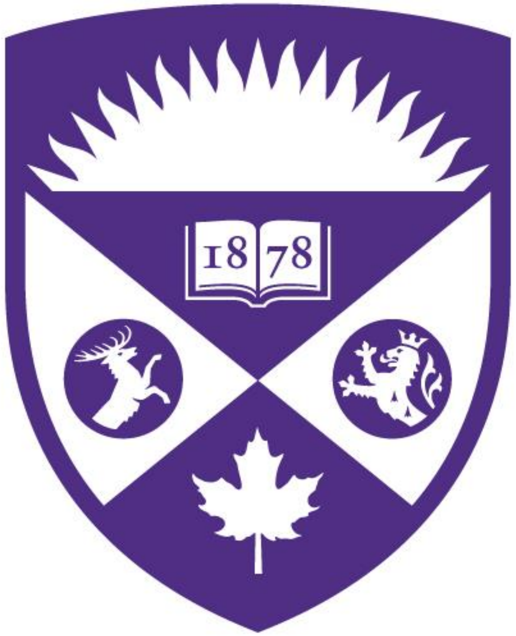

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Thermal Heterogeneity Induced by Smouldering Combustion in Homogeneous Porous Medium

Seyed Ziaedin Miry

Dr. Marco A.B. Zanoni

Prof. Jason Gerhard

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Part I: Introduction

Smouldering Combustion

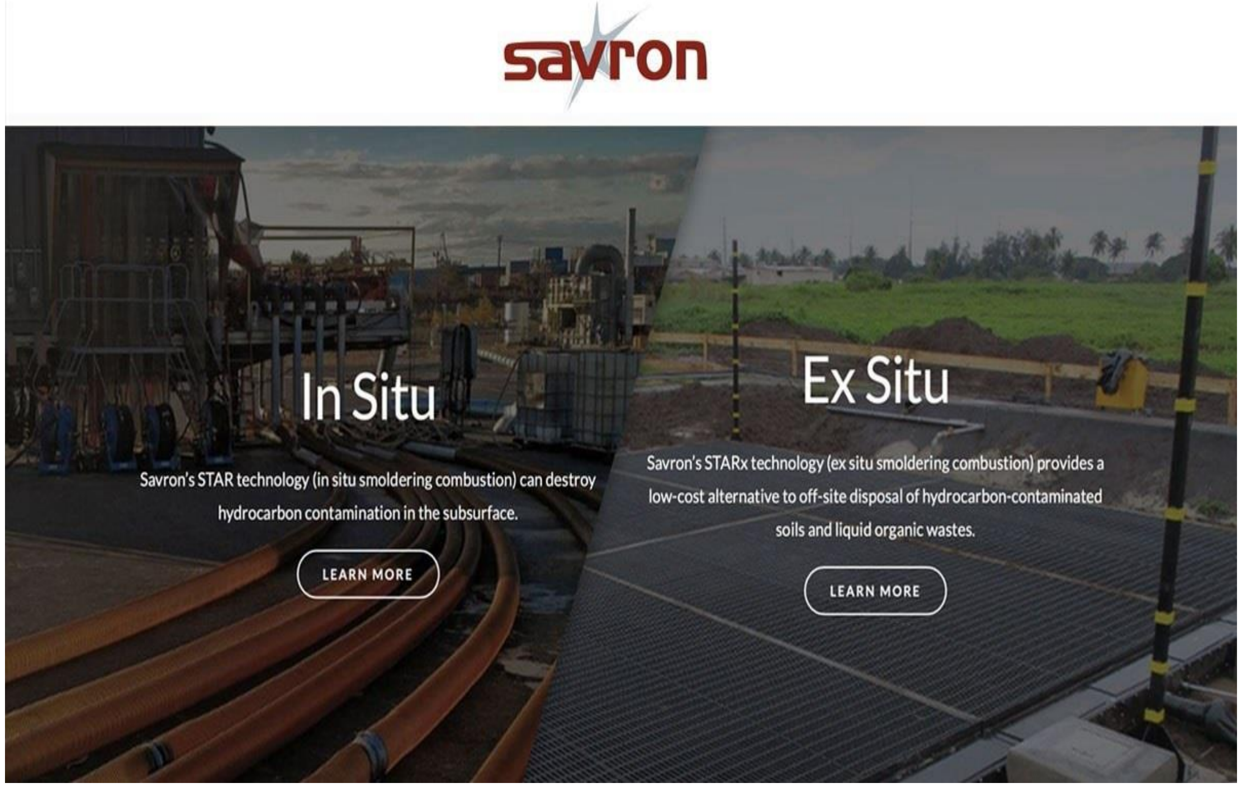
Smouldering Combustion is defined as an **Exothermic Oxidation Reaction** occurring on the **Surface of an Organic Fuel**.

Characteristics

- ✓ Slow Phenomenon
- ✓ Flameless
- ✓ Sustained by the Heat Recirculation
- ✓ Required Oxygen

Smouldering Combustion in Charcoal Barbecue

https://en.wikipedia.org/wiki/Smouldering



savron

In Situ

Savron's STAR technology (in situ smoldering combustion) can destroy hydrocarbon contamination in the subsurface.

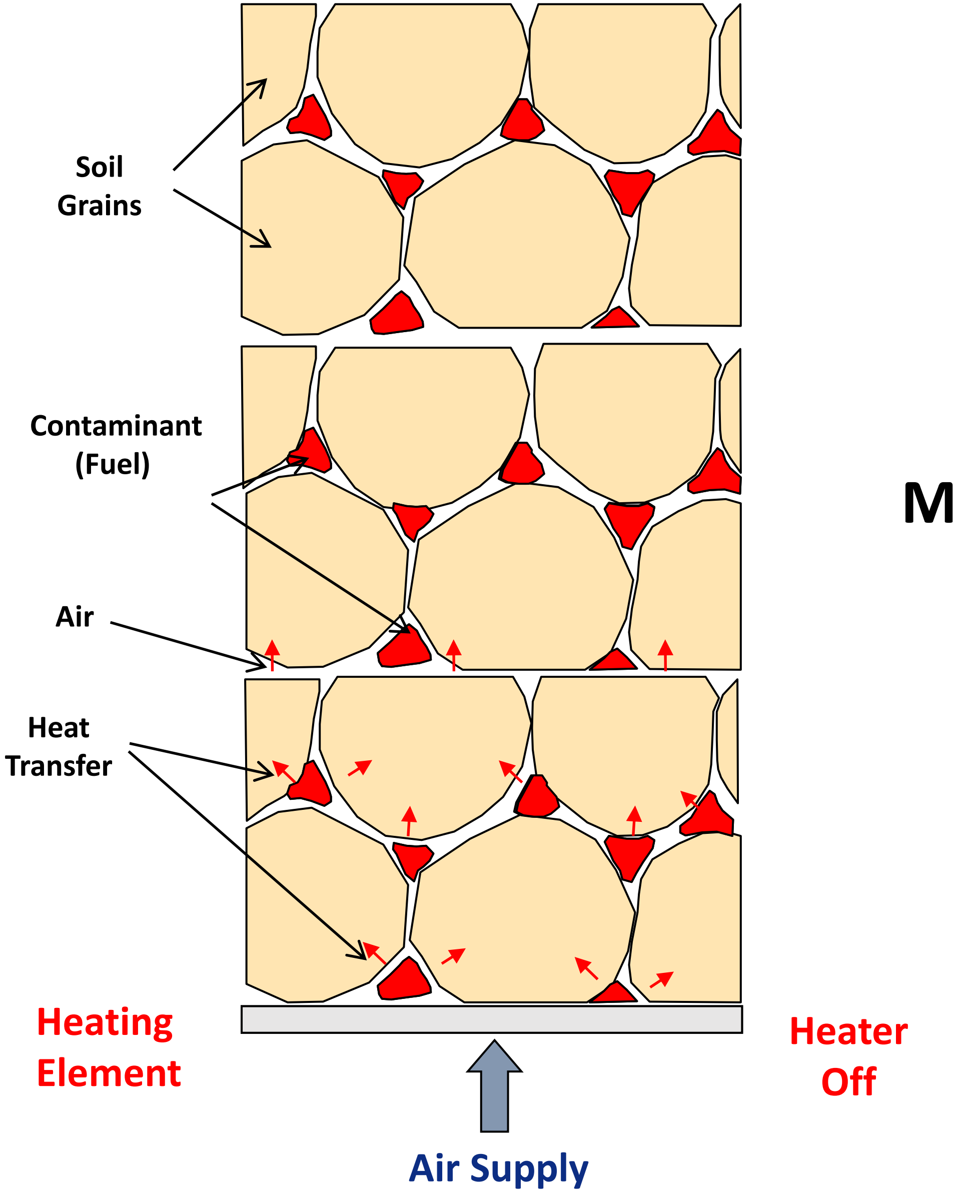
Ex Situ

Savron's STARx technology (ex situ smoldering combustion) provides a low-cost alternative to off-site disposal of hydrocarbon-contaminated soils and liquid organic wastes.

