Air Ingress Benchmarking with Computational Fluid Dynamics Analysis

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Air Ingress Accident

- Objectives and Overall Strategy
- Theoretical Study
- Verification of Japan's Experiments
- Verification of NACOK experiments
- Proposals for Real PBMR analysis
- Future work and Conclusions

Characteristics of the Accident

- 3 Stages:
  - Depresurization
  - Pure Diffusion
  - Natural Convection
- Challenging:
  - Natural convection
  - Multi-component Diffusion (air and graphite reactions)
  - Multiple Dynamic Chemical Reactions
  - Complicated geometry

Overall Strategy

1. Theoretical Study (Aided by HEATING-7)
   - To understand the dominant physical processes qualitatively
2. Verification of Japan's Experiments (CFD)
   - Isothermal Experiment: Pure Diffusion
   - Thermal Experiment: Natural Convection
   - Multi-component: Chemical Reaction
3. Verification of Germany's NACOK experiments (CFD)
   - Natural Convection Experiment: Flow in Pebble Bed
   - Chemical Reaction Experiment: Chemical Reactions in Porous Media
4. Model the real MPBR (CFD)

Theoretical Study

- HEATING-7 and MathCad Code
- The gas temperature is assumed to follow the temperature of the solid structures → 5-minute time step
- The reaction rate is proportional to the partial pressure of the oxygen
- There is enough fresh air supply and the inlet air temperature is 20 °C.

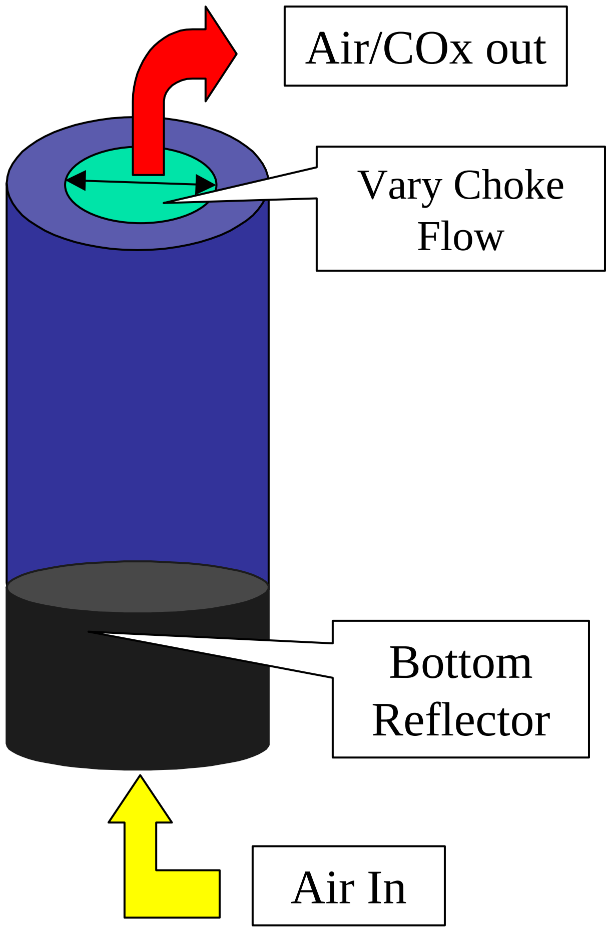


Figure 14: Open-Cylinder Model

Operative Equations

- Chemical Reaction: $C + O_2$ ---> CO_2 (H = -393.51 KJ/mole)
- $R=K_1*\exp(-E_1/T)(PO_2/20900)$
  - When T<1273K: $K_1=0.2475$, $E_1=5710$;
  - When 1273K<T<2073K, $K_1=0.0156$, $E_1=2260$;
- Buoyancy: $P_b = (\overline{\rho_c} - \overline{\rho_h})gh$
- Pressure drop in Pebble Bed [3]

$$\Delta p = \psi \frac{H}{d} \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho}{2} u^2 \qquad \psi = \frac{320}{\frac{\mathrm{Re}}{1-\varepsilon}} + \frac{6}{(\frac{\mathrm{Re}}{1-\varepsilon})^{0.1}}$$

Theoretical Study (Cont.)

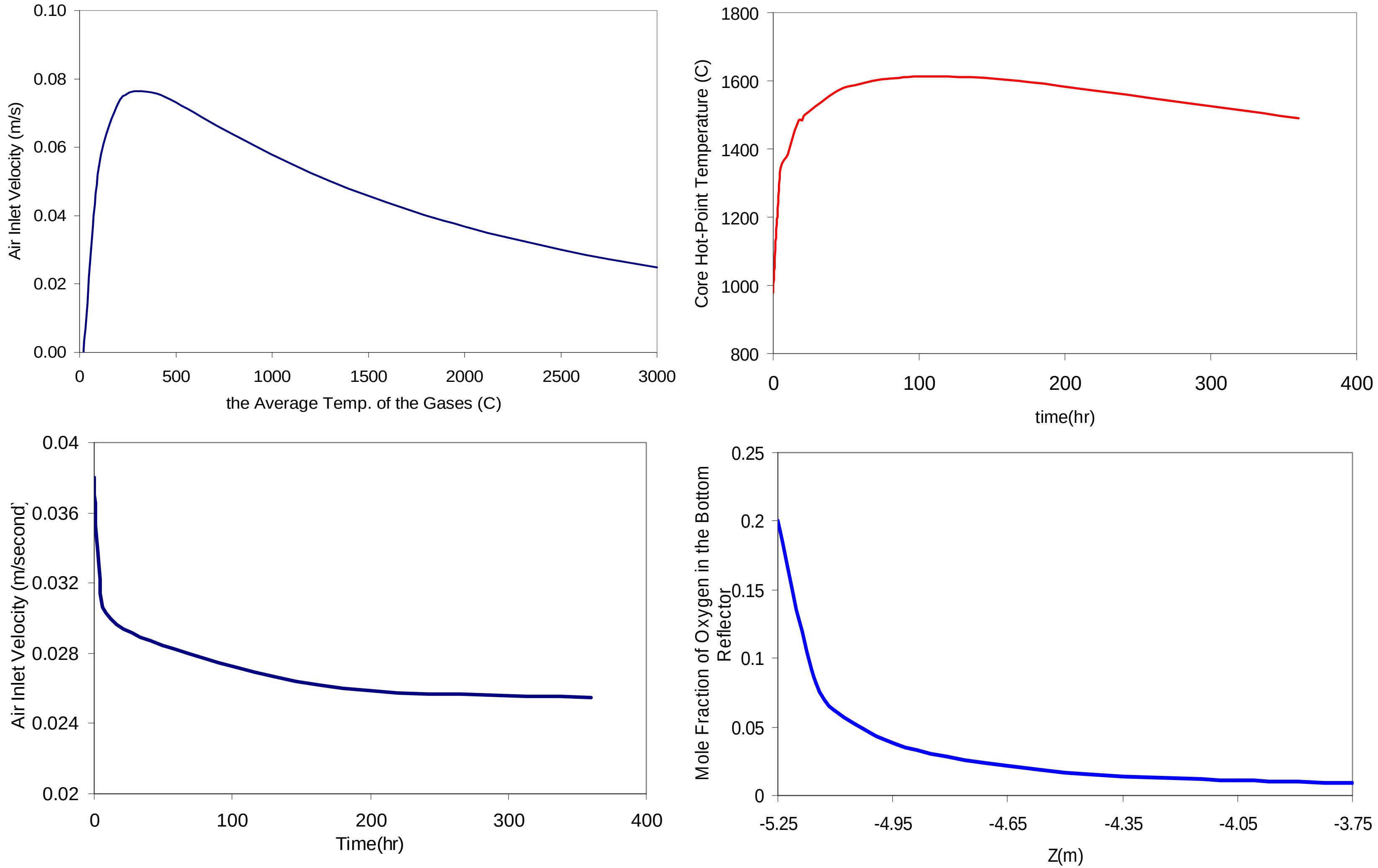


Figure 15: Results of the Open-Cylinder Model

Theoretical Study (Cont.)

PBR_SIM Results with Chemical Reaction (By Hee Cheon No)

- Considering only exothermic C + O_2 reactions
- Without chemical reaction - peak temperature 1560 C @ 80 hrs;With chemical reaction - peak temperature 1617 C @ 92 hrs
- Most of the chemical reaction occurs in the lower reflector
- As temperatures increase chemical reactions change; As a function of height, chemical reactions change
- Surface diffusion of Oxygen is important in chemical reactions

Theoretical Study (Cont.)

Preliminary Conclusions for an open cylinder of pebbles:

- Inlet air velocity will not exceed 0.08 m/s.
  - Viscosity increases with the increase of the temperature
  - Pressure loss in the pebble region increases rapidly with the increase of the velocity
- The negative feedback: the Air inlet velocity is not always increase when the core is heated.
- No meltdown for the core peak temperature is lower than 1650 C even with the conservative assumptions

Verification of JAERI's Experiments

- Solver used: FLUENT6.0
- GAMBIT for the mesh generation
- Subroutines(UDF) for special problems

JAERI Experiments

- Diffusion - Isothermal
- Natural Circulation - Thermal
- Thermal with graphite and air - Multi-component

Experimental Apparatus - Japanese

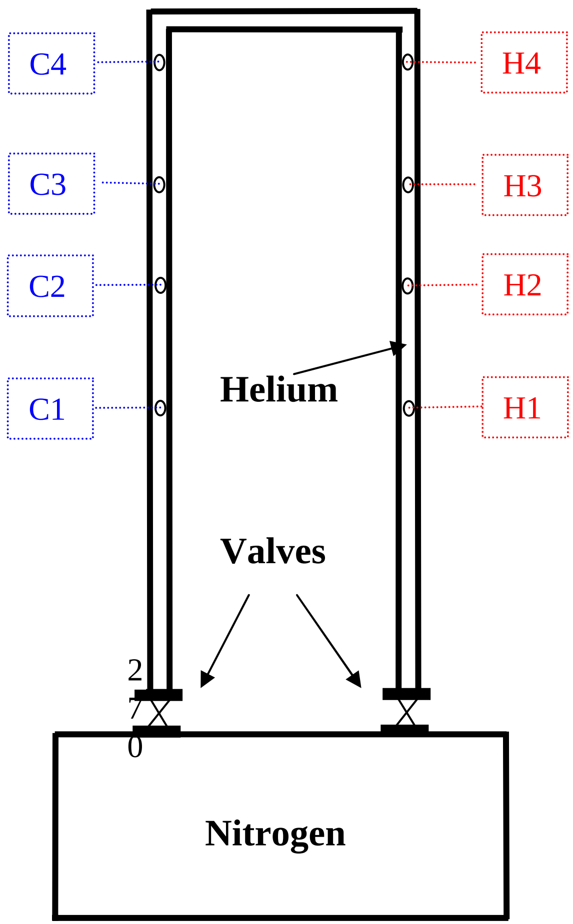


Figure 16: Apparatus for Isothermal and Non-Isothermal experiments

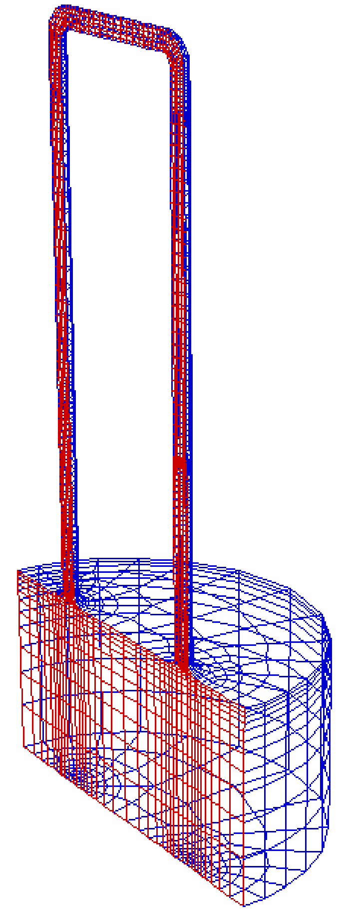


Figure 17: Structured mesh

Isothermal Experiment

- Pure Helium in top pipe, pure Nitrogen in the bottom tank
- Only Diffusion Process and no Natural convection

$$D_{A-B} = \frac{10^{-7} T^{1.75} [(M_A + M_B) / M_A M_B]}{P(\Sigma_A^{1/3} + \Sigma_B^{1/3})^2}$$

