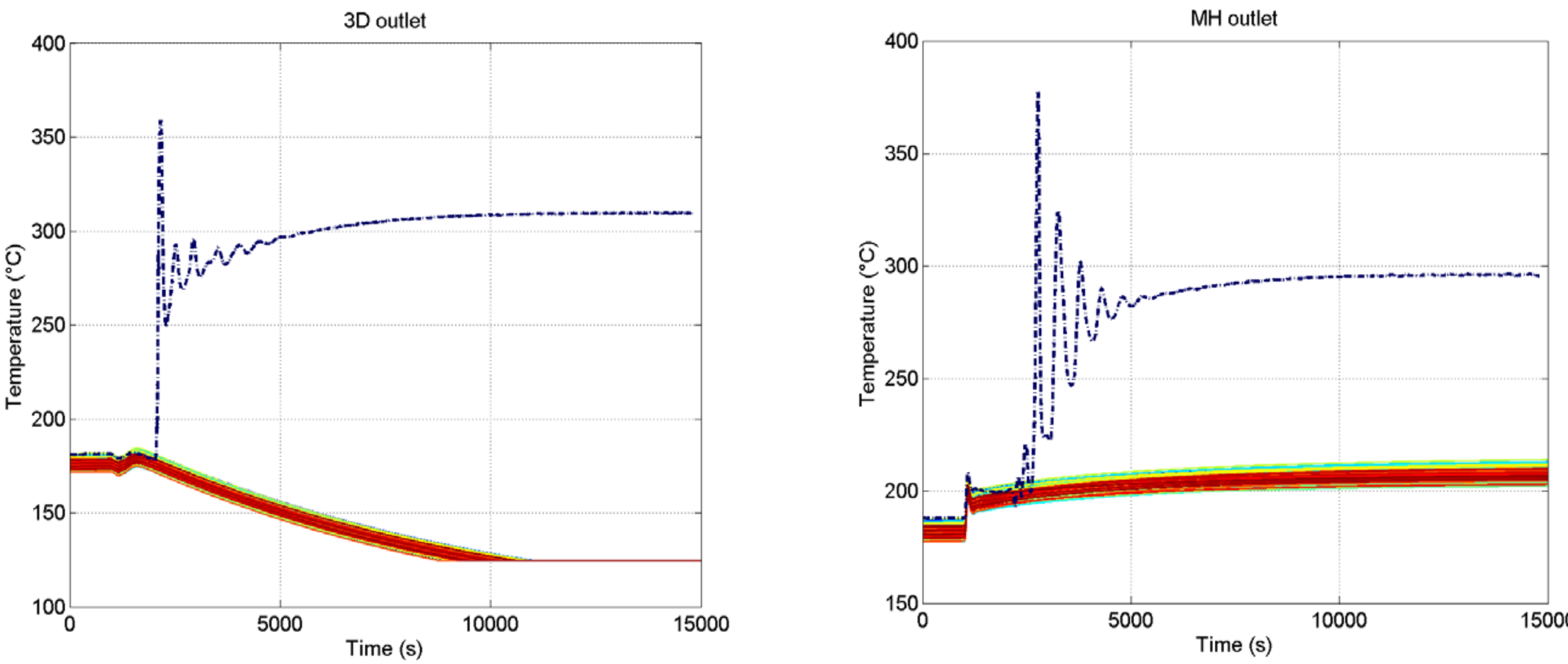






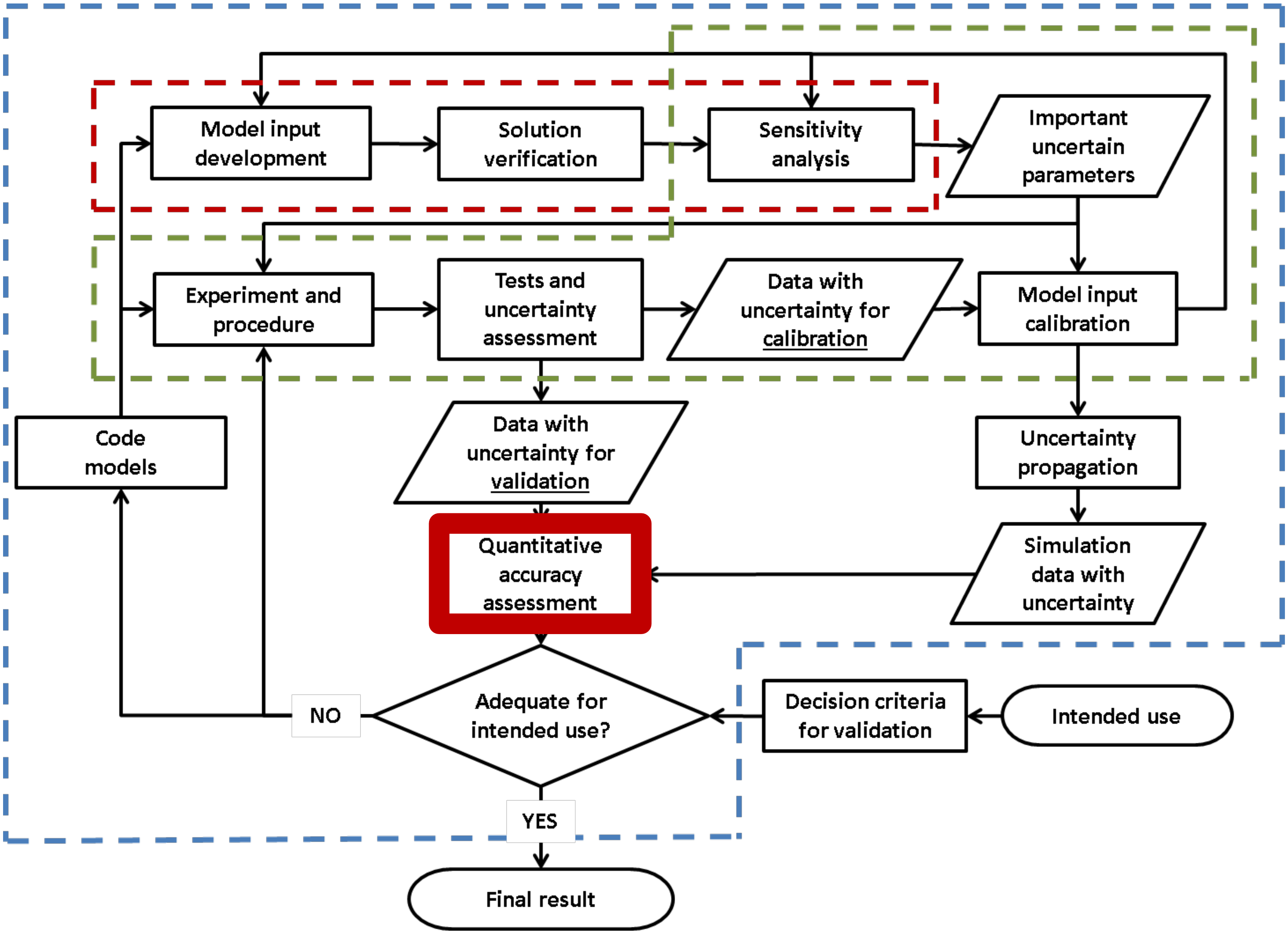
Mass flow rate in simulation does not recover in the 3D leg after reversal

T02.06: LBE temperatures



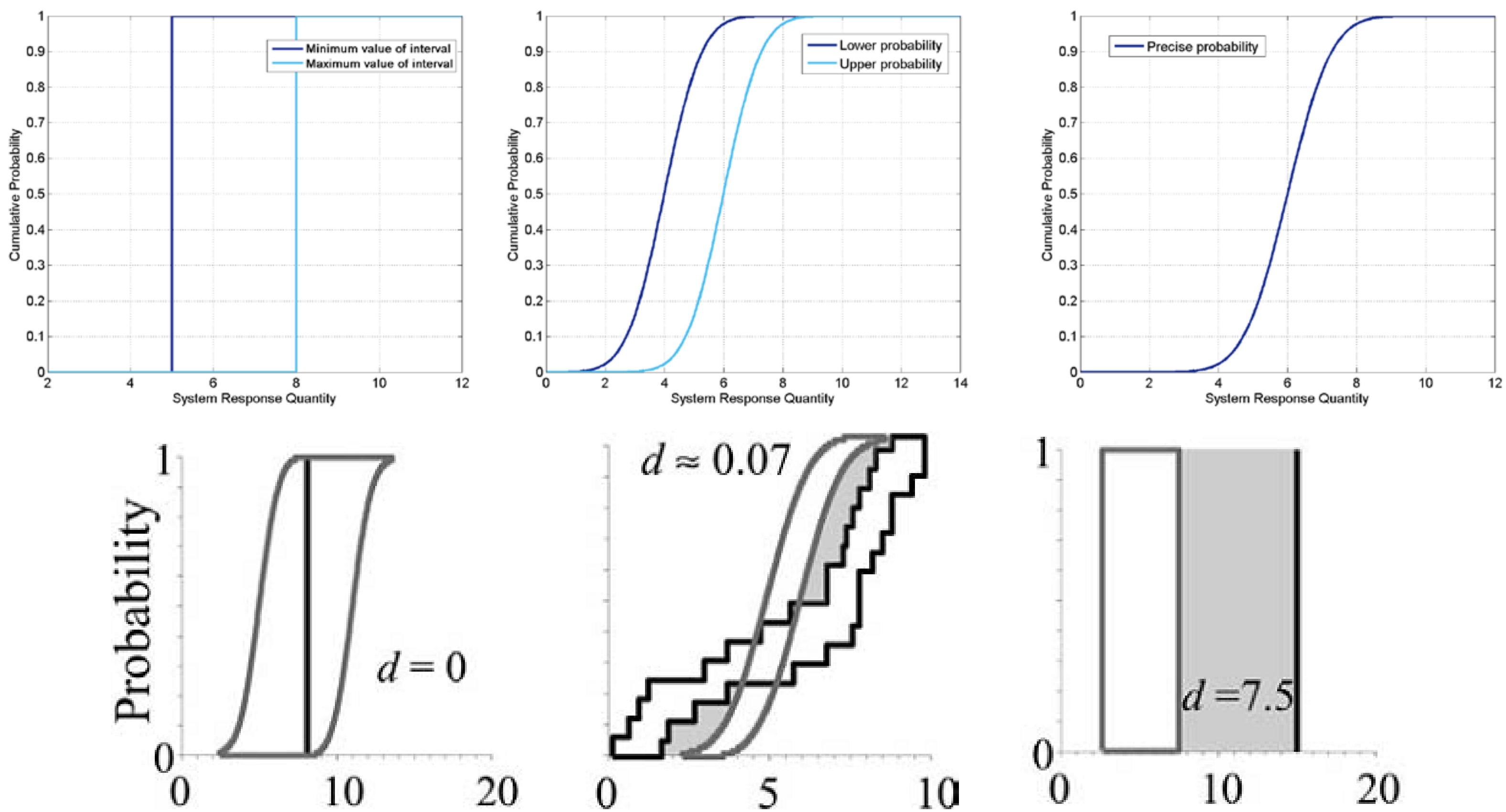
- Nearly stagnant flow in the 3D leg
- The LBE reaches (at ~10000 s) freezing temperature (124.5 °C) due to heat losses in the 3D leg raiser.
- Different transient characteristics in the MH leg.
- These results suggest, that given strong 3D effect influence, a stand-alone STH simulation might predict completely different transient behavior.
- For proper resolution of such cases STH-CFD coupling is necessary.