STAR Technology based on Smouldering Combustion

https://www.savronsolutions.com/

Smouldering Combustion in Inert Porous Medium



Main Mechanisms:

- **Fluid Flow** (Darcy equation)
- **Heat Transfer** (LTNE Energy equation)
- **Chemical Reaction** (Arrhenius equation)

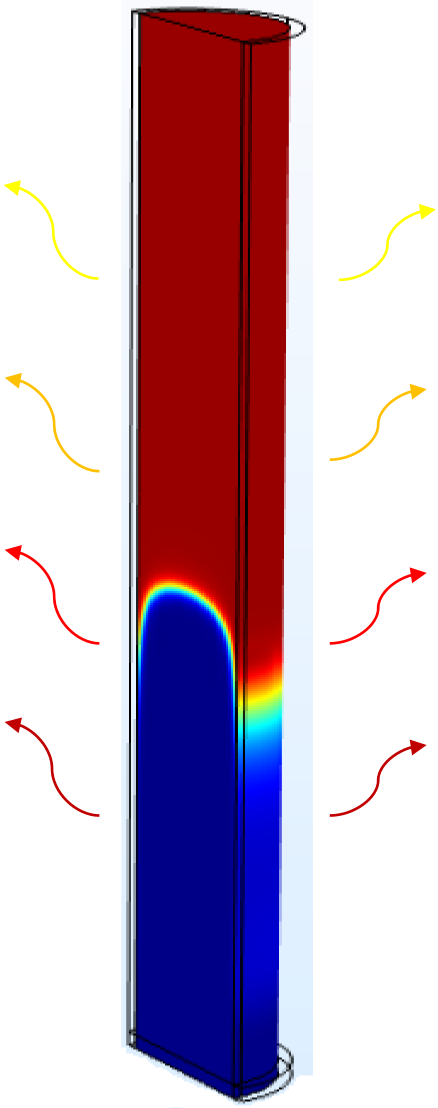
https://www.comsol.com/

Objective

✓ Validating a 2D Smouldering Model.

✓ Investigating Energy Balance and Thermal Heterogeneity.

✓ Performing Sensitivity Analysis of Radial Heat Transfer Coefficient.



Smouldering Front

Part II: Methodology

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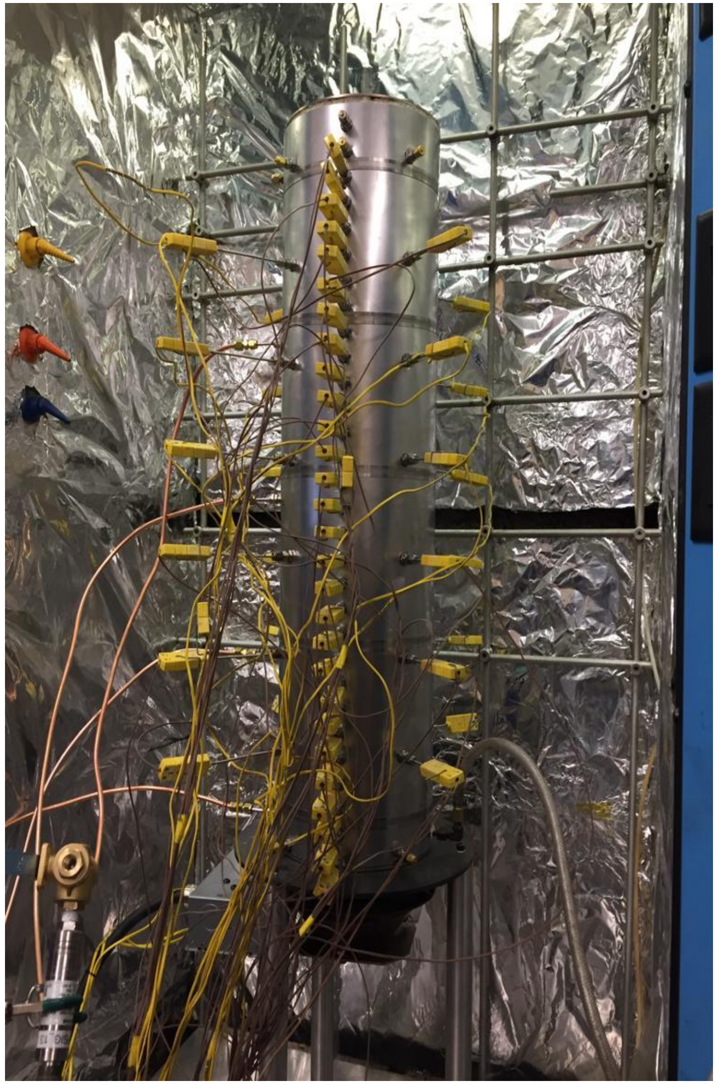
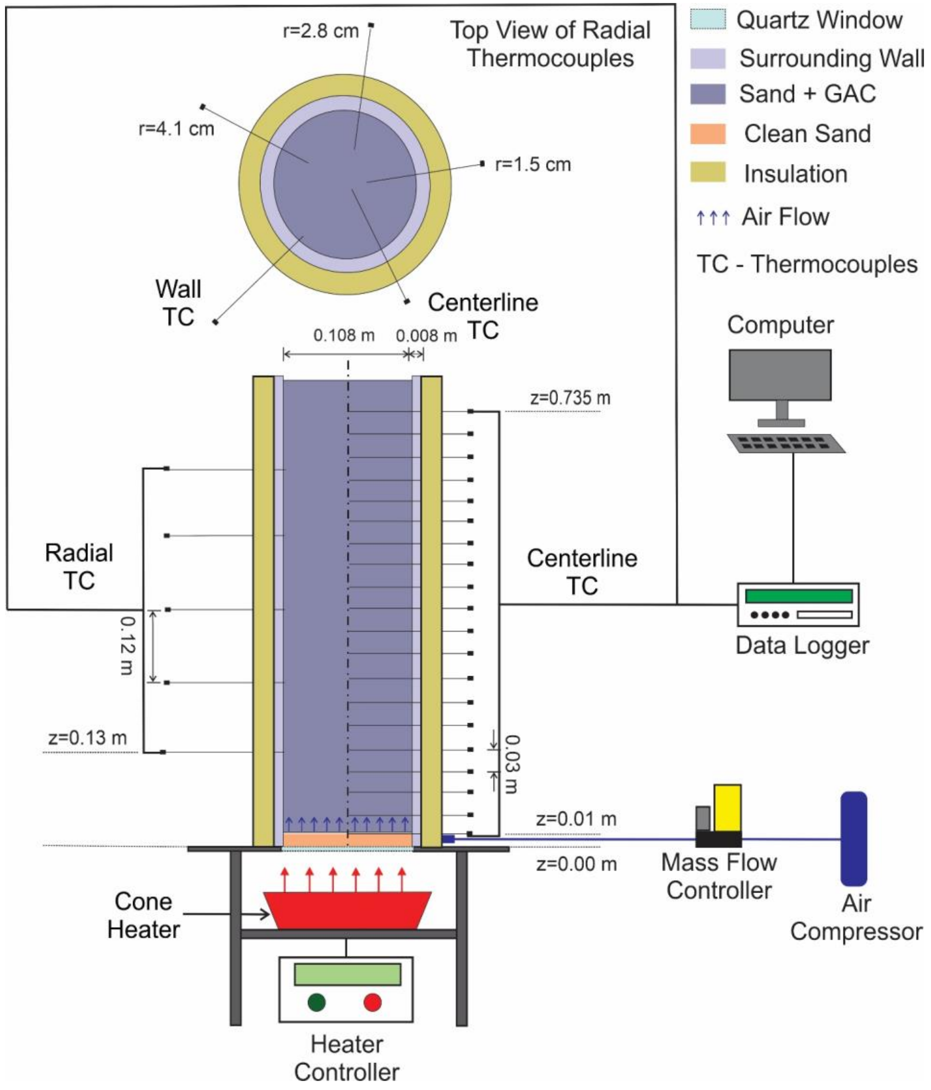
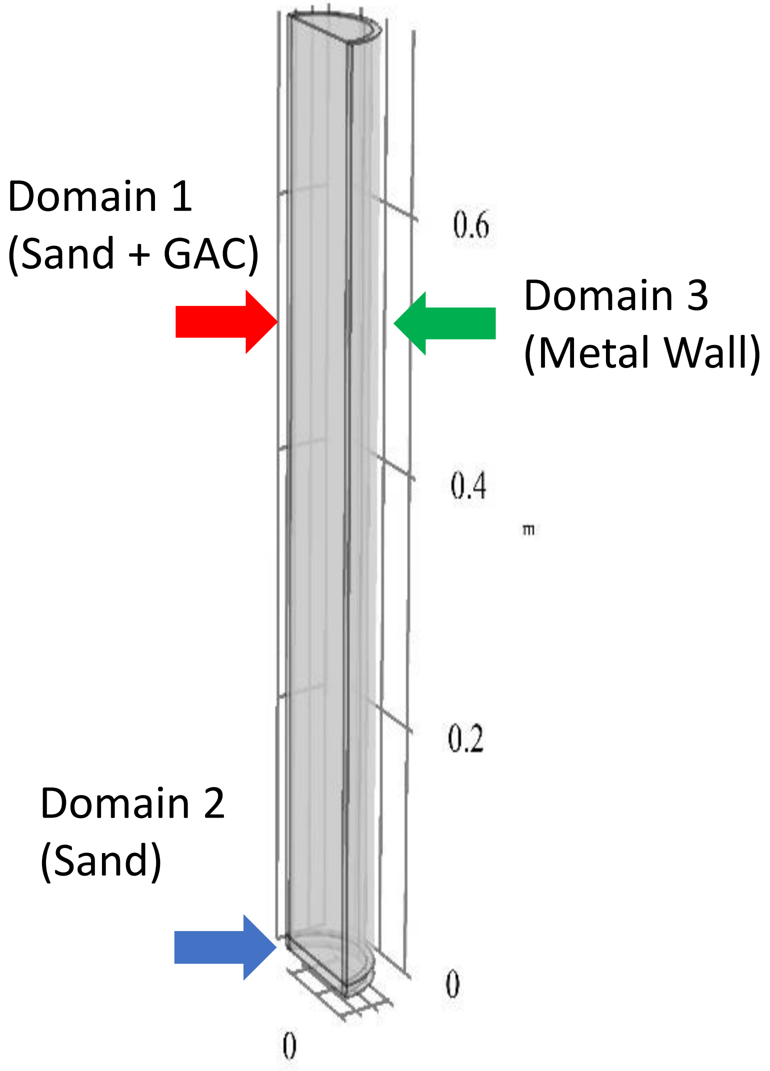
Experimental Setup Vs Numerical Domain