- Taylor Expansion to convert diffusion coefficients into the following form:

$$D_{A-B} \approx A_0 + A_1 T^1 + A_2 T^2 + A_3 T^3 + A_4 T^4$$

Isothermal Experiment

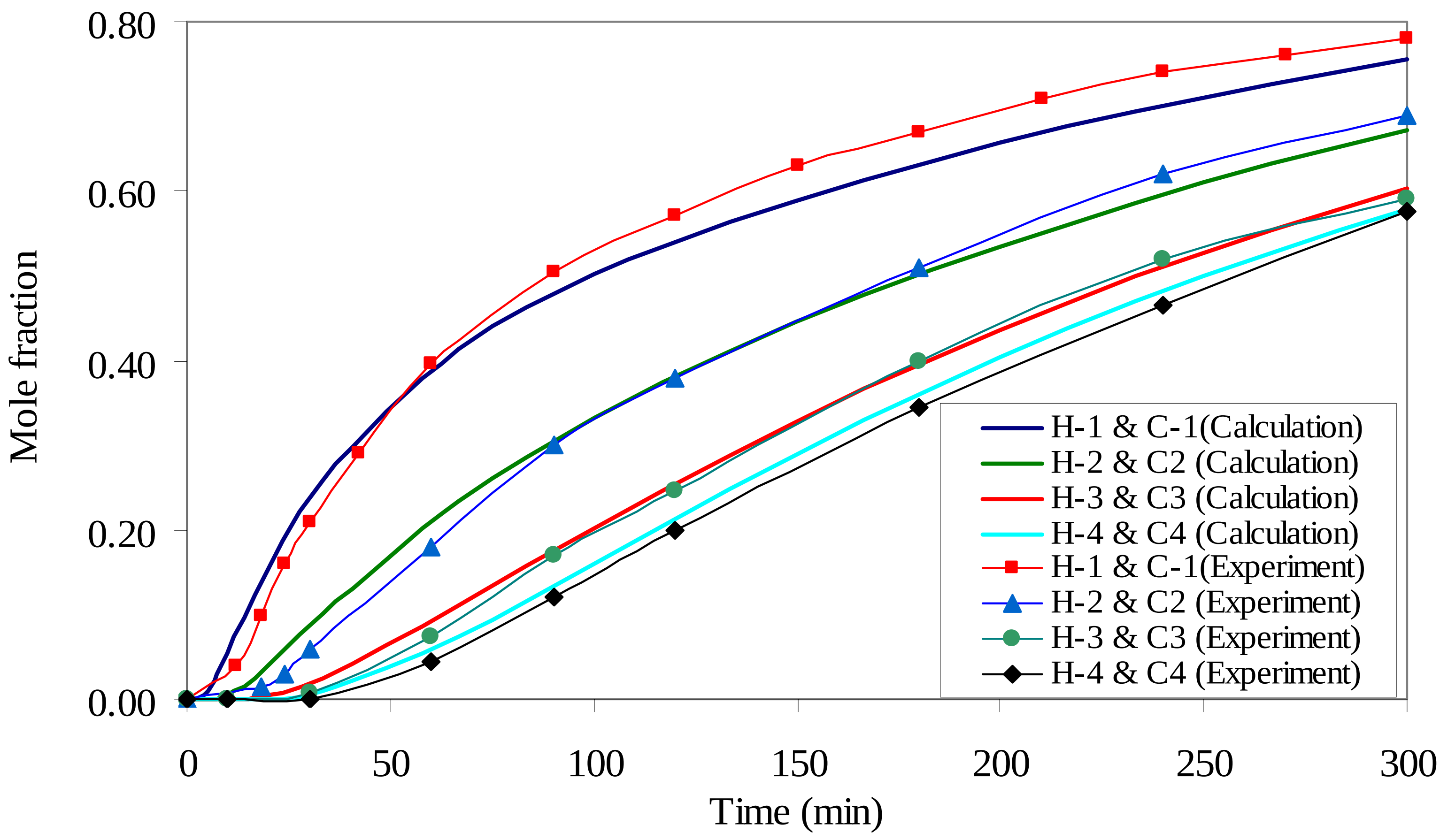


Figure 18: Mole fraction of N_2 for the isothermal experiment

Thermal Experiment

- Pure Helium in top pipe, pure Nitrogen in the bottom tank
- N_2 Mole fractions are monitored in 8 points
- Hot leg heated
- Diffusion Coefficients as a function of temperature

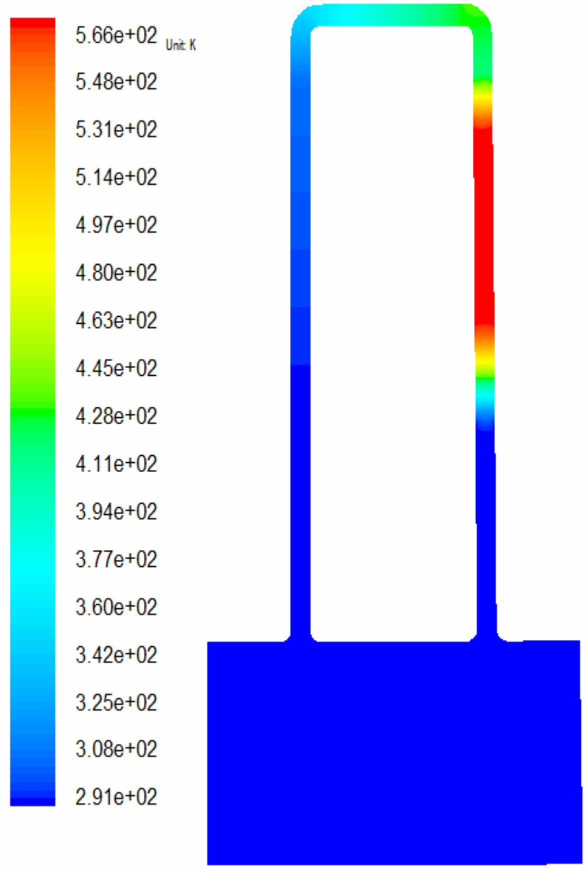


Figure 19: The contour of the temperature bound4ary condition

Additional Dynamic Force Analysis

- Diffusion
- Buoyancy
- Pressure drop
- Natural Circulation

CFD Initial Conditions and Assumptions

- Subroutine to define the wall temperature distribution and the initial gas mole fraction
- Structured Mesh
- Grid Adaptation
- Time step times: from 0.0001 second to 3 seconds

Thermal Experiment

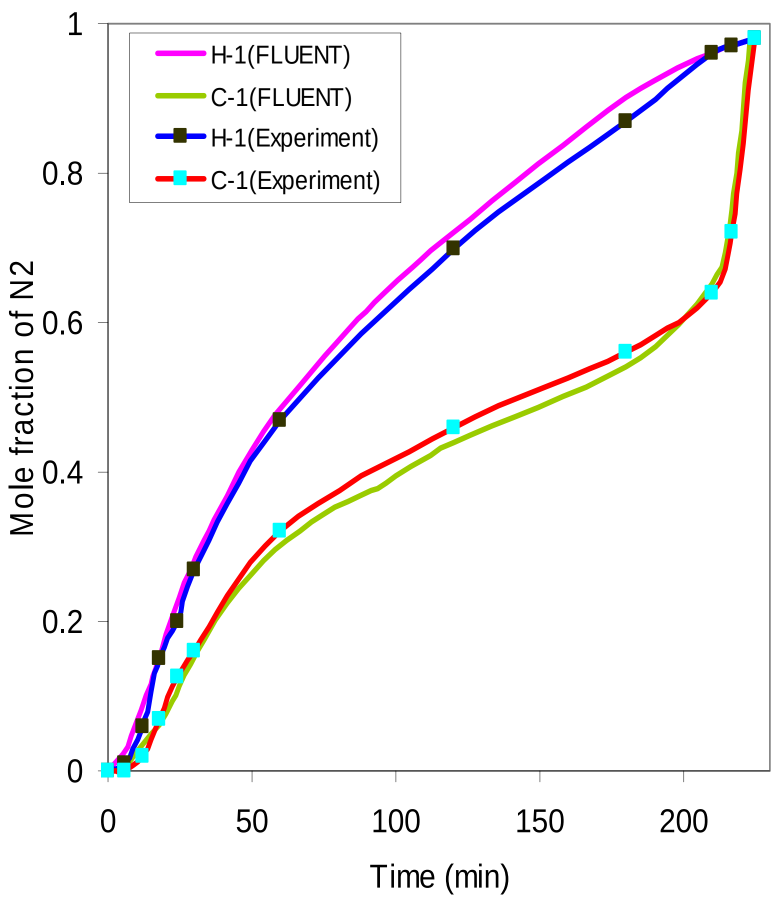


Figure 20: Comparison of mole fraction of N_2 at Positions H-1 and C-1

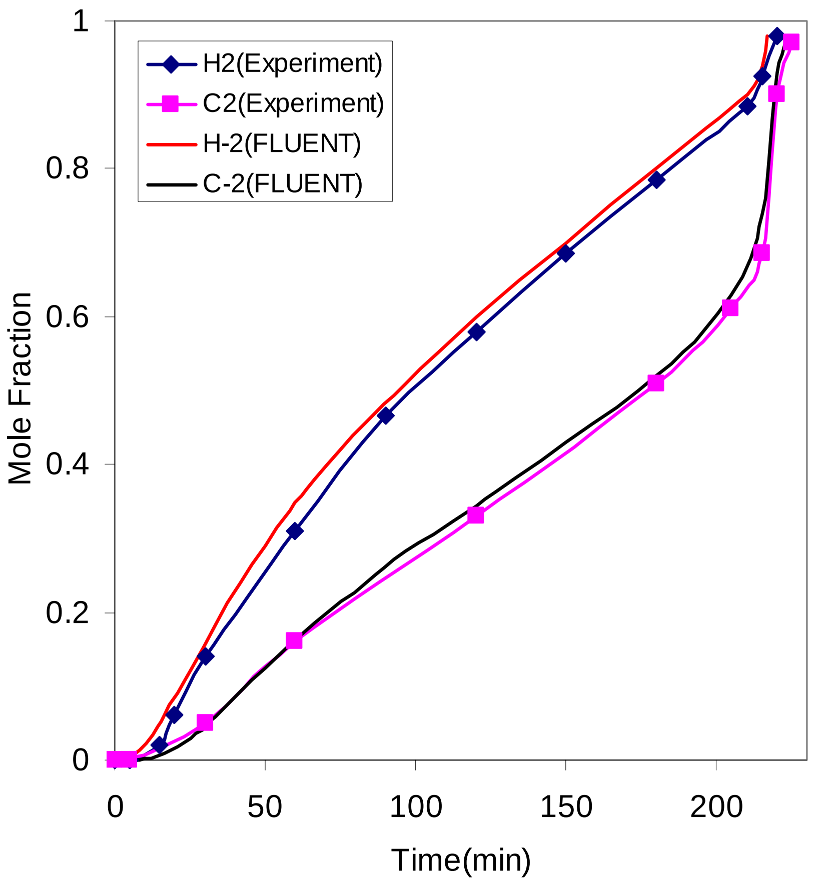


Figure 21: Comparison of mole fraction of N_2 at Positions H-2 and C-2

Thermal Experiment (Cont.)