Approach to Validation



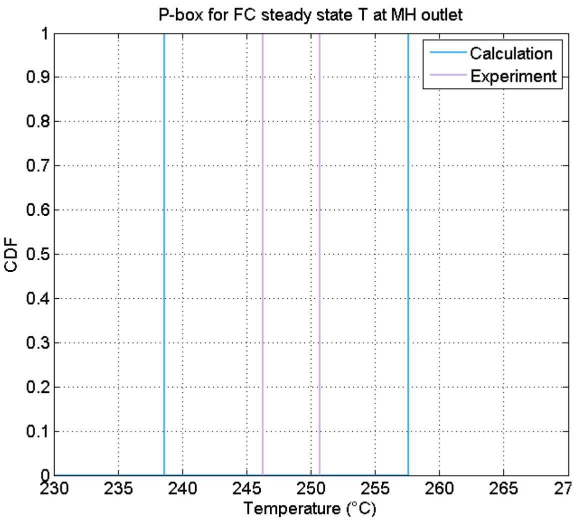
Validation Metric Definition

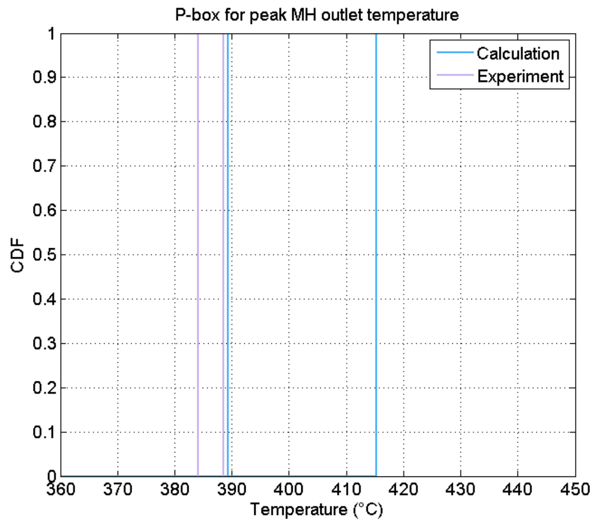
- Validation metric – mathematical operator which measures <u>difference between simulation and experiment</u> considering the uncertainties
  - Validation metric for comparing p-boxes used in this work
  - $d(F, S_n) = \int_{-\infty}^{+\infty} |F(X) - S_n(X)| dx$
  - Can deal with aleatory/epistemic, mixed aleatory-epistemic uncertainties