Photograph of Column



Schematic of Experimental Set up



Numerical Domain

Governing equations (Smouldering Test)

1- Chemical Reaction:

$$GAC + \vartheta_{O_2} O_2 \xrightarrow{R_{GAC}} Gas$$

2- Continuity equation:

$$\frac{\partial(\rho_g \varphi_g)}{\partial t} + \frac{1}{r}\frac{\partial(r \rho_g u_r)}{\partial r} + \frac{\partial(\rho_g u_z)}{\partial z} = (\rho_{GAC})(R_{GAC})$$

(Gas)

$$\frac{\partial(Y_{GAC})}{\partial t} = -R_{GAC}$$

(GAC)

3- Oxygen Transport Equation:

$$\varphi_g \frac{\partial\left(\rho_g Y_{O_2}\right)}{\partial t} + \frac{\partial\left(\rho_g u_r Y_{O_2}\right)}{\partial r} + \frac{\partial\left(\rho_g u_z Y_{O_2}\right)}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \varphi_g \rho_g D_g \frac{\partial Y_{O_2}}{\partial r}\right) + \frac{\partial}{\partial z}\left(\varphi_g \rho_g D_g \frac{\partial Y_{O_2}}{\partial z}\right) - (\rho_{GAC})\, \vartheta_{O_2} R_{GAC}$$

4- Energy equation in solid:

$$\left(\rho\, C_p\right)_{eff} \frac{\partial T_s}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_{eff} \frac{\partial T_s}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_{eff} \frac{\partial T_s}{\partial z}\right) + h_{sg}\left(\frac{A_{s,sp}}{V_{sp}}\right)(T_g - T_s) - \rho_{GAC}(\Delta H_{GAC} R_{GAC})$$

5- Energy equation in gas:

$$\varphi_g \rho_g C_{P_g} \frac{\partial T_g}{\partial t} + \rho_g C_{P_g}(u_r \frac{\partial T_g}{\partial r} + u_z \frac{\partial T_g}{\partial z}) = \frac{1}{r}\frac{\partial}{\partial r}\left(r \varphi_g k_g \frac{\partial T_g}{\partial r}\right) + \frac{\partial}{\partial z}\left(\varphi_g\, k_g \frac{\partial T_g}{\partial z}\right) + h_{sg}(\frac{A_{s,sp}}{V_{sp}})(T_s - T_g)$$

Part III: Results

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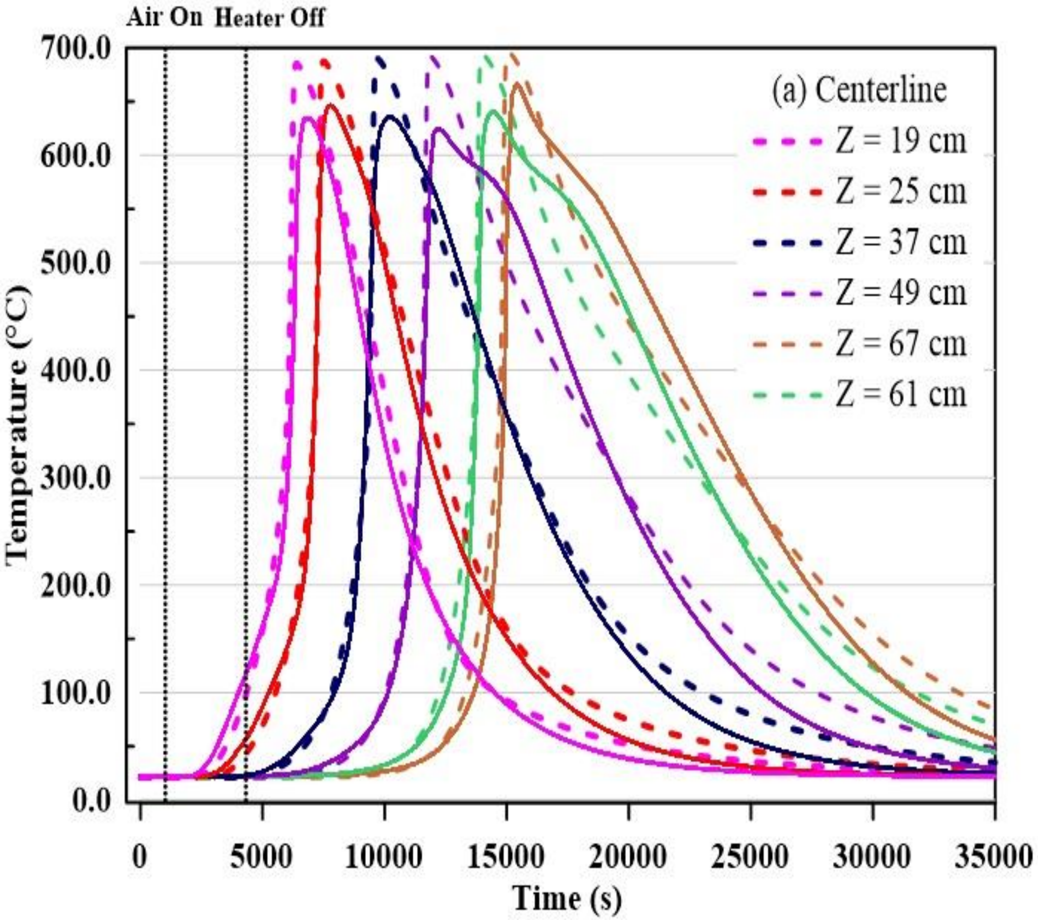
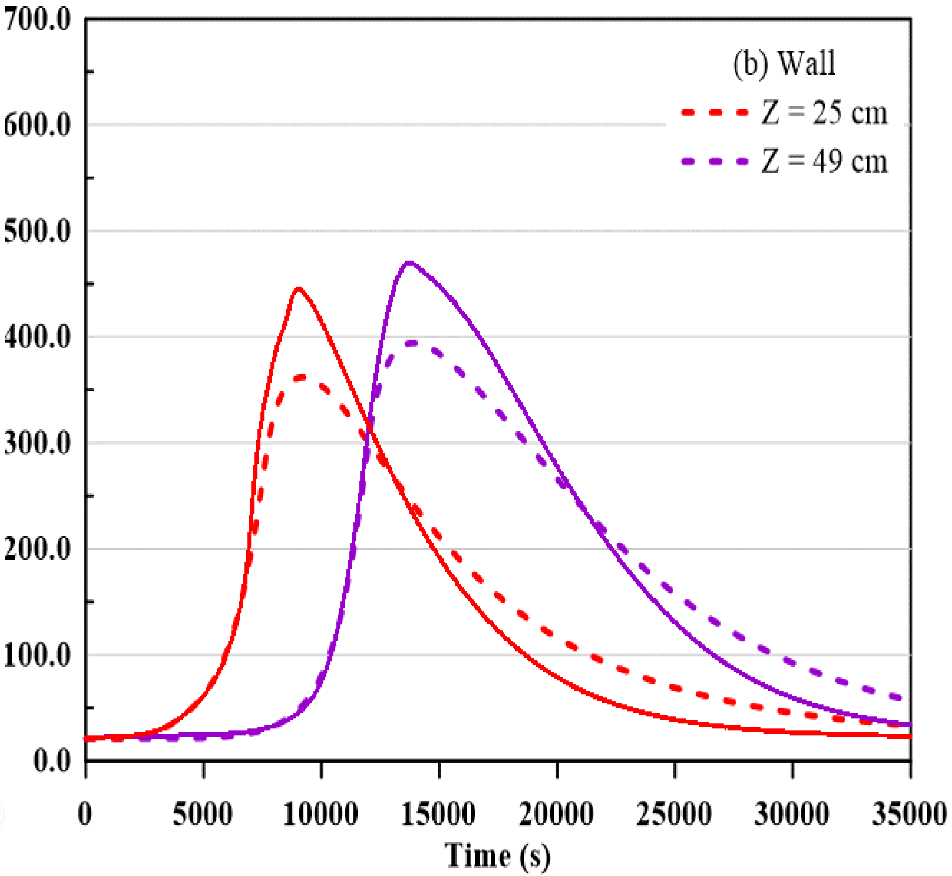
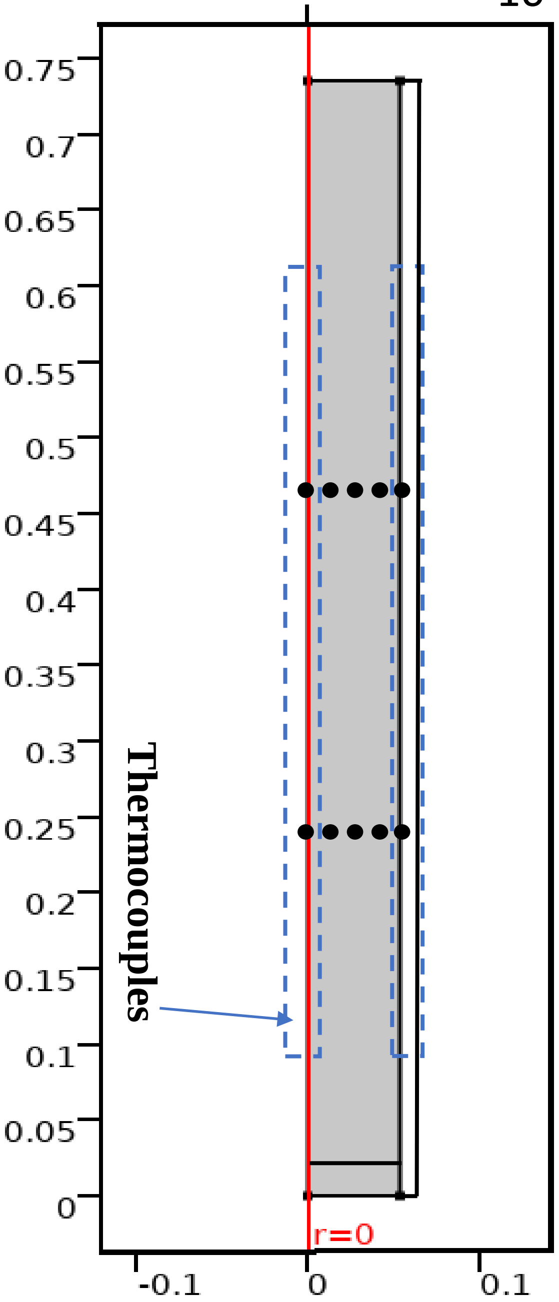
Experimental vs Numerical Results (Model Calibration)



