Continuous Casting Consortium

MechSE

CCC Annual Report

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Modeling SEN Preheating

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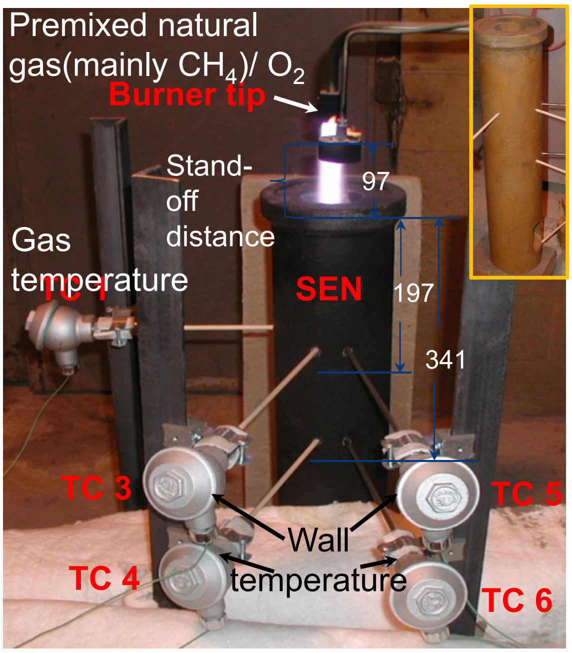
Objectives

- Develop an accurate preheating model to optimize preheating process:
  - Fuel composition;
  - Preheating time;
  - Torch configuration;
  - Insulation;
  - Refractory conductivity.
- Obtain **air entrainment**, flow and temperature distributions from combustion model.
- Evaluate Flame Temperature Model (in spread-sheet).

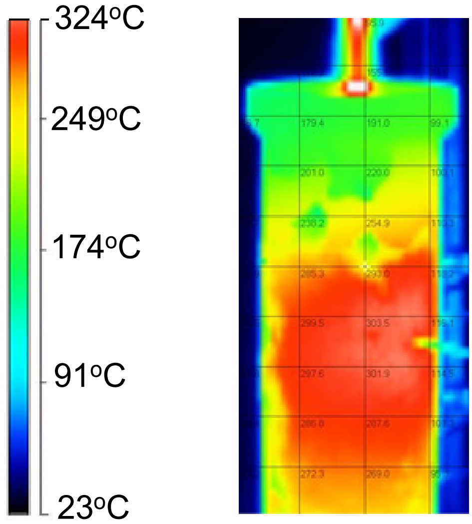
Preheating experiment setup[1]

Two-port SEN



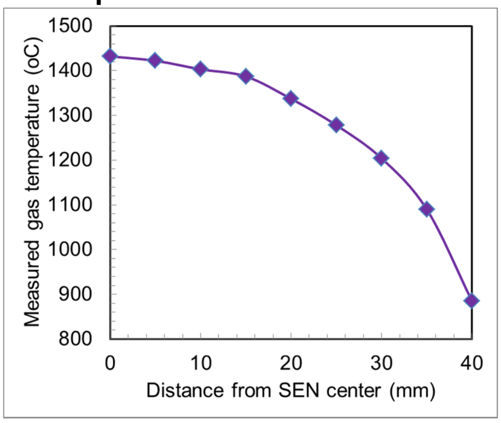
Unit: mm

Infra-red photo of SEN outside wall



Measurements[2] (for model validation)

1. Gas temperature 197mm below SEN top



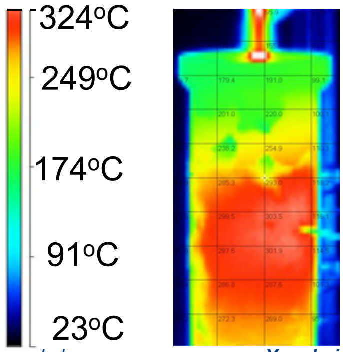
2. Wall temperature (transient are not listed here.)

Thermocouple	*TC3*	*TC4*	*TC5*	*TC 6*
X (mm)*	394	538	394	538
Y (mm)*	48	48	69	69
Temp. (°C)	584	554	453	397

X: Distance from top air inlet;
Y: Distance from SEN centerline.

