THE DEVELOPMENT OF A REDUCED ORDER MODEL TO PREDICT THE TEMPERATURE DISTRIBUTIONS IN AN INDUSTRIAL OVEN

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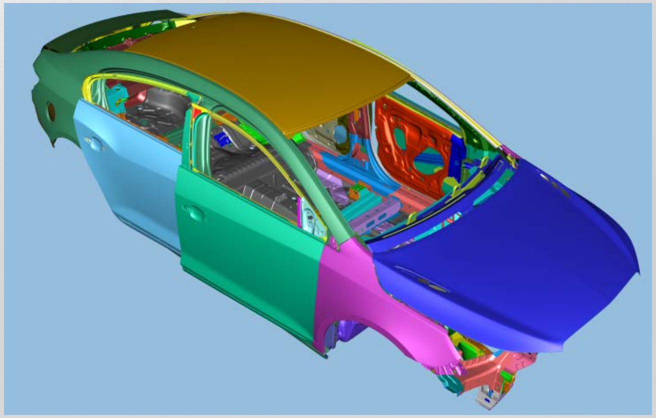
Introduction

- Automotive parts are subjected to various critical heat treatment processes.
- Heat treatment is achieved by using large ovens with radiating walls and nozzles blowing hot air.
- Understanding the temperature history of different components is important for effective heat treatment.
- Due to the complex nature, numerical simulation of the heat treatment processes is carried out.
- Complex geometry and process make it challenging to simulate the heat treatment process within critical time lines of the development process

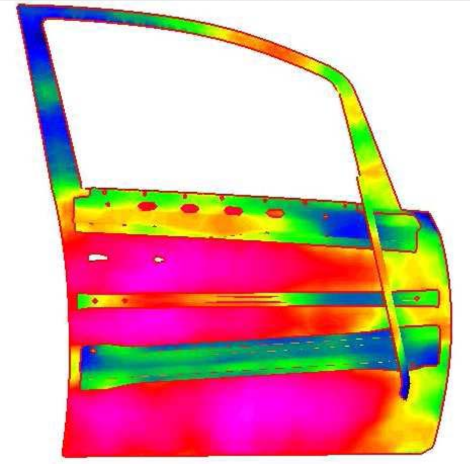


Simulation Approaches

- Present day CFD solvers are capable of simulating fluid-thermal processes. Coupled solution approach using CFD and thermal solvers is also possible.
- Due to complex nature of the process, the physics and geometries involved, simulations are time consuming; sometimes in the order or weeks.
- To access manufacturability of new designs within development timelines, engineers need tools that can evaluate process parameters much faster.
- This study focuses on a Lumped Parameter Model approach to simulate heat treatment processes in an oven.
- Lumped Parameter or Reduced Order models are widely used in various automotive heat transfer applications

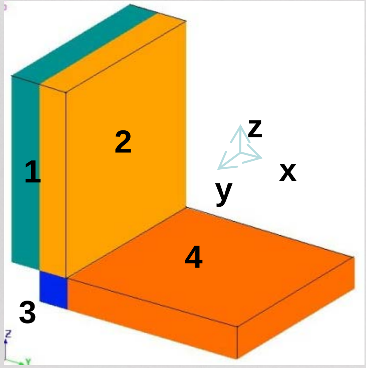
The ROM Concept

- The main idea is to represent components as lumped thermal masses.
- Components and sub-components are lumped together based on uniformity of temperature distribution and size. Smaller components are assumed to be at a fairly constant temperature.
- Based on Biot Number considerations, every partition is assumed to have a single temperature.
- A thermal equilibrium equation is formulated for each lumped thermal mass and a system of ODEs is obtained.
- Such a system of ODEs is solved using generic ODE system solvers like MATLAB.