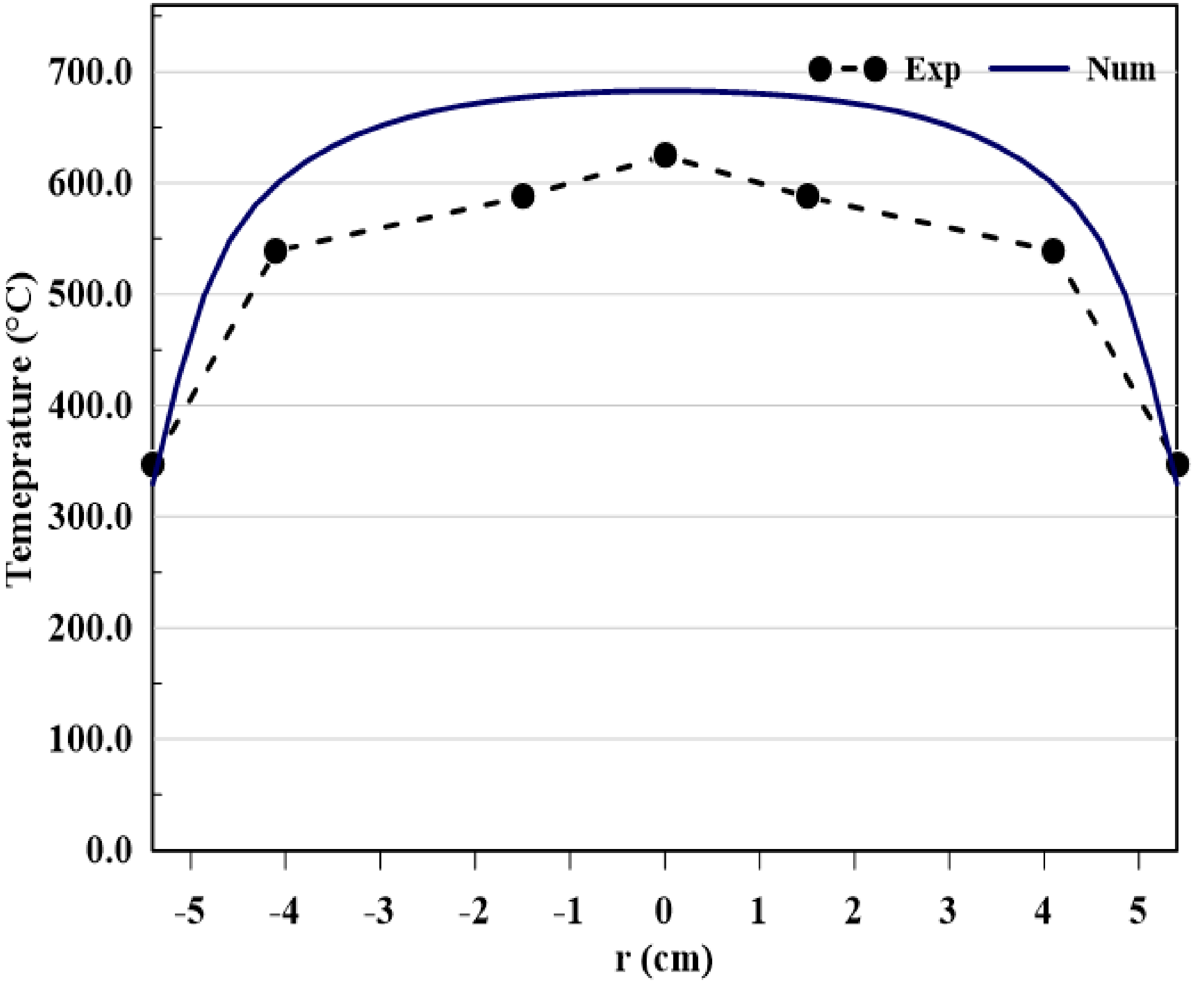
Centerline (Error = 4.6%)



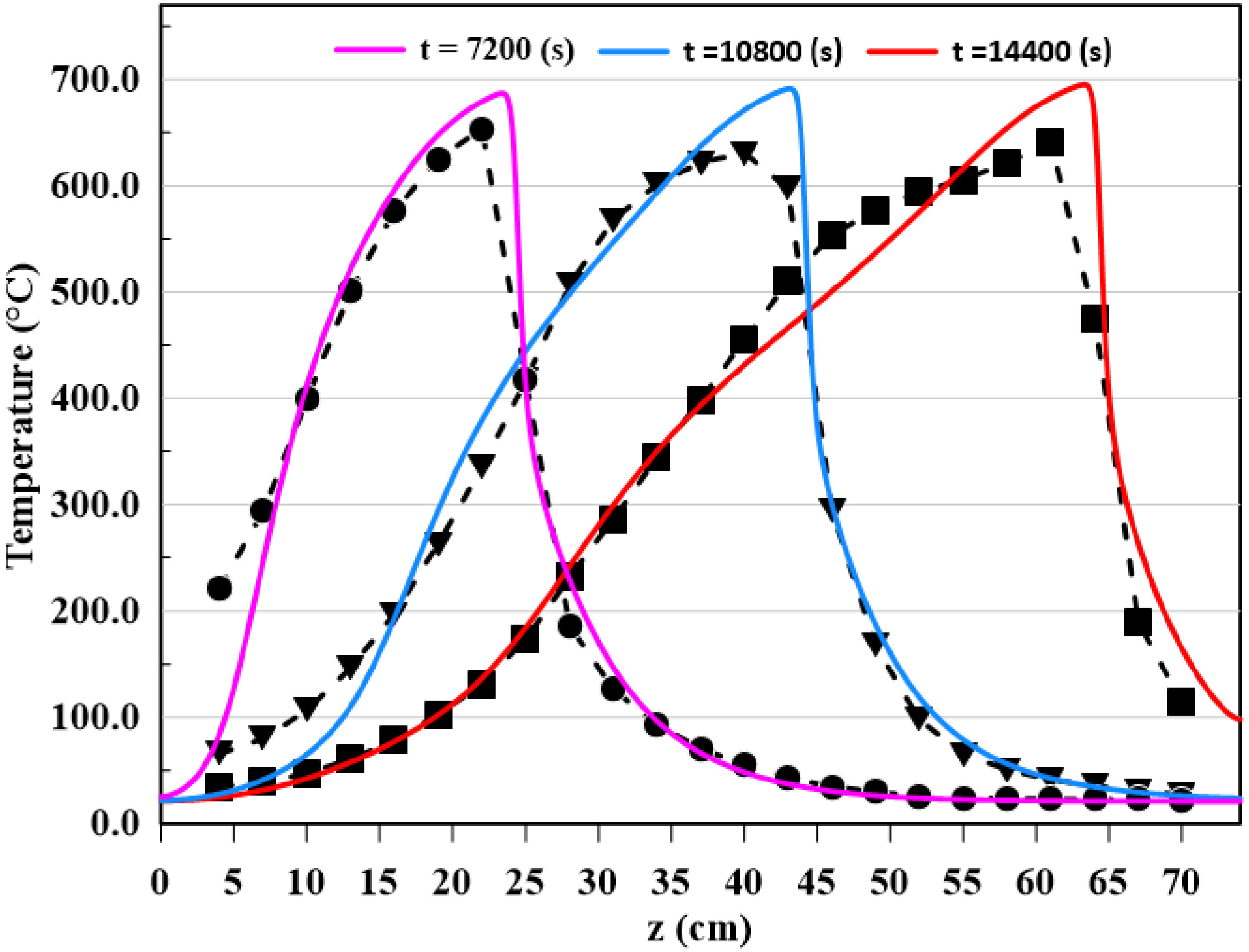
Wall (Error = 15.3%)



