ANS Winter Meeting & Expo
2018
Joining Forces to Advance Nuclear

Thermal Stratification Modeling and Analysis for Sodium Fast Reactor Technology

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Project Objectives

- Conduct a series of thermal stratification experiments with advanced temperature and fluid measurement instrumentation. A specific geometry will be considered both experimentally and computationally.(UW, MIT,VCU, ANL)

- Use the STRUCT modeling approach along with URANS methods to analyze the low Prandtl number (sodium) heat transfer, thermal stratification and thermal striping experiments (UW-MIT)

- Development of improved models for thermal stratification and thermal striping to be implemented in system level codes such as SAM and SAS4A/SASSYS-1. (VCU-ANL)

- Train several students in the aspects related to the SFR technology from working with sodium by conducting the experiments to detailed state of the art CFD for the low Prandtl number fluids and ultimately development and implementation of models into relevant systems code (UW, VCU, MIT)
  - Sodium Fast Reactors are a leading candidate for Generation IV Reactors for commercial deployment, training students on SFR function and safety is important for the future of nuclear power

Experimental Data → CFD Modeling → Reduced Order Modeling

Overview of Completed Tasks in NEUP Project

Milestone / Activity	Status	Start Date	Finish Date	% Comp	Actual Finish Date
Final Report	On Schedule	10/1/2016	12/29/2019	0%	
Experimental measurement and CFD modeling of thermal gradients in sodium to qualify the fiber optic probe for use in thermal stratification tests	On Schedule	10/1/2016	9/30/2017	100%	9/30/2017
Literature review of different models for thermal stratification for systems codes	On Schedule	10/1/2016	9/30/2017	100%	9/30/2017
Development of simple 0D thermal stratification models for SAS4A/SASSYS-1	Missed Deadline (more time requested)	10/1/2016	9/30/2018	50%	
Shake down tests and initial data on pool type thermal stratification	On Schedule	3/30/2018	9/30/2018	100%	9/30/2018
Design and construction of thermal stratification test section	On Schedule	10/1/2017	3/30/2018	100%	3/30/2018
Experimental measurement and modeling of low temperature jet into pool geometry	On Schedule	10/1/2018	9/30/2019	10%	
System code Benchmarking/validation against thermal stratification experiments	On Schedule	10/1/2018	9/30/2019	0%	

- First Year Highlights:
  - Completed design for the thermal stratification testing facility (TSTF) and begun construction
  - Used CFD techniques to simulate thermal mixing in proposed designs to validate proposed design
  - Completed in-depth literature review of past thermal stratification computational and experimental campaigns

- Second Year Highlights:
  - Completed construction of TSTF and begun taking data
  - Conducting detailed comparison of CFD results to experimental results
  - Began development of physics based stratification model

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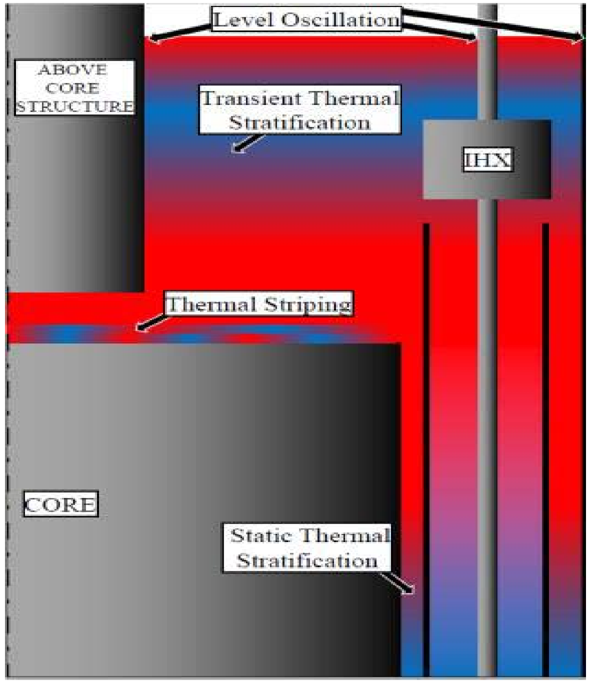
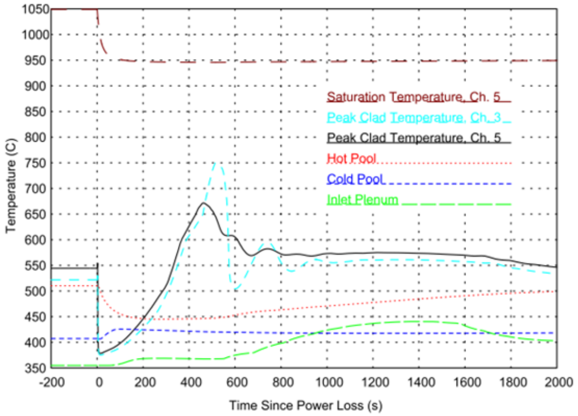
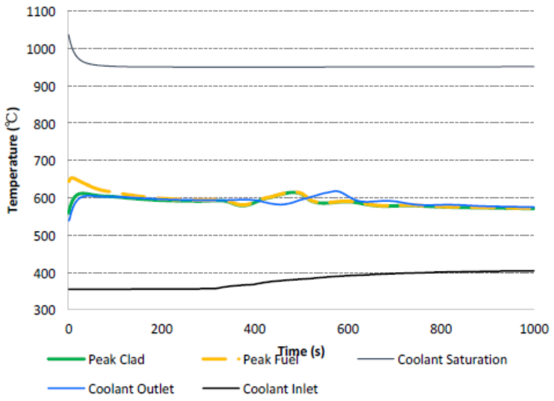
Thermal Stratification Overview

- Thermal Stratification is the formation of a temperature gradient in a volume of fluid due to thermal mixing
- Understanding thermal behavior in the upper plena of a Liquid Metal Fast Breeder Reactor (LMFBR) is important for assessing reactor safety and fatigue
  - Thermal oscillations in a reactor pool can cause thermal fatigue and cracking
  - Must be considered when conducting reactor operation calculations
- Thermal Stratification in the Upper Plenum of a LMFBR
  - Protected loss of flow (PLOF-SCRAM)
  - Unprotected loss of flow (ULOF)

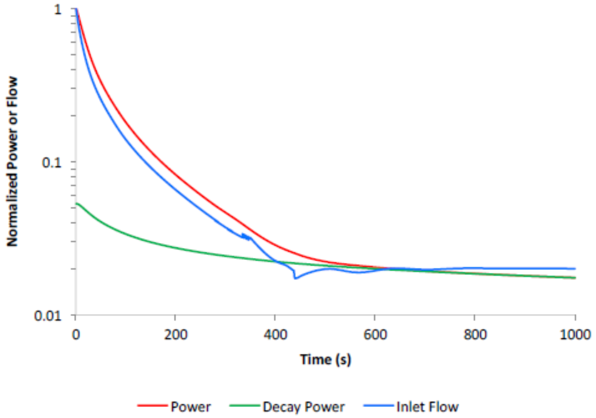




PLOF accident temperature transient [1]



