Symposium on Advanced Sensors and Modeling Techniques for Nuclear Reactor Safety

Stratification and Mixing in the Hot Plena of Liquid Metal-Cooled Reactors

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Presenter Information

Hitesh Bindra, Brendan Ward, Graham Wilson, and Abhinav Gairola

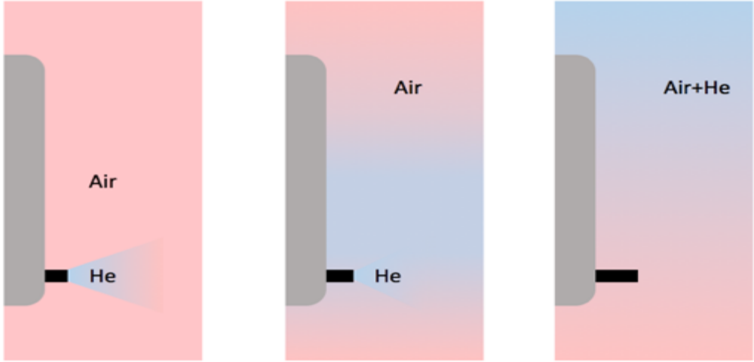
Thermal stratification and mixing in hot plena of Liquid Metal-cooled Reactors

Speaker: Hitesh Bindra

Contributors- Brendan Ward, Abhinav Gairola, Graham Wilson

General: Stratification and mixing in large enclosures

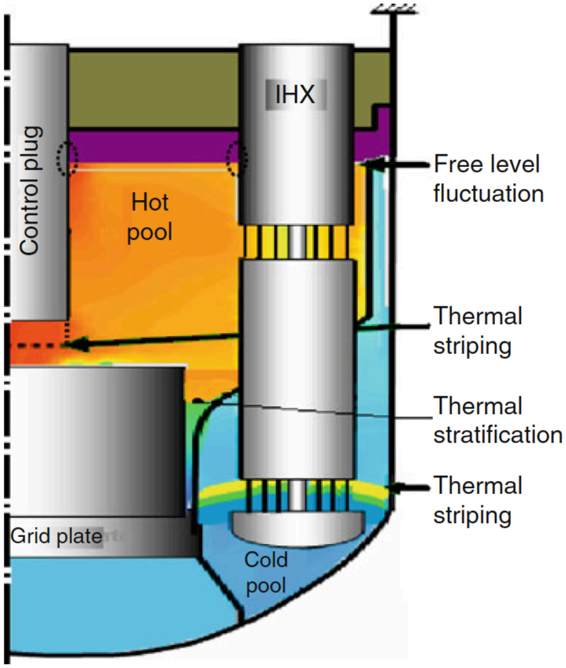
- Hydrogen release in containment under severe accidents
- Helium jets entering reactor cavity- High Temperature Gas-cooled Reactors



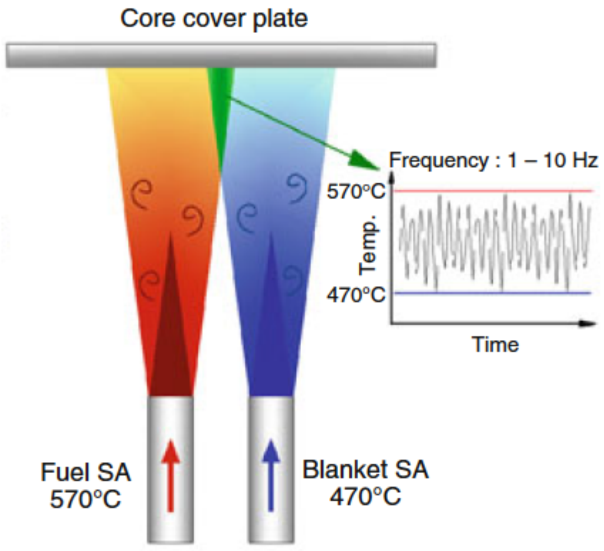
  - Distribution of Helium concentration.
  - Impacts safety

- Reactor plena- Buoyancy, Free Jets, Stratified flows

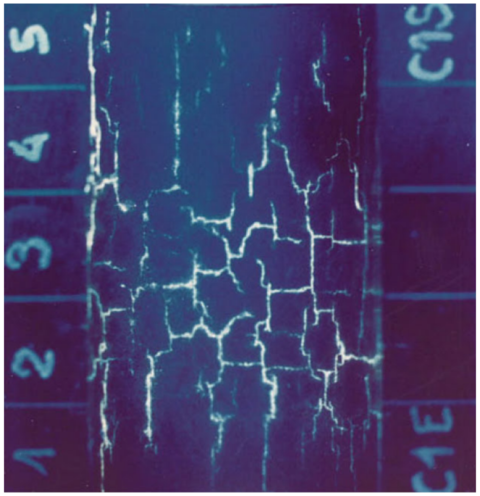
Thermal transients in the pools of Liquid Metal-cooled Reactors



P. Chellapandi et al. / Nuclear Engineering and Design 239 (2009) 2754–2765



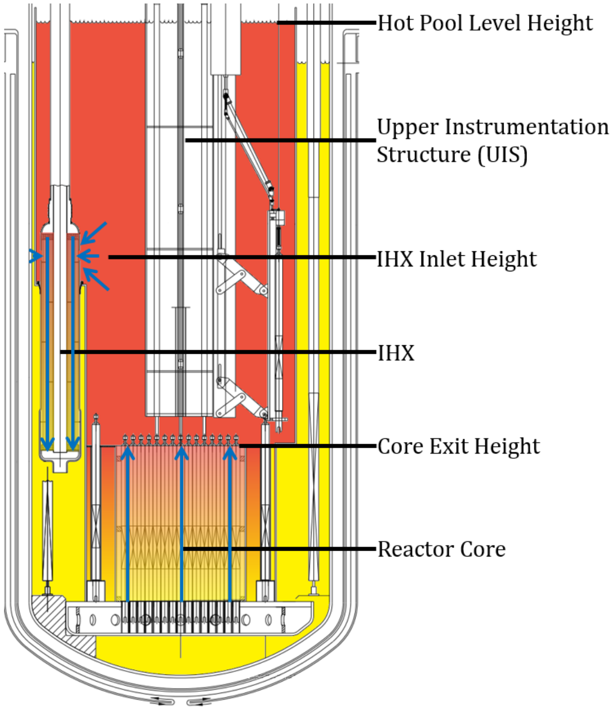
Thermal Stripping



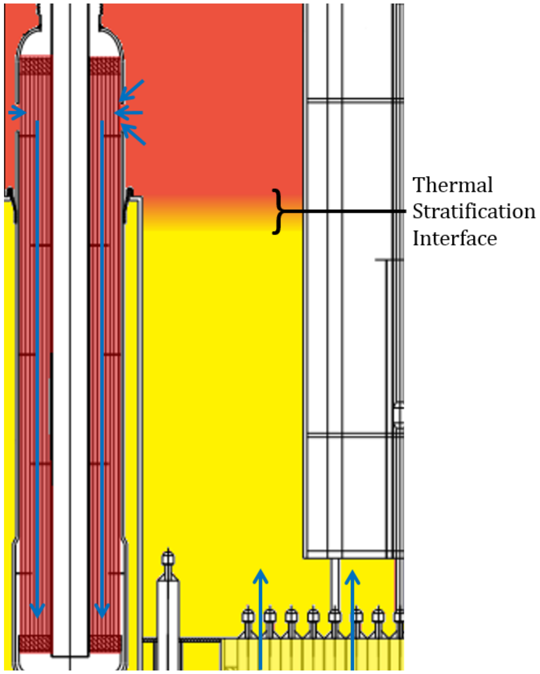
Laboratory stainless steel exposed to hot and cold sodium flows

Handbook of Nuclear Engineering: Vol. 4. New York: Springer, 2010. Print.

Thermal stratification – Natural circulation

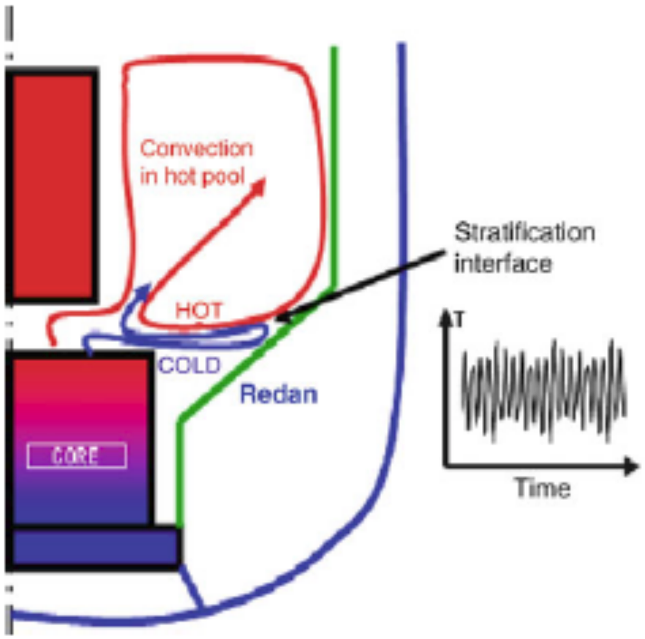


- Natural circulation
- Low flow
- Cold transients
- Unprotected loss of flow
- Unprotected loss of heat sink