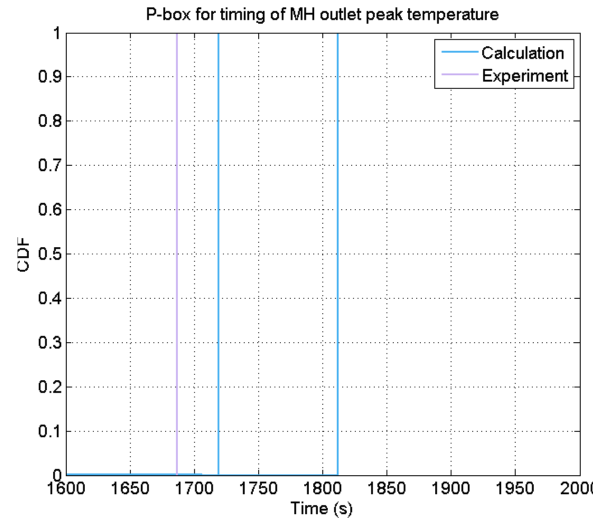


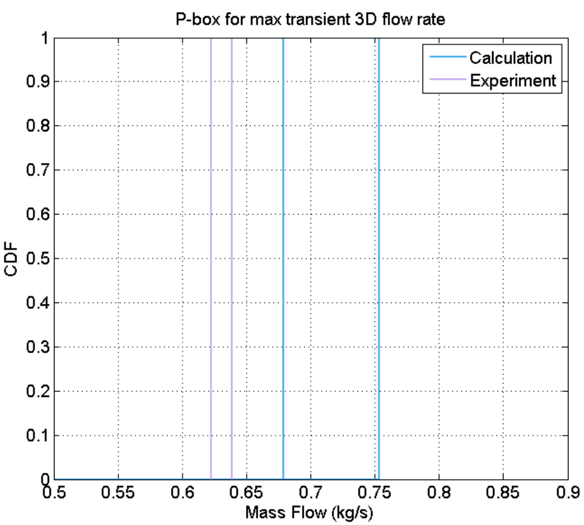
Images adapted from Oberkampf and Roy (2010)

T01.10: Validation Metric Results









System Response Quantity	Validation Metric Result
LBE mass flow rate in 3D leg (FC SS)	0 kg/s
LBE temperature at MH section outlet (FC SS)	0 °C
LBE mass flow rate in HX leg (NC SS)	0 kg/s
LBE mass flow rate in MH leg (NC SS)	0 kg/s
LBE temperature at MH section outlet (NC SS)	0 °C
LBE temperature at HX section outlet (NC SS)	0 °C
Maximum transient LBE mass flow rate in 3D leg	0.06 kg/s
Timing of the maximum transient LBE mass flow rate peak in 3D leg	9 s
Maximum transient LBE temperature at MH outlet	1 °C
Timing of the maximum transient LBE temperature peak at MH outlet	32 s

Zero metric in steady states, non-zero metric in transient

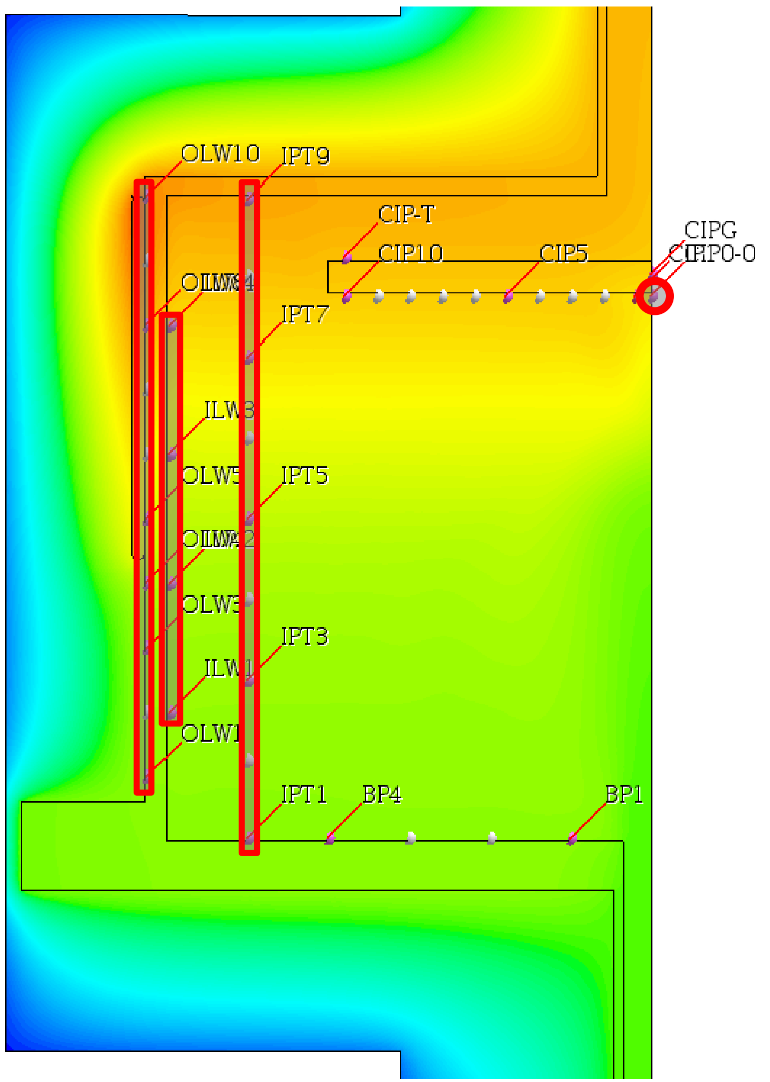
Summary of APROS validation

- An iteration of quantitative validation process is demonstrated
  - Simulation uncertainty is reduced through sensitivity analysis and calibration.
  - Convergence of the iterative validation process is yet to be demonstrated
    - User effect is controlled by applying a uncertainty quantification, multiple iterations of sensitivity analysis and calibration
- The code has noticeable discrepancies in predicting TALL-3D transients
  - Feedback between 3D phenomena in the test section and integral loop behavior causes non-zero validation metric results in transients.

