Numerical simulation of heterogeneous porous media burners using volume averaged modeling

Aniruddha Saha, Sadaf Sobhani
Department of Mechanical and Aerospace Engineering, Cornell University, NY, USA

RemPlex Global Summit 2023

PNNL, Washington, USA

MODELING FRAMEWORK

Porous media combustion

Solid

Fluid

Heat transfer properties

Microstructures

Closure models

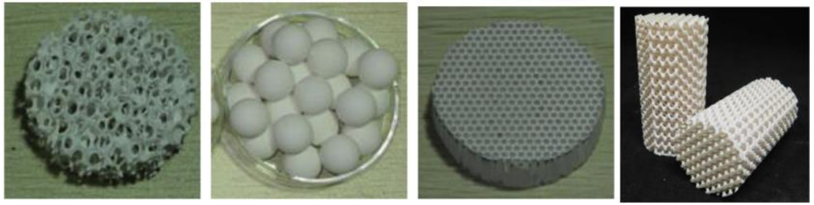
Flame stability

Emissions

Packed beds of spheres, arrays of staggered cylinders, fiber lamellae, ceramic or metal foams.

Reaction mechanism

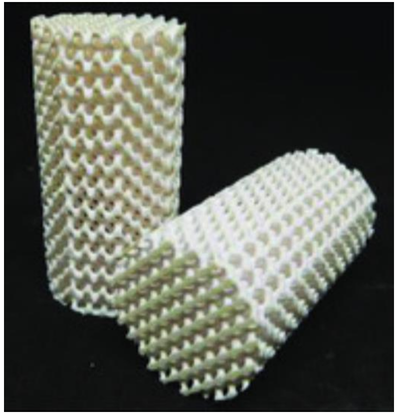
Flow conditions



How can we modulate these properties to obtain desired combustion characteristics?

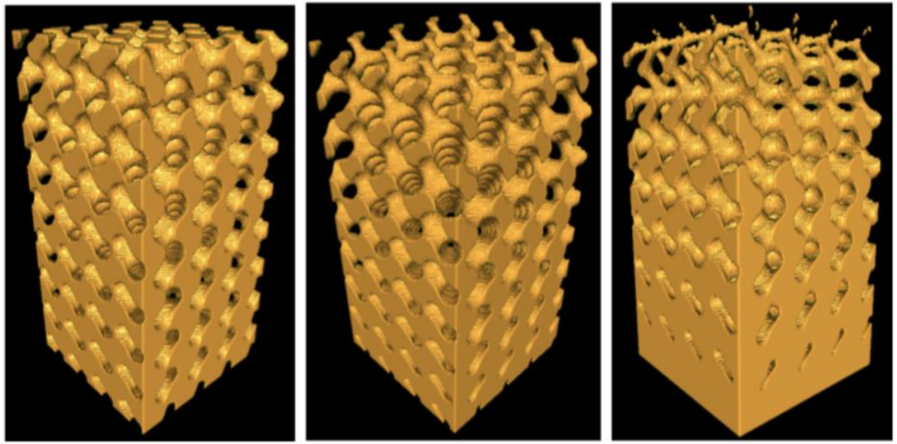
MOTIVATION

- Porous media allows combustion to take place in lower fuel/air ratio (leaner equivalence ratio)
- Microstructure affects the performance of porous media combustion