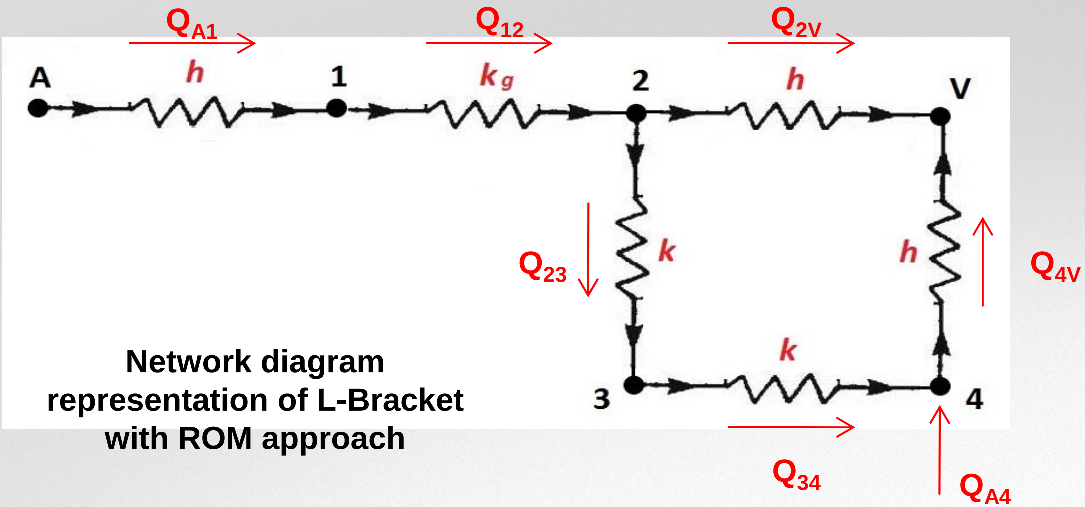


The ROM Concept

- Inter-partition connections are important
- Inter-partition connections are a result of direct contact between partitions and surface contact between partitions due to welds and other types of joints.
- Simple L-bracket system is used to illustrate the concept.



4 partition L-Bracket Thermal System



Network diagram representation of L-Bracket with ROM approach

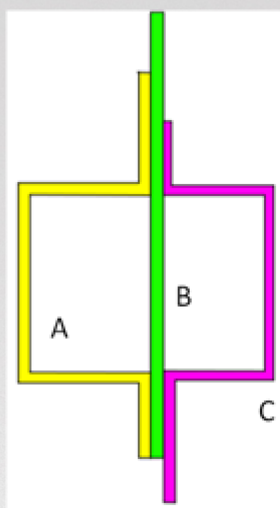
Thermal equilibrium equation (generic form)

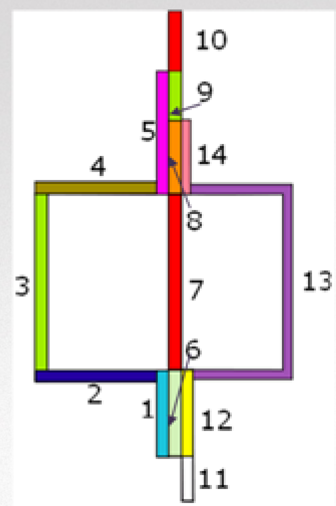
$$mC_p \frac{dT_2}{dt} - Q_{12} + Q_{23} + Q_{2V} = 0$$

ROM Inputs and Partitioning

- Inputs to the ROM code: Heat Transfer Coefficients and Bulk Fluid Temperatures
- Inputs can be obtained from **CFD simulations**, **semi-empirical and semi-numerical calculations**.
- Standard flow configurations (like flow over bluff bodies and flow over flat plates) can be used to generate the input values.
- Partitioning is based on the shape, orientation, connectivity with neighbouring components and exposure to ambient of a component

Representative Geometry



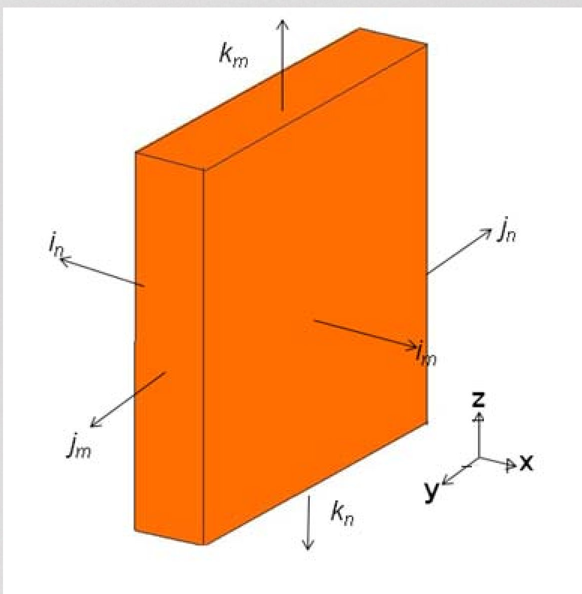


Partitioned Geometry

ROM Formulation

- The spatial locations of the partitions and the potential heat flow paths are resolved in the 3 Cartesian directions