ULOF accident temperature transient [1]



ULOF accident power transient [1]

[1] ANL, Advanced Burner Test Reactor Preconceptual Design Report

Experimental Facility Thermal Stratification Objectives

- Use pool-type reactor geometry to observe thermal stratification during loss of flow scenarios
  - PLOF – *protected loss of flow (cold sodium into hot pool)*
  - *ULOF – unprotected loss of flow (hot sodium into cold pool)*
- Use high fidelity temperature measurements to validate CFD analysis
- Use best practices in safety and design to produce an organized, well documented, and high functioning experiment

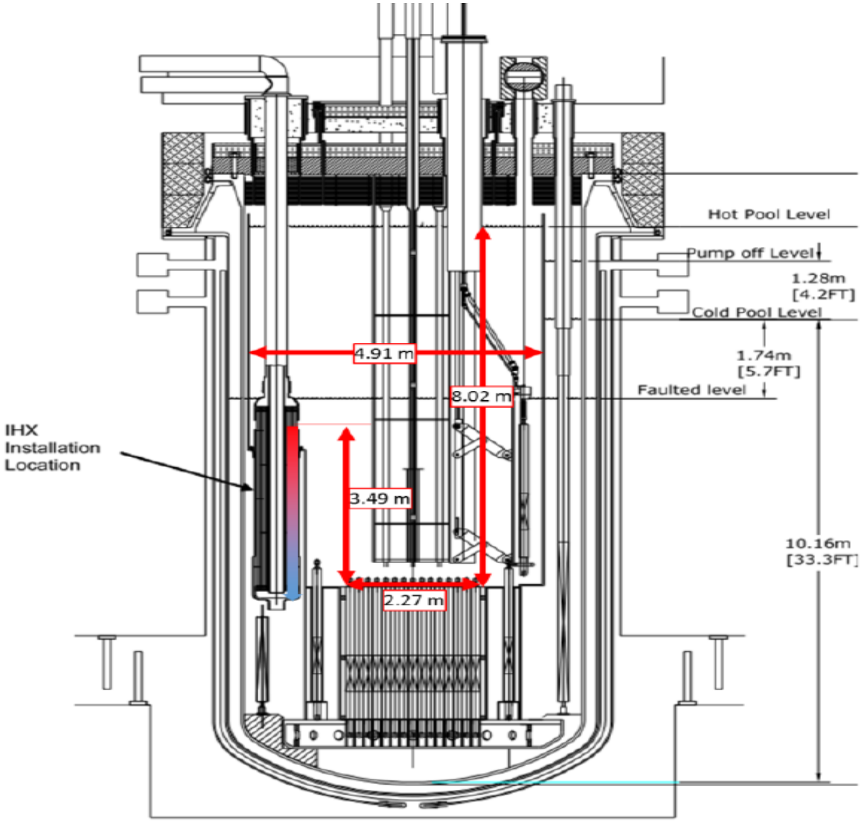
<table>
<tr><th>Outlets</th><th># of Inlets</th><th>UIS Height</th><th>UIS Diameter</th><th>DELTA T</th><th>Flow Rate</th></tr>
<tr><td rowspan="4">High or Low</td><td rowspan="4">2 or 3</td><td rowspan="4">0-4.5"</td><td rowspan="4">0-5.5"</td><td rowspan="4">0-100 (max temp. 300[C])</td><td>20 [gpm]</td></tr>
<tr><td>10 [gpm]</td></tr>
<tr><td>5 [gpm]</td></tr>
<tr><td>20-5 [gpm]</td></tr>
</table>

Dimensionless Numbers

β=coefficient of thermal expansion
α=thermal diffusivity
ΔT is the temperature difference between the two fluid
u=the velocity of the sodium being jetted from the core
v=is the kinematic viscosity
D=diameter of the core
H=the height of the pool; g=gravity

- Grashof, $Gr = \frac{buoyancy}{viscous} = \frac{g\beta\Delta T {H_p}^3}{\nu^2}$
- Reynolds, $Re = \frac{inertial}{viscous} = \frac{uD_c}{\nu}$
- Richardson, $Ri = \frac{buoyancy}{inertial} = \frac{Gr}{Re^2} = \frac{\beta\Delta T g H_p^3}{D_c^2 u^2}$
- Peclet, $Pe = \frac{advective\ transport}{diffusive\ transport} = \frac{uH_p}{\alpha}$

- Determination of the Characteristic Length:
  - Grashof number analyzes the viscous forces acting on the fluid in the pool as a buoyancy driven thermal wave travels along the height of the reactor pool
  - Reynolds number is calculated as the bulk flow from the reactor core
  - Peclet important to stratification because it describes the transport of heat during fluid that creates the stratified layers



$$L_{char} = \frac{{H_p}^3}{{D_c}^2}$$

[1] ABTR Design

[1] ANL, Advanced Burner Test Reactor Preconceptual Design Report

Proposed Design for Experimental Test Section

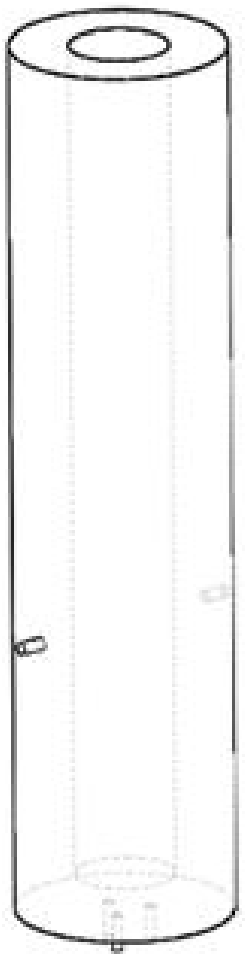
- Use definition of Richardson number to determine height of the vessel (H_p)
  - 1:1 similitude between the ABTR and the Experimental vessel (Ieda)
  - Selected a pool height that yielded a similar ratio of the Peclet number between the experimental design and the ABTR
  - Knowing: *g, β, ΔT, u, and* H_p $-D_p$ are found
  - *u* is the velocity of the slug flow coming from the core (*Q* = *u**A_c)

Parameter	Experimental Design	ABTR	Ratio
H_{pool} [m]	1.2	8.02	0.15
$H_{outlet,1}$ [m]	0.4	2.673	0.15
$H_{outlet,2}$ [m]	0.8	5.347	0.15
D_{pool} [m]	0.3147	4.91	0.065
D_{UIS} [m]	0.1455	2.27	0.065
D_{core} [m]	0.1455	2.27	0.065
Q_{ULOF} [m^3/s]	0.001429	0.3775	0.0038
V_{core} [m/s]	3.759	0.2960	12.7
T_{hot} [C]	300	575	0.52
T_{cold} [C]	250	525	0.48
Peclet [-]	1616	12520	0.13
Reynolds [-]	28349	788237	0.04
Richardson [-]	1616	1616	1

$$Ri = \frac{g\beta\Delta T {H_p}^3}{U^2 {D_c}^2}$$

$$L_{char} = \frac{{H_p}^3}{{D_c}^2}$$

Stratification Vessel Design



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): 403-414.