Uniform pore size

Two stage pore size

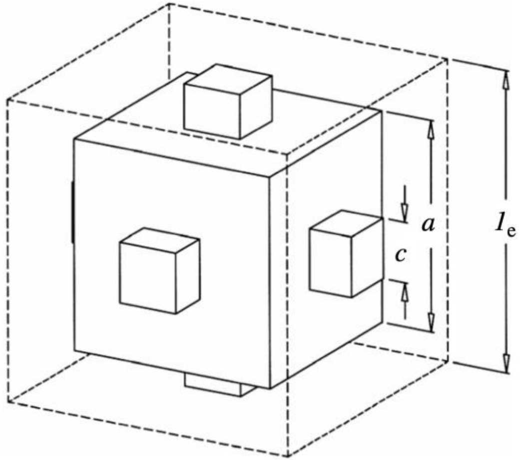


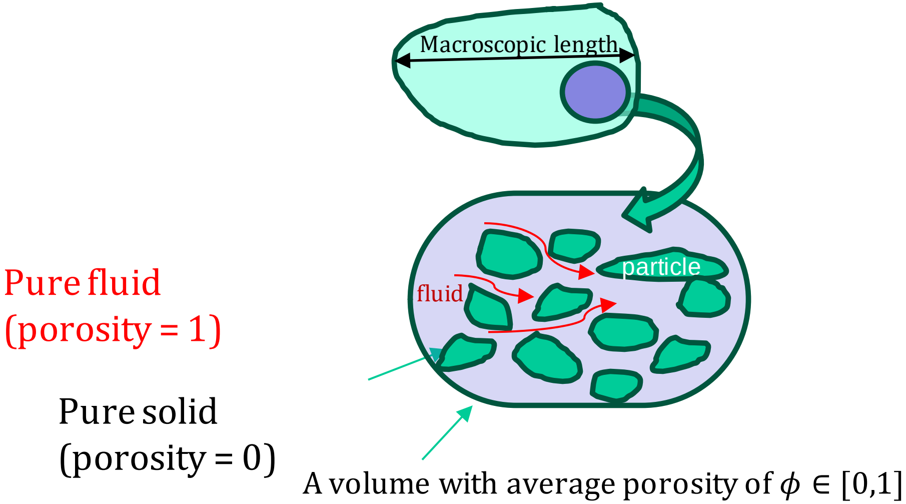
Graded pore size

Sobhani, Sadaf, et al. "Experimental feasibility of tailored porous media burners enabled via additive manufacturing." *Proceedings of the Combustion Institute* 38.4 (2021): 6713-6722

BACKGROUND

- Combustion simulations using pore resolved model is computationally expensive
- The microstructure affects heat transfer and performance of the burner
- The microscopic variations in the microstructure is absorbed in an averaged macroscopic model
- Volume Averaged Modeling can easily capture the global performance of the system





Hsu, Chin Tsau, Ping Cheng, and Ka Wai Wong. "A lumped-parameter model for stagnant thermal conductivity of spatially periodic porous media." (1995): 264-269.

EQUATIONS

$$\overline{\nabla} \cdot \mathbf{U} = 0$$

Continuity equation

$$\rho \left[\frac{\partial}{\partial t}(\mathbf{U}) + \overline{\nabla} \cdot (\mathbf{U}\mathbf{U}/\epsilon) \right] = -\overline{\nabla}(\epsilon P) + \rho \overline{\nabla} \cdot [\nu \overline{\nabla}(\mathbf{U})]$$

Momentum conservation

$$\rho c_{\mathrm{pg}} \frac{\partial(\epsilon \overline{T})}{\partial t} + \rho c_{\mathrm{pg}} \overline{\nabla} \cdot (\mathbf{U}\overline{T}) = \lambda_g \overline{\nabla} \cdot (\epsilon \nabla \overline{T}) + h_v(\overline{T}_{\mathrm{s}} - \overline{T})$$

Fluid energy conservation

$$\rho_{\mathrm{s}} c_{\mathrm{ps}} (1 - \epsilon) \frac{\partial \overline{T}_{\mathrm{s}}}{\partial t} = \overline{\nabla}(\lambda_{s,\mathrm{eff}} \overline{\nabla T}_{\mathrm{s}}) - h_v(\overline{T}_{\mathrm{s}} - \overline{T})$$

Solid energy conservation

$$\epsilon\rho \frac{\partial Y_i}{\partial t} + \epsilon\rho \mathbf{U} \cdot \nabla Y_i = \rho \nabla \cdot (\epsilon D_{im} \nabla Y_i) + \epsilon \dot{\omega}$$

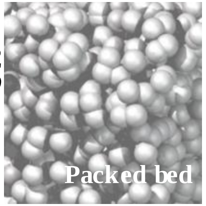
Species conservation

The closure of the volumetric heat transfer coefficient h_v depends on the microstructure

CLOSURE MODELS

- Closure models
  - Coupling of the heat transfer between the solid and the gas phases
  - Heat transfer properties depends on the flow, microstructure and the material

$$h_v = 6k_g(1-\epsilon)\left[2 + 1.1\mathrm{Pr}^{1/3}\mathrm{Re}_p^{0.6}\right]/d_p^2$$



$$h_v = 0.146k_g\mathrm{Re}^{0.96}/d_p^2$$

- Flame stabilization
  - Anchoring the flame is important for stable combustion
  - Porous media enables flame stabilization at leaner equivalence ratios
  - Enhanced heat recirculation in the structure

Hashemi, S. M., & Hashemi, S. A. (2017). Flame stability analysis of the premixed methane-air combustion in a two-layer porous media burner by numerical simulation. *Fuel*, *202*, 56-65

Hoda, S. N., Nassab, S. A. G., & Ebrahim, J. J. (2019). Three dimensional numerical simulation of combustion and heat transfer in porous radiant burners. *international journal of thermal sciences*, *145*, 106024.