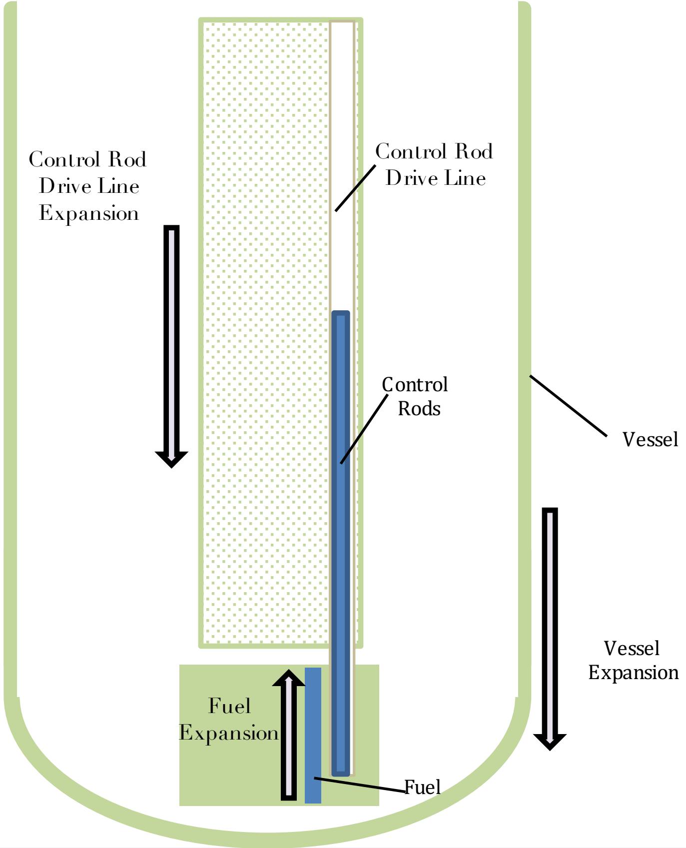


Interface location impacts natural circulation and passive safety

Thermal stratification - thermal fatigue & reactivity feedback

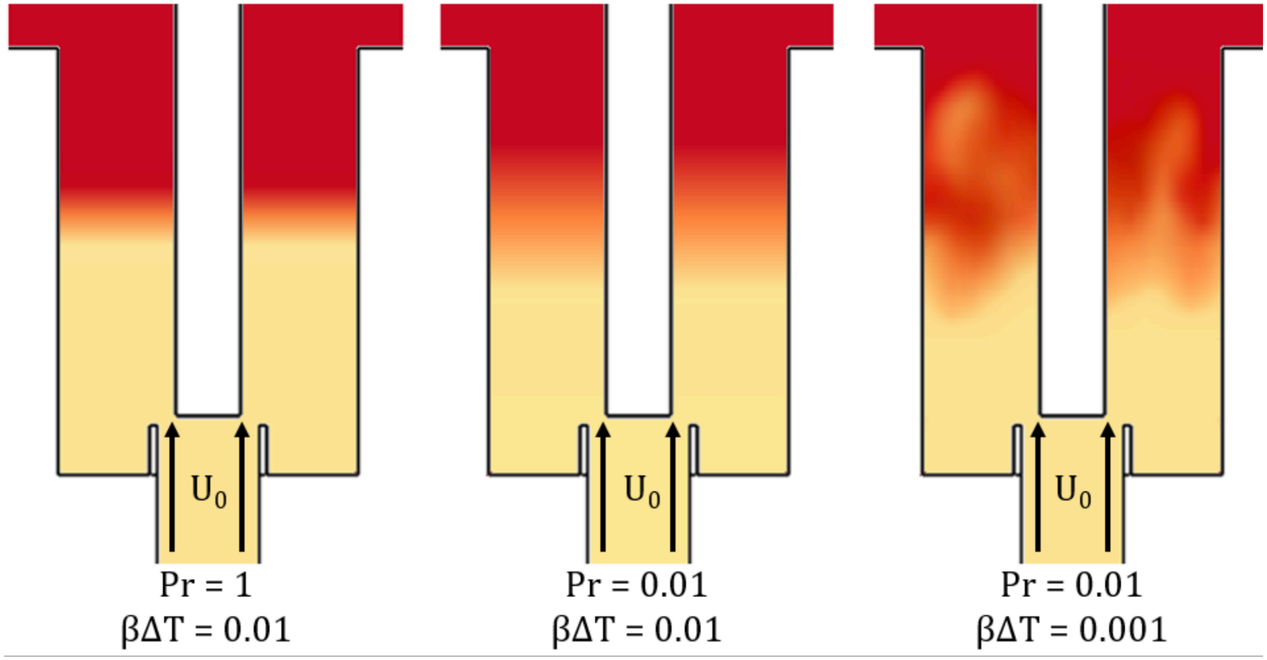


- Thermal fatigue
- Extensional strain
- Buckling
- Ratcheting



[1] *Handbook of Nuclear Engineering: Vol. 4.* New York: Springer, 2010. Print.

Thermal stratification – Cold transients

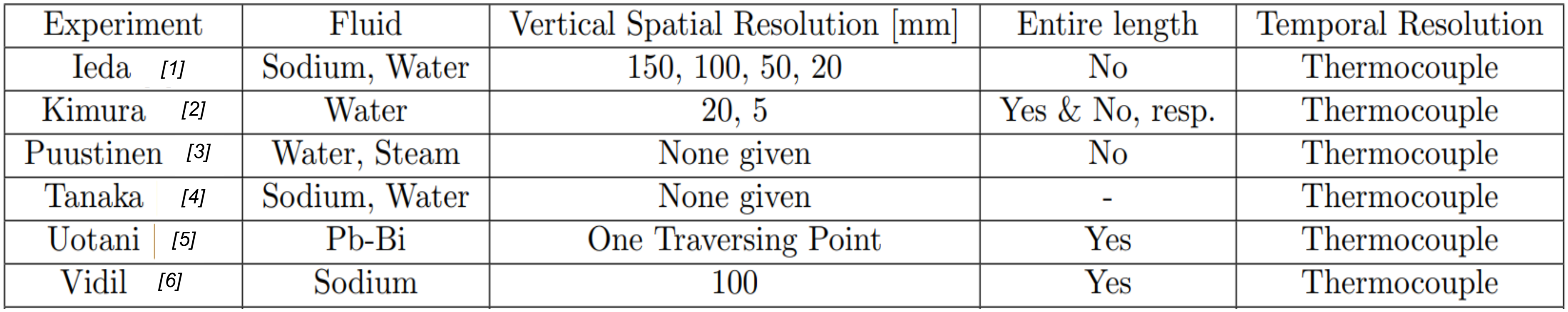


- Buoyant dissipation
- Turbulent generation
- Pr<<1

$$Ri_f = \frac{g\beta\overline{w'T'}}{\overline{u'w'}dU/dz}$$

  - Experiments
  - CFD simulations

Experimental studies to understand thermal stratification in LMRs



Experiment	Fluid	Vertical Spatial Resolution [mm]	Entire length	Temporal Resolution
Ieda [1]	Sodium, Water	150, 100, 50, 20	No	Thermocouple
Kimura [2]	Water	20, 5	Yes & No, resp.	Thermocouple
Puustinen [3]	Water, Steam	None given	No	Thermocouple
Tanaka [4]	Sodium, Water	None given	-	Thermocouple
Uotani [5]	Pb-Bi	One Traversing Point	Yes	Thermocouple
Vidil [6]	Sodium	100	Yes	Thermocouple

[1] Y. Ieda, et. al. Experimental and analytical studies of the thermal stratification phenomenon in the outlet plenum of fast breeder reactors. *Nuclear engineering and design*, 120(2-3):403–414, 199
[2] N. Kimura, et. al. Experimental study on thermal stratification in a reactor vessel of innovative sodium-cooled fast reactor— … *Journal of Nuclear Science and Technology*, 47(9):829–838, Jan 2
[3] M. Puustinen, J. Laine, and R. Antti. Ppoolex experiments on thermal stratification and mixing. Technical report, NKS, 2009.
[4] N. Tanaka, S. Moriya, S. Ushijima, T. Koga, and Y. Eguchi. Prediction method for thermal stratification in a reactor vessel. *Nuclear Engineering and Design*, 120:395–405, 1990
[5] M. Uotani. Natural convection heat transfer in thermally stratified liquid metal. *Journal of Nuclear Science and Technology*, 24(6):442-451, June 1987.
[6] R. Vidil, D. Grand, and F. Leroux. Interaction of recirculation and stable stratification in a rectangular cavity filled with sodium. *Nuclear Engineering and Design*, 105:321–332, 1988

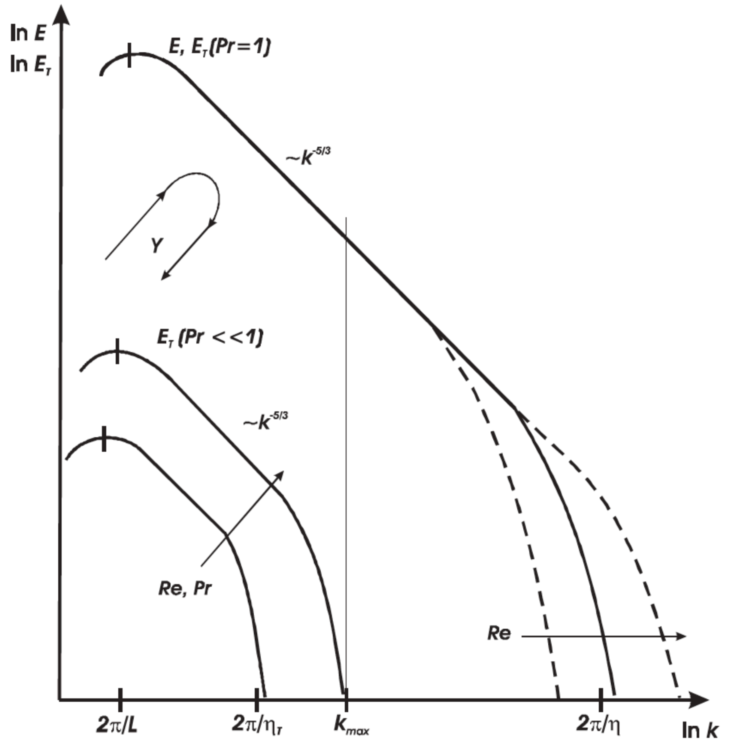
Low Prandtl number fluids- Completely different than Pr~1

- Eddy thermal diffusivity is larger than molecular thermal diffusivity at much higher Re (Re>100,000 for Pr~0.005)