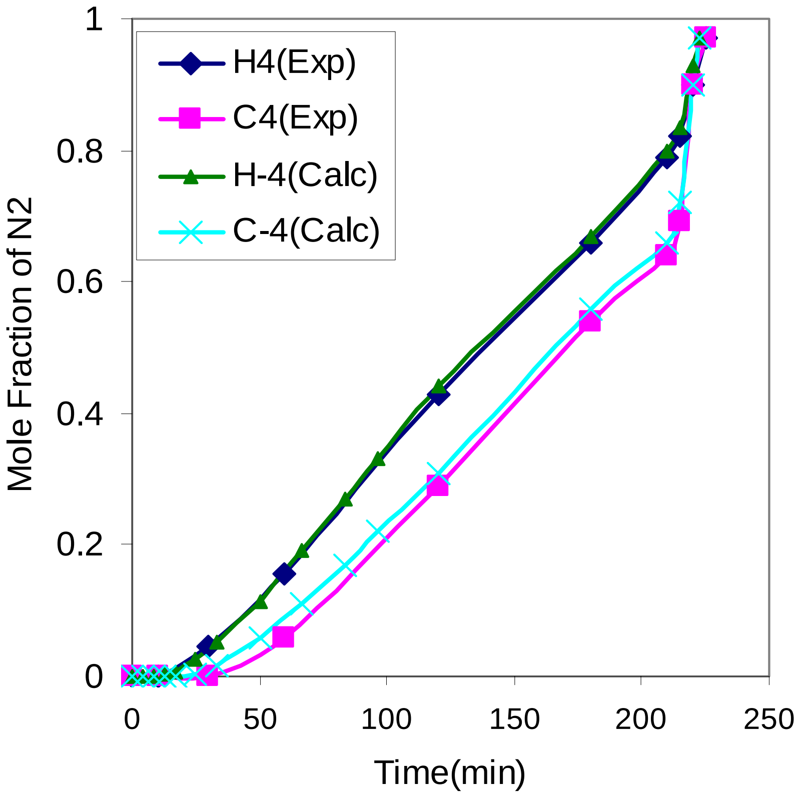


Figure 22: Comparison of mole fraction of N_2 at Positions H-1 and C-1

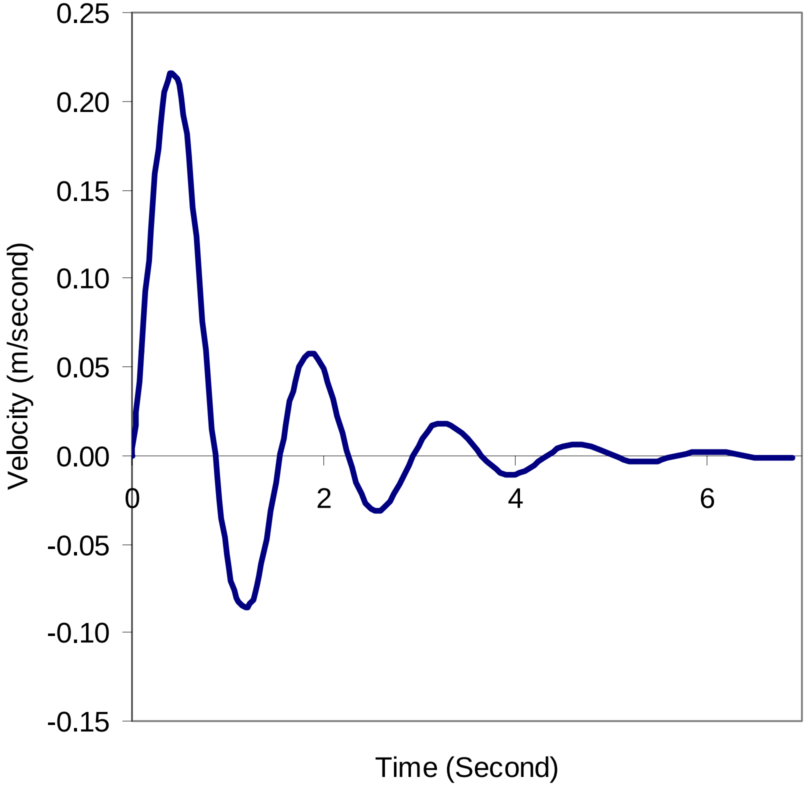


Figure 23: The vibration after the opening of the valves.

Thermal Experiment (Cont.)

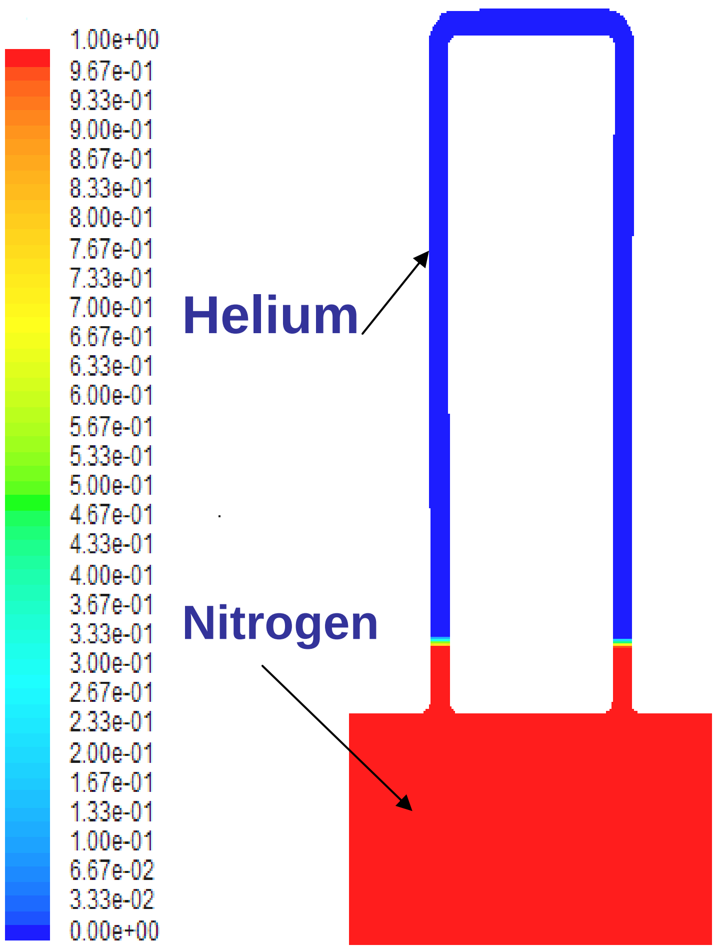


Figure 24: Nitrogen Contour:
T=0.00 min

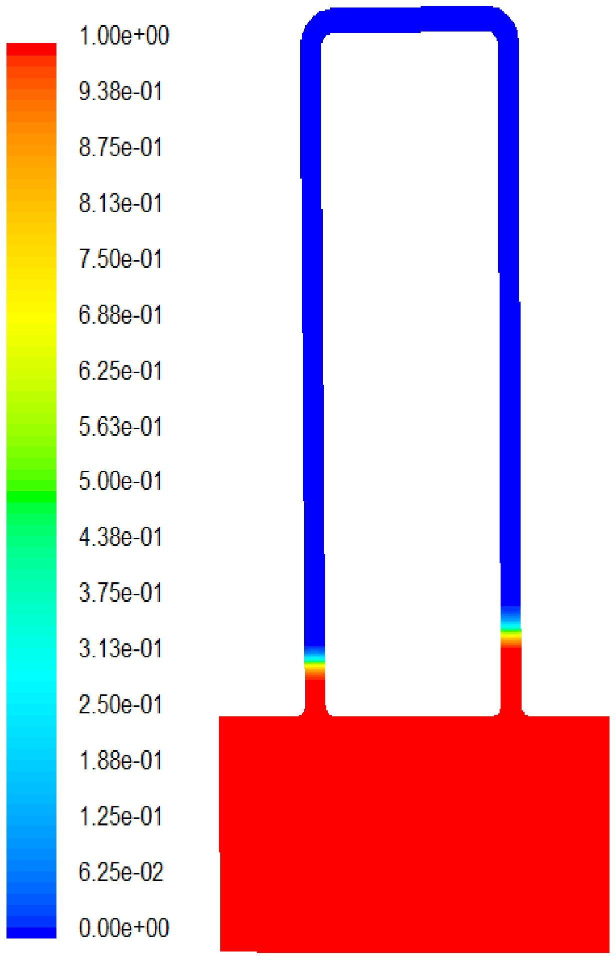


Figure 25: Nitrogen Contour:
T=1.60 min

Thermal Experiment (Cont.)