- The spatial resolution and the partition neighbourhood described by the surface normal can be easily represented in a matrix format.



Spatial resolution and normal of a partition

Spatial position and connection information in matrix form

#	i	j	k	i_m	i_n	j_m	j_n	k_m	K_n
1	1	1	2	1	0	0	0	0	0
2	2	1	2	0	1	0	0	0	1
3	2	1	1	1	0	0	0	1	0
4	3	1	1	0	1	0	0	0	0

ROM Formulation

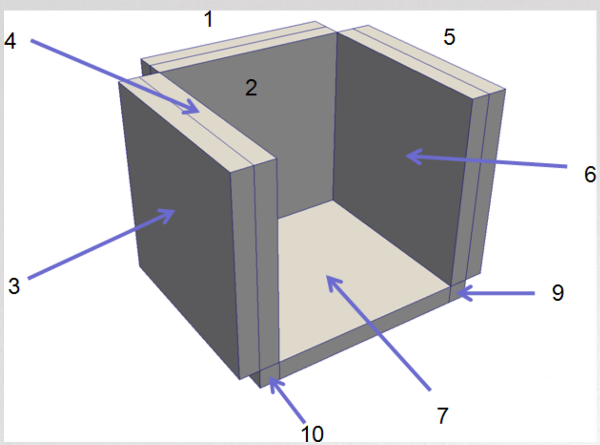
- Heat transfer matrix is defined. This matrix links partitions with the type of heat transfer mechanism between them.

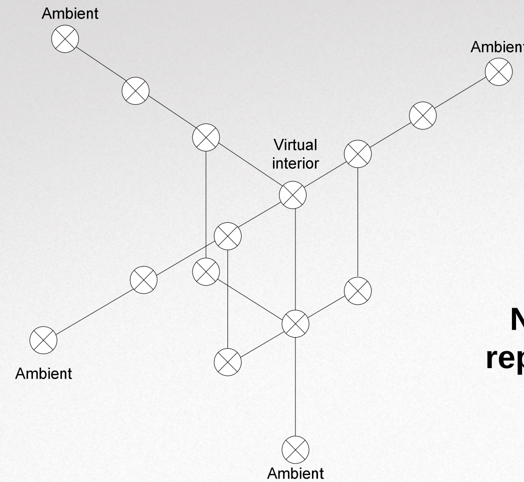
- 1st law of thermodynamics gives the rate of temperature change of a partition,

$$\frac{dT_i}{dt} = \frac{1}{\left(\rho C_p V\right)_i} \sum_{3directions} \left[K(i) \times Conductive - Term + H(i) \times Convective - Term\right]$$

- *K(i)* and *H(i)* are the conduction and convection terms of the heat transfer matrix.