- LMRs- Transition zone between conduction and convection

- Amplitude of thermal fluctuations is much higher than velocity fluctuations

- Spectrum shifts for all length-scales



G. Grštzbach / Nuclear Engineering and Design 264 (2013) 41– 55

Temperature field information is difficult to gather experimentally

Previous experiments have used thermocouples

- Error in gradient- spatial resolution
- Information on thermal fluctuations
- Too much interference in the experiment

Experiment	Fluid	Vertical Spatial Resolution [mm]	Entire length	Temporal Resolution
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[4] N. Tanaka, S. Moriya, S. Ushijima, T. Koga, and Y. Eguchi. Prediction method for thermal stratification in a reactor vessel. *Nuclear Engineering and Design*, 120:395–405, 1990
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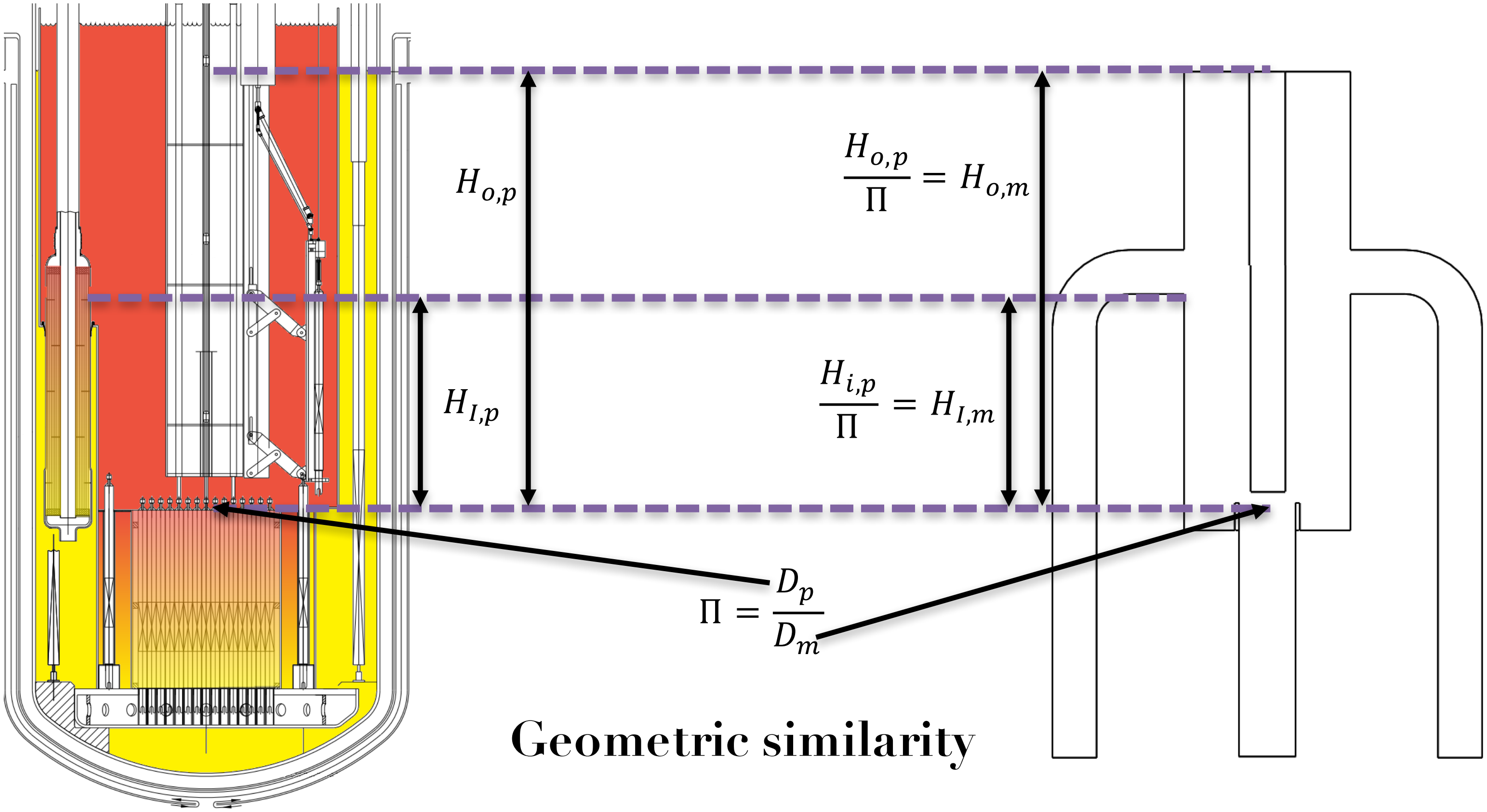
[6] R. Vidil, D. Grand, and F. Leroux. Interaction of recirculation and stable stratification in a rectangular cavity filled with sodium. *Nuclear Engineering and Design*, 105:321–332, 1988

Scaled outlet plenum design – Reference geometry (ABTR)



$H_{o,p}$

$H_{I,p}$

$$\frac{H_{o,p}}{\Pi} = H_{o,m}$$

$$\frac{H_{i,p}}{\Pi} = H_{I,m}$$

$$\Pi = \frac{D_p}{D_m}$$

Geometric similarity

Scaling to conserve both Richardson number and Peclet Number

$$U_{Sc} = \sqrt[3]{\frac{Pe_{ABTR}\,\frac{\Delta\rho}{\rho}\,g\,\kappa}{Ri_{ABTR}}}$$

$$D_{Sc} = \frac{Ri_{ABTR}\,U_{Sc}^{2}}{\frac{\Delta\rho}{\rho}\,g}$$

$\rho_0 = density\ at\ reference\ temperature, T_{Cold}$

$\frac{\Delta\rho}{\rho} = normalized\ density\ difference\ at\ T_{Hot}$

$g = body\ force$

$\kappa = thermal\ diffusivity$

$D_{Sc} = scaled\ length$
$U_{Sc} = scaled\ velocity$

$Pe_{ABTR} = 213$
$Ri_{ABTR} = 553$

Ward et al. Annals of Nuc. Ener. (2018)

Scaling cannot feasibly conserve both Ri and Pe

	Temperature Range (℃)	Fluid	Diameter (m)
ABTR	355 to 510	Sodium	1.02
Scaled Na	120 to 200	Sodium	0.83
Scaled Ga	50 to 200	Gallium	0.27

Richardson number conservation alone is acceptable along with geometric scaling [3] [4] [5]

[4] Aoki, Tadao, and Keizo Okada. "Experimental study on thermal stratification." Proc. IAEA Specialists. Meeting Internal Working Group on Fast Reactors, Grenoble. 1982.

[5] Tenchine, D., and P. Gauthé. "Occurrence of thermal stratification in sodium cooled fast reactor piping." Nuclear Engineering and Design 274 (2014): 1-9.

[6] Ieda, Y., et al. "Experimental and analytical studies of the thermal stratification phenomenon in the outlet plenum of fast breeder reactors." Nuclear engineering and design 120.2-3 (1990)

Gallium can be used to meet the experiment's requirements

UDV Sensors can only go up to 200°C

Melting point of sodium is 97°C (Pr=0.006) giving a small working temperature range

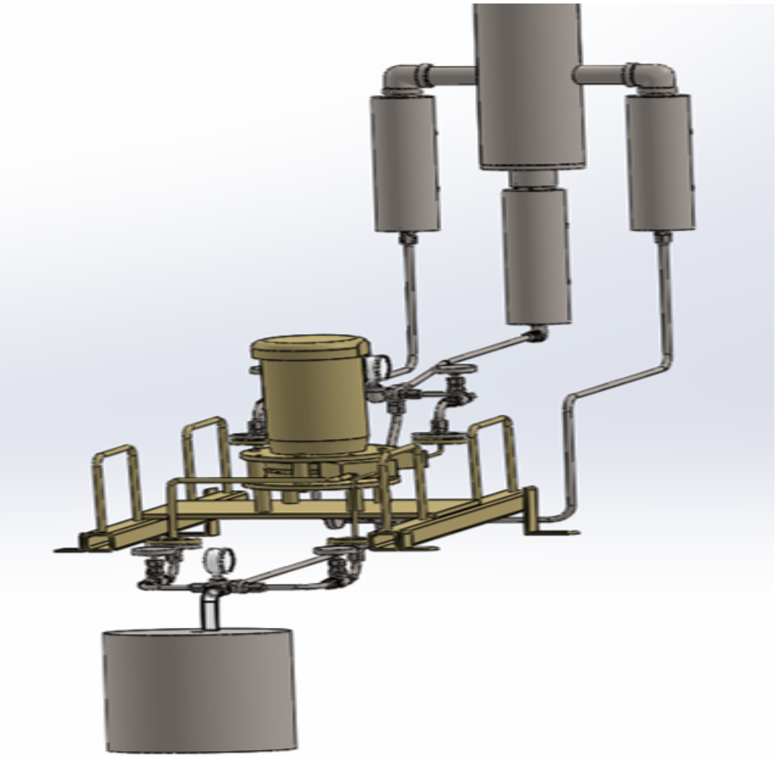
Other Candidates (low Pr): Mercury, Potassium

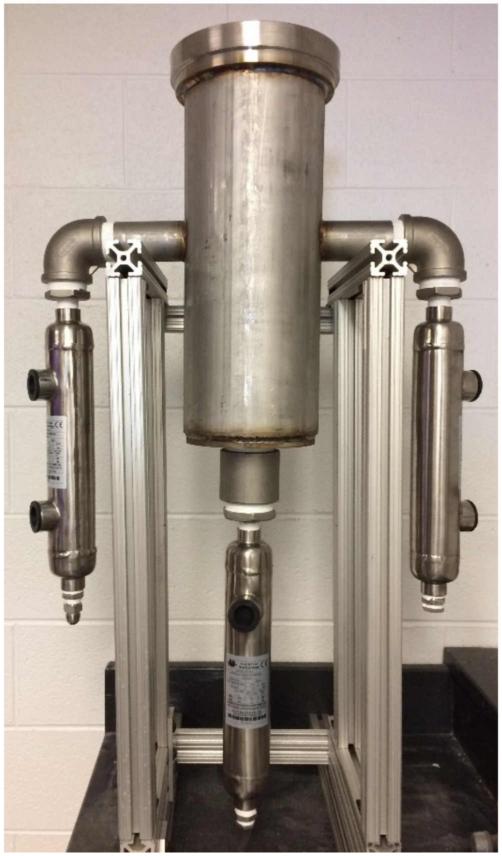
Gallium is not toxic, reactive with air/water, nor prohibitively expensive