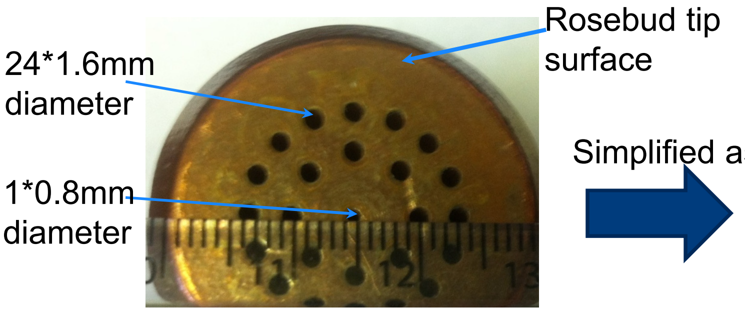
3. The shape of flame

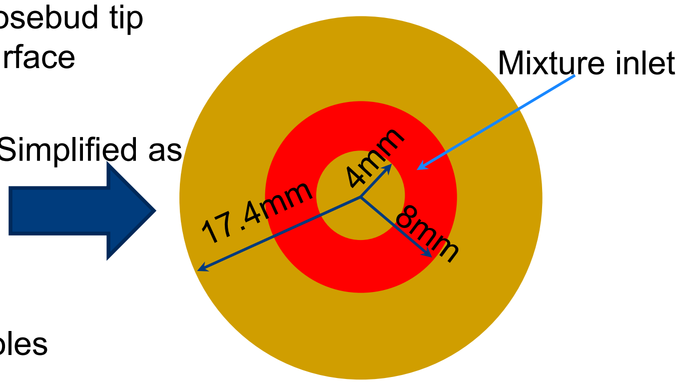
4. SEN outside wall temperature



Thermal – Flow Model

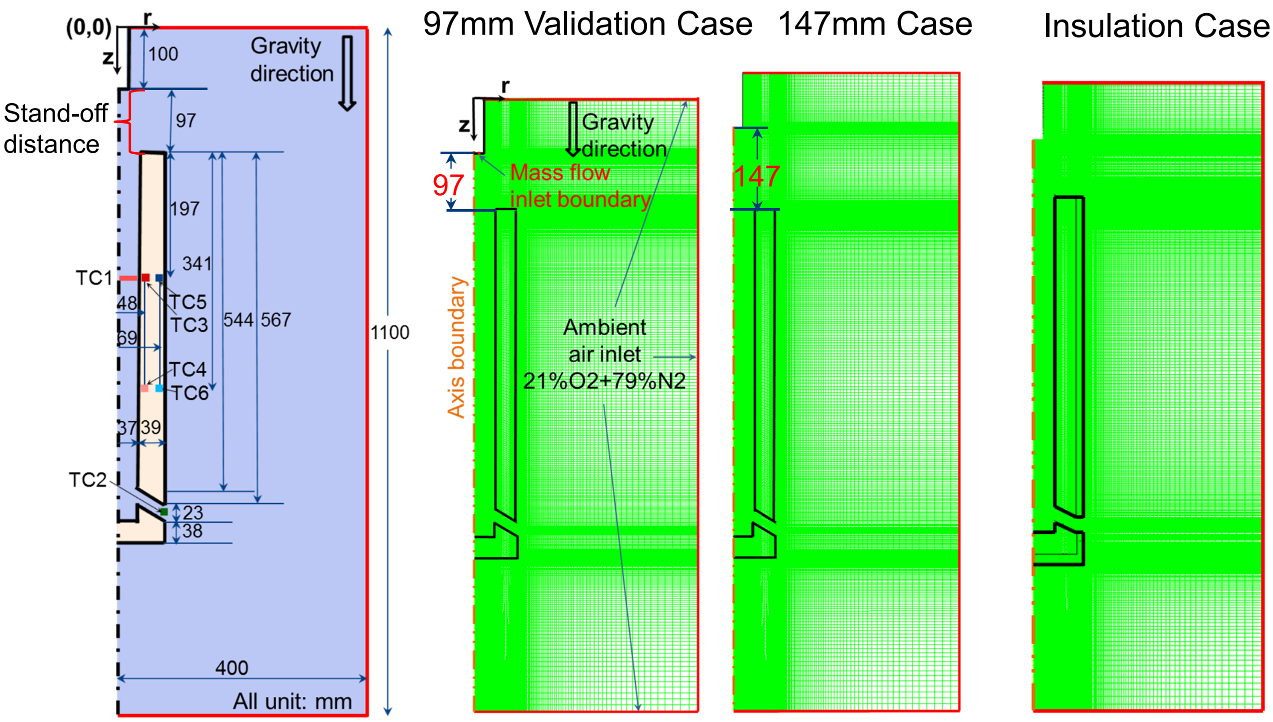
- FLUENT simulation is 2D axisymmetric.
  - The two-port SEN is simplified as a ring shaped port with the same exit area.
- The burner tip is assumed as annular shape with 3× bigger area.
  - To avoid supersonic and mesh refinement at burner tip, accounting for gas expansion.