More complex geometry: Cavity



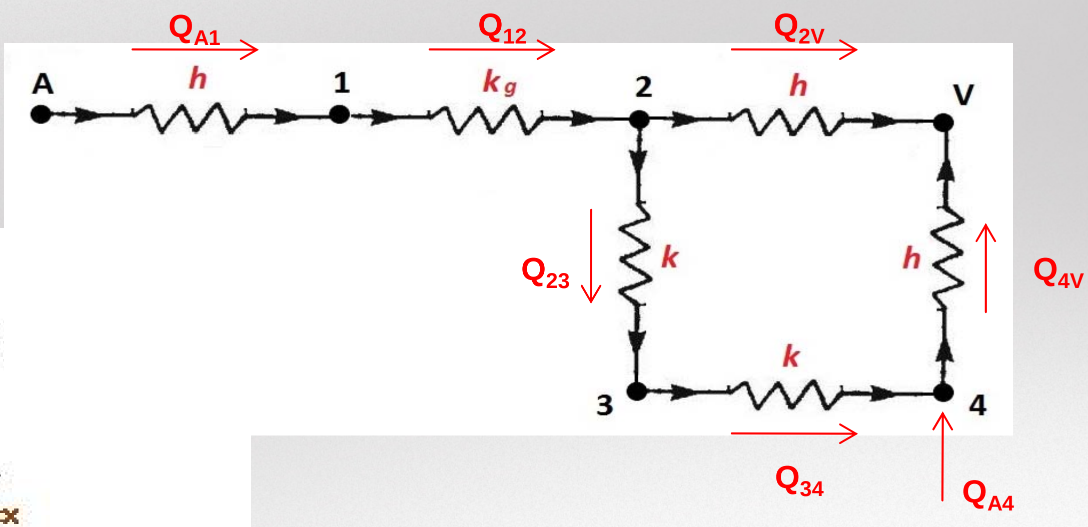


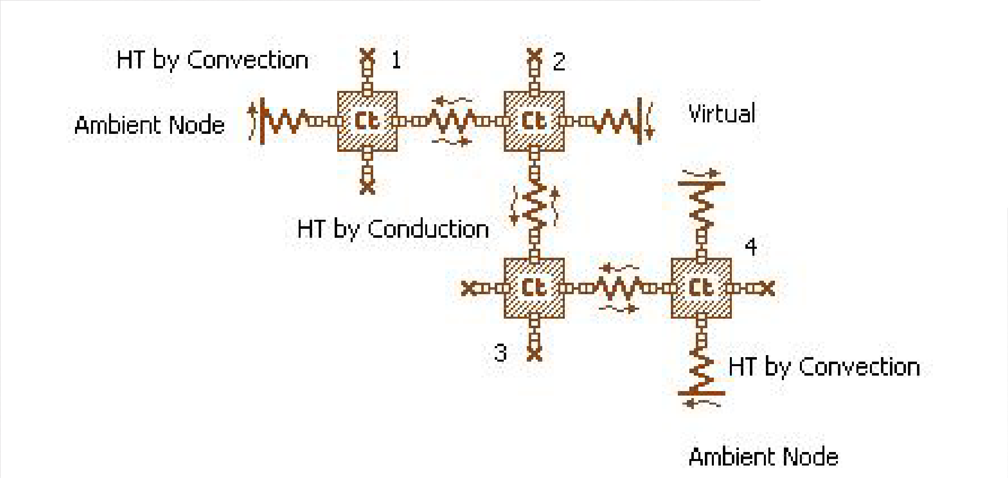
Node network representation of 'cavity'.

Validation

- ROM code predictions were validated with exact solution and industry standard Lumped Parameter Modelling tool AMESim.

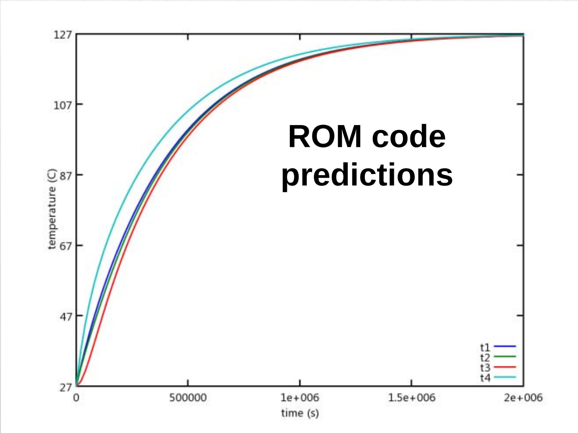
Node network representation and AMESim model of L-bracket