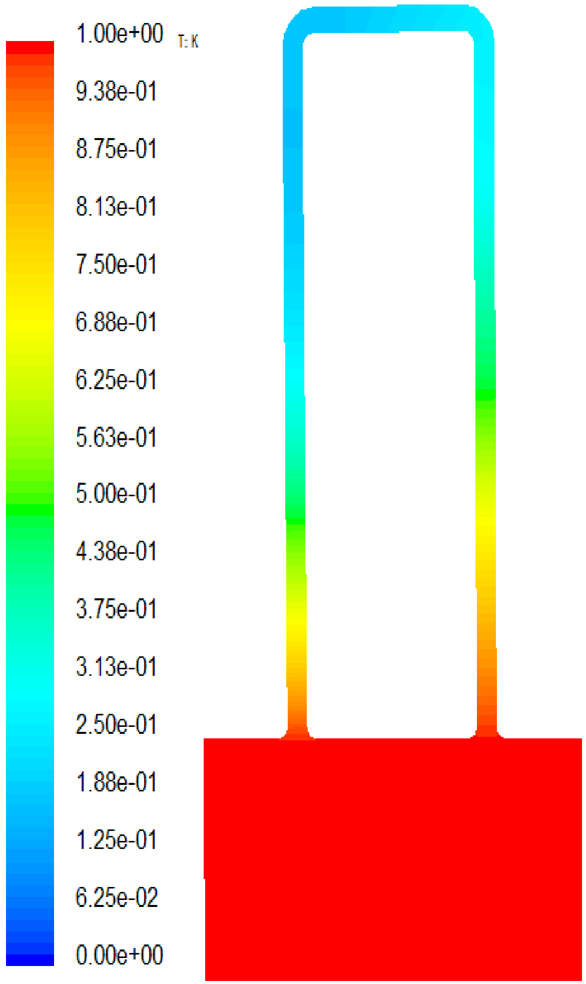


Figure 26: Nitrogen Contour: T=75.50 min

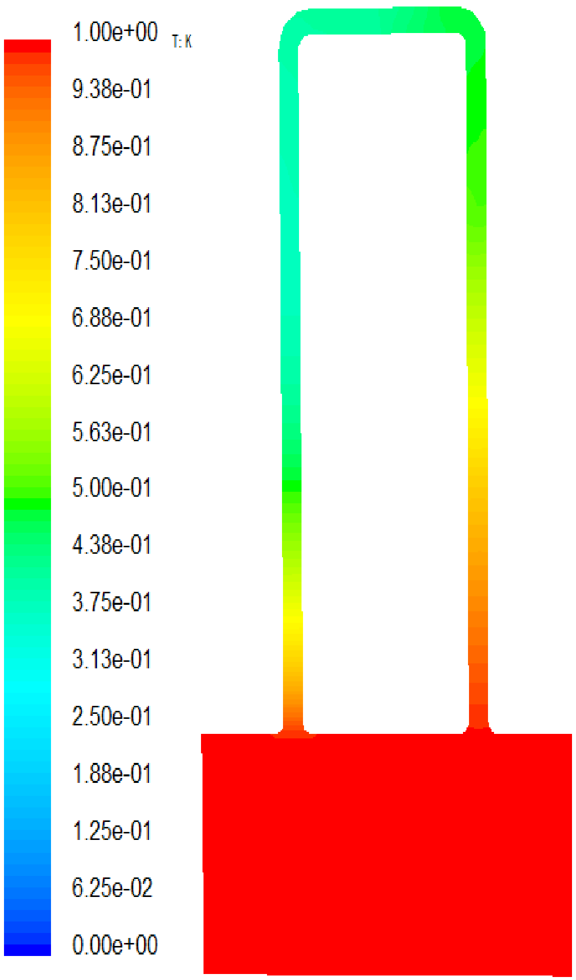


Figure 27: Nitrogen Contour: T=123.00 min

Thermal Experiment (Cont.)

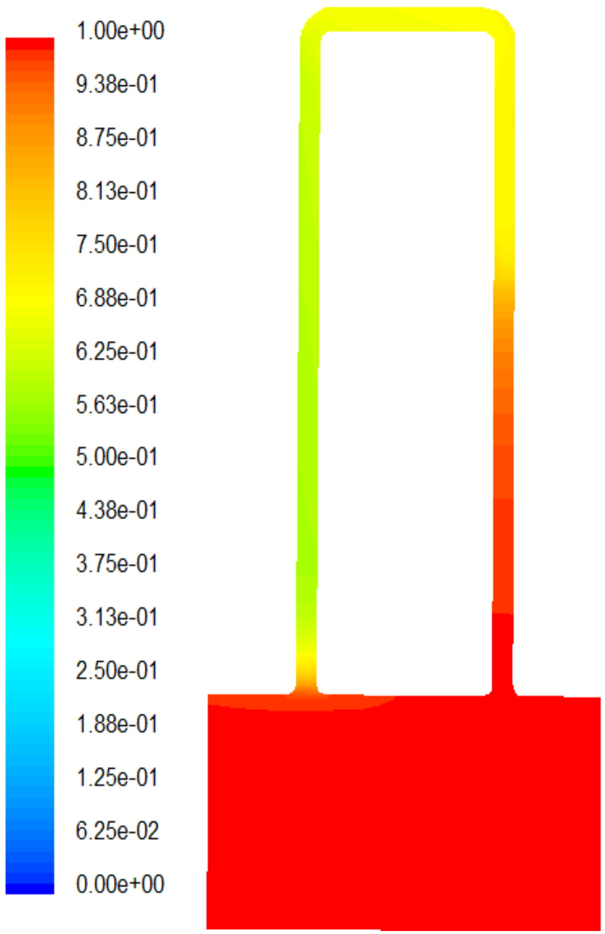


Figure 28: Nitrogen Contour: T=220.43 min

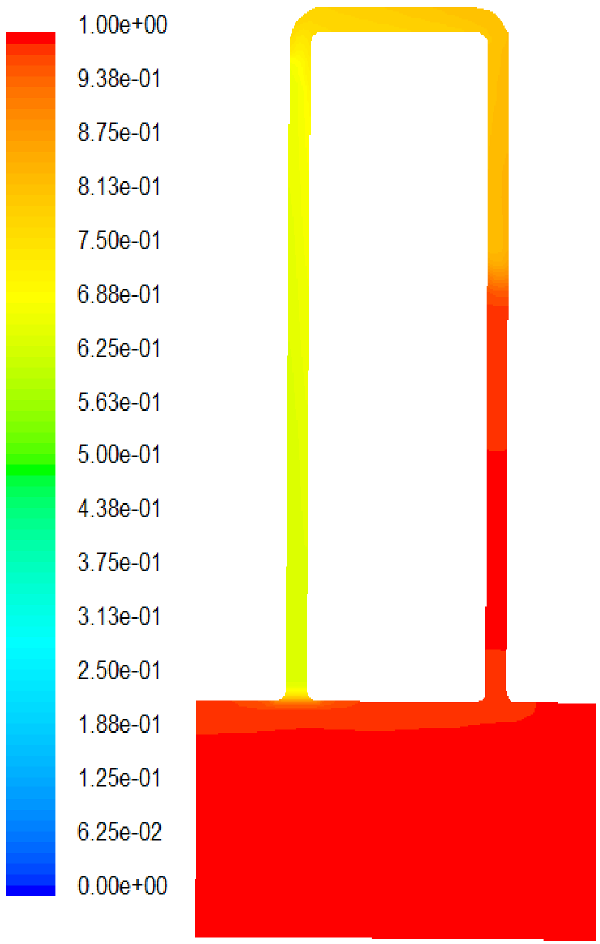


Figure 29: Nitrogen Contour: T=222.55 min

Thermal Experiment (Cont.)

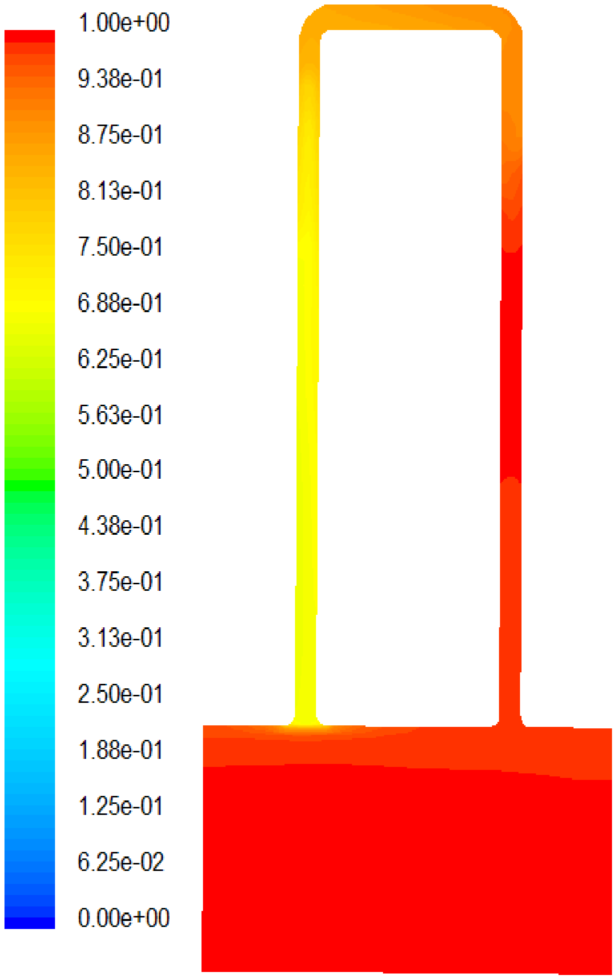


Figure 30: Nitrogen Contour: T=223.03 min

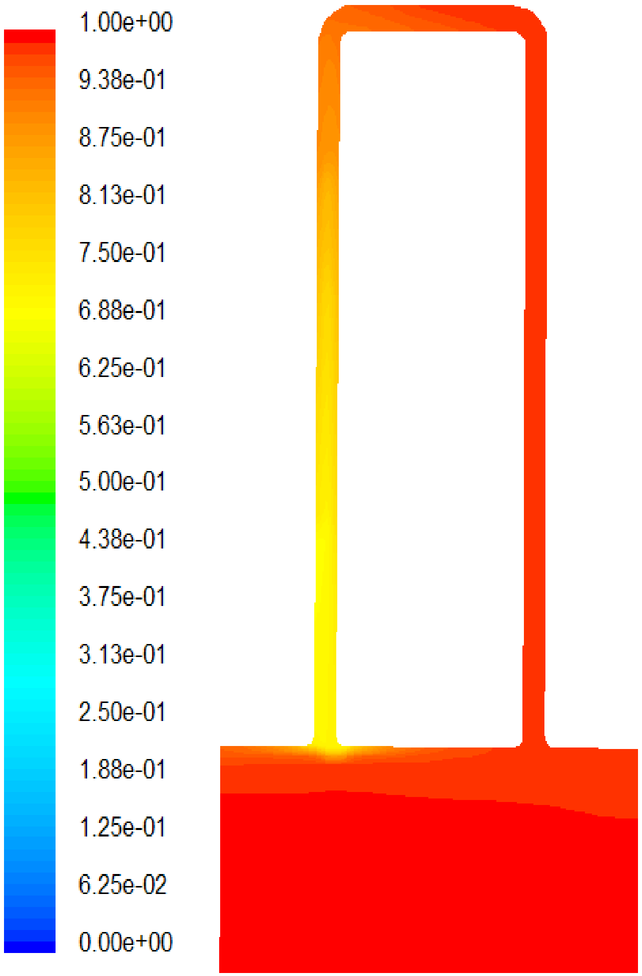


Figure 31: Nitrogen Contour: T=223.20 min

Thermal Experiment (Cont.)