Experimental vs Numerical Results (Spatial Temperature Distribution)



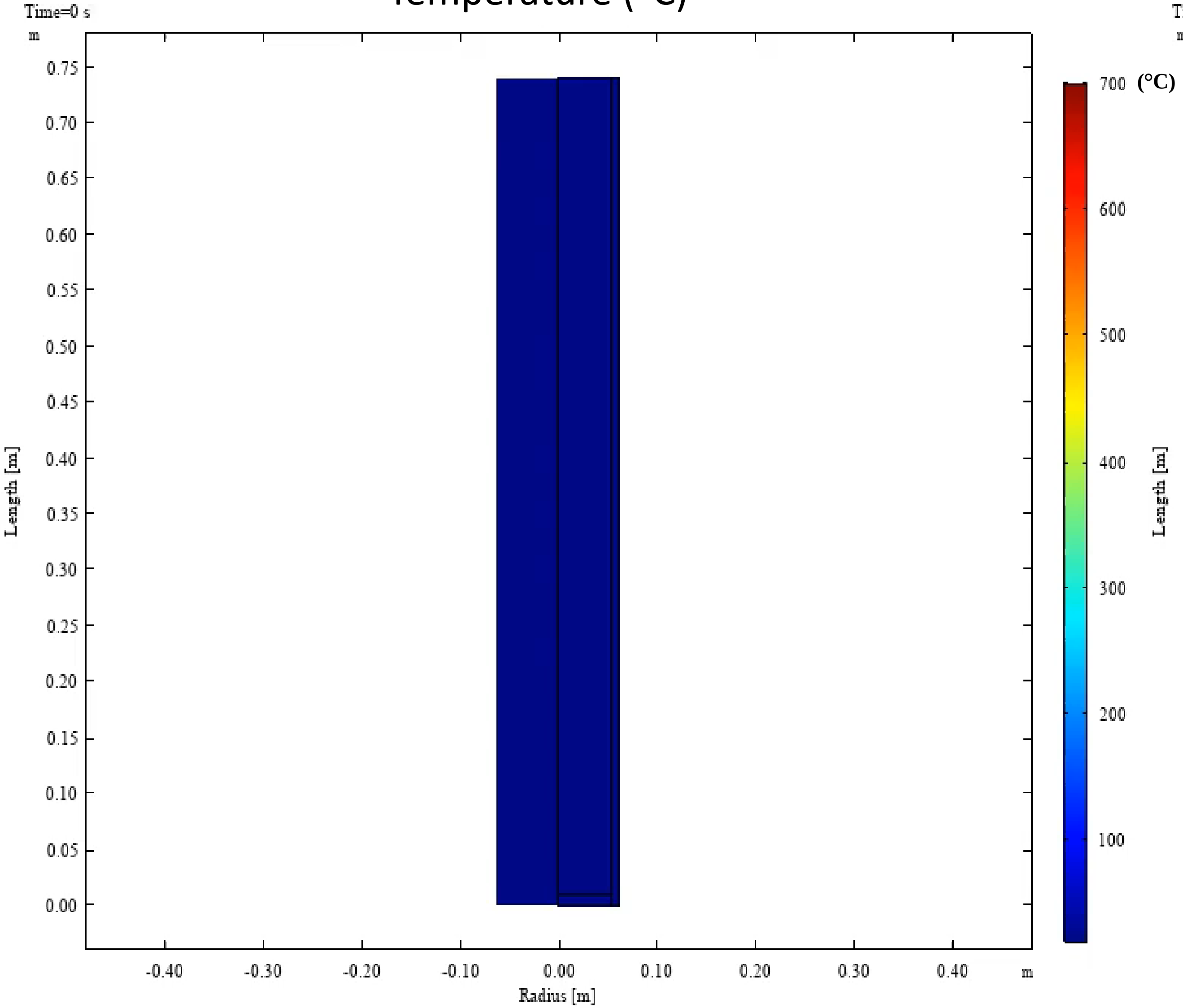
Radial Temperature Distribution



Longitudinal Temperature Distribution

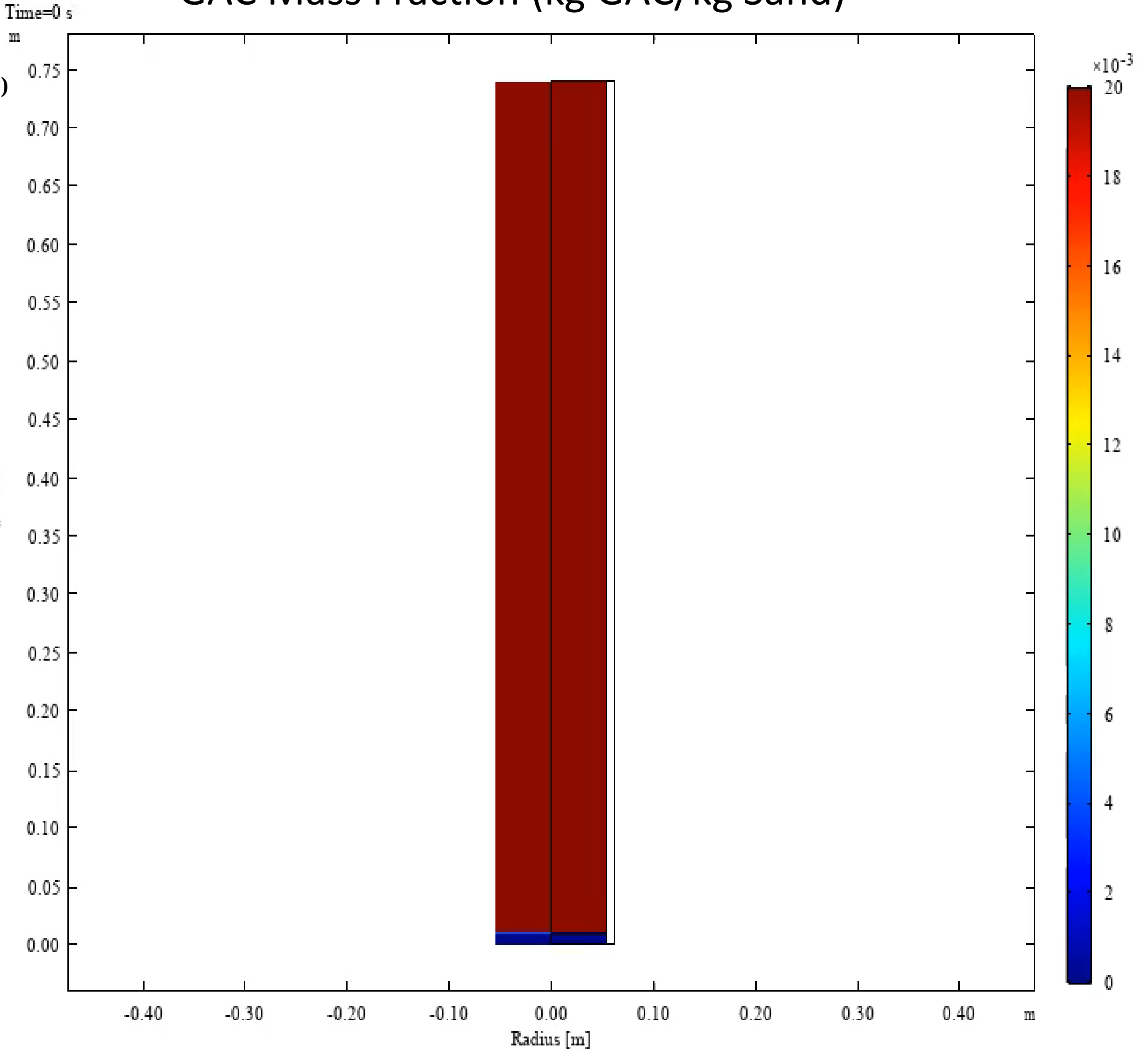
Numerical Simulation

Temperature (°C)