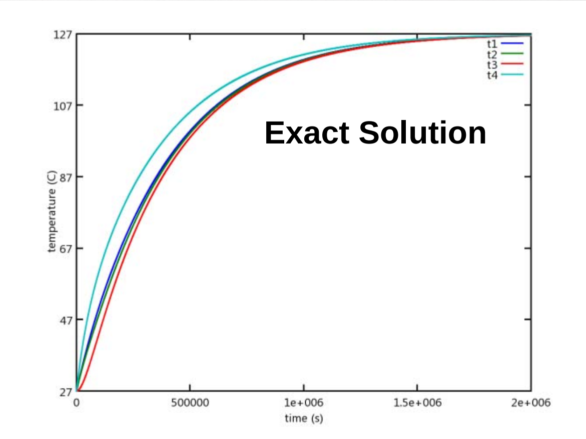




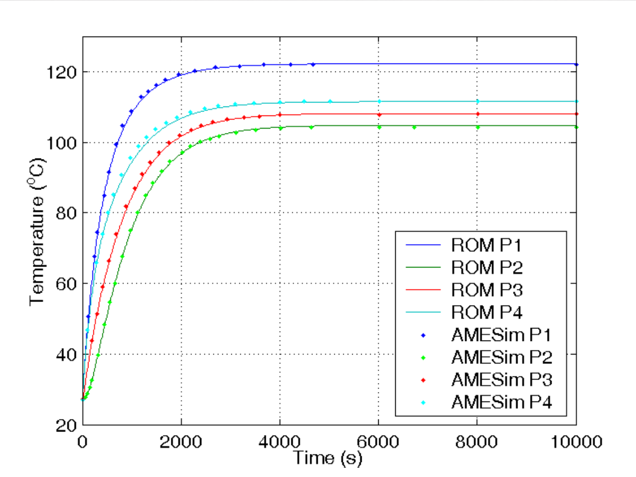
Validation

- Using Exact Solution



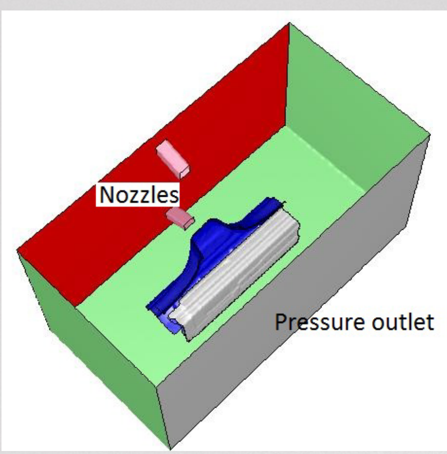


- Using AMESim

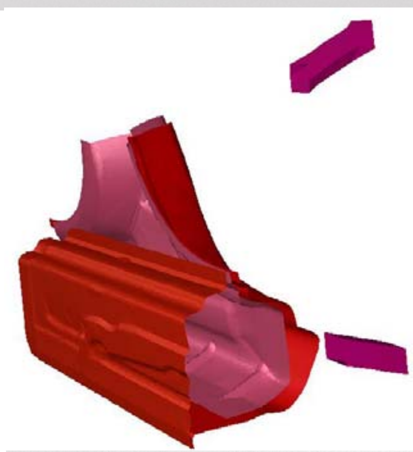


Implementation

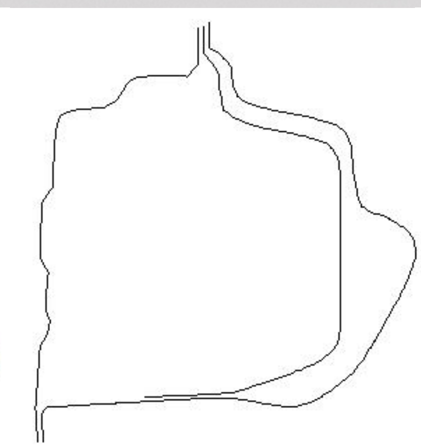
- To test robustness, the code was implemented in a complex, real world situation
- 3D component is represented in a 2D section for ease of implementation
- A tool chain with Paraview as the pre- and post- processor and MatLab as the solver was developed.