→ Gallium Thermal-hydraulic Experiment (GaTE) facility

→ 1/20th scaled upper plenum

GaTE facility

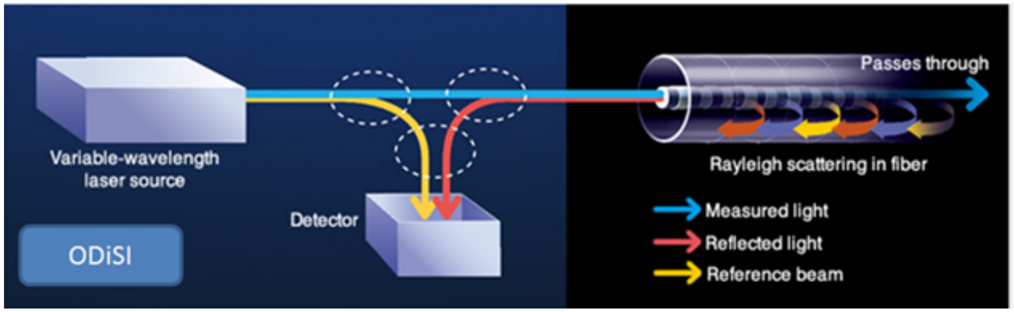




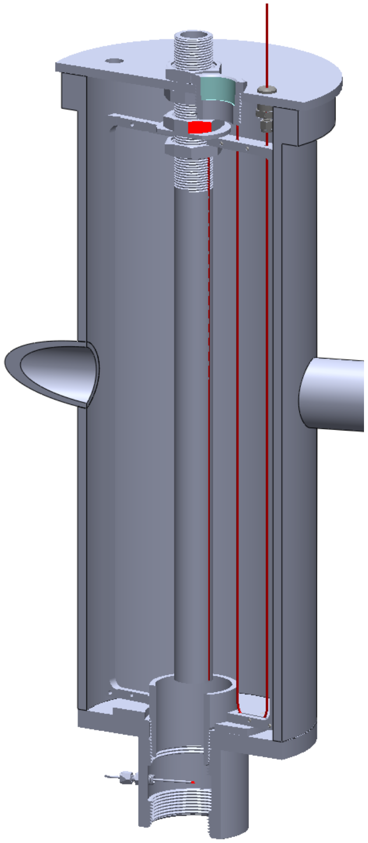
SWI-DTS can be used to measure temperature data

Swept-wavelength interferometry based distributed temperature sensors are based on **Rayleigh backscattered** signal

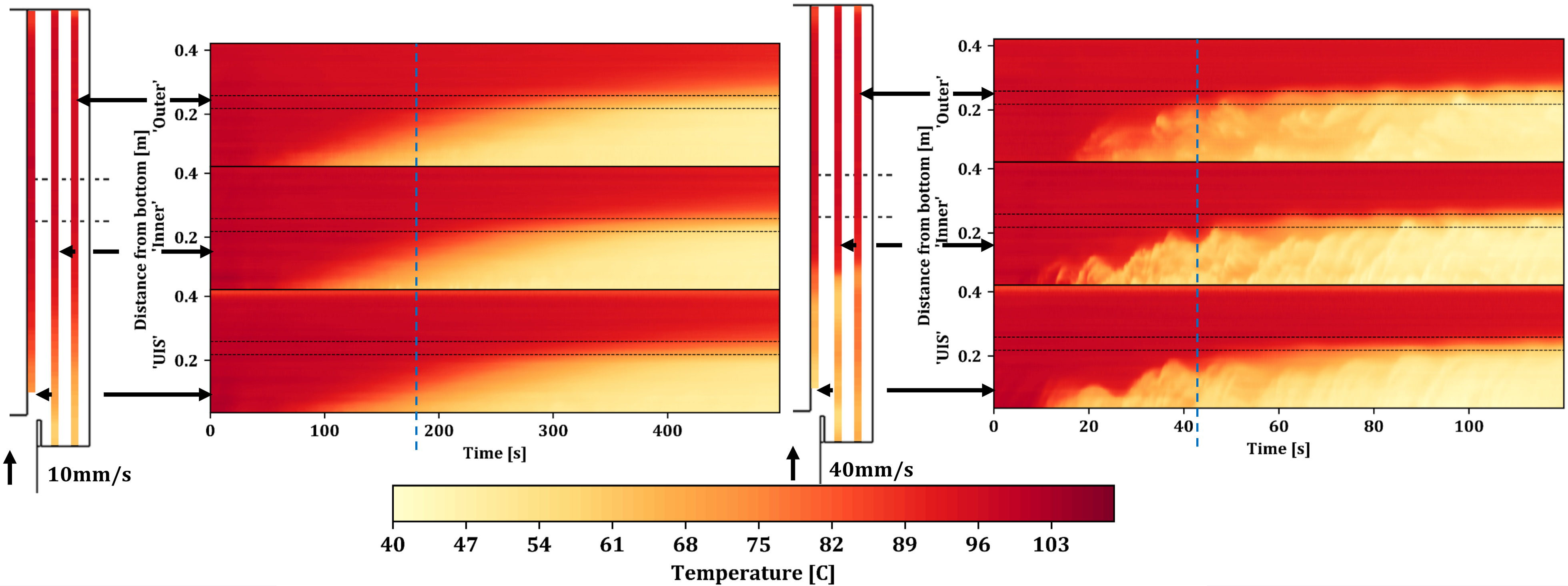
There is a fast response time along the entire length of the probe (250Hz, 2.5mm)



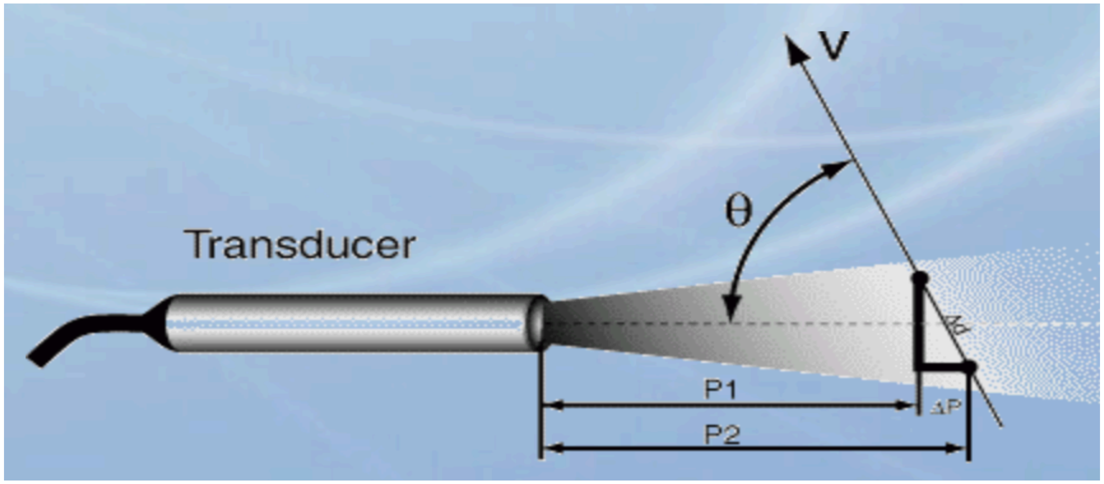
[1] (2018). *Technology*. Retrieved from http://lunainc.com/technology/



Thermal stratification front behavior is a function of the core exit velocity



Velocity measurements- UDV or Acoustic Backscattering

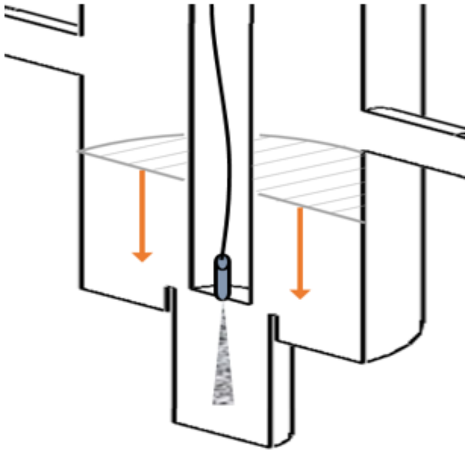


Signal Processing Inc. (SUI)