Temperature Distribution

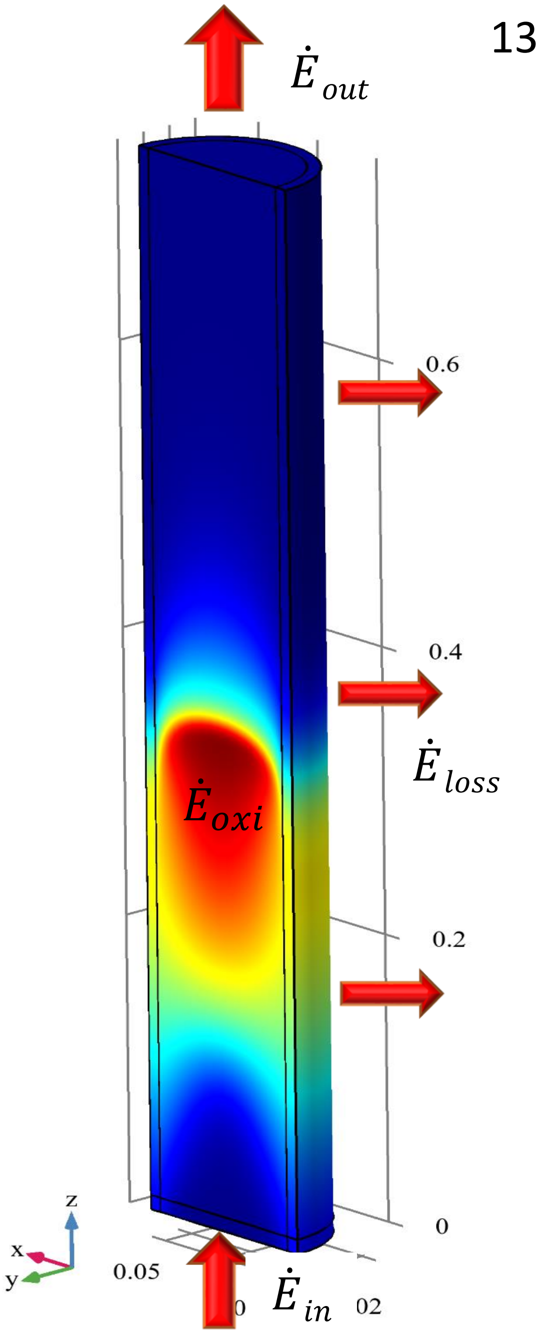
GAC Mass Fraction (kg GAC/kg Sand)



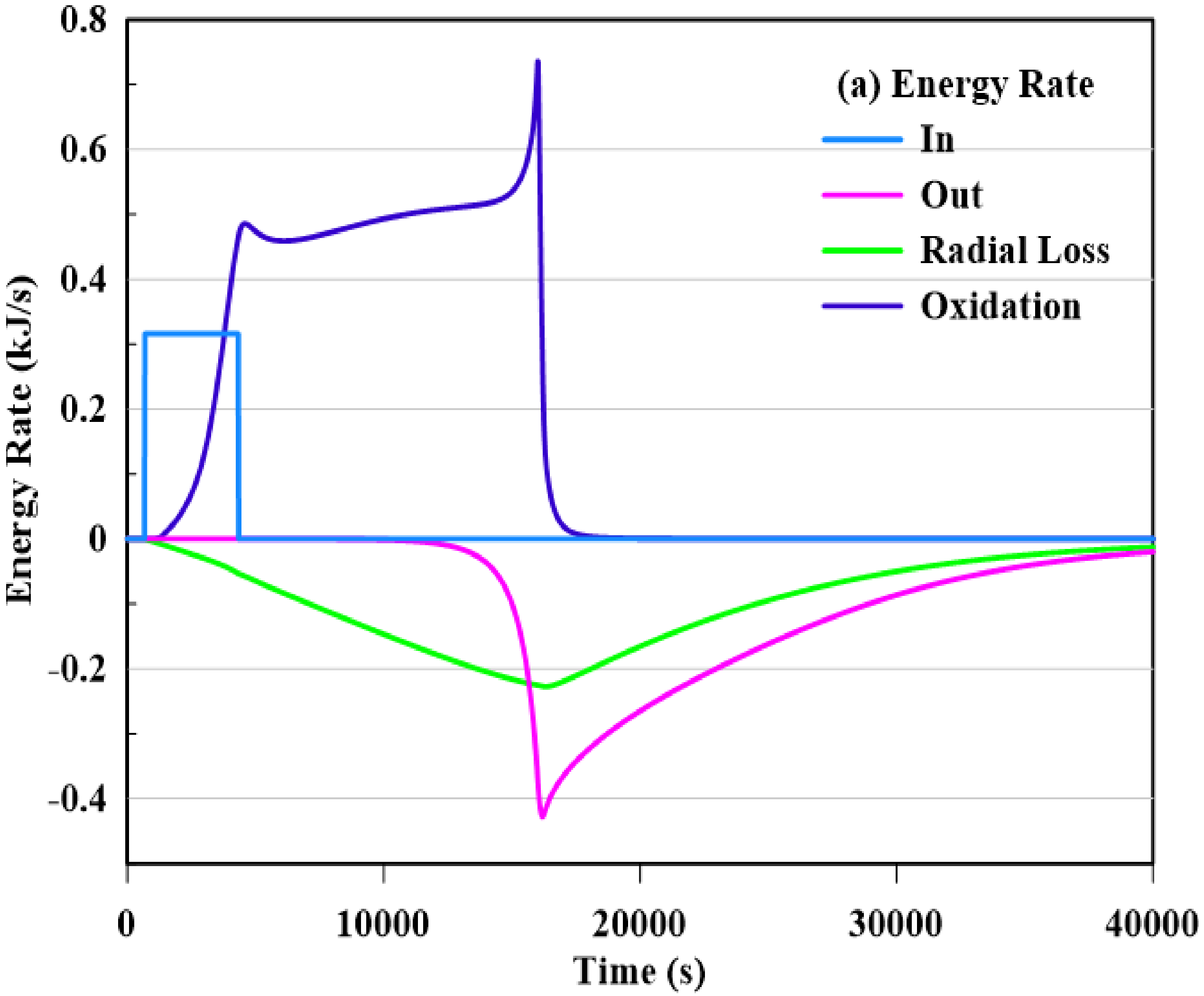
Smouldering Front

Energy Balance Equations

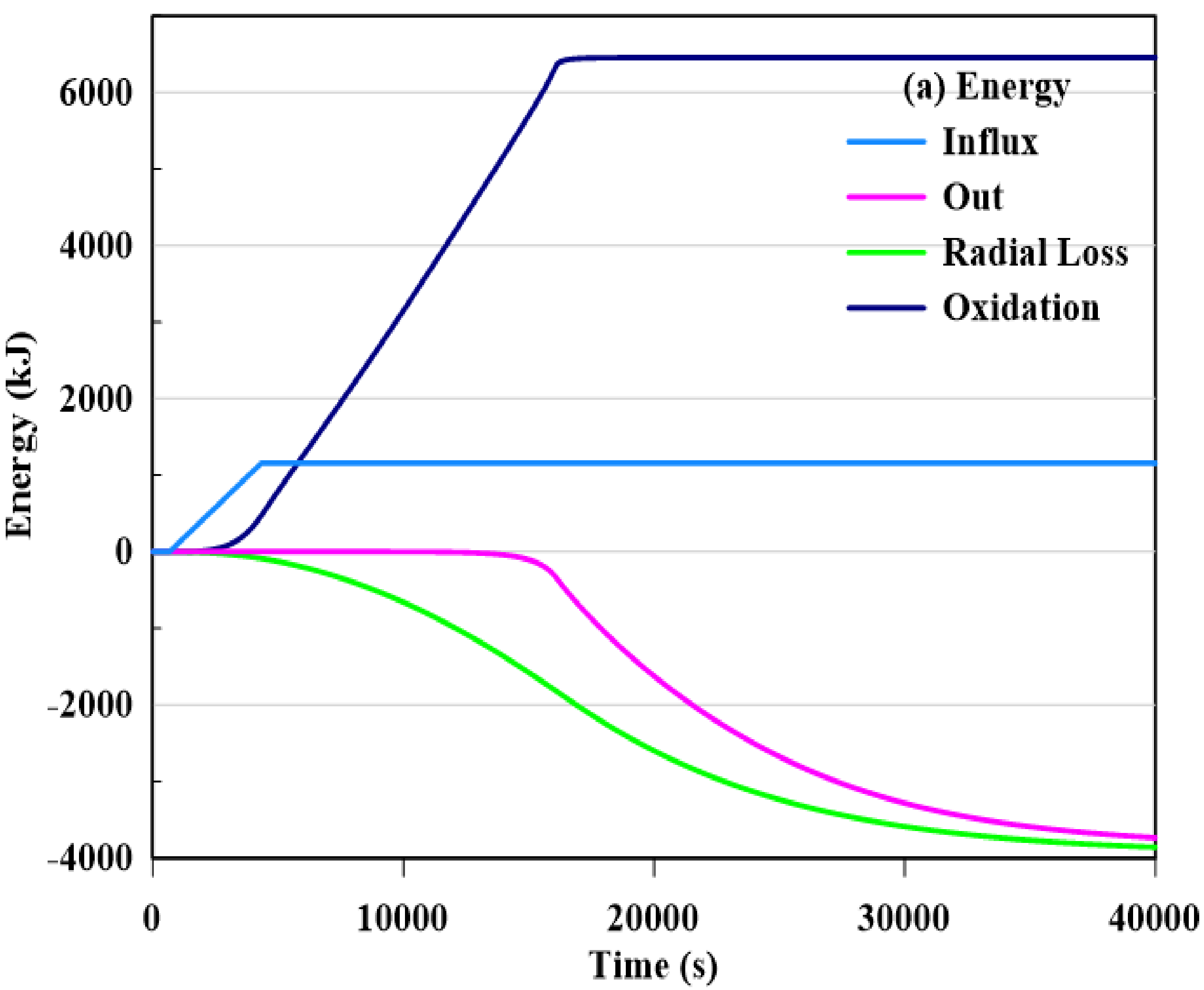
- $\dot{E}_{in} = \int_0^R Q_0 \, 2\,\pi \,\mathrm{rdr}$
- $\dot{E}_{loss} = \int_0^L H\,(T_{s_{(r=0.062)}} - T_\infty) 2\,\pi\,\mathrm{R}\,\mathrm{dz}$
- $\dot{E}_{out} = \int_0^R (\rho_g u_g)\; C_{p_g} \left(T_{g_{(z=0.735)}} - T_\infty\right) 2\pi\, r\, dr$
- $\dot{E}_{oxi} = \iint_0^L -\Delta H_{GAC} (\rho_{GAC}) R_{GAC} \;\; 2\,\pi\; r\, dr\, dz$