DETAILS OF SOLVER

- Pore size is modelled as a continuous distribution - A continuous pore size distribution leads to a continuous h_v distribution instead of a two section burner

- Reaction is modelled as a GRI3.0 mechanism - 53 species and 325 reactions

- Solid is inert and does not react with the gas mixture. Thermal non-equilibrium is present between the fluid and the solid matrix

- Solid loses heat through radiation

- The model captures the influence of pore size, thermal conductivity, Reynolds number, fuel mass fractions and is computationally less expensive than a detailed pore scale simulation

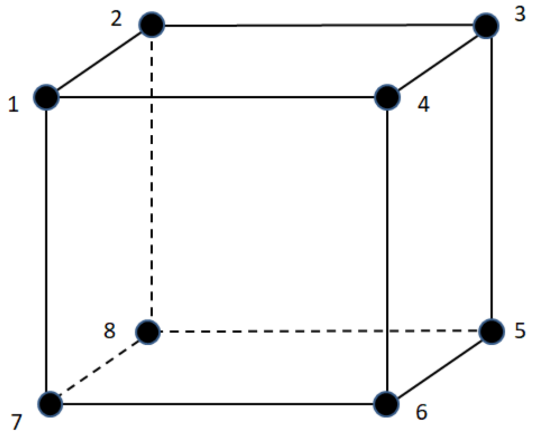
DETAILS OF SOLVER

- Finite volume method solver implemented on OpenFOAM
- Compressible reactive flow solver that uses PIMPLE algorithm
- Utilizing the power of OpenFOAM through continuous distribution of variables

$$(\mathbf{u}, p, Y_i, T)_j \Rightarrow (\epsilon, h_v, \mathbf{u}, p, Y_i, T)_j$$

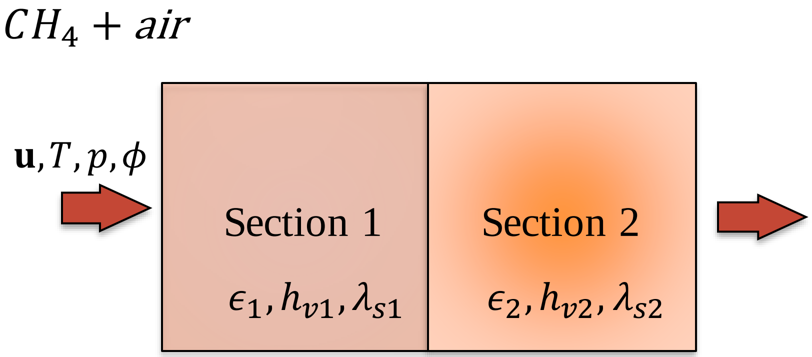
- OpenFOAM supports TDAC for faster chemistry calculation
- Reactions are solved using the Arrhenius rate model