Principle: Doppler frequency shift

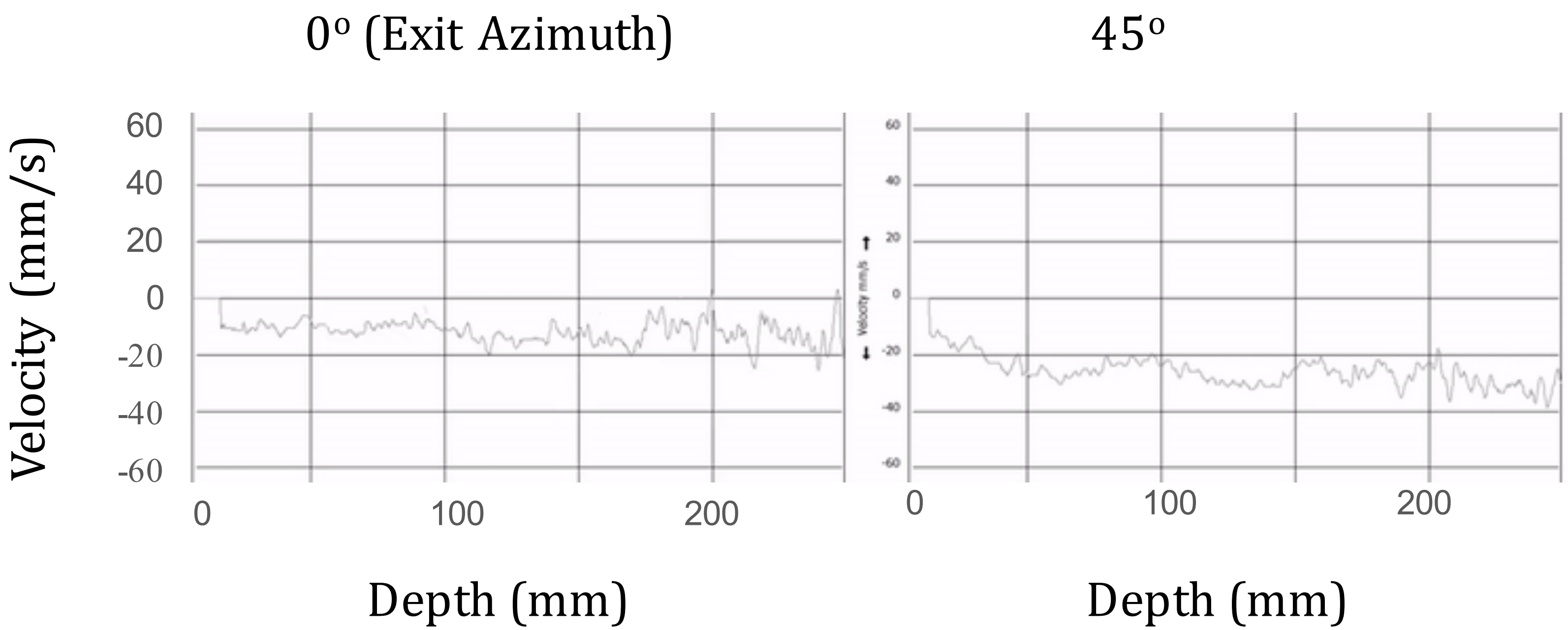
$$v = \frac{c \cdot \delta}{4\pi \cdot f_e \cdot \cos\Theta \cdot T_{prf}} = \frac{c \cdot f_d}{2 \cdot f_e \cdot \cos\Theta}$$

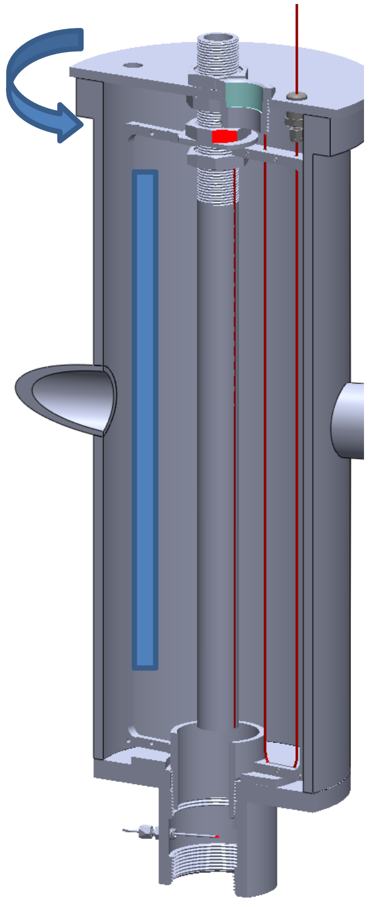
- Opacity of liquid metals
- Time resolution is important to capture velocity fluctuations



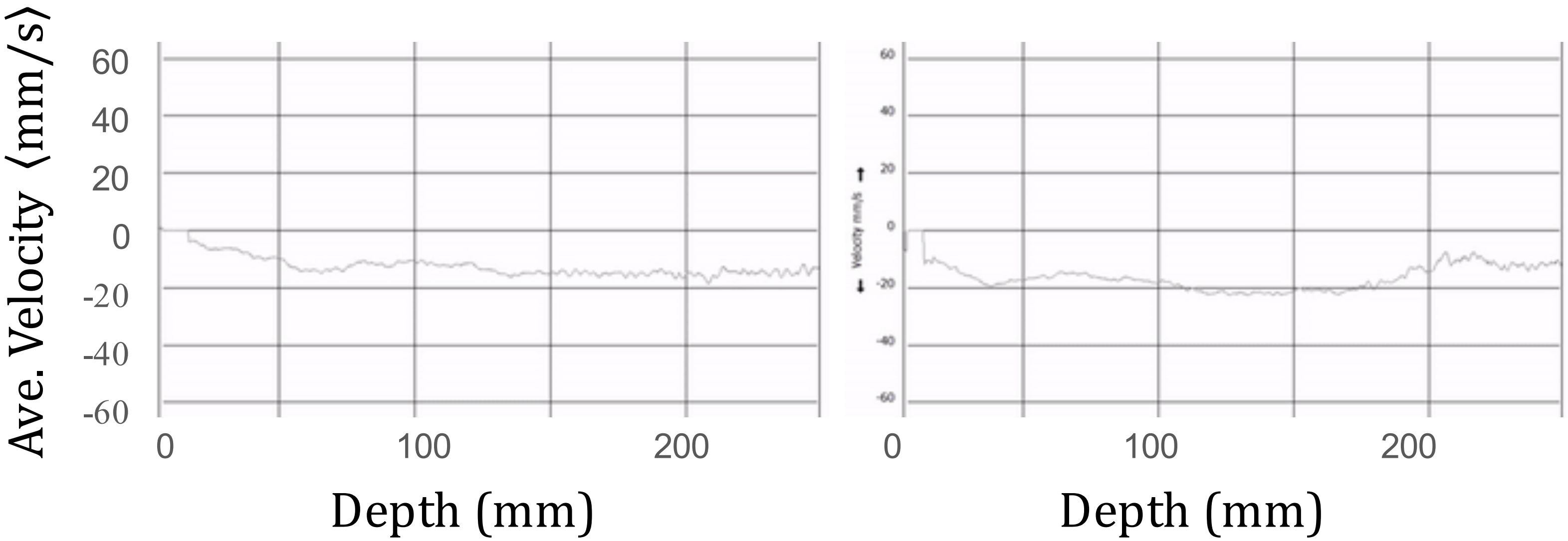
4 probes in scaled plenum

Velocity measurements- UDV or Acoustic Backscattering



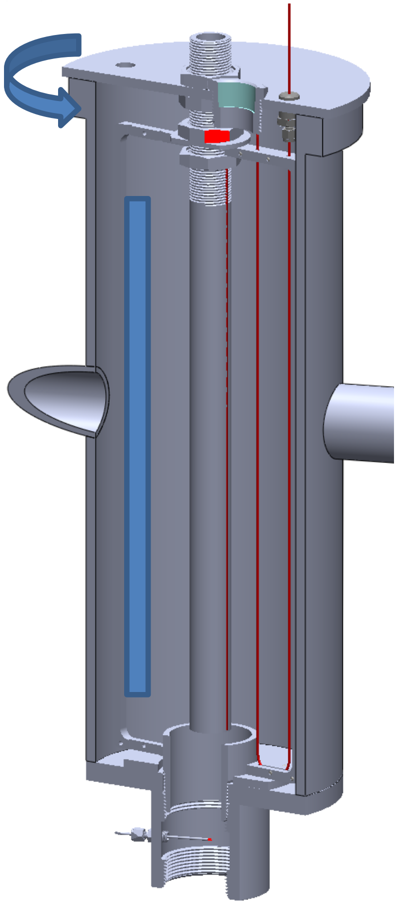


Velocity measurements- UDV or Acoustic Backscattering



0° (Exit Azimuth)

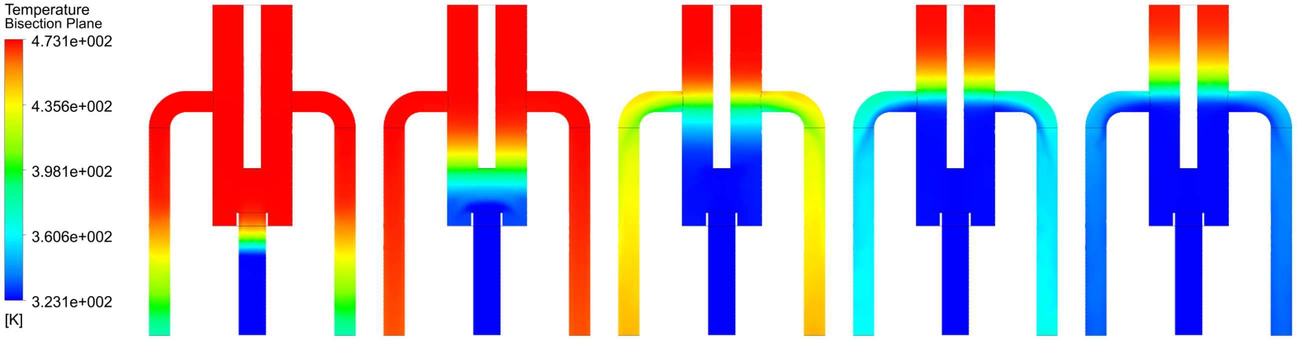
45°



Low flow vs high flow rates-CFD (Large eddy simulations) for GaTE facility

<<κ

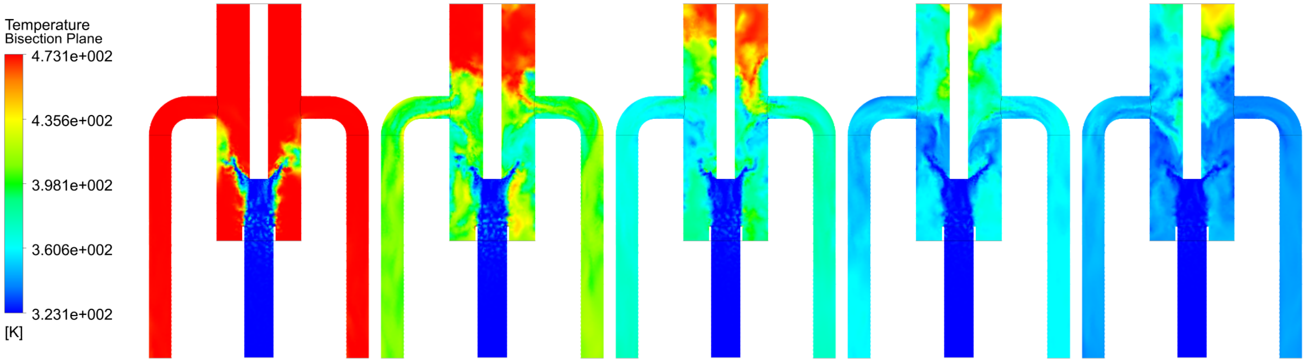
Corresponding to Natural circulation flow rates