17.4mm diameter of outer ring of holes

Model geometry and mesh



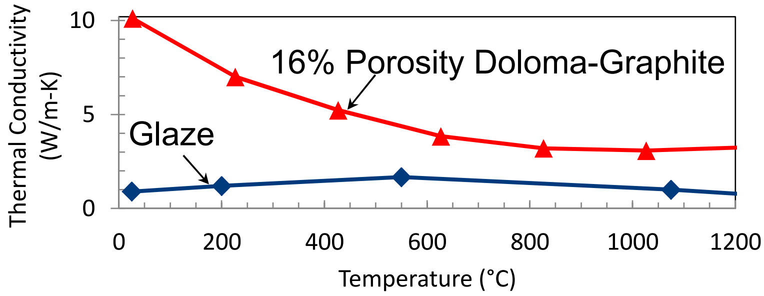
88843 quadrilateral cells total

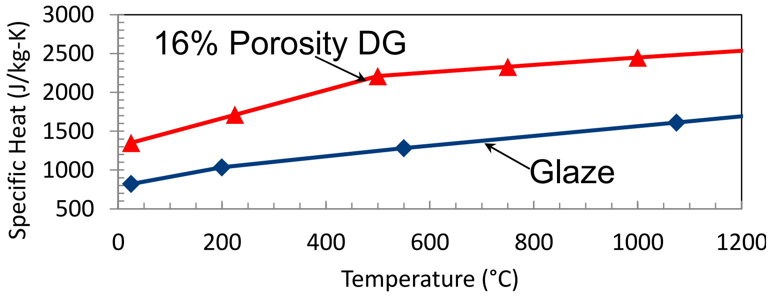
1-mm coating layer with 4 cells through thickness

Material Properties

- Flow
  - ✓ Species thermodynamic properties: thermo.db
  - ✓ Gas average [3] thermal conductivity 2.7006 W/mK
  - ✓ viscosity 9.32×10^{-5} kg/m

- SEN [1,4,5]





Key features--combustion

- Non-premixed species model.
- Fuel inlet: perfectly mixed CH_4 and O_2 in 1:2 mole ratio in a total mass flow rate of 3.8 g/s[2].
- Ambient air entrainment.
- Non-adiabatic energy treatment.
- GRI-Mech 3.0[6] natural gas combustion mechanism, contains 325 reactions and 53 species.