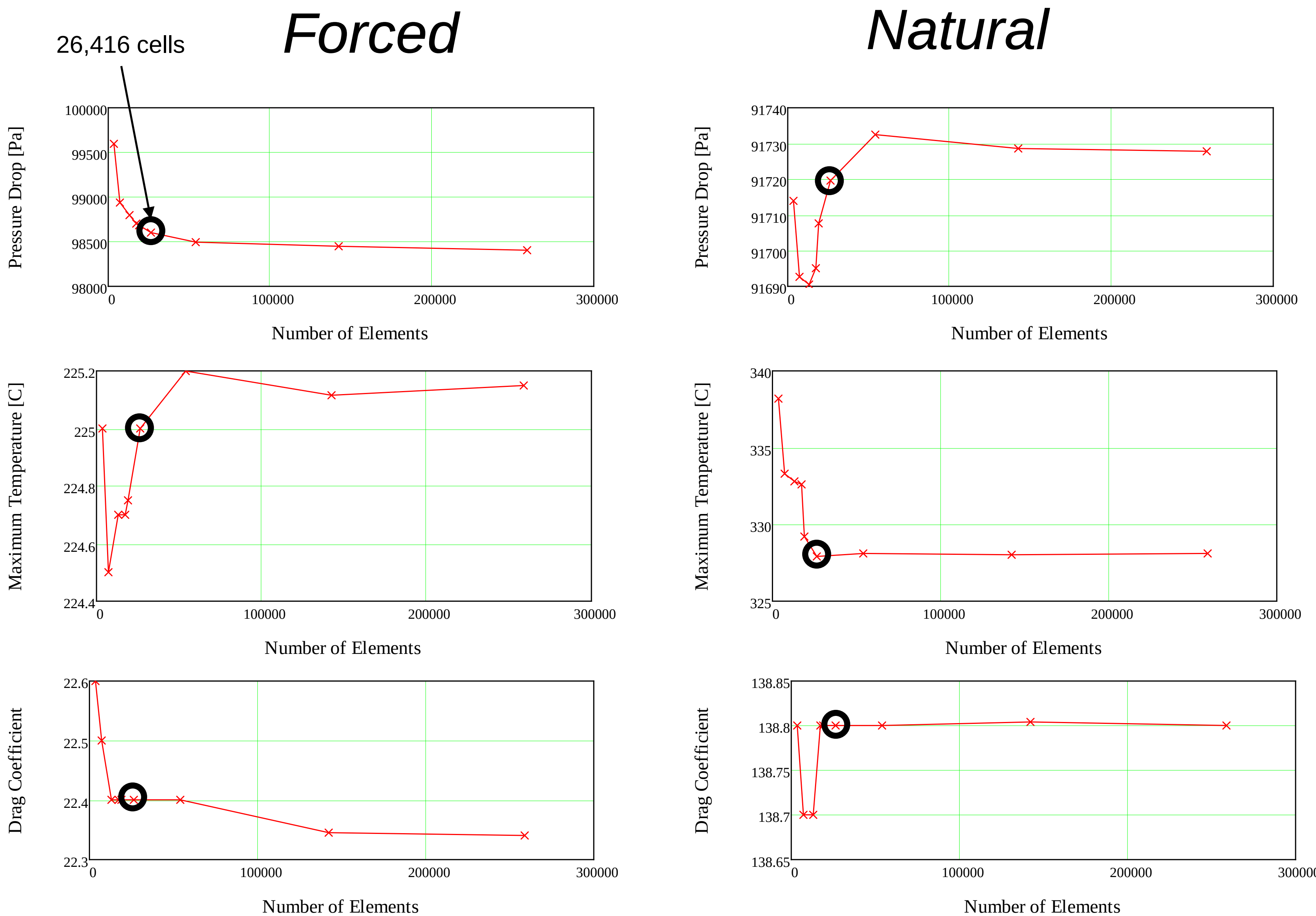
- CFD validation

Definition of SRQs

- Proposed list of SRQs in the 3D test section (CFD and coupled STH-CFD validation):
  - Steady state
    - Heat losses/input
      - ΔT over the 3D test section (TC2_2111 - TC2_1211) or,
      - T_{out} of the 3D test section
    - Stratification/mixing
      - ∇T along the vertical TC tray (IPTs), and/or
      - ∇T along the inner wall of the test section (ILWs), and/or
      - ∇T along the outer wall of the test section (OLWs).
      - NB! Gradient (slope) of a linear approximation can be used as a value here.
    - Heat transfer in solids
      - Temperature in the insulation (4 thermocouples at the outer wall of the insulation).
        - » TC2_TS_INS_01_1530,
        - » TC2_TS_INS_01_1600,
        - » TC2_TS_INS_02_1530,
        - » TC2_TS_INS_02_1600.
    - Max temperature in the pool