(a) 10 sec (b) 60 sec (c) 120 sec (d) 180 sec (e) 240 sec

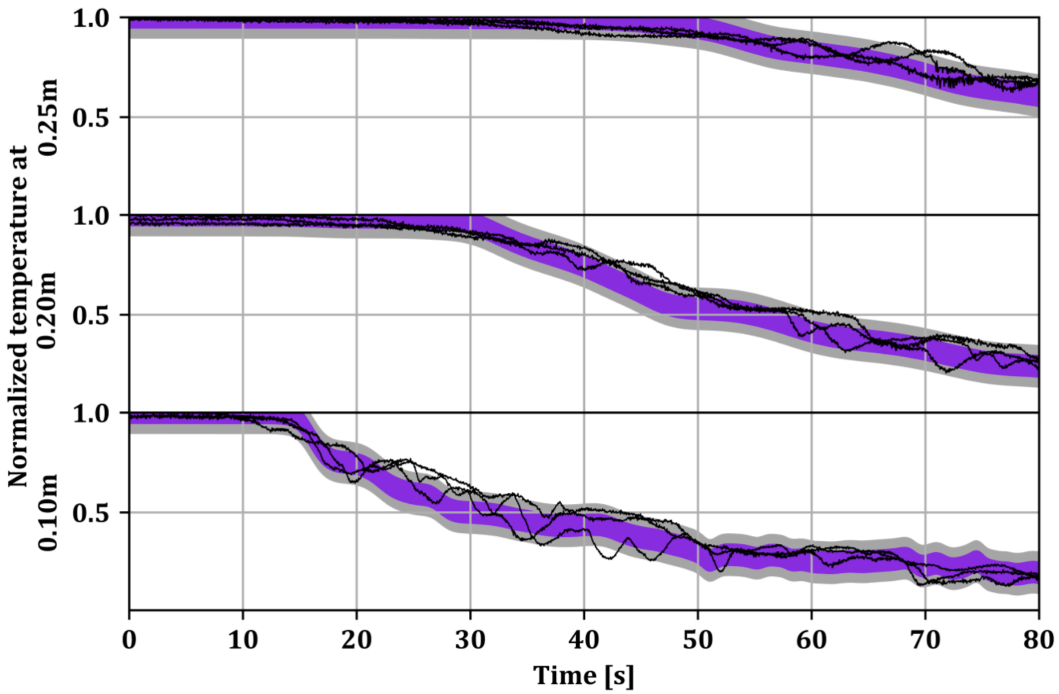
>>κ

Corresponding to Forced convection flow rates



(a) 0.5 sec (b) 2.5 sec (c) 4.5 sec (d) 6.5 sec (e) 8.5 sec

Experiments vs CFD



Multiple realizations are performed.

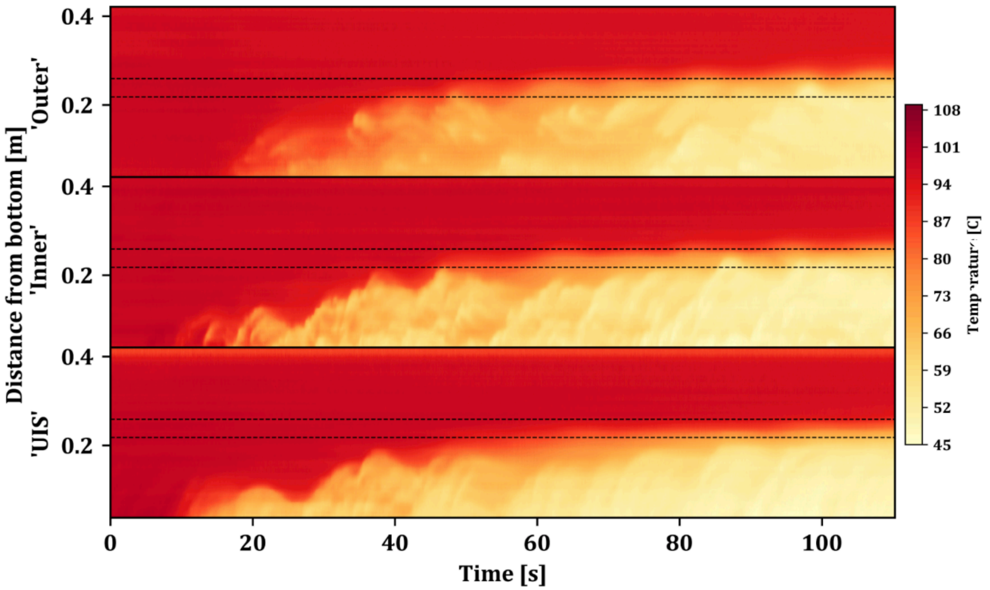
Purple - 95% confidence band

Grey – 90% confidence band

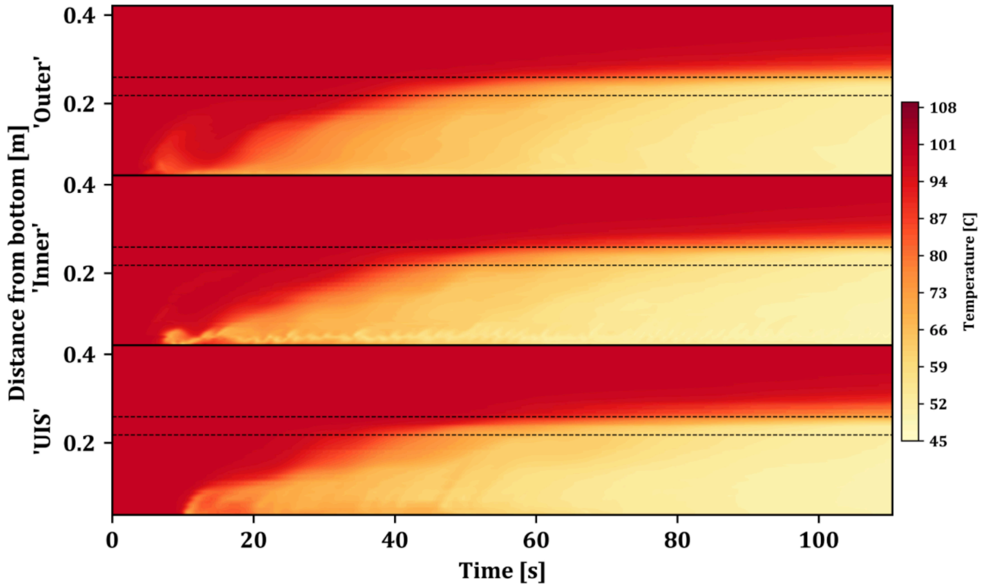
Good Agreement

Detailed comparison

Experiments



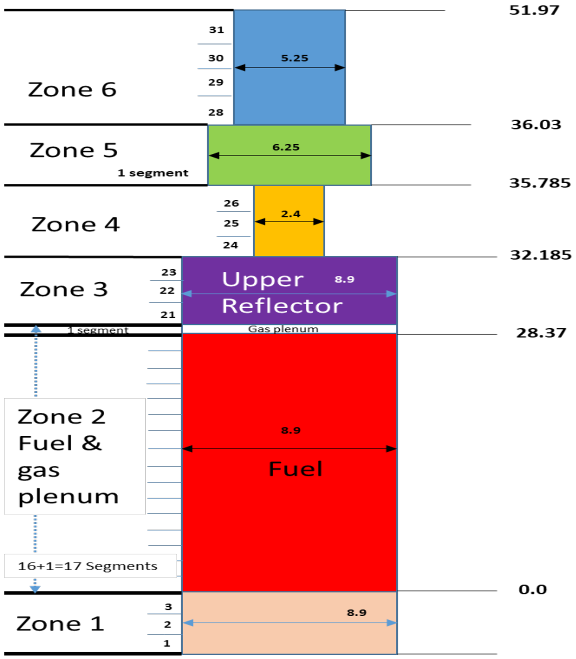
CFD



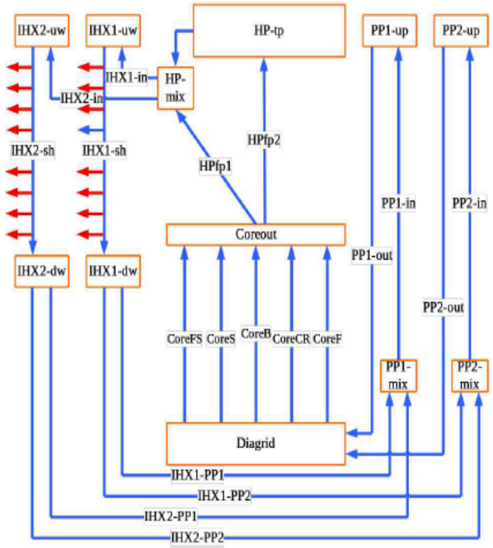
Time resolution of the data becomes really important