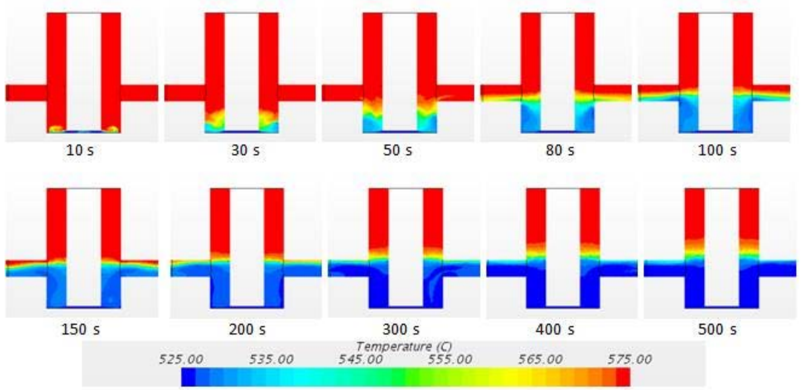
Design Benchmark Validation

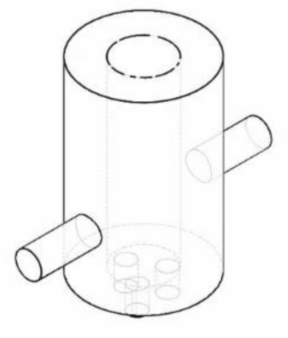
- Goal: use current CFD modeling tools to validate designs for experimental facilities
- Process: run models to observe if stratification occurs for high flow rate scenarios in the ABTR and proposed design

ABTR Geometry	H_pool [m]	8.02
	H_inlet [m]	2.673
	D_pool [m]	4.91
	D_UIS [m]	2.27
	D_inlet [m]	0.743
ULOF	Q [m3/sec]	0.3775
	T_hot [C]	575
	T_cold [C]	525
Core Velocity	u (m/s)	0.2906

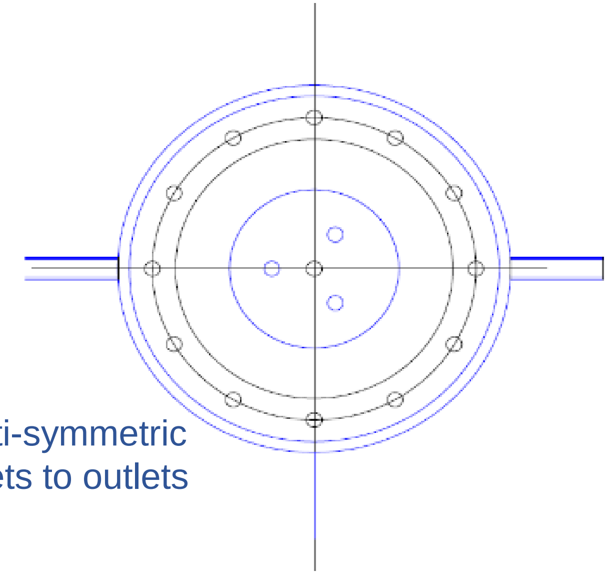
Design-I Geometry	H_pool [m]	1.25
	H_inlet_1 [m]	0.416666
	H_inlet_2 [m]	0.833333
	D_pool [m]	0.3048
	D_UIS [m]	0.1397
	D_core [m]	0.1397
ULOF	High Q [m3/sec]	0.001384
ULOF	Low Q [m3/sec]	0.0006919
	T_hot [C]	275
	T_cold [C]	225
Core Velocity	High_u (m/s)	3.641
Core Velocity	Low_u (m/s)	1.8205

$$L_{char} = \frac{{H_p}^3}{{D_c}^2}$$

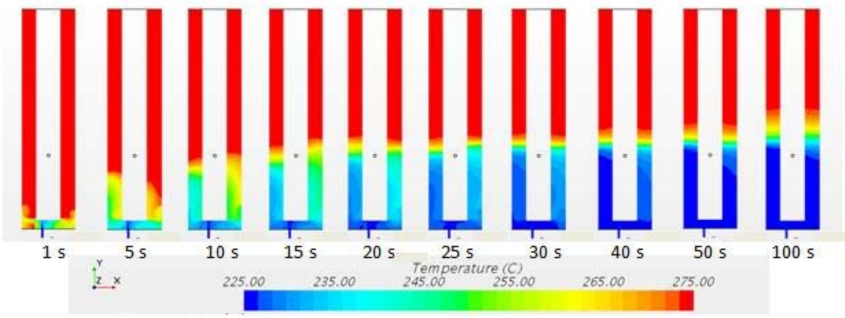




ABTR



Anti-symmetric inlets to outlets



Proposed Design

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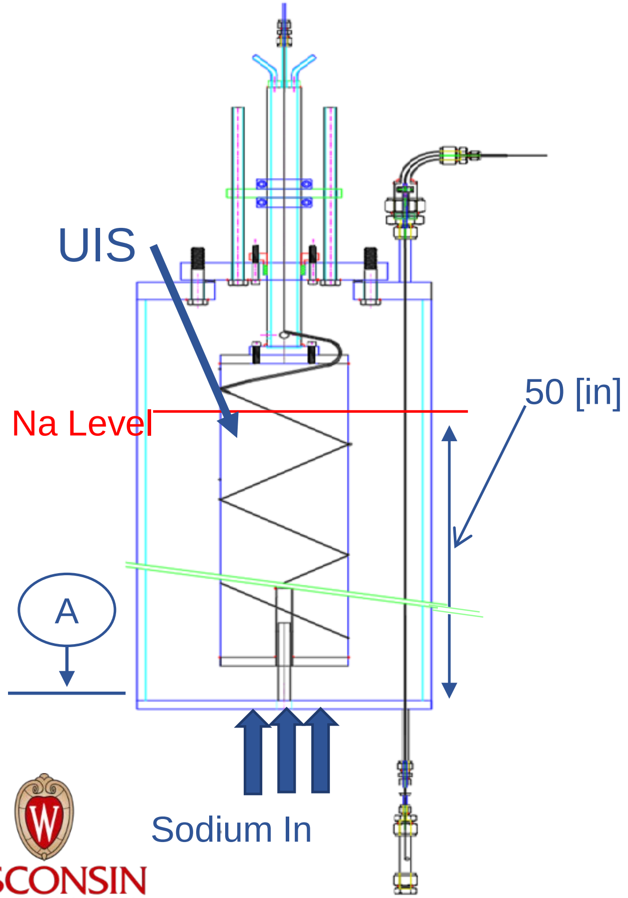
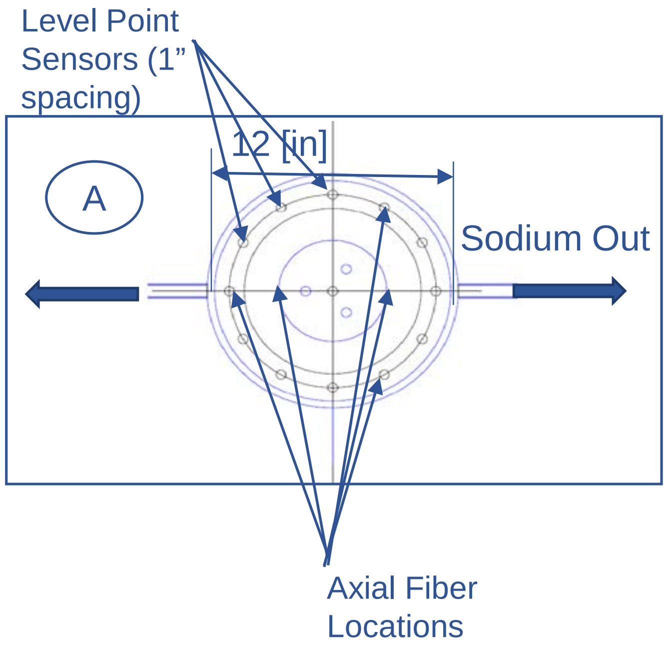
Experimental Vessel