$$k = AT^{\beta} e^{(-T_a/T)}$$

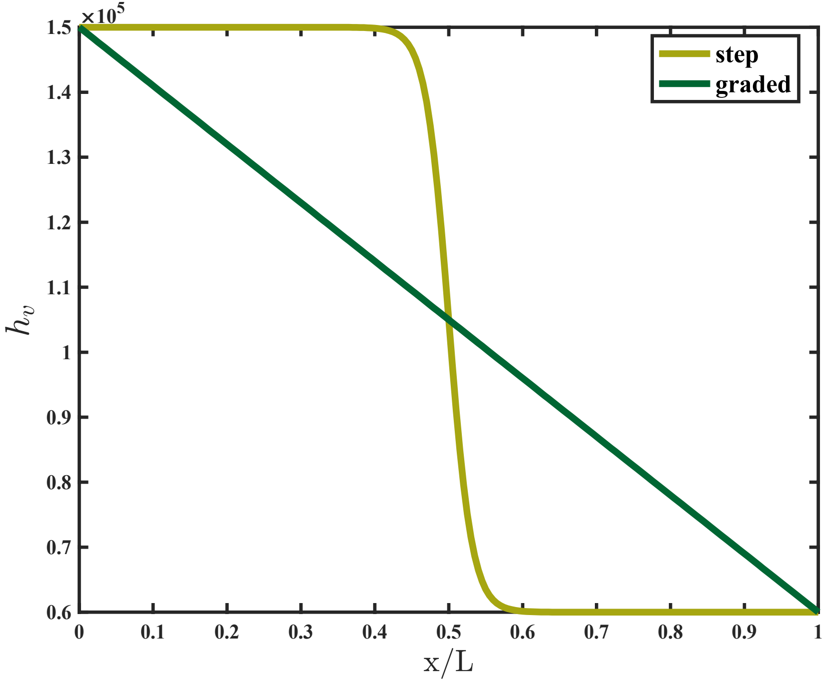


Contino, Francesco, et al. "Coupling of in situ adaptive tabulation and dynamic adaptive chemistry: An effective method for solving combustion in engine simulations." *Proceedings of the Combustion Institute* 33.2 (2011): 3057-3064.