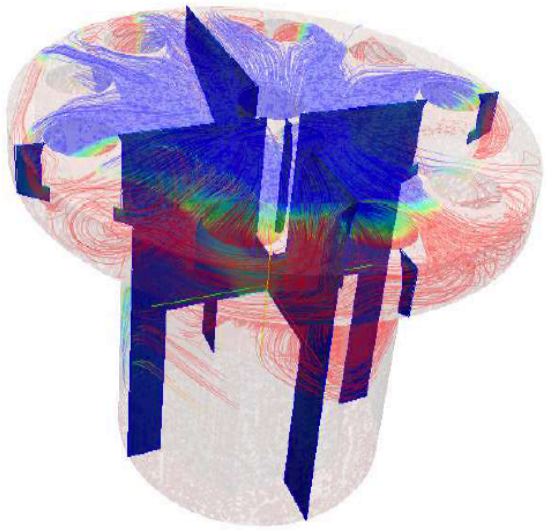
System level safety analysis

- SAS4A/SASSYS-1 system level code : 0-D models



- Couple with 3-D CFD, Possible but expensive





Perfect Mixing Model

$$\rho V c_p\left(T_{avg} - T_0\right) = \rho V c_p\left(T_{IC} - T_0\right) - \int_0^t \rho A u c_p\left(T_e - T_0\right) dt'$$

1-D Scalar Transport Model

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial x}\left(uT\right)$$

$$\overline{u_i' T'} = -\kappa_\tau \frac{\partial \overline{T}}{\partial x_i}$$

$$K = \kappa_\tau + \kappa$$

Eddy Thermal diffusivity

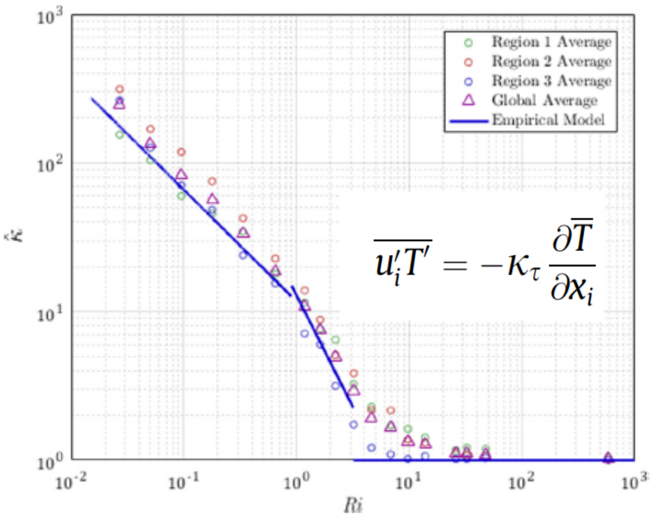
Molecular Thermal diffusivity

Empirical- Eddy Thermal Diffusivity

Regime	Re_τ/Ri Interval	$\kappa_\tau + \kappa$
Molecular	$Re_\tau/Ri < 150$	κ
Transitional	$150 < Re_\tau/Ri < 1000$	$0.015\kappa\left(\frac{Re_\tau}{Ri}\right)$
Energetic	$Re_\tau/Ri > 1000$	$0.4\kappa\left(\frac{Re_\tau}{Ri}\right)^{1/2}$

$$Ri = \frac{g\beta\Delta T D}{u^2}$$

$$Re_\tau = \frac{q^2}{\nu\epsilon}$$

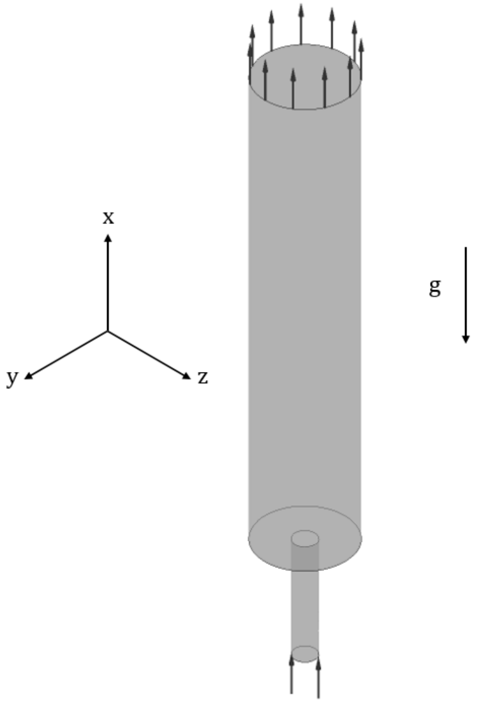


$$\overline{u_i'T'} = -\kappa_\tau \frac{\partial \overline{T}}{\partial x_i}$$

Ward et al. Annals of Nuc. Ener. (2018)

Problem Description

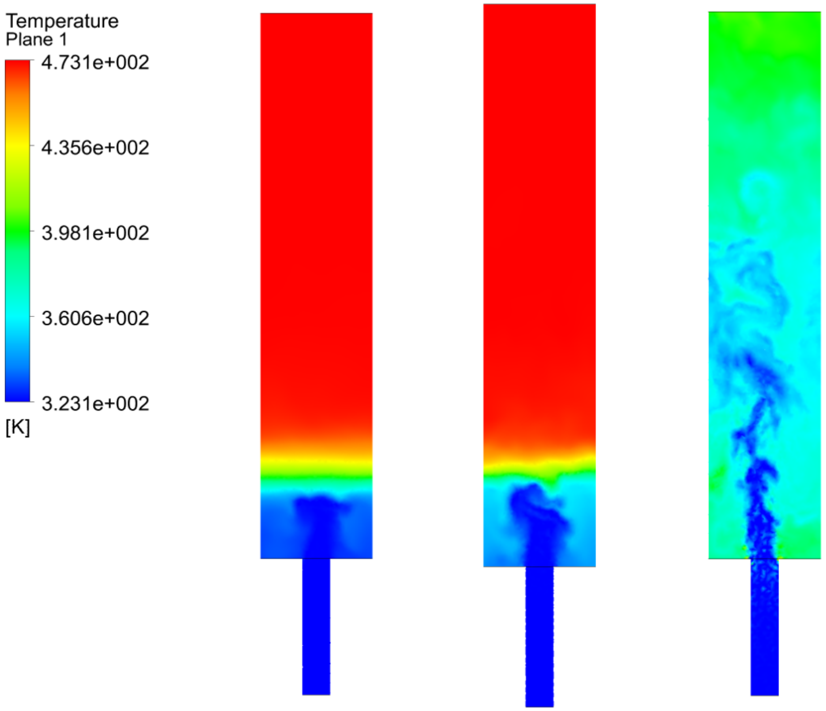
- Adiabatic walls
- Inlet velocity varied
  - Re_τ/Ri in the realm of 10^0 to 10^5
- $T_{IC} = 200°C$
- $T_{BC} = 50°C$

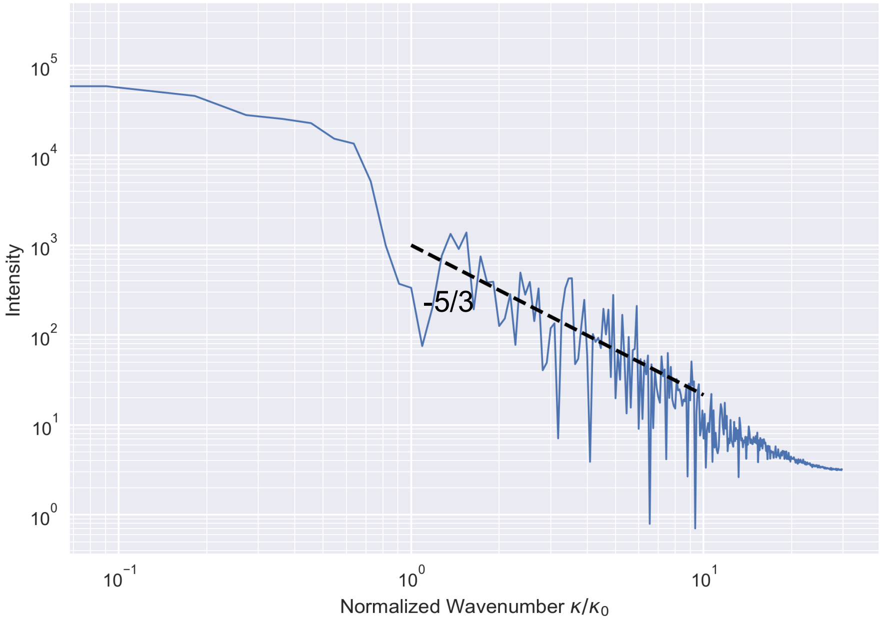


Computational Fluid Dynamics

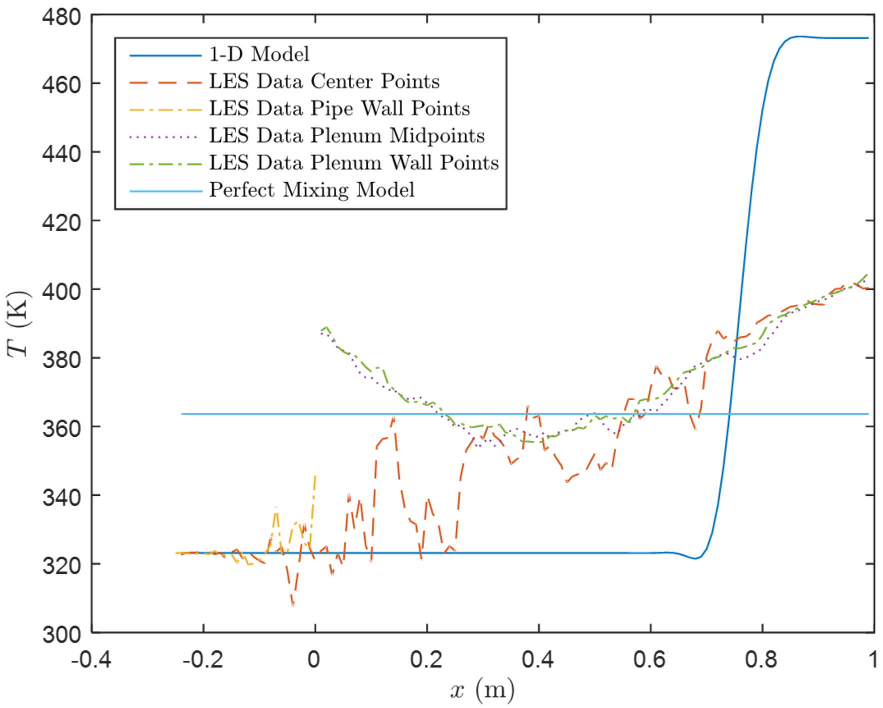
- Large Eddy Simulation
- Wall-adapted local eddy-viscosity model
- Second Order Backward Euler Transient Scheme
- ANSYS- CFX