Model validation

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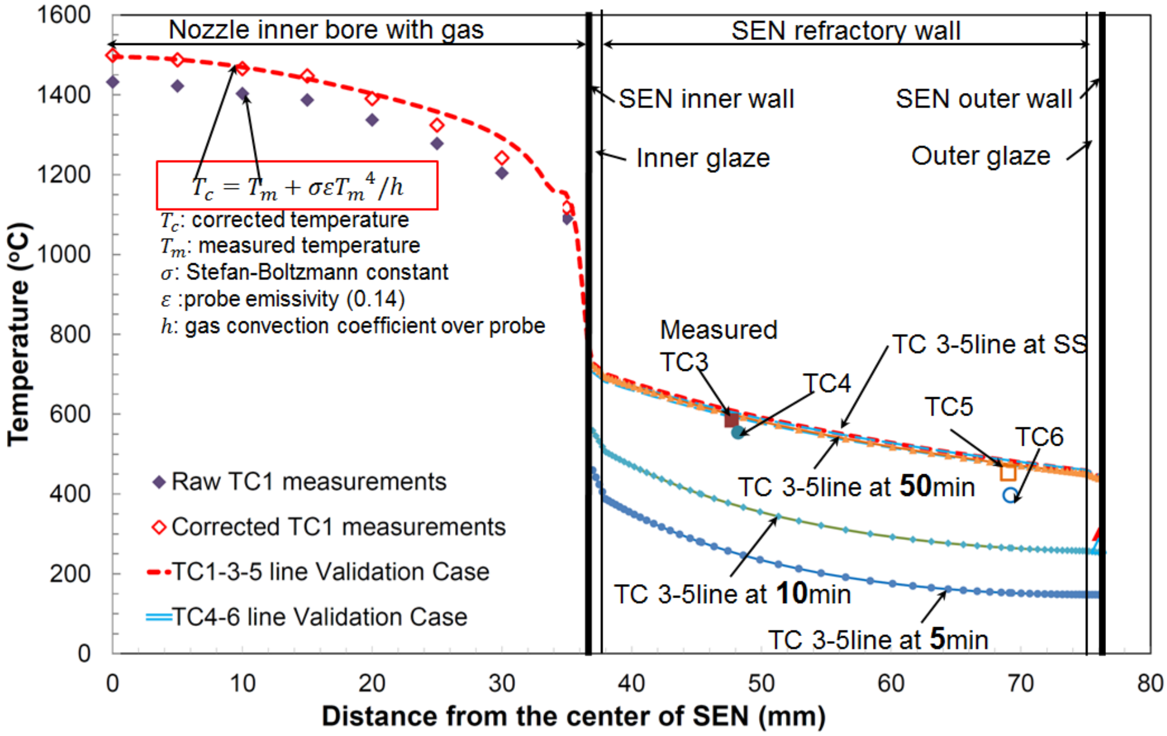
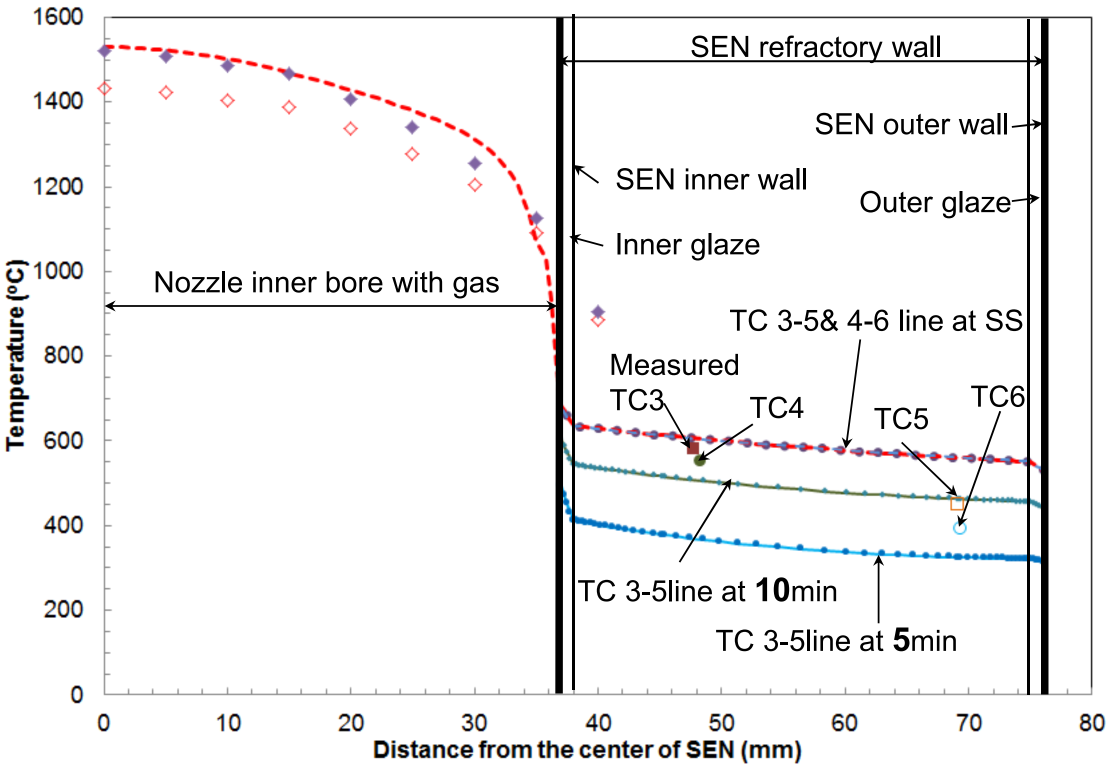
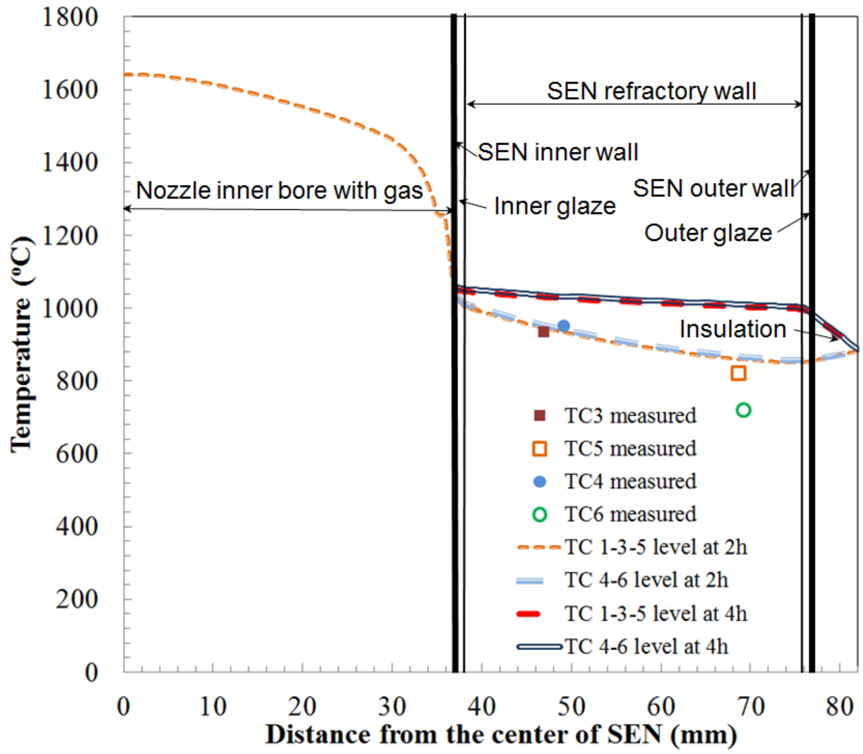
Temperature across SEN: 97mm Validation Case