Energy Analysis (Energy Rate – Cumulative Energy)



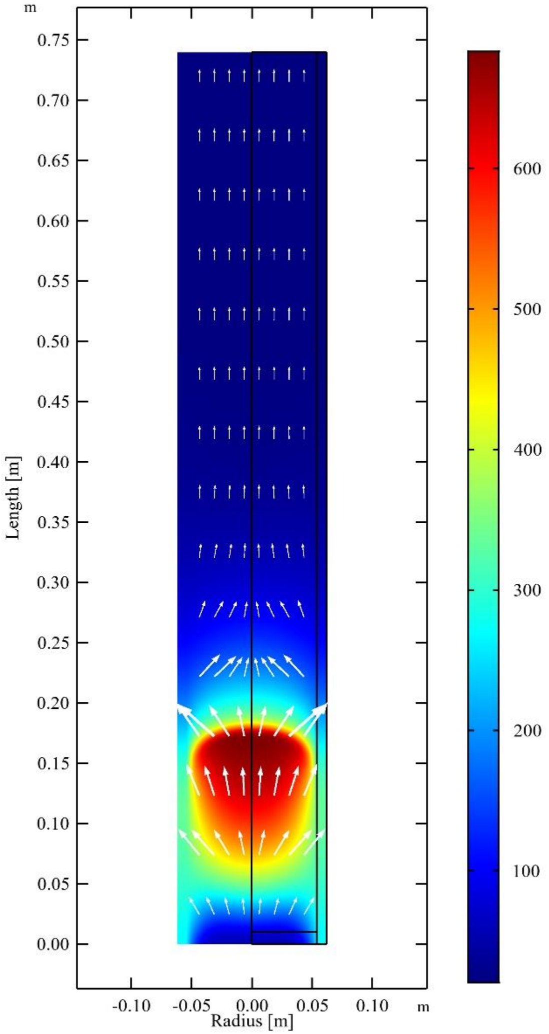
Rate of Energy



Cumulative Energy

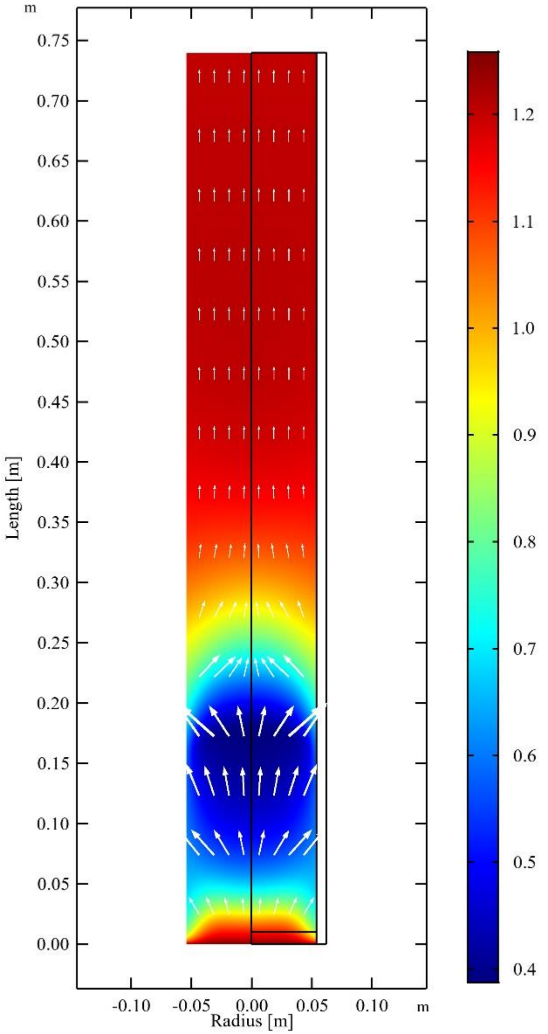
Thermal Heterogeneity

Temperature (°C)



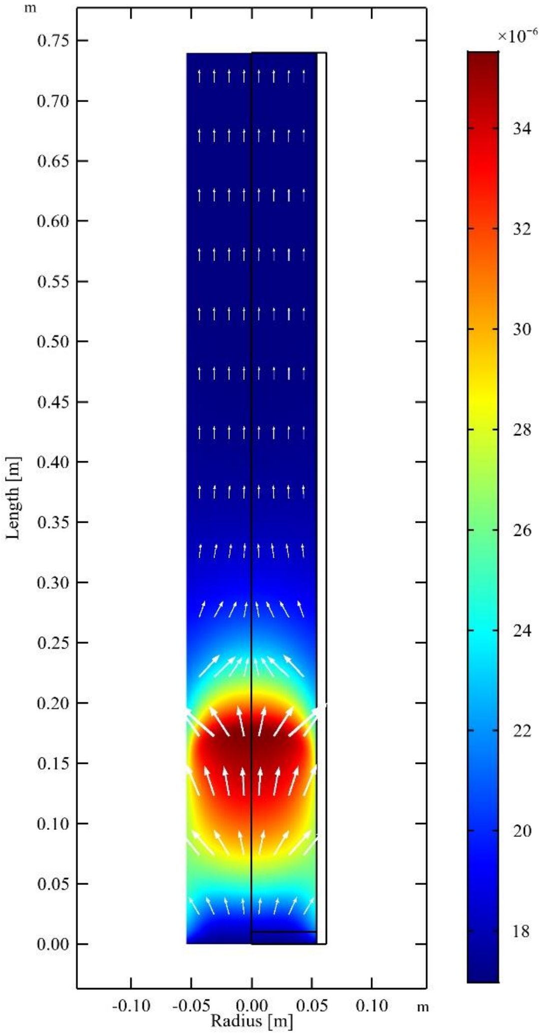
$$T_s$$

Density (kg/m^3)



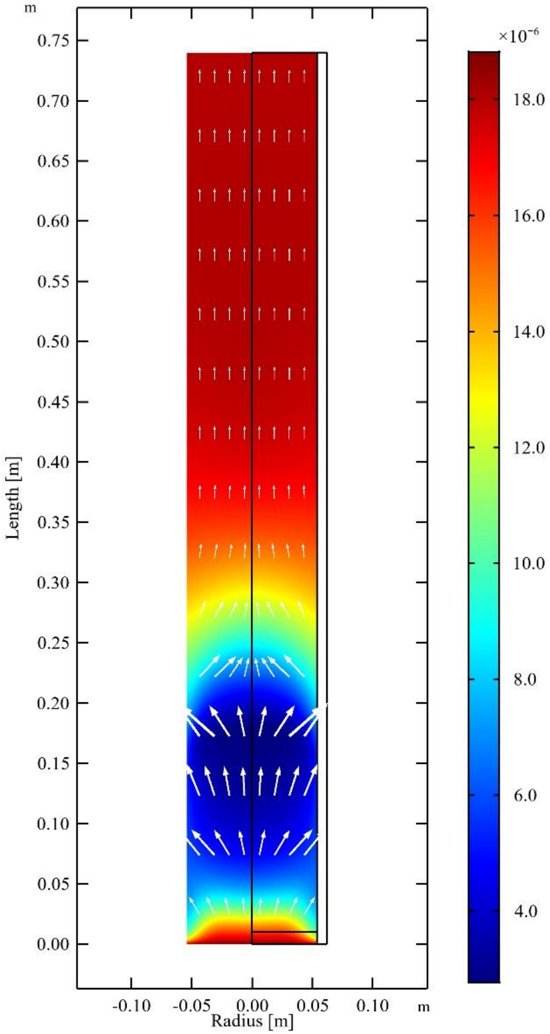
$$\rho_g = \frac{p}{R\,T_g}$$

Viscosity (Pa.s)