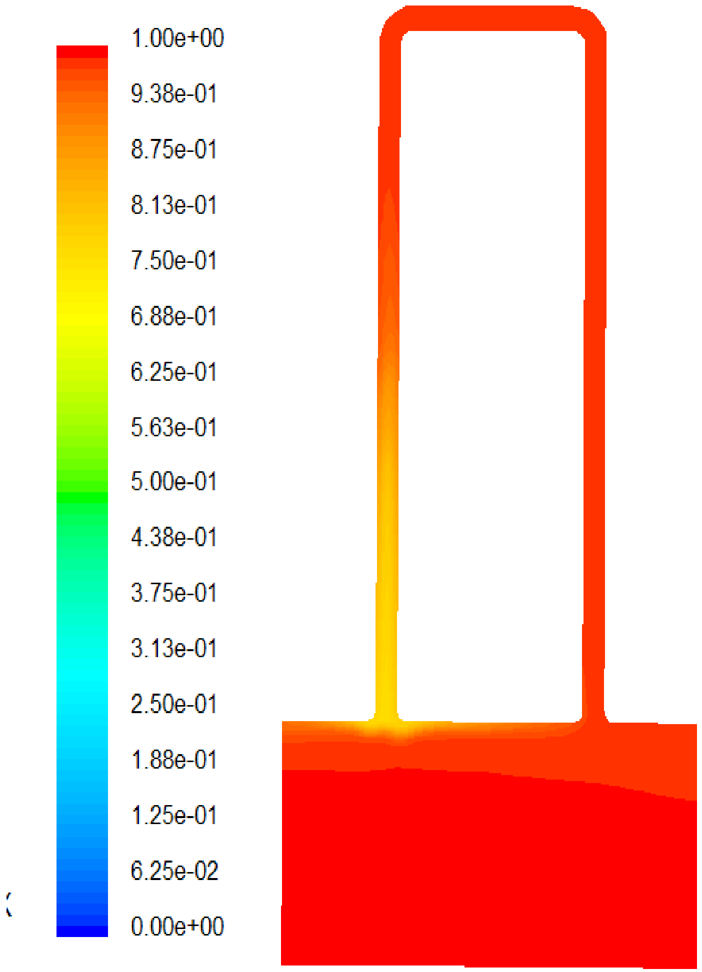


Figure 32: Nitrogen Contour: T=223.28 min

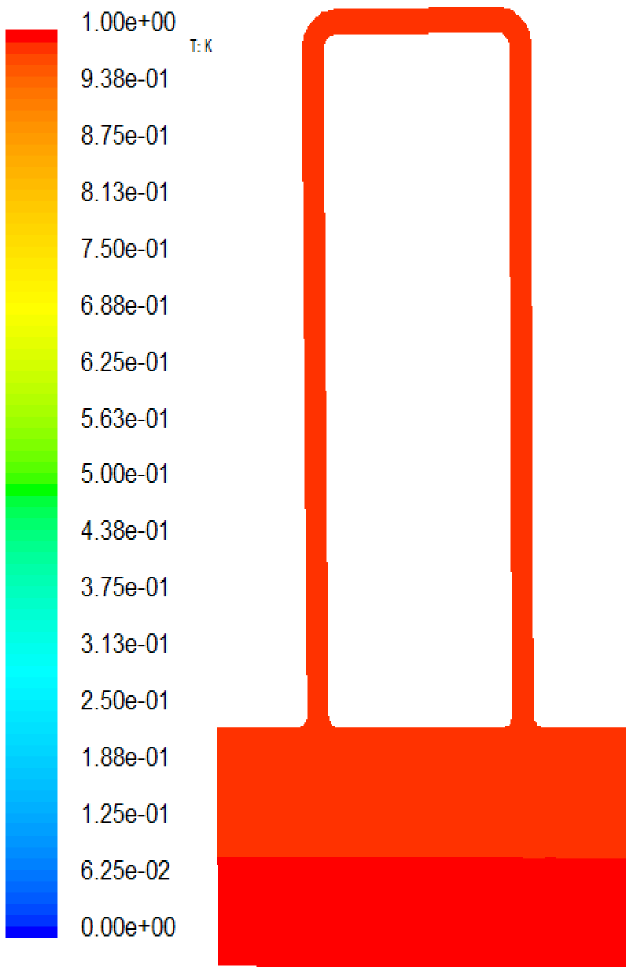


Figure 33: Nitrogen Contour: T=224.00 min

Multi-Component Experiment

- Graphite Inserted
- Multiple gases: O_2, CO, CO_2, N_2, He, H_2O
- Mole fraction at 3 points are measured
- Much higher calculation requirements
- Diffusion Coefficients

$$D_{A-B} = \frac{10^{-7} T^{1.75} [(M_A + M_B)/M_A M_B]}{P(\Sigma_A^{1/3} + \Sigma_B^{1/3})^2}$$

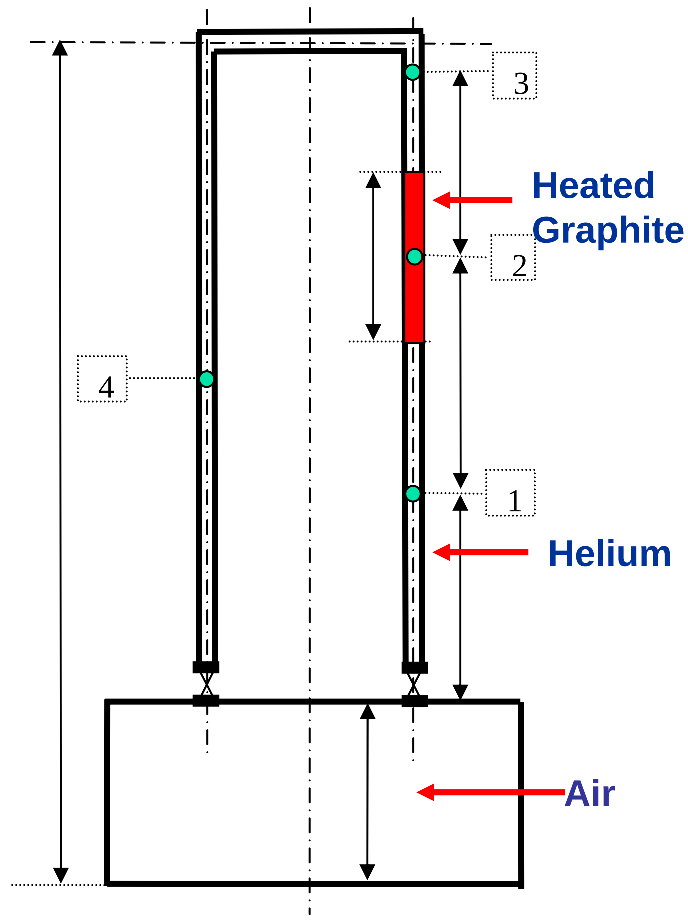


Figure 34: Apparatus for multi-Component experiment of JAERI

Multi-Component Experiment(Cont.)

- Chemical Reactions
  - 1 surface reaction:

    C + O2 = x CO + y CO2 (+ Heat)

$$r_{c-o} = K_0 \exp(-\frac{E_0}{RT}) p_{o_2}^n$$

  - 2 volume Reactions:

    2 CO + O2 = 2CO2 (+ Heat)

    2 CO2 = 2 CO + O2 (- Heat)

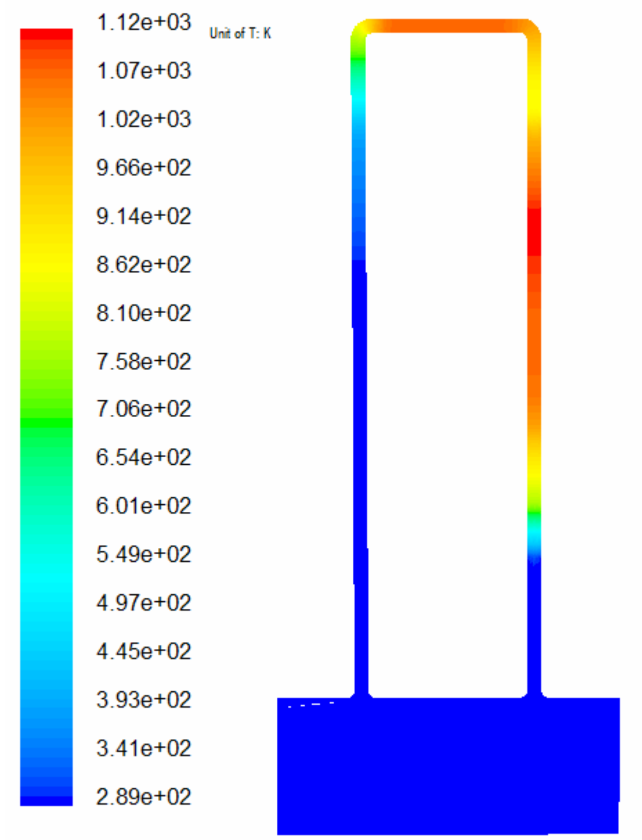


Figure 35: The temperature boundary conditions for the multi-component experiment

Multi-Component Experiment(Cont.)

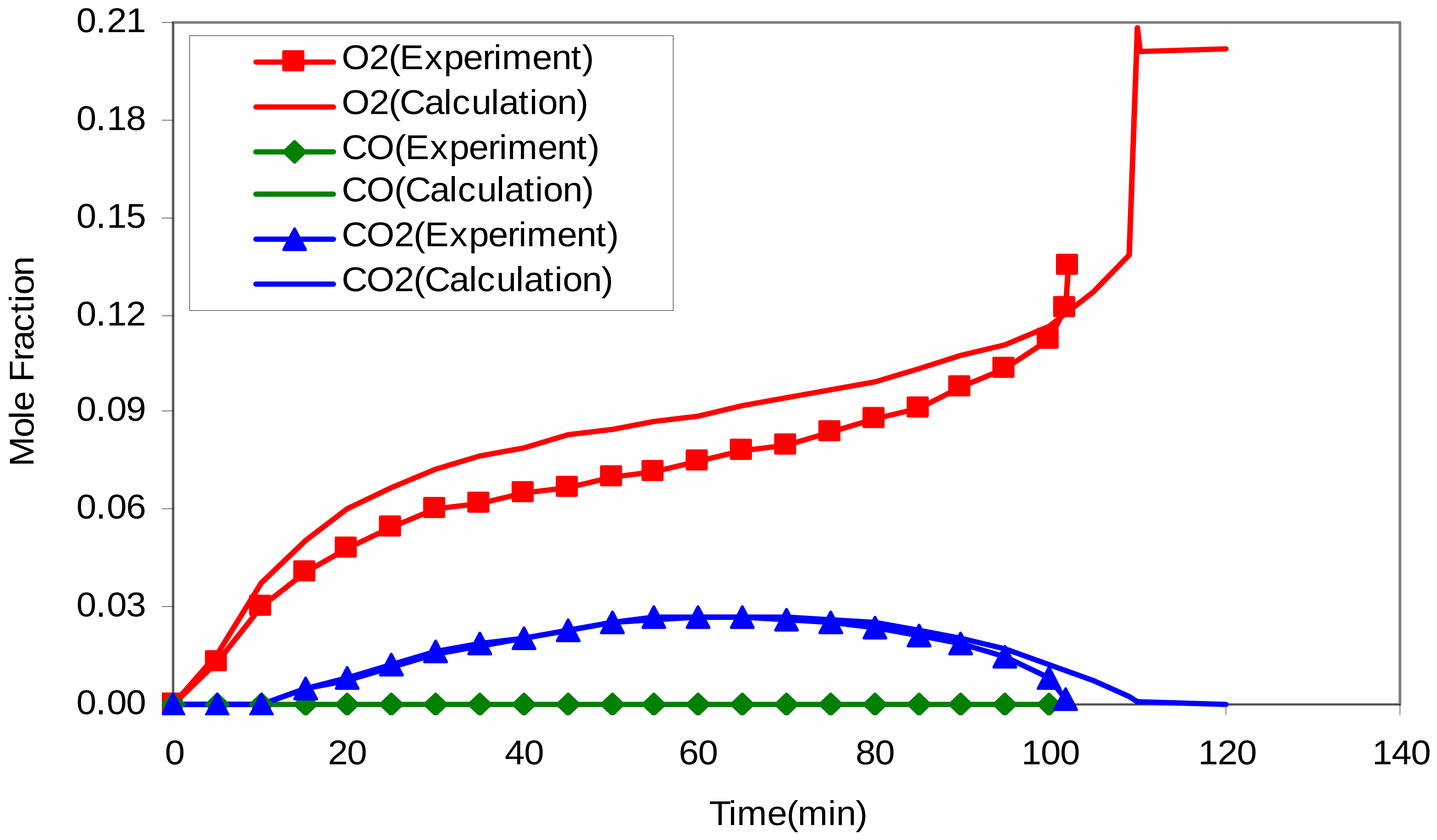


Figure 36: Mole Fraction at Point-1 (80% Diffusion Coff.)