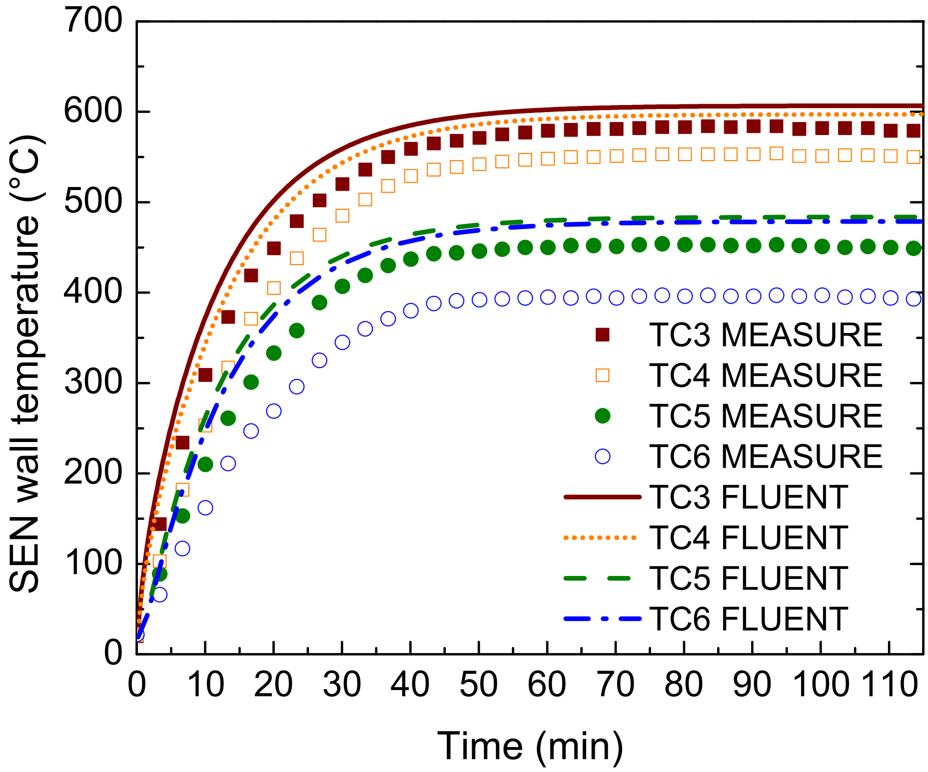
Temperature across SEN: High-k Refractory Case