- Desired Experimental Capabilities:
  - Upper internal structure (UIS) with interchangeable diameters and ability to change height
  - Axially deployed fiber with graphite packed (UIS) seal allows for continuous temperature resolution
  - Optical fibers possess 0.653 mm resolution. 14 possible axial fiber locations
  - Axial thermocouple locations for acquiring different radial measurements and fiber data validation
  - Fiber optic level sensor for sodium pool height control

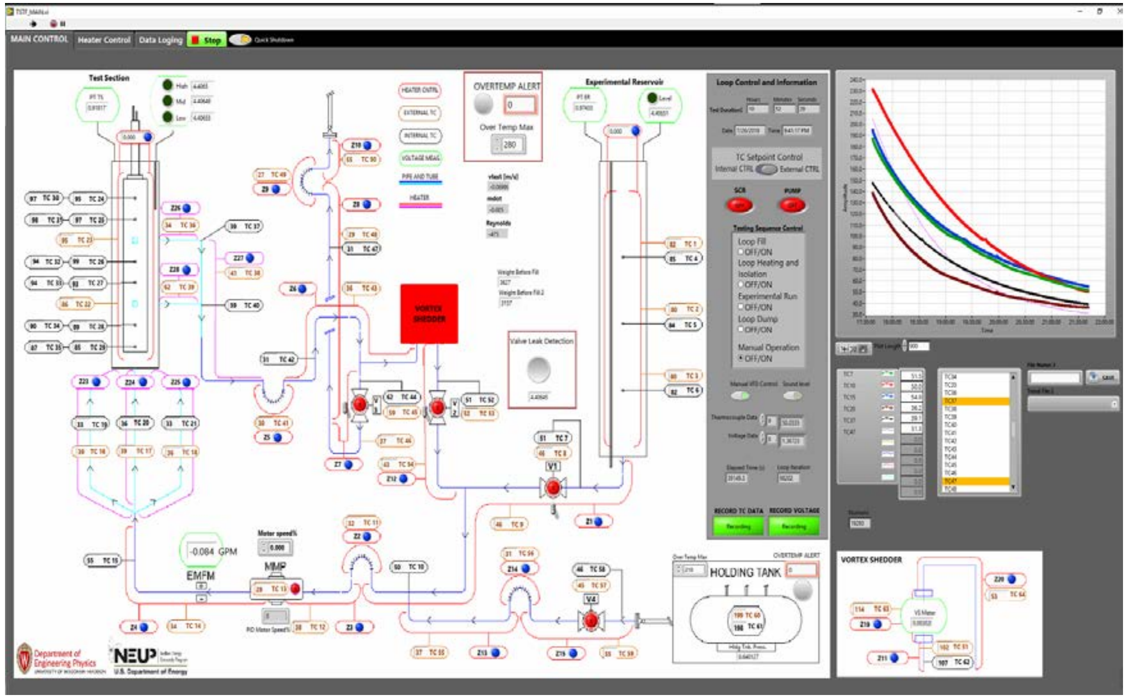
Outlets	# of Inlets	UIS Height	UIS Diameter	DELTA T	Flow Rate
High or Low	2 or 3	0-4.5" 2.5”	0-5.5"	250 into 200 [C] or 200 [C] into 250[C]	20 [gpm] 10 [gpm] 5 [gpm] 20-5 [gpm]

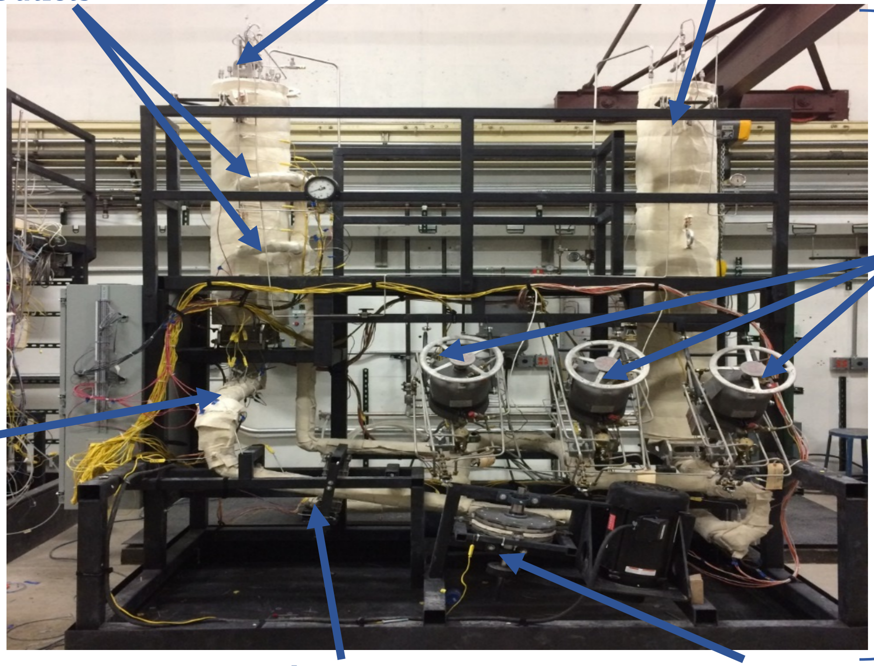


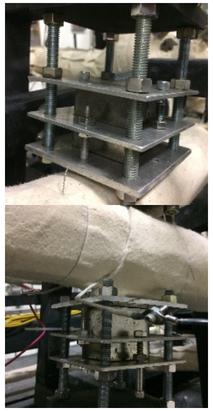


Thermal Stratification Test Facility (TSTF)