DOMAIN SETUP



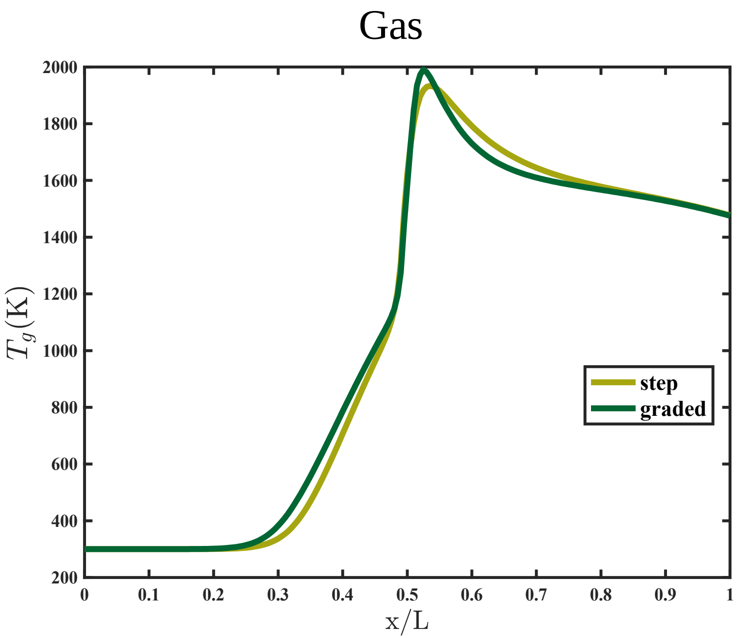
A typical two section porous burner

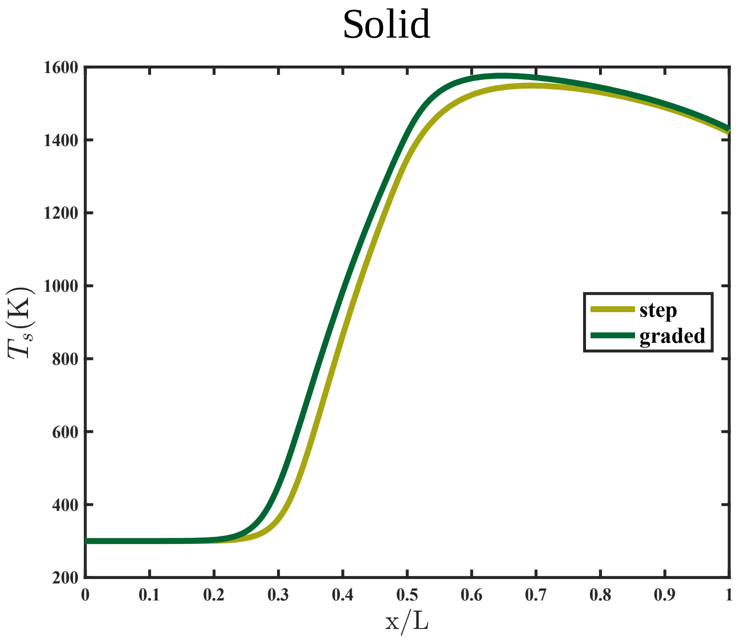


The different burners have different h_v variation

RESULTS

Temperature distribution is responsive to changes in geometry

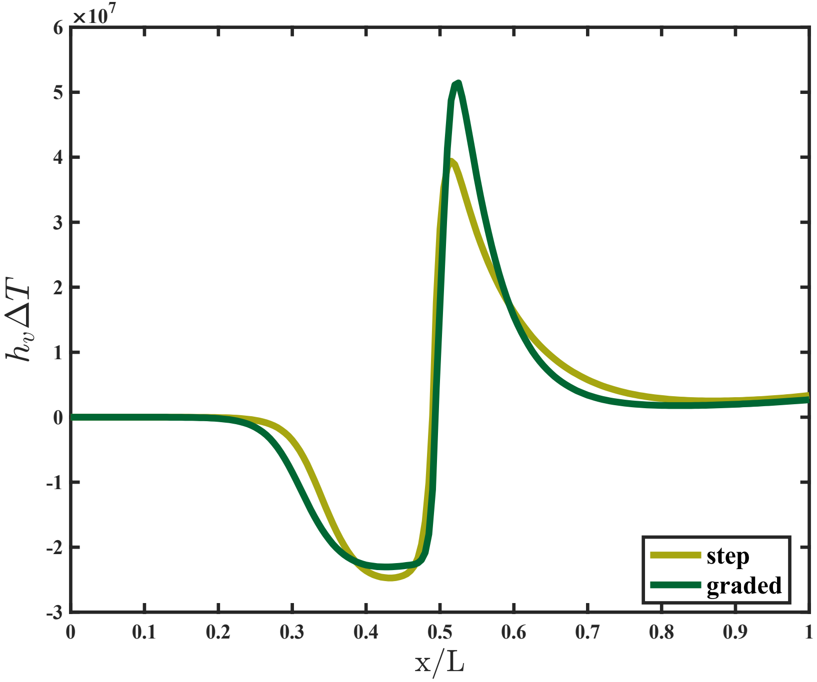




Gas and solid temperature profiles for different burners

RESULTS

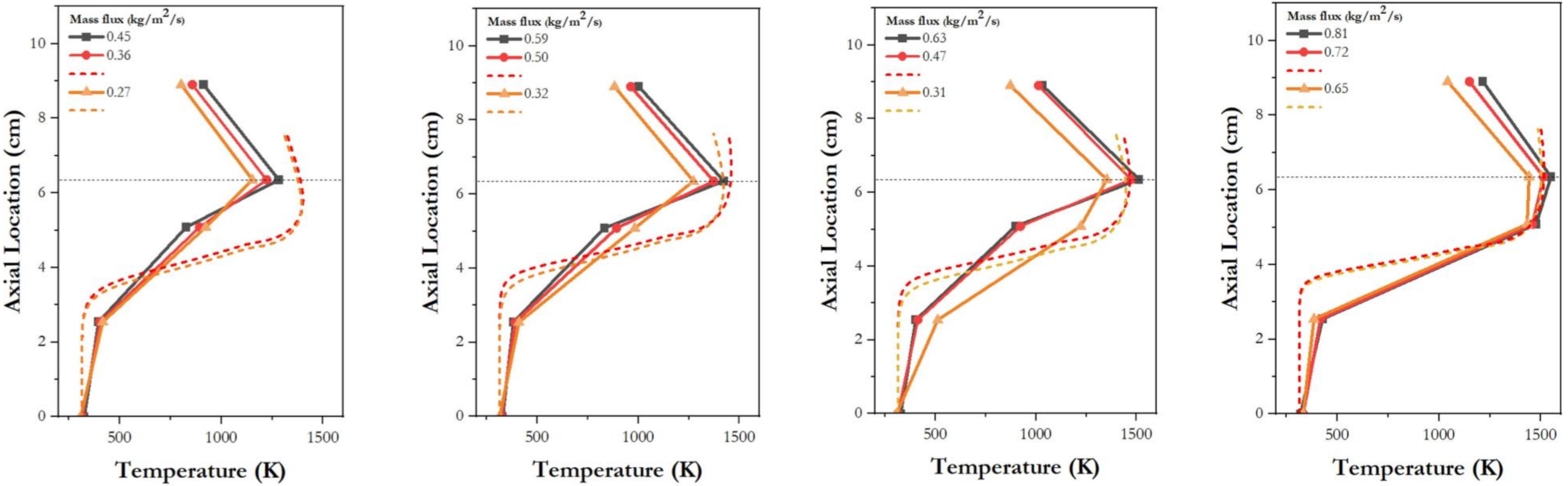
Heat exchange profile shows the relative direction/magnitude of heat flow (Gas⟺ Solid)