Multi-Component Experiment(Cont.)

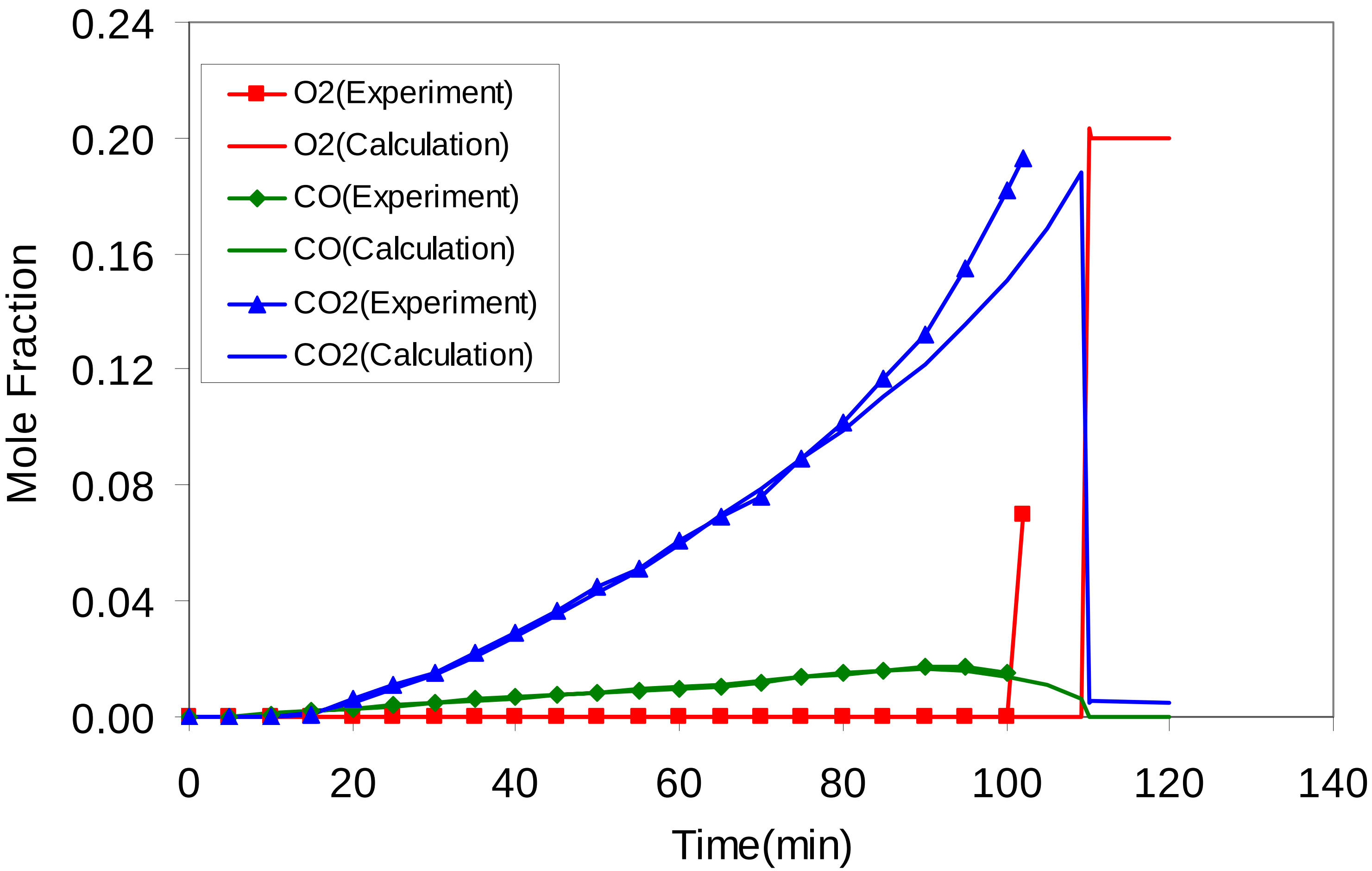


Figure 37: Mole Fraction at Point-3

Multi-Component Experiment(Cont.)

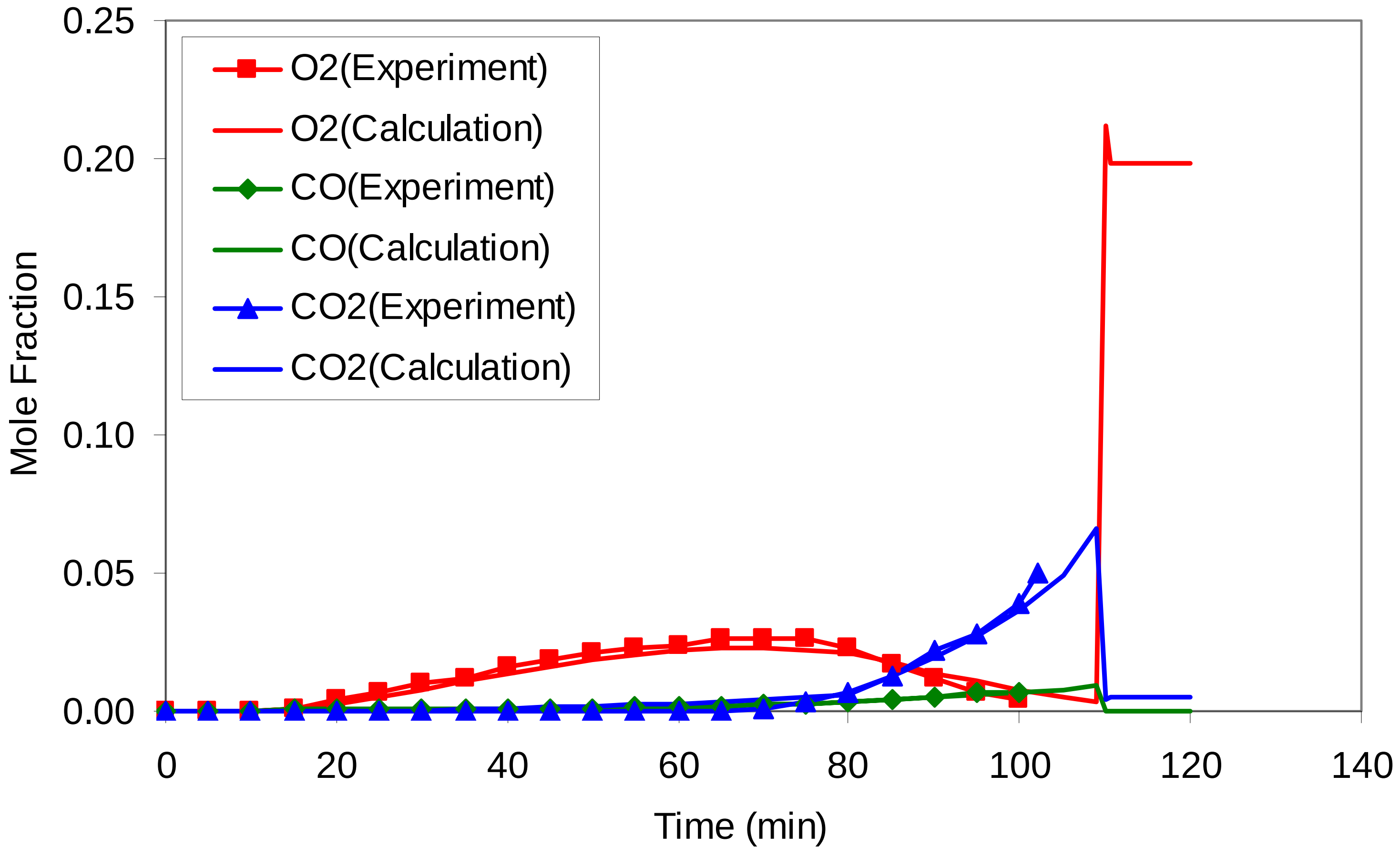


Figure 38: Mole Fraction at Point-4

NACOK Natural Convection Experiments no cont.

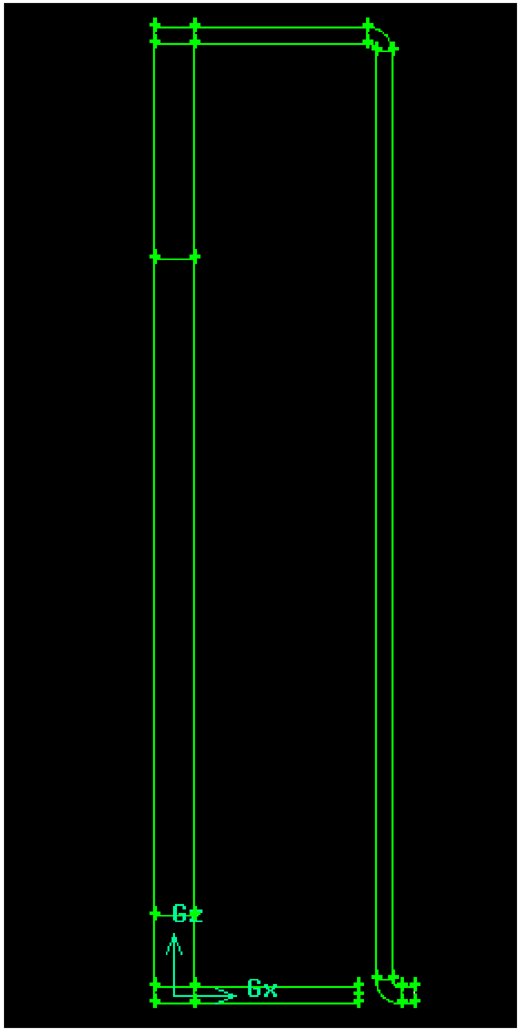


Figure 39: NACOK Experiment

NACOK Natural Convection Experiments

- Square column on pebble side with pipe on cold leg
- Actual Size (6 cm) Ceramic Pebbles in a 5x5 Array
- Four Series of Tests
  - Hot and Cold Legs Maintained at Constant Wall Temperature
  - Cold Leg temperature at 200 °C, 400 °C , 600 °C and 800 °C .
  - The hot leg temperatures are higher than the cold leg by 50 °C, 100 °C, 150 °C etc., and the highest hot leg temperature is 1000 °C.
  - Output Measurements: Mass Flow Rate of Air
- Steady State Calculation