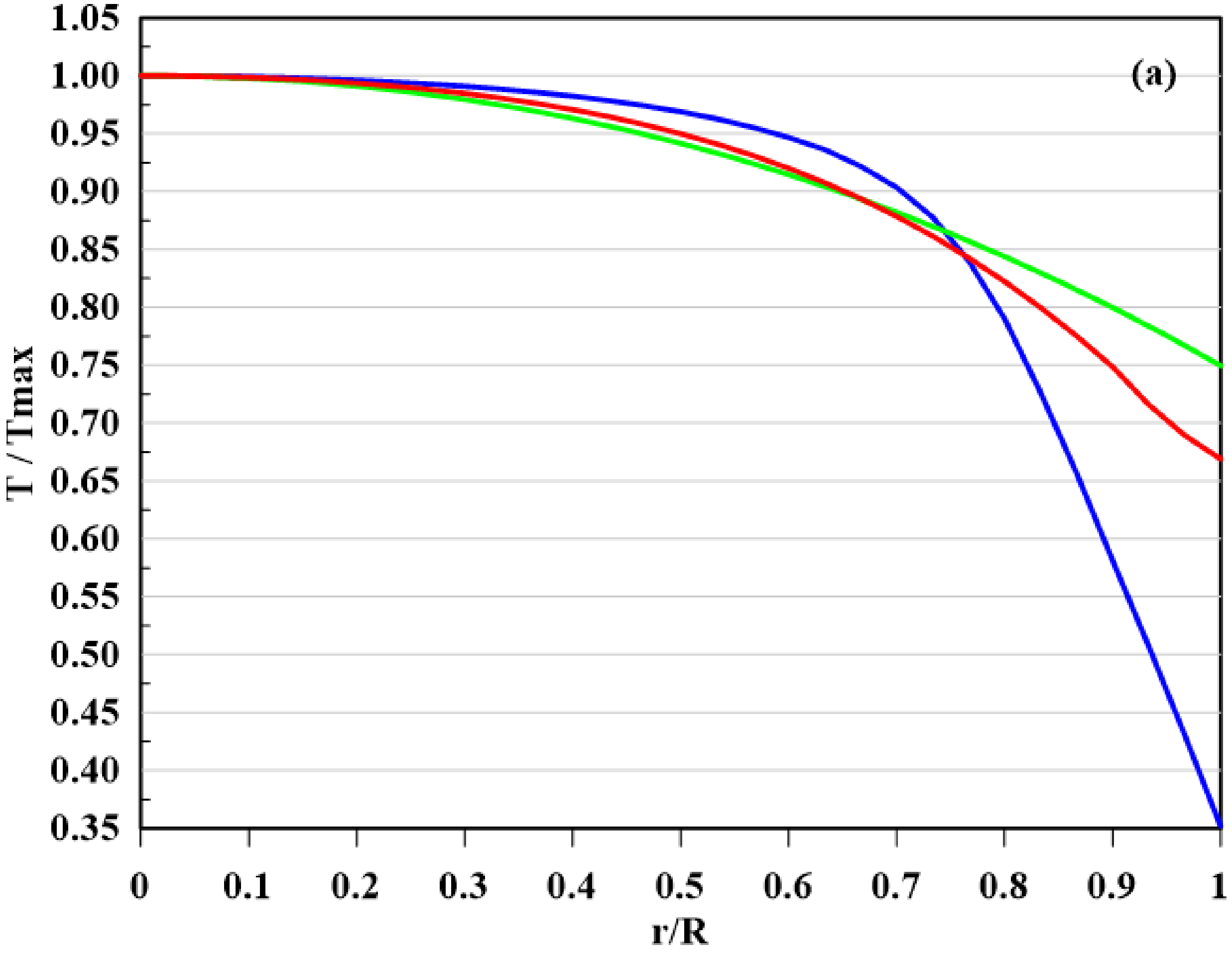
$$\mu$$

Pneumatic Conductivity (m/s)

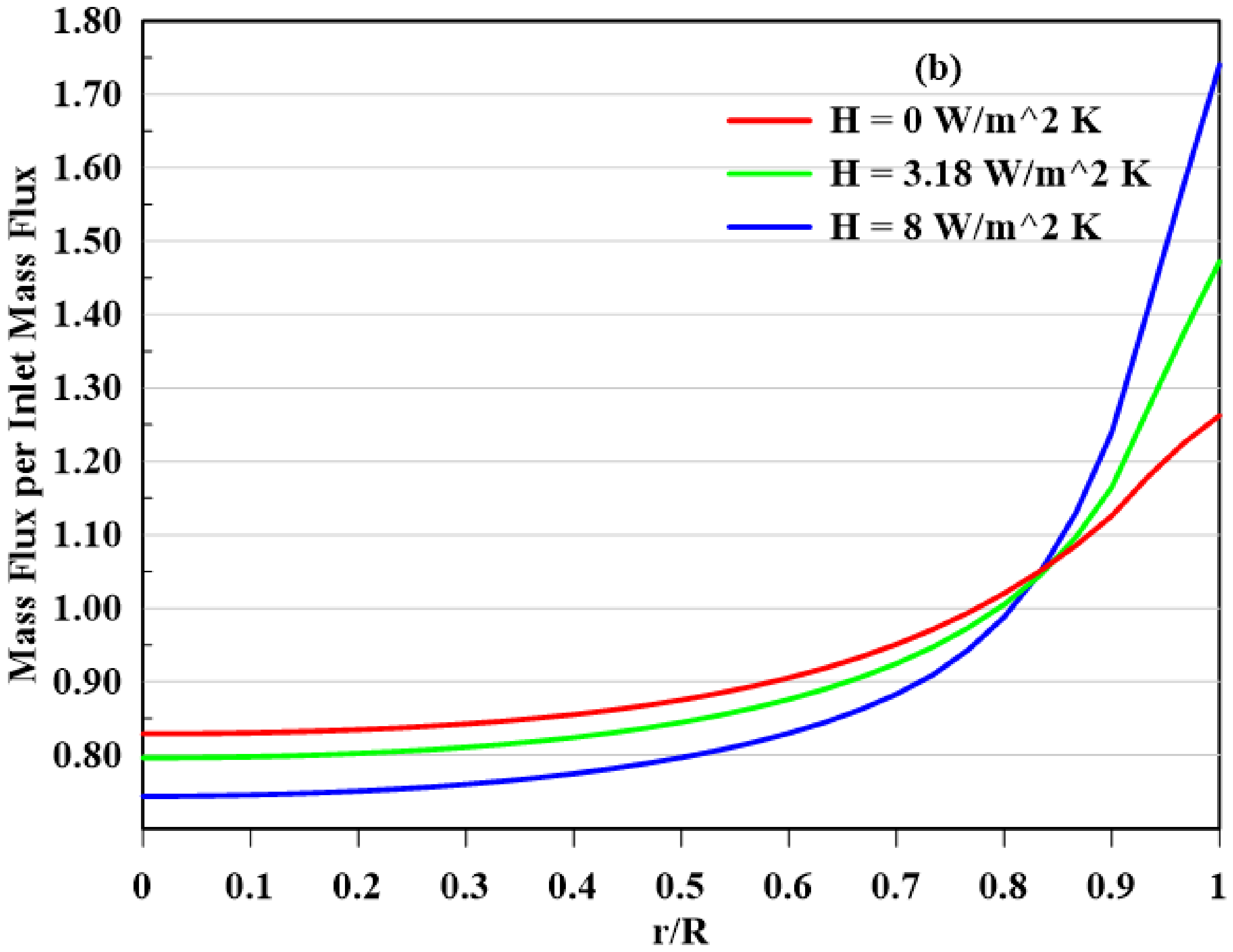


$$K = \frac{k_p\,\rho_g\,g}{\mu}$$

Sensitivity Analysis (Radial Heat Transfer Coefficient (H(W/m2 K)))



Temperature Distribution



Mass Distribution

Part IV: Conclusion

Conclusion

- **Radial Heat loss** transferred **52% of Total Energy** out of the system.
- **Outward trajectory of the air flux vectors** around the **Hot Region** is associated with **Higher Pneumatic Conductivity** pathways near the wall.
- **Thermal Heterogeneity** effects increases by increasing the **Radial Heat loss**.

Thank you!

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Research for Subsurface Transport and Remediation

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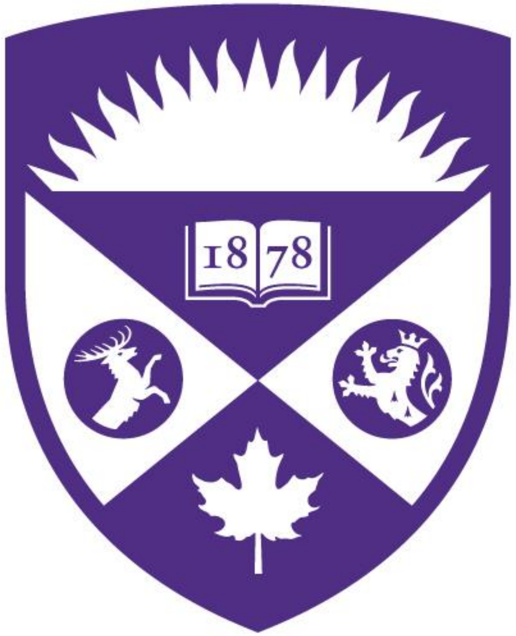

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