Temperature across SEN: Insulation Case



Transient temperature validation



TC 3 error= 25°C

TC 4 error= 45°C

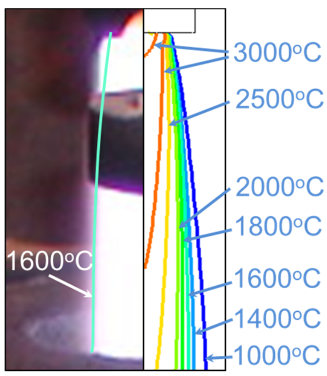
TC 5 error= 32°C

TC 6 error= 83°C

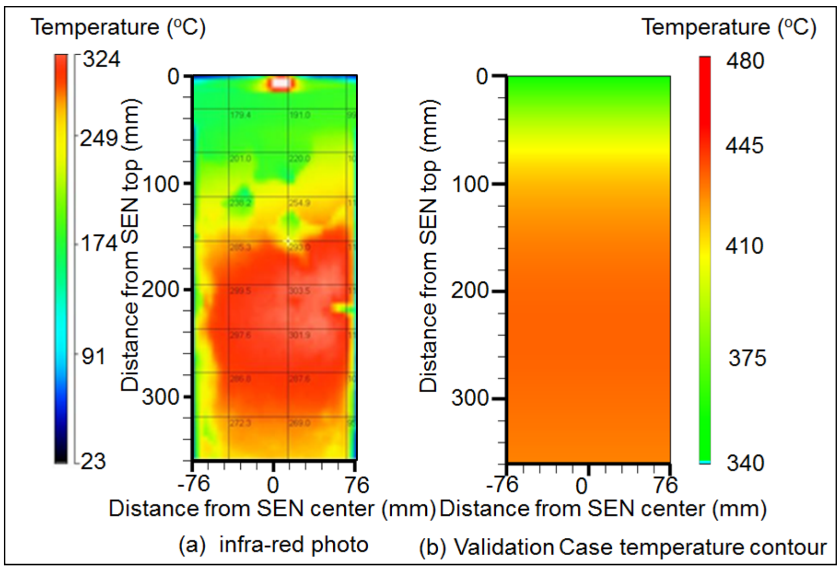
Error causes:

- Excessive thermal conductivity/diffusivity due to uncertain refractory properties
- Neglect of Zirconia sleeve at lower part of SEN
- Neglect of contact resistance at TC tip

Flame shape & Outer wall temperature contour validation



Flame shape comparisons of predicted temperature contours and close-up photograph



SEN outer wall temperature comparison

Model Parametric study

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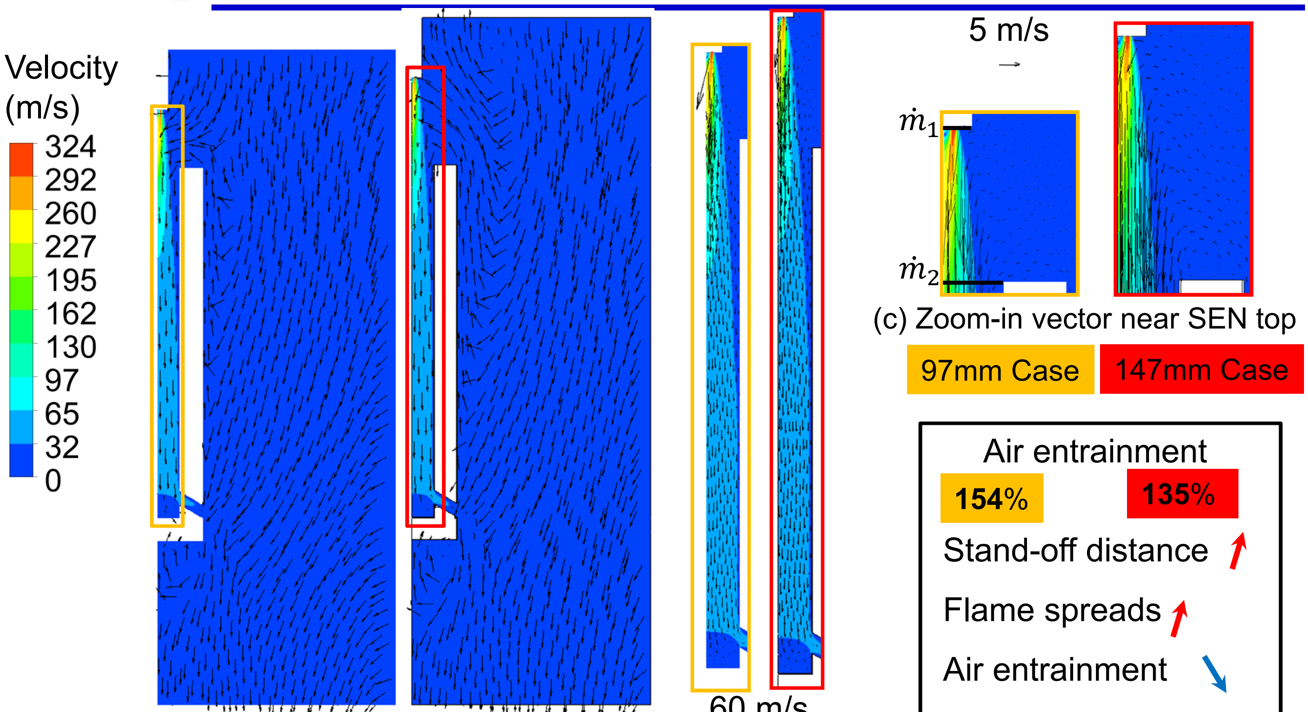
Inputs of 4 cases