Mesh Applied

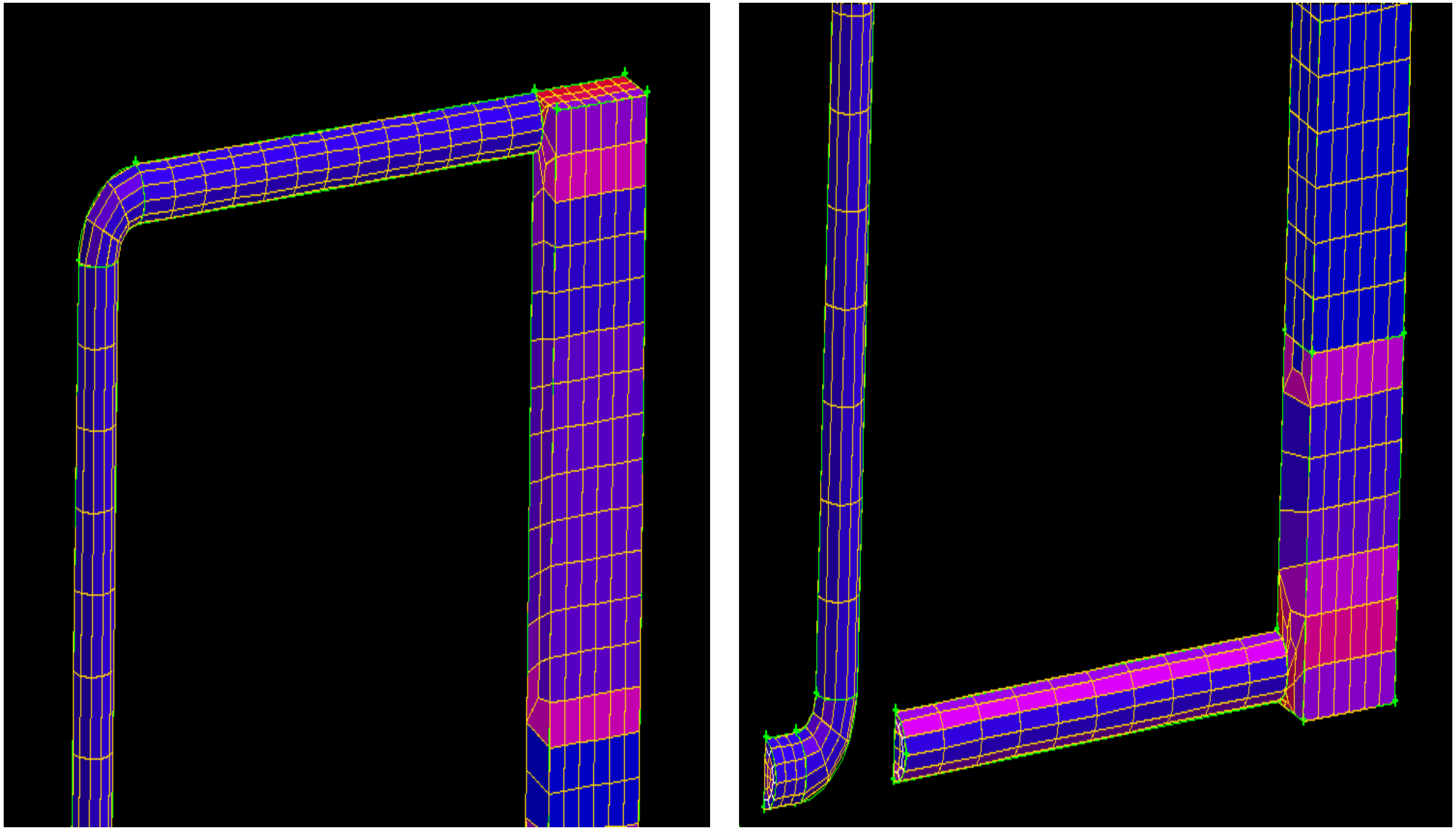


Figure 40: Meshes for the NACOK Experiment

Pressure Drop in Pebble Bed Using UDF

- Porous media to model the pebble bed

$$\Delta p = \frac{-205}{\mathrm{Re}/(1-\varepsilon)} - \frac{0.1}{(\mathrm{Re}/(1-\varepsilon))^{0.1}}$$

- Convert the pressure drop into:

$$\Delta P = -1.7 * 10^{5} * \eta * u_{z} - 10.3 * \rho^{0.9} * \eta^{0.1} * u_{z}^{1.9}$$

- UDF to calculate the pressure drop
- Modifications made on the laminar pressure drop proposed by NACOK experiment
- Density, conductivity, specific heat, viscosity are defined using 12 points respectively.

Boundary Conditions

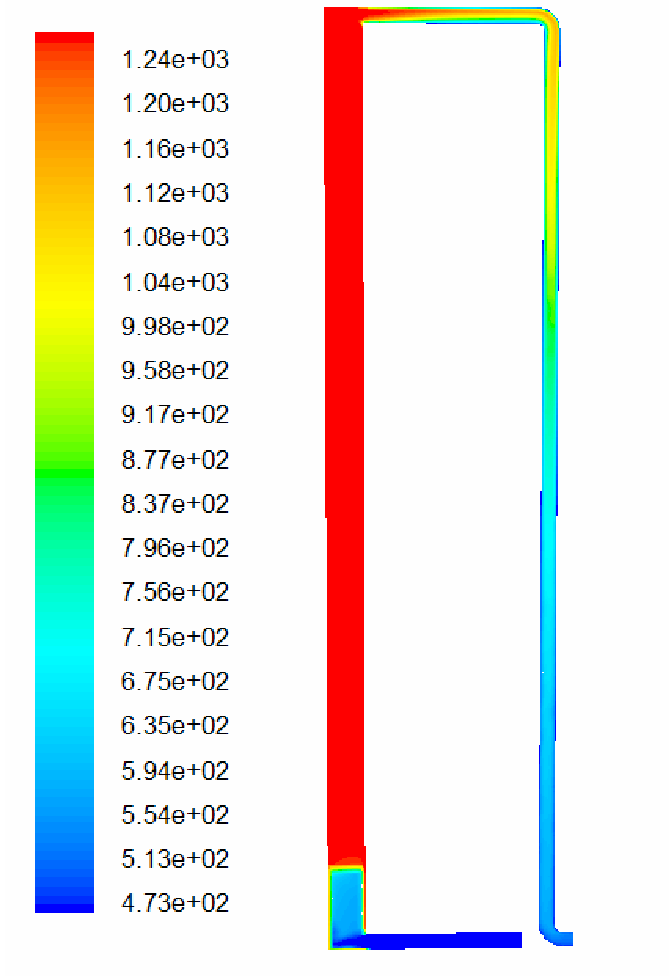


Figure 41: Temperature Profile for one experiment

The Mass Flow Rates

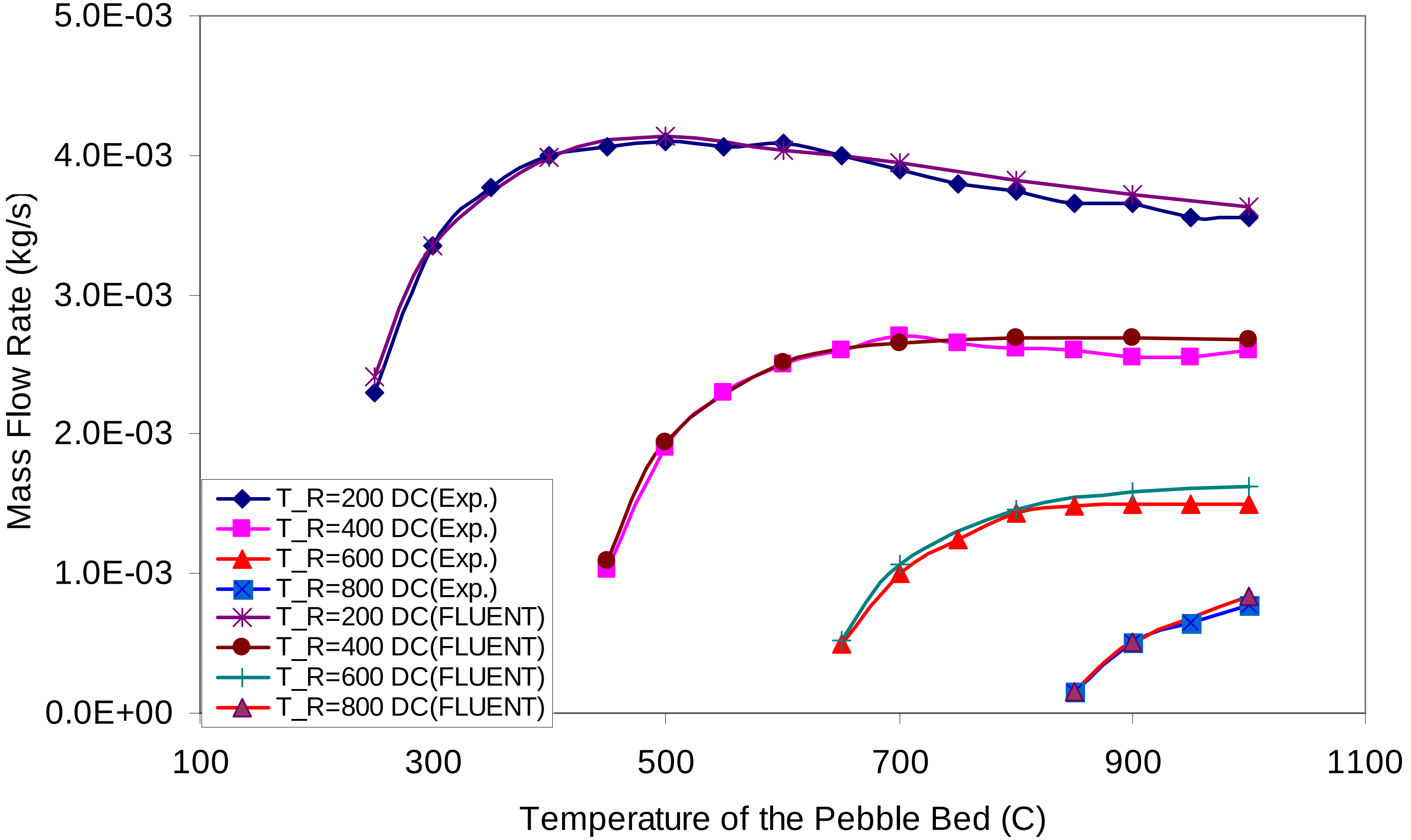


Figure 42: Mass Flow Rates for the NACOK Experiment

Future Work

- Benchmark Chemical Corrosion Tests and other upcoming NACOK Tests
- Develop PBMR model using FLUENT 6.1 to consider corrosion of graphite (loss of material in lower reflector)
- Integrate with systems analysis codes (RELAP-ATHENA)
- Conduct PBMR analysis showing slow corrosion - low inlet air velocity and no burning.

Future Work (Cont.)

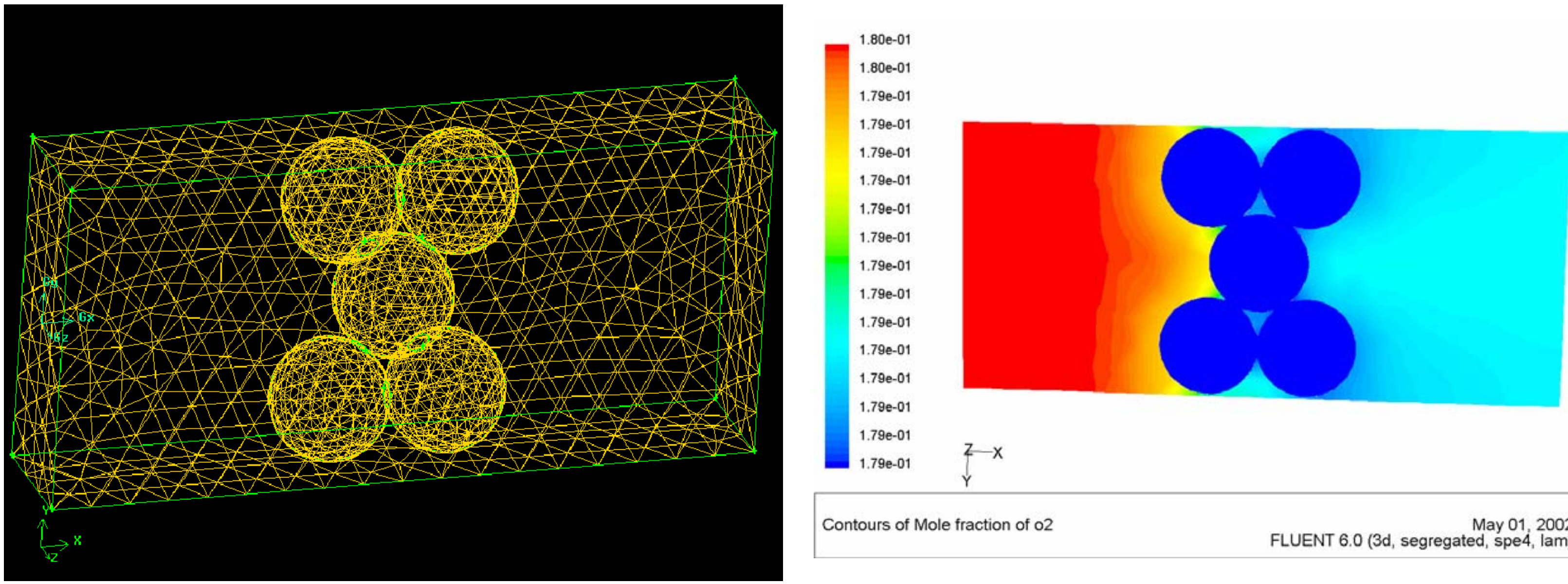


Figure 43: The proposed models to study the chemical reactions in pebble bed

Future Work (Cont.)