      - Value of the T_{max} and the name of the thermocouple measuring it.
    - (Steady state pressure loss)
      - ΔP measured between the inlet and the outlet of the test section.
        - » DP4
      - NB! Pressure drop correction needs still attention.
  - Transient
    - Jet characteristics
      - Timing and value of the T_{max} at the CIP-0-0 thermocouple right before the jet hits the plate (refers to a point in time when stratification is strongest before flow acceleration)
      - NB! Other TC readings can be used depending on the nature of transient (how strong is the jet, circulation etc.)
    - Max temperature in the pool
      - Timing and value of the T_{max} and the name of the TC measuring it.



Verification: Mesh study – bulk



Mesh study – Flow field (2.0 kg/s)

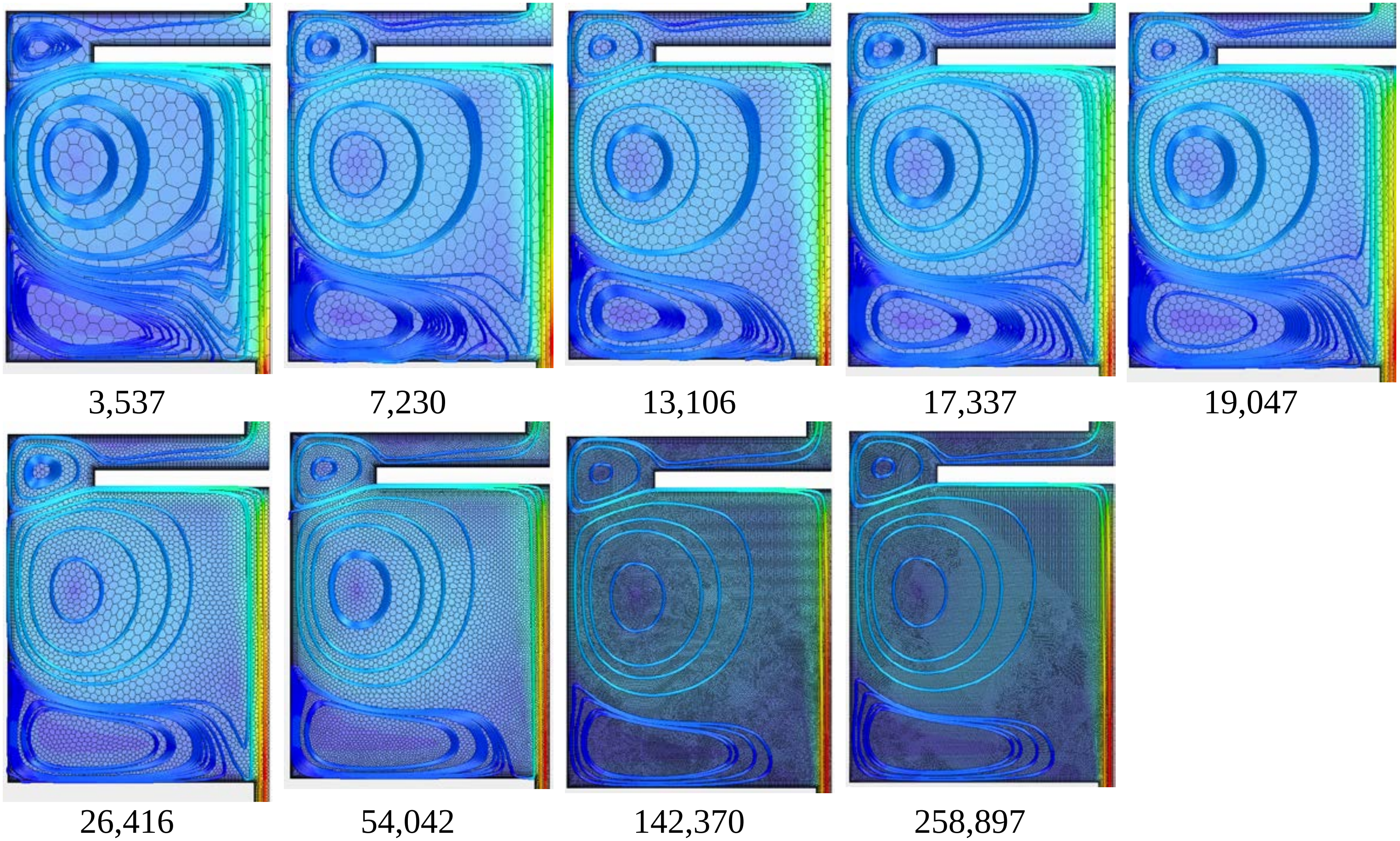


Figure 1: Flow structures as a function of number of elements at 2.0 kg/s.