Heat exchange between solid and gas for different burners

RESULTS

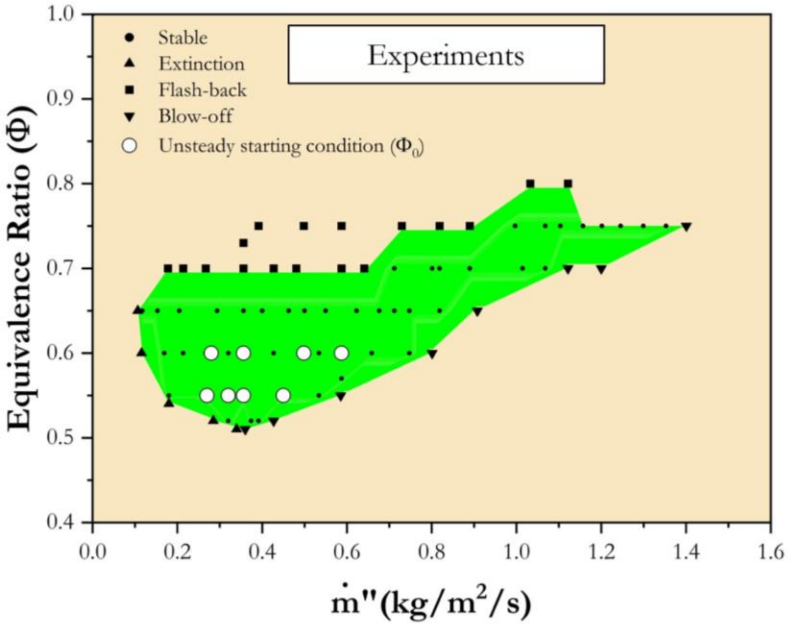
Temperature predictions using solver and experiments

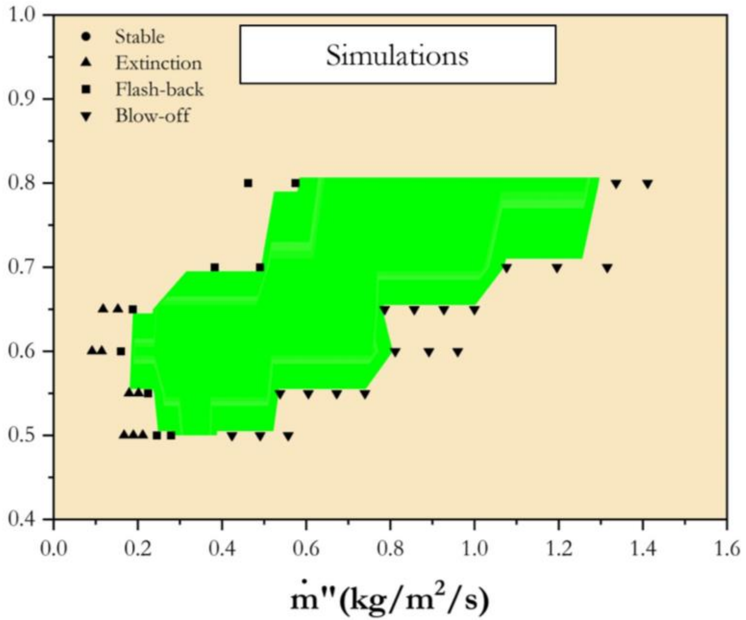


Axial temperature profiles for SiC burner

RESULTS

Sensitivity towards fuel/air ratio and inlet fuel flux





Stability map highlighting the effect of equivalence ratio and mass flux of fuel

CONCLUSIONS

- OpenFOAM solver has been developed for volume-averaged porous media combustion simulations
- A volume averaged model can be leveraged to quickly analyse the flame under certain conditions
- Flame profile can be changed through different microstructures keeping inlet and fuel conditions same
- Possibility of designing structures to attain required combustion characteristics

FUTURE WORK

- Additive manufacturing can enable easier combustion validation for different morphologies
- Combustion of different fuels can be simulated for wide range of applications
- Experimental data for extensive relations pertaining to different closure models

THANK YOU!

Any questions ?