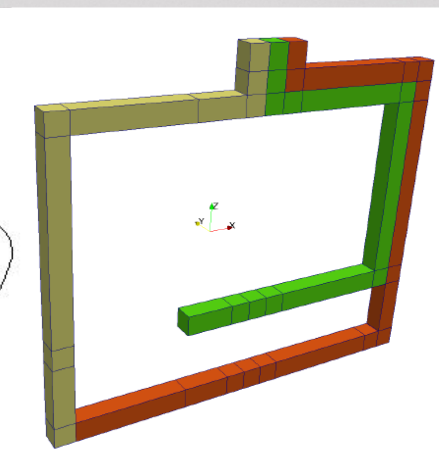
CFD solution domain



Complex geometry



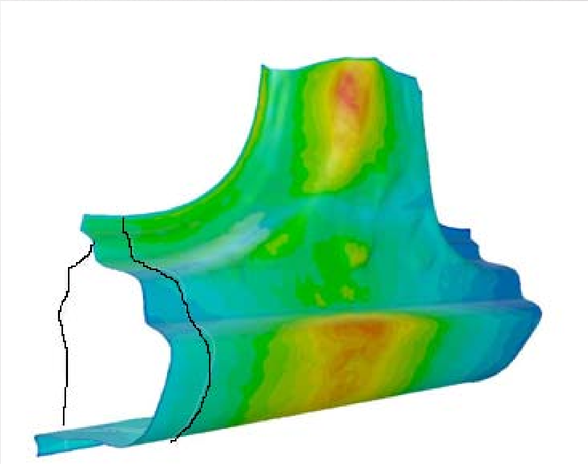
Sectioned geometry for ROM adaptation



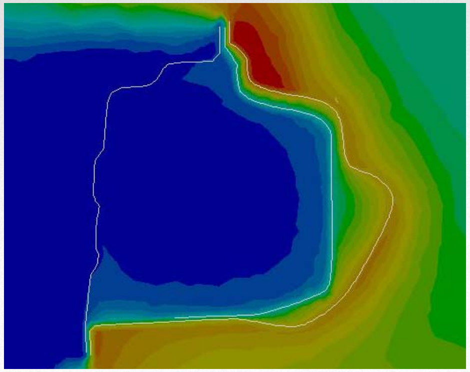
ROM geometry (output of Paraview)