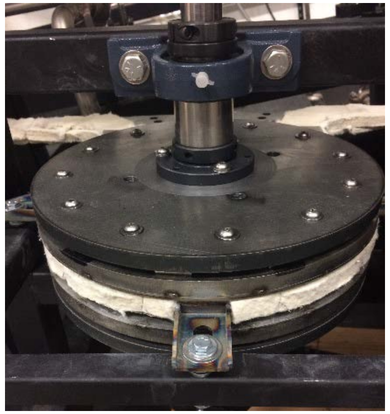
- Total Volume: ~70 [gal]
  - Experimental Vessel: ~20[gal]
  - Sodium Reservoir: ~40[gal]
  - Loop Piping: ~10[gal]
- Moving Magnet Pump
- Thermocouples and optical fiber temperature sensors
- Actuating Liquid Metal Valves
- Electro Magnetic Flow Meter
- Fiber optic level sensors
- 300 [gal] of workable sodium
- Remote control of Data Acquisition and Control



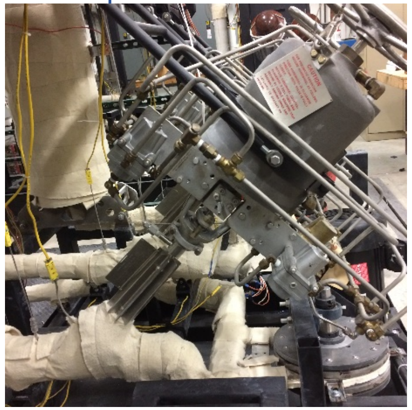




EMFM

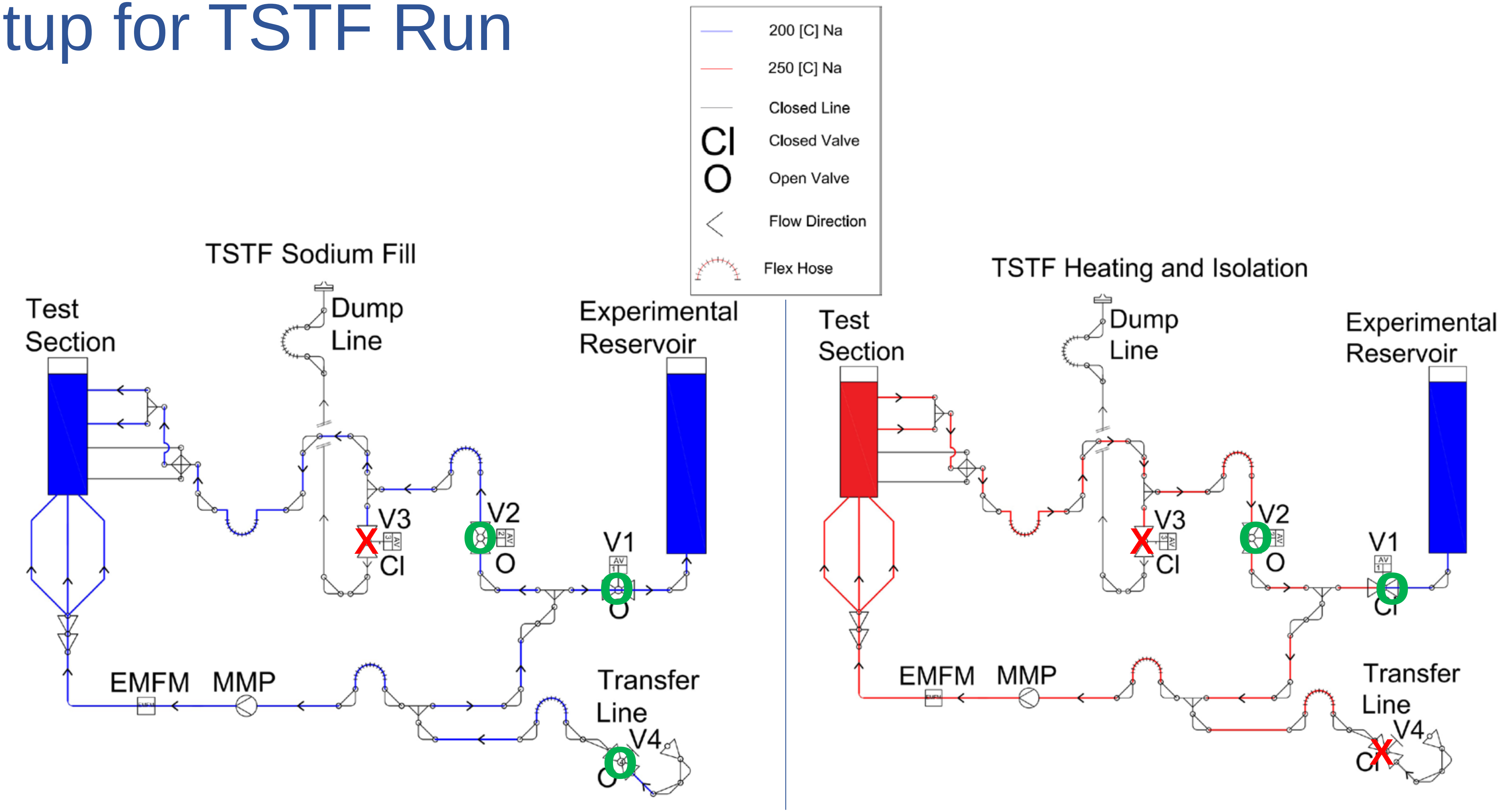


MMP

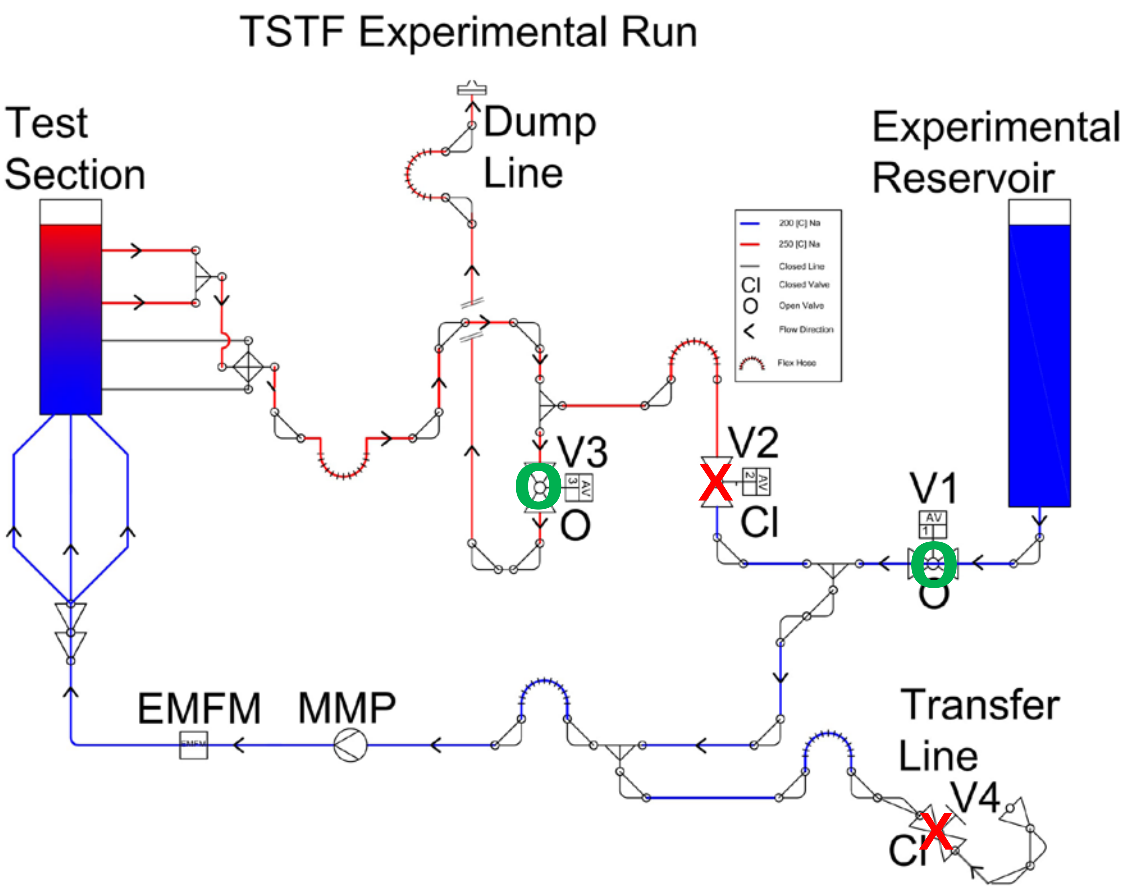


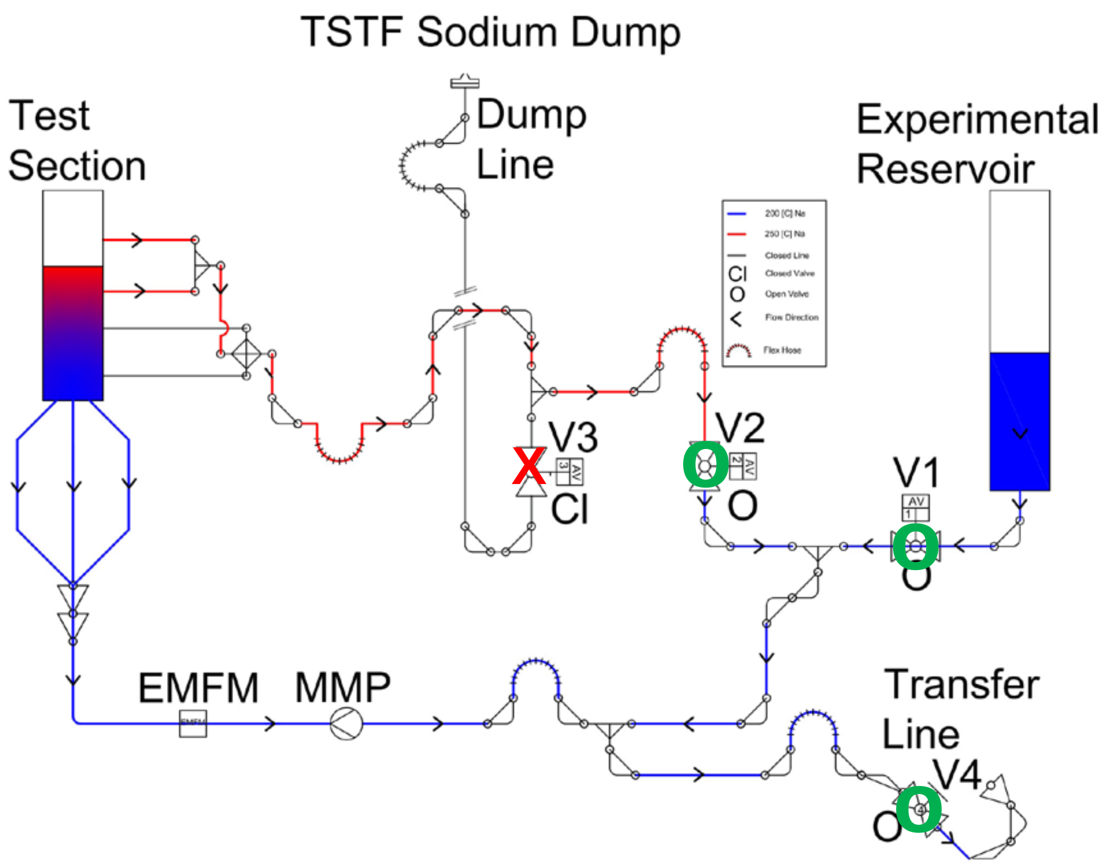
Liquid Metal Freeze Valves

Setup for TSTF Run

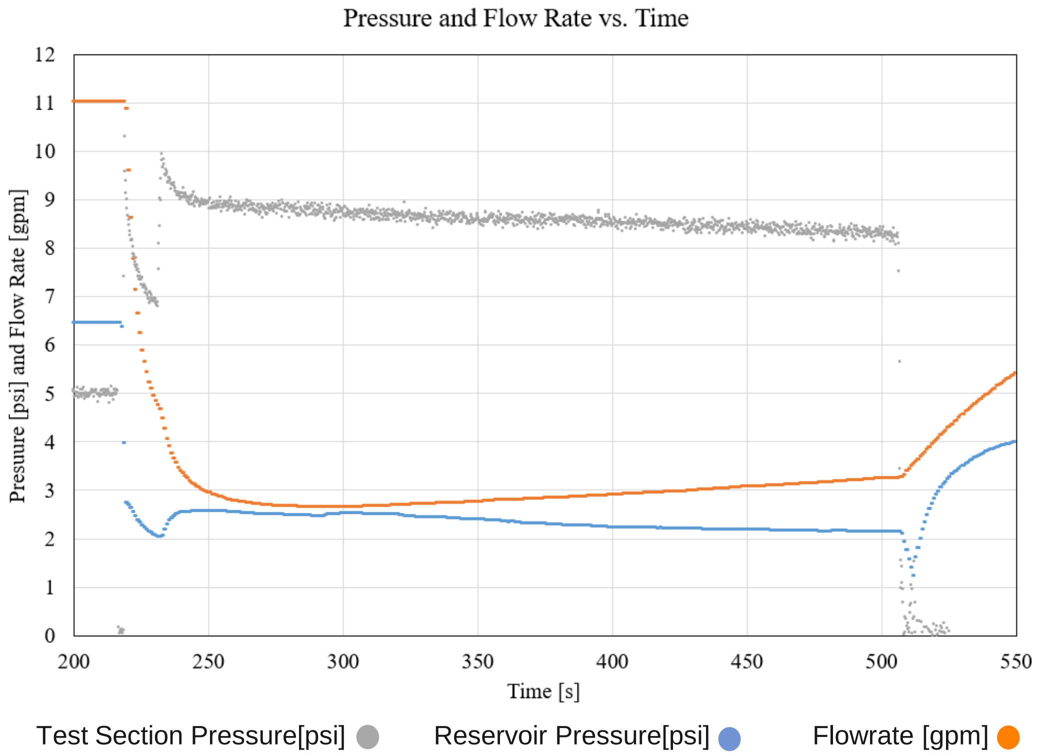


Protected Loss of Flow Operation: Run





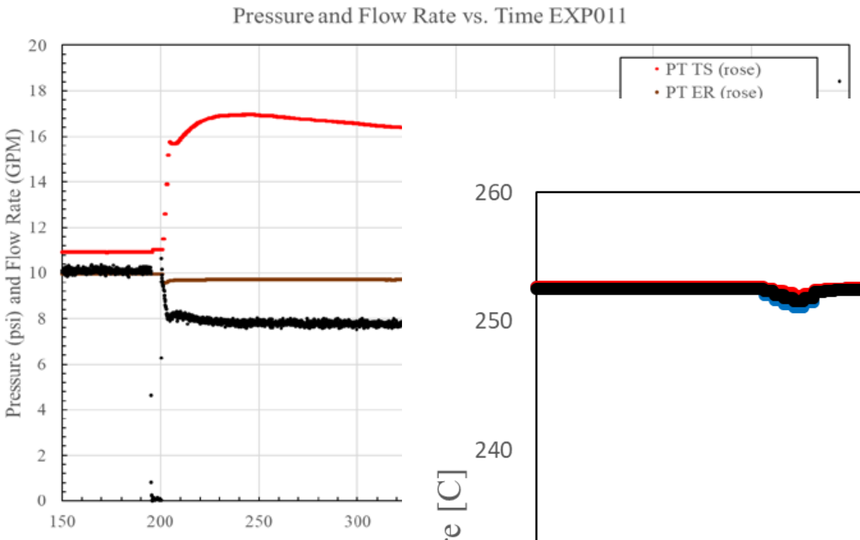
First Run Test Results

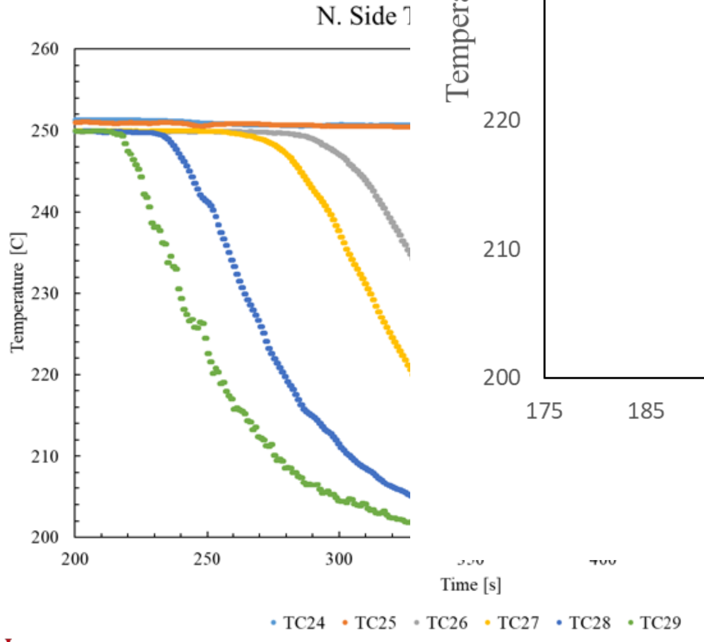


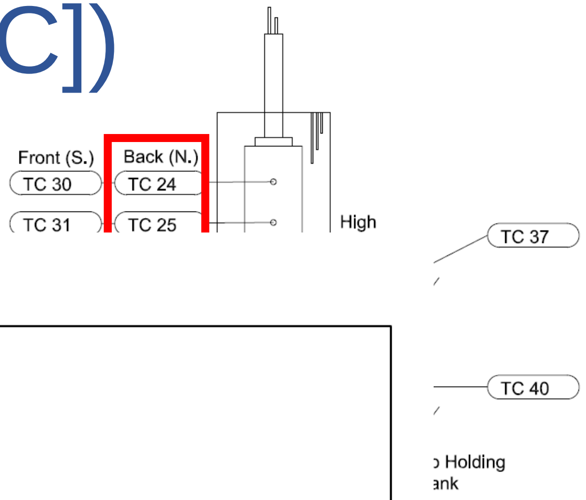