Model Inputs	97mm Validation Case	147mm Case	Insulated Case	High-k Case
Thermal conductivity	DG, Glaze	DG, Glaze	DG, Glaze, Insulation	DG, Glaze
Specific heat	DG, Glaze	DG, Glaze	DG, Glaze, Insulation	DG, Glaze
Stand-off distance	97mm	147mm	97mm	97mm
Insulation layer	No	No	Yes	No

Flow distribution



(a) Direction arrows in the whole domain

(b) Velocity vector inside SEN

(c) Zoom-in vector near SEN top

Air entrainment

154% | 135%

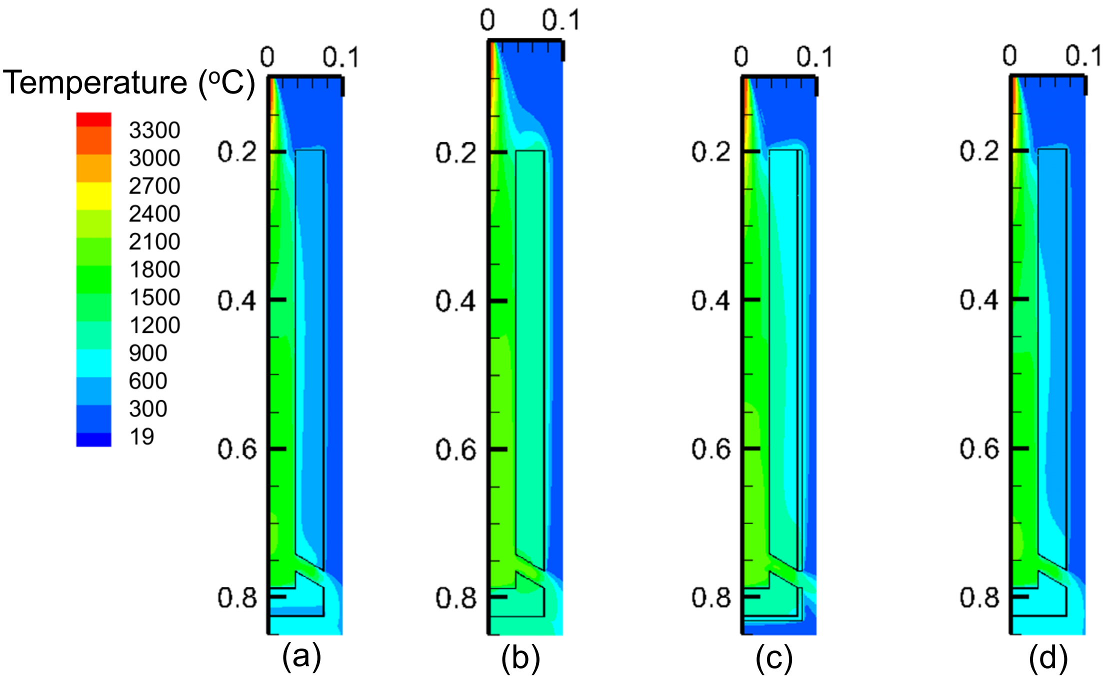
Stand-off distance ↑

Flame spreads ↑

Air entrainment ↓

Flame temperature ↑

Temperature distribution



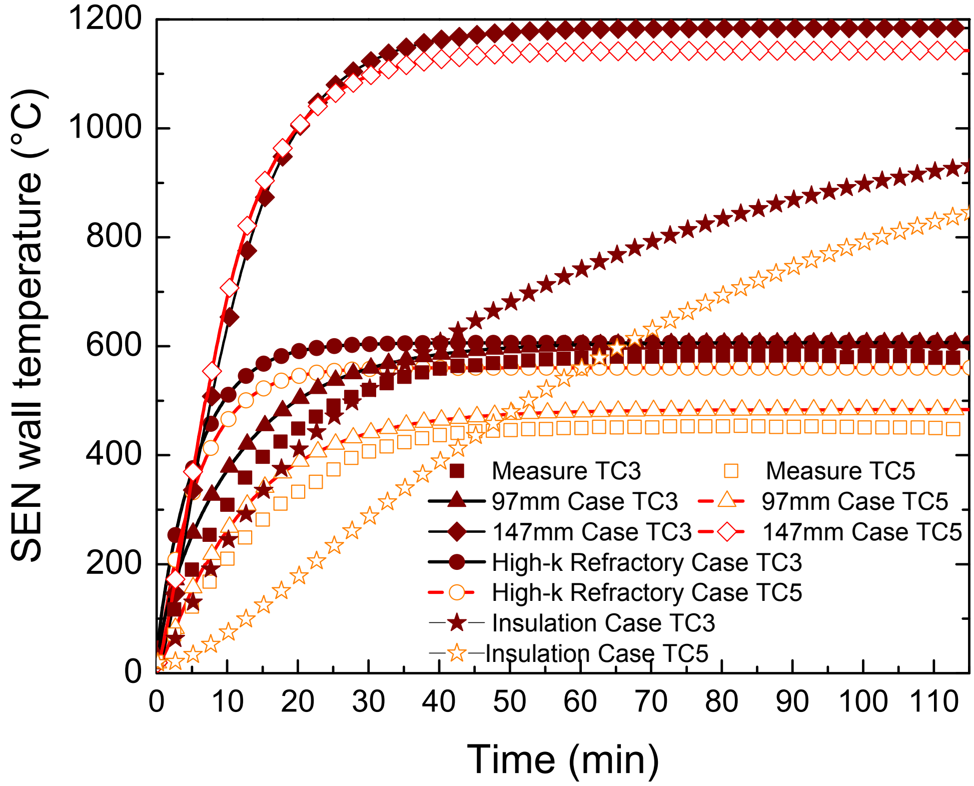
(a) 97mm Validation Case

(b) 147mm Case

(c) Insulation Case

(d) High-k Refractory Case

Transient temperature comparisons among 4 cases



Flame Temperature Model in Excel VBA

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Flame Temperature Model(VBA)

Inputs
Fuel type
Oxygen source
Oxygen source fraction
Air entrainment
Reactants temperature
Reactants pressure

Gaseq[7] →

Outputs
Flame/Products temperature
Products pressure
Species component
Products properties
Force convection coefficient
Free convection coefficient

- Gaseq[7]: a chemical equilibrium program which can predict adiabatic temperature and composition at constant pressure.

- Oxygen Source Fraction = $\frac{\textit{mole of oxygen input}}{\textit{mole of oxygen required for stoichiometric reaction}}$
- Air Entrainment = $\frac{\textit{mole of entrained air}}{\textit{mole of air needed for stoichimetric reaction}}$

Flame Temperature Model Results

	Combustion Model	Measurement		Result	Comb. Model