Implementation

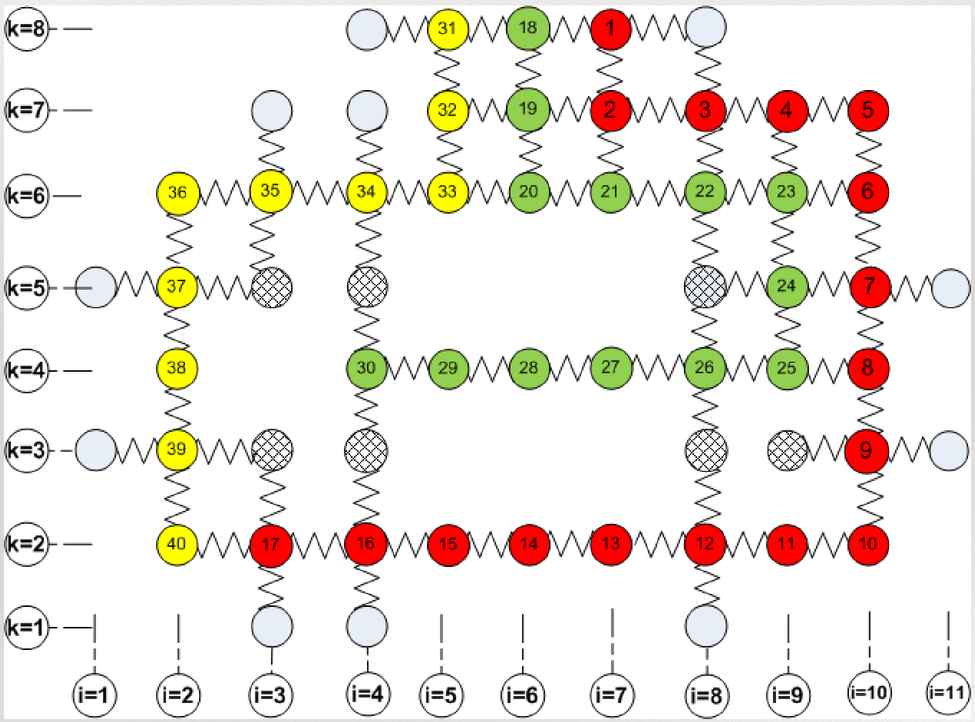
CFD solution used as input to ROM code



HTC Values



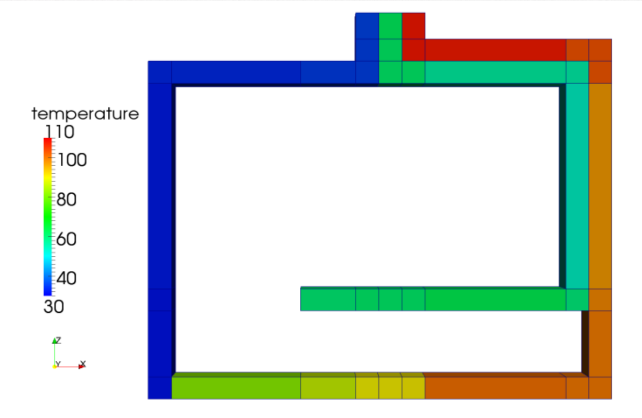
Fluid bulk temperatures



ROM code interpretation of the complex geometry: Network diagram representation

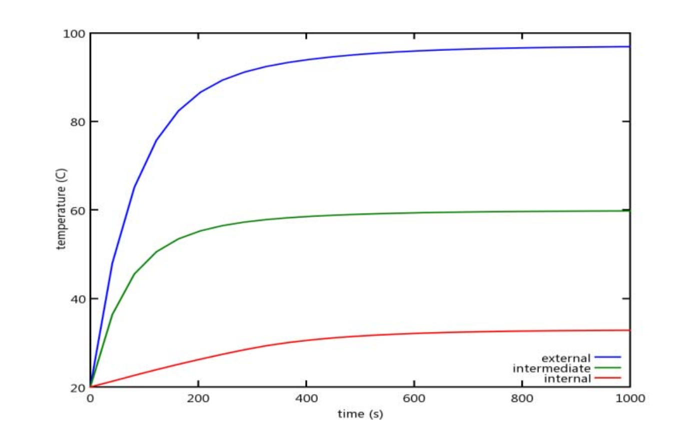
Implementation

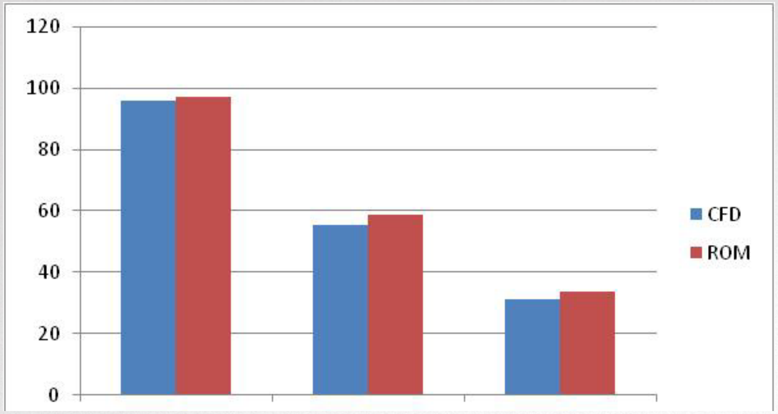
- Results - Temperature distribution (steady state) and Temperature time history



Result representation on ROM geometry

Average temperatures: Partition clusters: Outer, Embedded and Inner





Average temperatures: Partition clusters; CFD vs ROM code

Conclusion

- Heat treatment is a critical process in vehicle manufacturing and it's effectiveness is influenced by component or part design.
- Conventional methods of analysis are very time consuming. .
- Lumped Parameter approach has been chosen as an alternate.
- The complexity of the problem is reduced to achieve solution speed-up.
- Time – accuracy trade-offs as a result of the approximations made in lumped parameter approach are within acceptable limits.
- This work is a proof of concept and still needs further improvements to make it robust for implementation in a real production scenario.

Future Work

- Inclusion of radiation heat transfer mode.
- Automating the process of creating partitions based on some user defined guidelines. Include a CAD modelling tool or FE modelling tool.
- Develop coupling between CFD simulations and ROM code for effective exchange of data.
- Validate ROM code using experimental measurements.