Iterative SA

- Process
  1. Define initial ranges
     - Conservative, and
     - Based on limited knowledge at the time.
  2. Perform first SA
     - Screening of influential/non-influential parameters is obtained
  3. Revise ranges based on new evidence (e.g. additional experiments)
     - Use calibration to reduce conservative ranges, and
     - Some ranges may be enlarged based on new knowledge available.
  4. Perform second SA
  5. Compare first and second SA results
  6. Iterate until importance of parameters converges
  7. Screening
     - Discard/fix non-influential input parameters

- SA matrix helps to find
  – UIPs with the largest effect (i.e. most influential) in terms of number of affected SRQs
     - Helps to focus on only important input parameters!
  – UIPs that affect a particular SRQ the most (normal Morris plot type info)
     - Tells which UIPs can be calibrated using that SRQ!
  – SRQs that are mostly affected by a particular UIP
     - Tells which SRQ should be used to calibrate this input parameter!

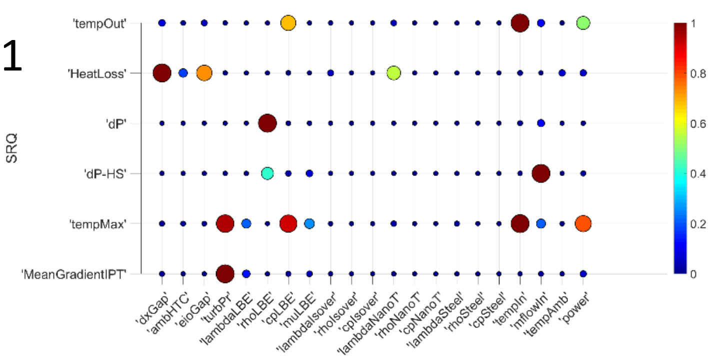
SA – Revised ranges

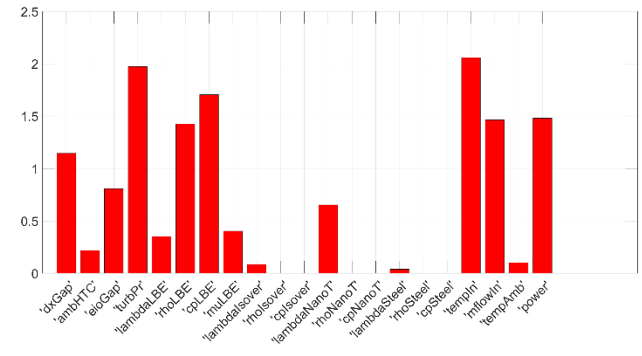
Type		#	Parameter	Range	Change	Unit	Reference
Numerics			mesh Δx	1.0 – 50.0		mm	
Geometry model		0	Gap thickness	0.2 – 5.0	-	mm	Eng. judgement
Geometry model		1	Gasket thickness	0.1 – 2.0	Added	mm	Eng. judgement
Physics model		2	Ambient heat transfer coefficient	5 – 100	Increased	$W/m^2/K$	Eng. toolbox HTC
Physics model		3	Gap surface emissivity (both sides)	0.1-1.0	-	-	Wiki „emissivity“
Physics model		4	Turbulent Prandlt number	0.5-5.0	Reduced	-	Chen et al. (2013)
Material model	LBE	5	Thermal conductivity of LBE	± 15%?		W/m/K	OECD NEA NSC Handbook (2015)
Material model	LBE	6	Density of LBE	± 0.8%		kg/m^3	OECD NEA NSC Handbook (2015)
Material model	LBE	7	Specific heat capacity of LBE	± 7%?		J/kg/K	OECD NEA NSC Handbook (2015)
Material model	LBE	8	Dynamic viscosity of LBE	± 8%?		Pa s	OECD NEA NSC Handbook (2015)
Material model	Isover wool	9	Thermal conductivity of Isover wool	Table ± 20%	Increased	W/m/K	See Appendix
Material model	Isover wool	10	Density of Isover wool	65-90		kg/m^3	See Appendix
Material model	Isover wool	11	Specific heat capacity of Isover wool	800-900		J/kg/K	See Appendix
Material model	Nano T Ultra	12	Thermal conductivity of Nano T Ultra	Table ± 20%	Increased	W/m/K	See Appendix
Material model	Nano T Ultra	13	Density of Nano T Ultra	230 ± 5%		kg/m^3	See Appendix
Material model	Nano T Ultra	14	Specific heat capacity of Nano T Ultra	Correlation ± 15%	Increased	J/kg/K	See Appendix
Material model	Steel	15	Thermal conductivity of steel	Table ± 10%		W/m/K	See Appendix
Material model	Steel	16	Density of steel	8000 ± 5%		kg/m^3	See Appendix
Material model	Steel	17	Specific heat capacity of steel	f(T) ± 5%		J/kg/K	See Appendix
Boundary conditions		18	LBE inlet temperature	± 2		K	Eng. judgement?
Boundary conditions		19	LBE mass flow rate	± 0.05	Increased	kg/s	Eng. Judgement for offset
Boundary conditions		20	Ambient air temperature	20-40		C	Eng. judgement
Boundary conditions		21	Heater power	± 5%		W	Eng. judgement?