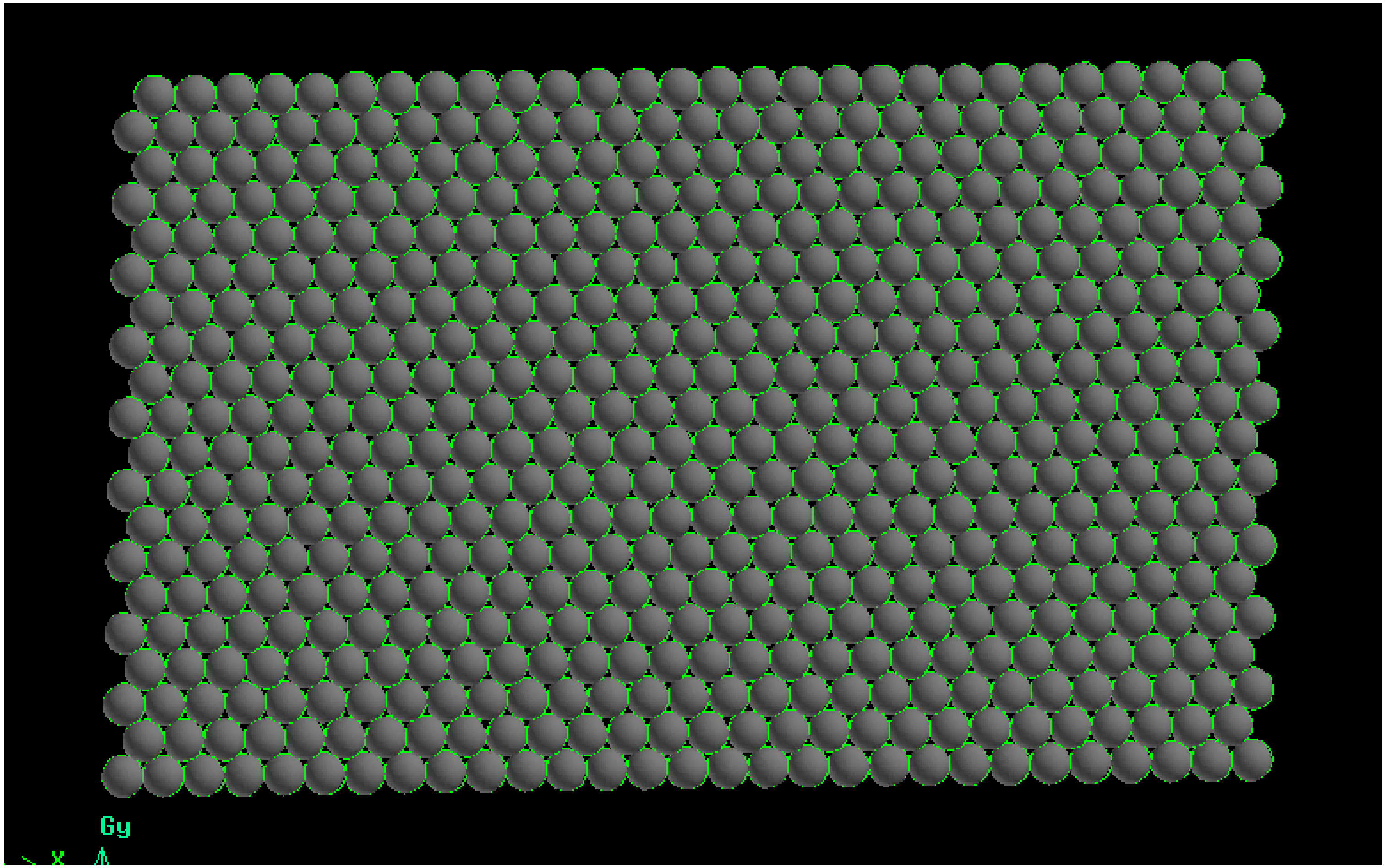
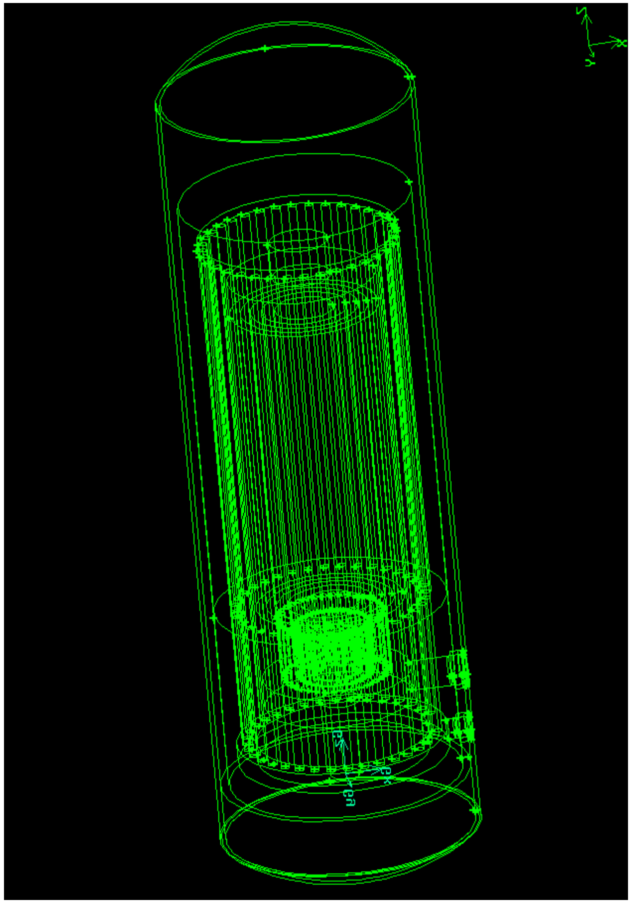


Figure 44: The models to study the chemical reactions in pebble bed

The Detailed Model of PBMR



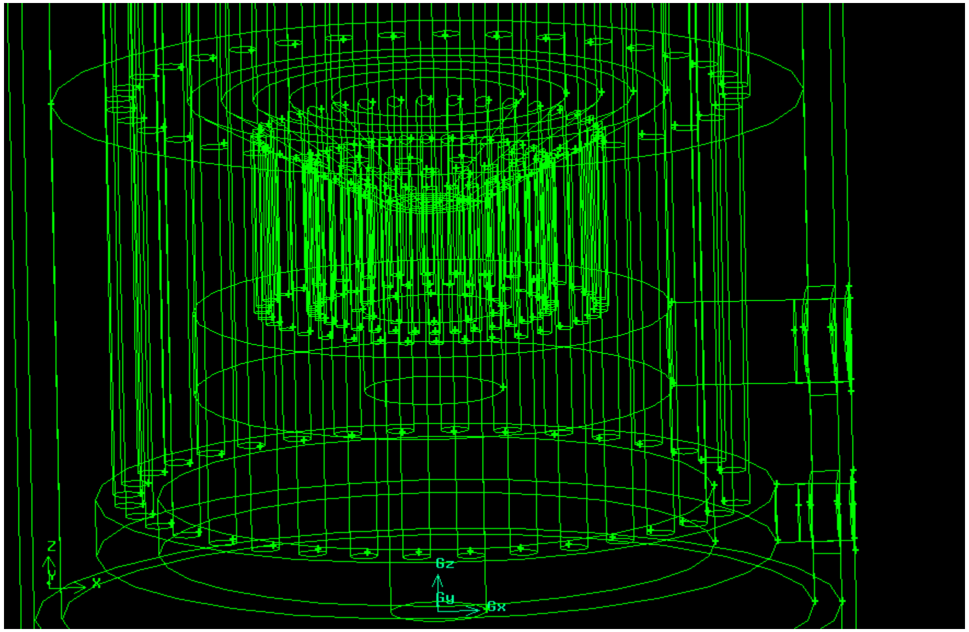


Figure 46: The geometry of the bottom reflector

Figure 45: The detailed model for PBMR

30 Degree Model

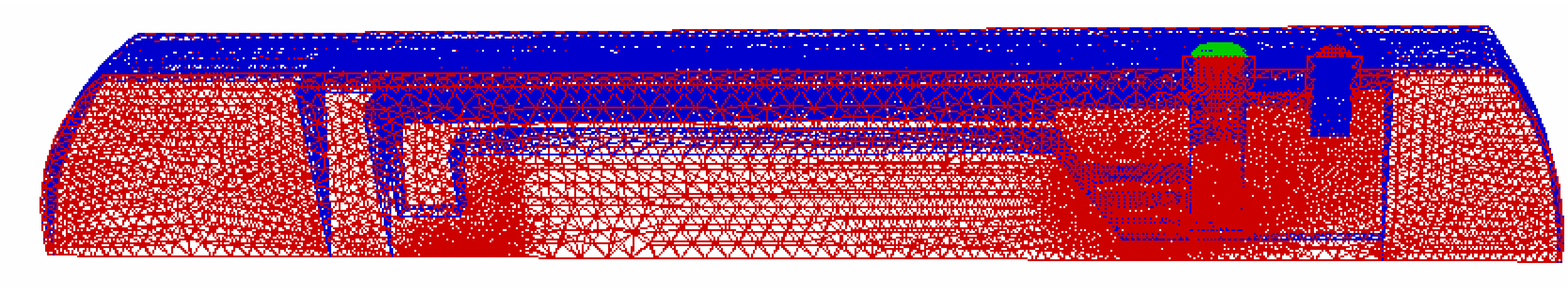


Figure 47: 3-D 30-degree Model

Summary

- Hope is that there is a long diffusion stage and the air inlet velocity after the natural circulation will be low enough not to support active burning but only slow corrosion.
- Need to expand the boundary conditions to assess the availability of air - incorporate systems code.
- Need to develop mitigation strategies for ultimate cessation of air ingress and reactor cool down post LOCA break spectrum.
- The surface reaction rate and the immediate products at the graphite surface are important information for the air ingress accident study.
- The methodology developed in this work using FLUENT 6 appears to be able to handle these challenges.

THANK YOU!