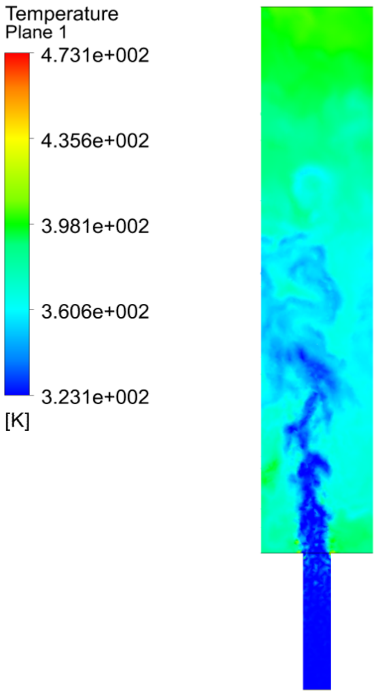
LES simulations-Cold Transients



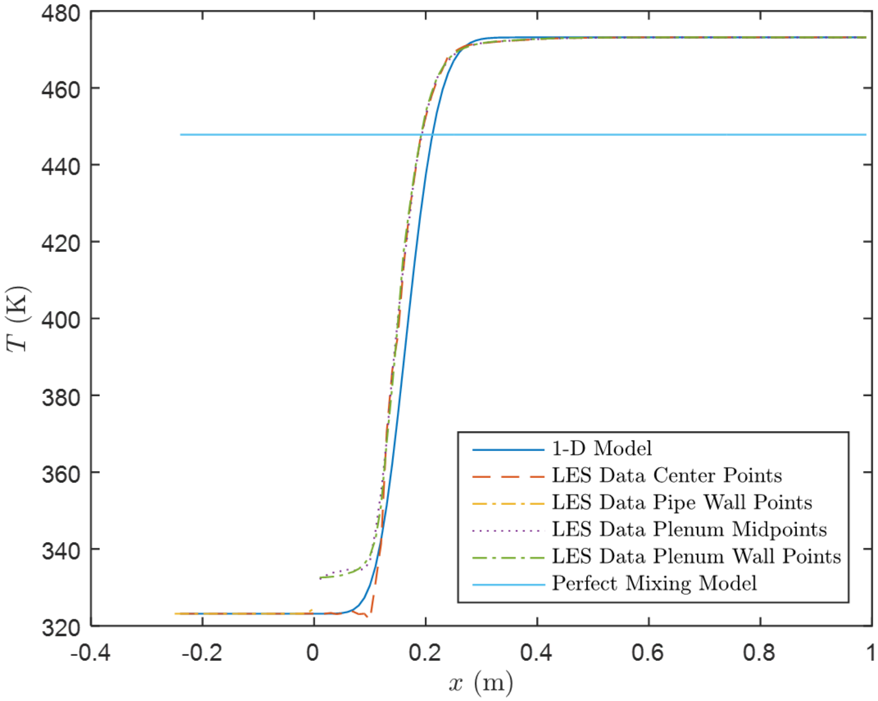


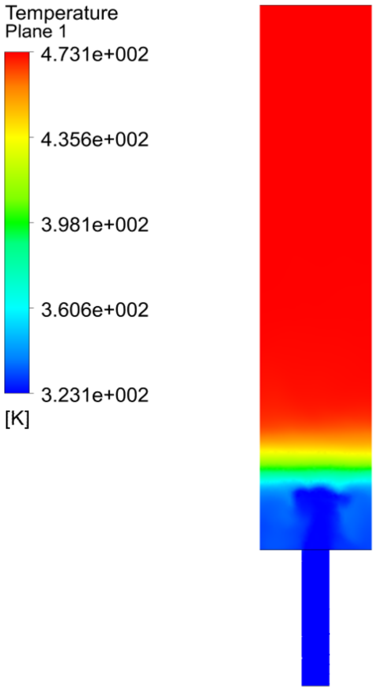
Energetic Regime



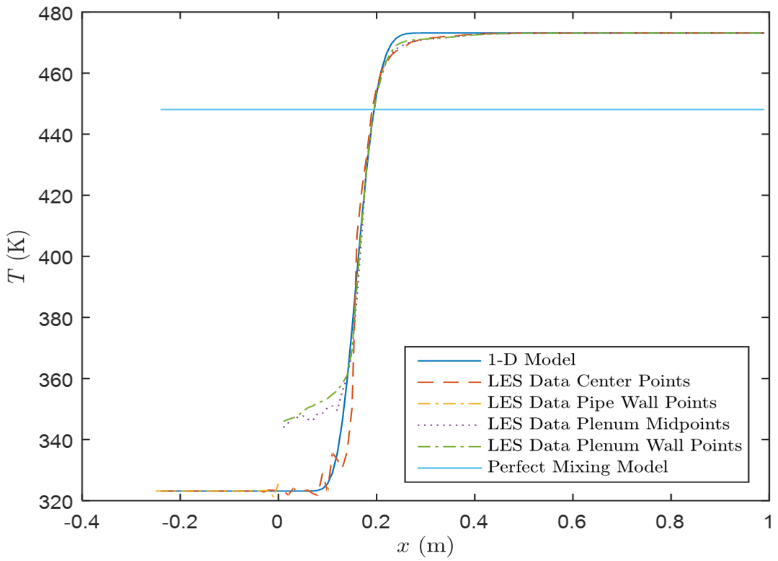


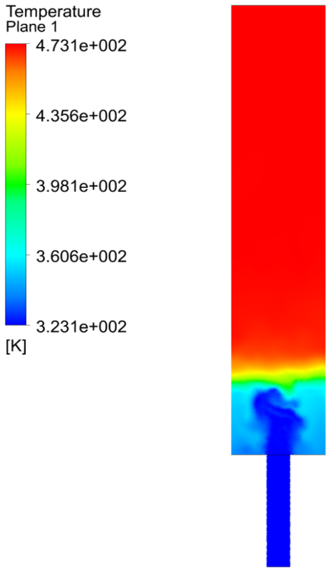
Molecular Regime





Transitional Regime



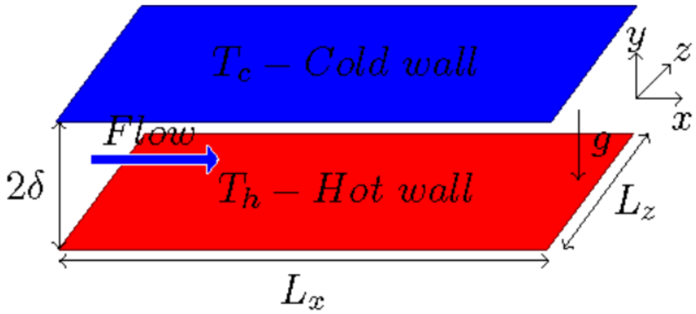


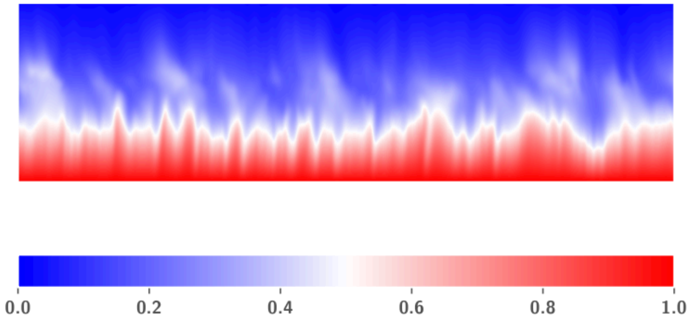
$$\overline{u_i'T'} = -\kappa_\tau \frac{\partial \overline{T}}{\partial x_i}$$

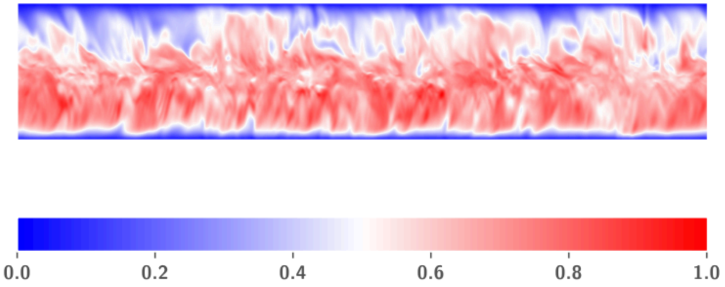
Can not capture thermal fluctuations at interface

Lost information

Scalar Turbulence- How can you learn from Scaled Experiments or DNS ?







$$\underbrace{M_n(x,t,\Delta t) = \lim_{\Delta t\to 0}\frac{1}{n!\Delta t}\int_{-\infty}^{\infty}(x'-x)^n P(x',t+\Delta t|x,t)dx}_{Moment-equation}$$

$$\underbrace{M_1 = \mu, M_2 = D}_{First-two-moments}$$

Learning from time series

$$\underbrace{dx = \mu dt + \sigma dW}_{Ito-SDE}$$

Lagrangian model for scalar turbulence

DNS data provided by Bojan Niceno et al. (Paul Scherrer Institute)

Conclusions

- Thermal stratification and associated fluctuations near the interface should be resolved.
- GaTE facility- Scaled plenum at KSU has been used to capture cold transient experiments such as under protected loss of flow.
- Rayleigh backscattering for temperature and Acoustic backscattering for velocity.
- CFD-LES time resolution is critical for modeling fluctuations.
- Even 1-D models are good but statistics must be preserved to capture time dynamics.
- Future Work- Unprotected transients, Advanced Reduced Order models, Understanding fluctuation characteristics

Questions ?

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