SA study summary

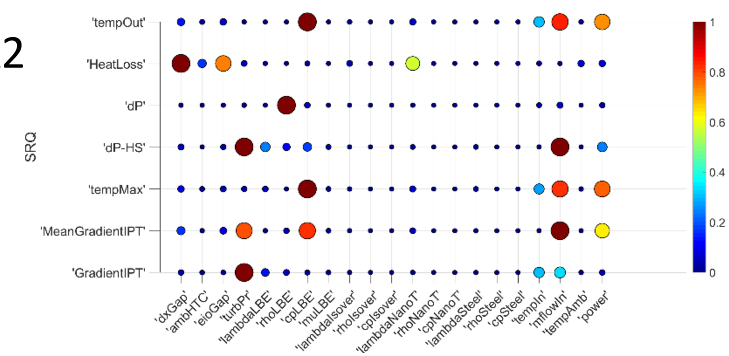
$$Value_i = \sum_{j=1}^{N_{SRQs}} \left(\frac{\mu^*_{UIP_i vsSRQ_j}}{\mu^*_{UIP_{max} vsSRQ_j} - \mu^*_{UIP_{min} vsSRQ_j}} \right), \qquad i = 1, \dots, number\ of\ UIPs$$

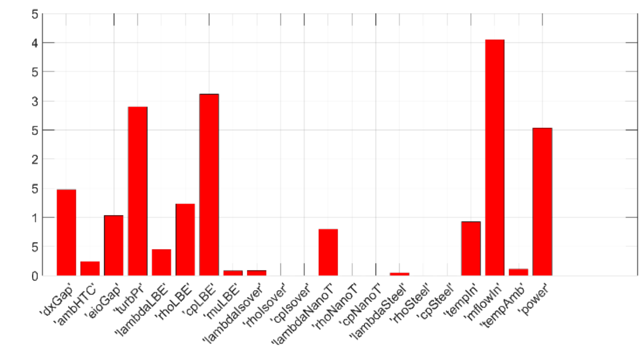
SA1



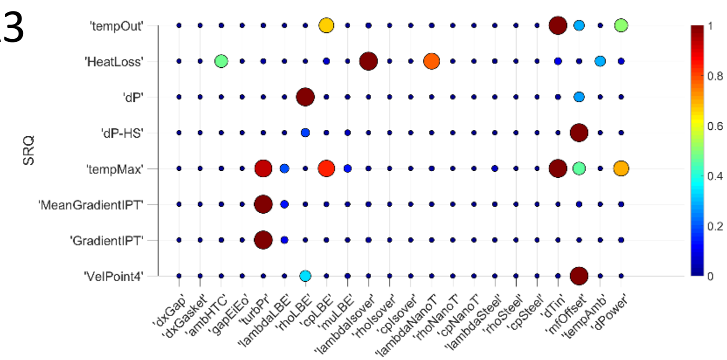


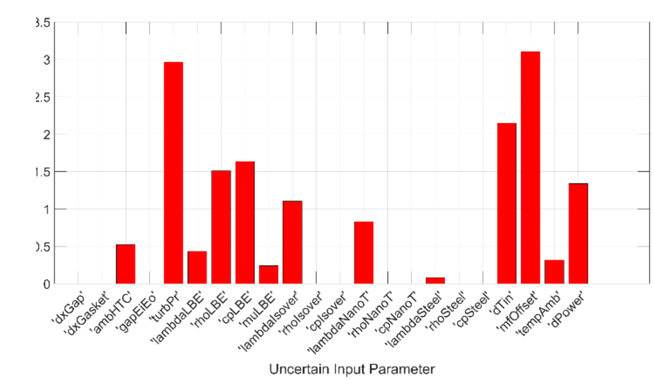
SA2





SA3





- Relative importance of the model parameter turbPr is increased as a result of the calibration process.

Outlook

- General SA, UQ and V&V methodology
  - Use of global optimization tools for “automated” calibration
    - Further reduction of user effect
  - Including spatial grid and time step in sensitivity analysis
    - To compare the magnitude of numerical effects with other sources of uncertainty
  - Resolving correlated (in calibration) input parameters
    - Correlated parameters can not (in principle) be sampled independently
  - Validation metric for combinations of multiple SRQs
    - E.g. are flow rate and temperature predicted correctly simultaneously
  - Demonstrating convergence of the validation process
- A vision for a “one click validation” tool is necessary.

Validation and verification summary:

" This is a process.
It is a process,
it is a process…"

- Brad Pit's character in "Moneyball"