Water loop used for component testing

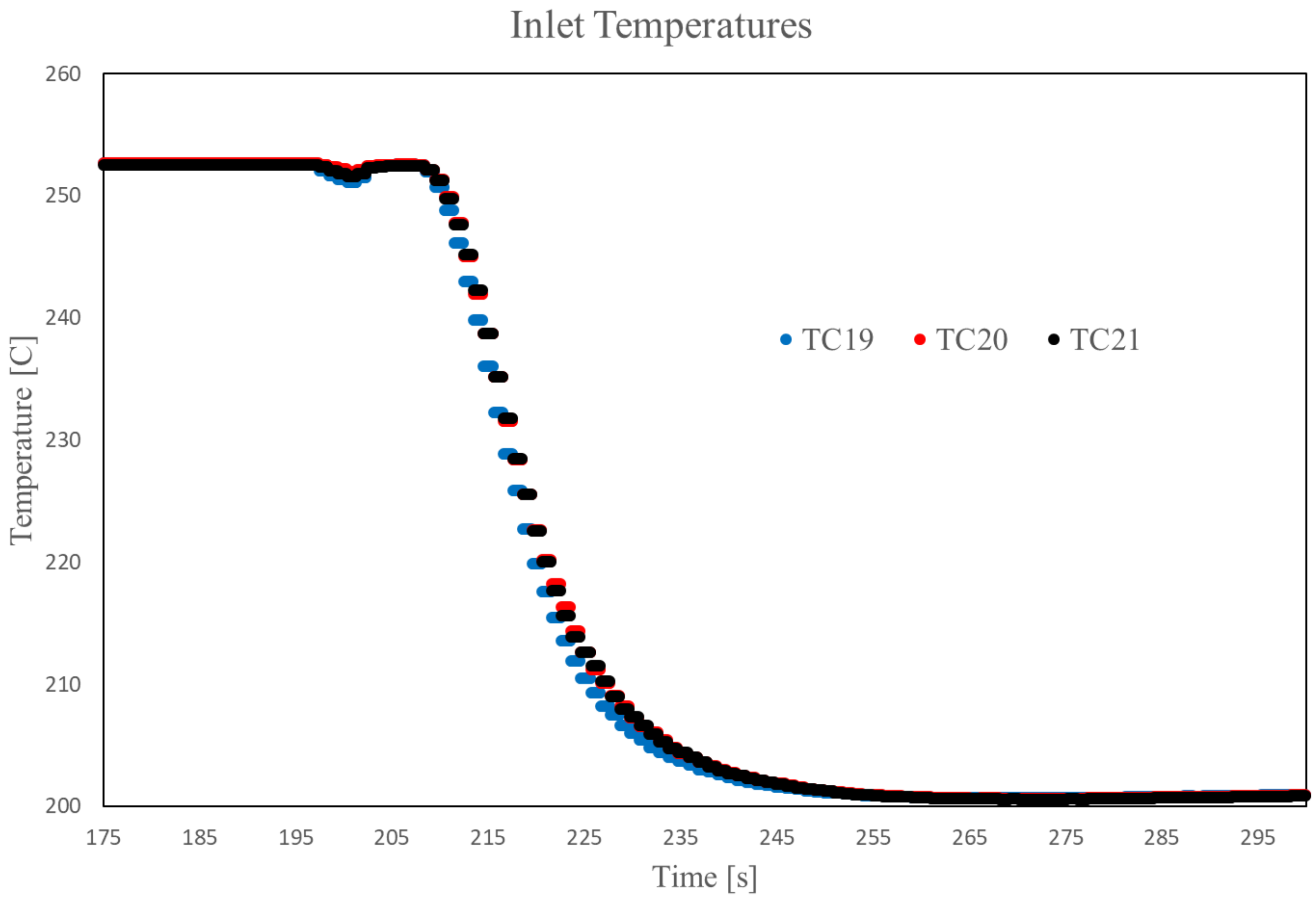
- Important Findings
  - Pressure lines supplying the test section and reservoir are not supplying gas fast enough to the vessels
  - Dump valve needs to be throttled to allow for desired flow rate to be achieved during run (completed water testing of valves to get idea of valve throttling capabilities at different flow rates