	Air entrainment	**Oxygen source fraction**	**Reactants Temp.**	**Flame Temp.**	**Flame temp.**
97mm Validation Case	154%	100%	19 ^oC	1328 ^oC	1343^oC
147mm Case	135%	100%	19 ^oC	1451 ^oC	1587^oC

Reactants, products pressure is 1atm.

Simple spread-sheet model can predict flame temperature approximately without sophisticated chemical reactions and thermal hydraulic models.

Conclusions

- A **2D axisymmetric** model of nozzle preheating is developed, including **325 chemical reactions with 53 species** of methane combustion.
- **Steady-state** fluid flow, heat transfer and gas combustion, and **transient** heat conduction in the SEN walls are simulated.
- **The model predictions were validated** with a preheating experiment, including the gas temperature across the flame, SEN wall temperature histories, flame shape, and SEN outer wall temperature distribution.
- Moving the burner further away from the SEN top leads to **higher** SEN temperature, due to flame expansion causing less air entrainment.
- Adding **an insulation layer** causes higher SEN wall temperatures and **milder temperature gradients**.
- **Increasing refractory conductivity** causes **milder temperature gradient** at SEN.
- To optimize preheating, a proper stand-off distance, stoichiometric fuel composition, proper refractory thermal properties , and insulation layers are recommended.
- A simple **spread-sheet model** of the adiabatic flame temperature **predicts gas temperature** approximately, based on knowing the **air entrainment**.

Acknowledgements

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