EXP Test Results (PLOF 200 => 250 [C])









ated with little
02 gpm)
n to be
from (5-10 gpm)
ameters

					Flow Rate
					20 [gpm]
High or Low	2 or 3	0-4.5"	0-5.5"	0-100 (max temp. 300[C])	10 [gpm]
					5 [gpm]
					20-5 [gpm]

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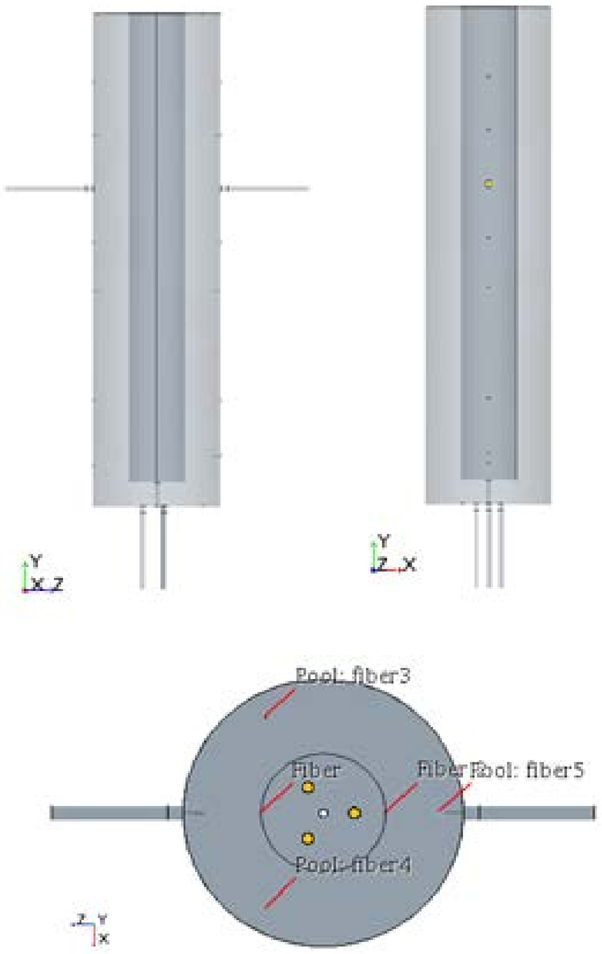
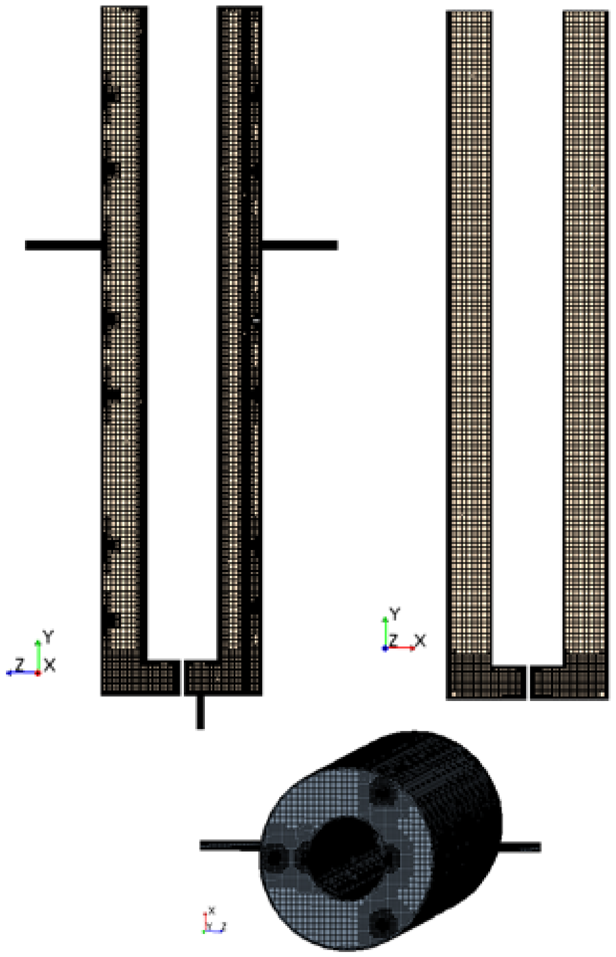
Simulation Results (PLOF 200 => 250 [C])



Test facility geometry in CFD simulation



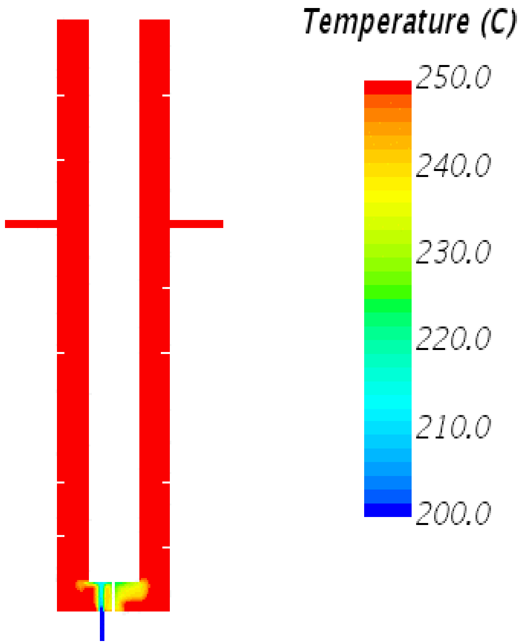
Mesh

Test Parameters

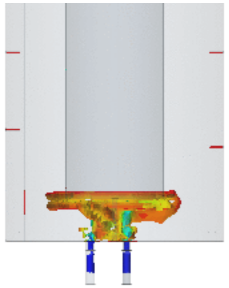
Geometry	H_pool	50.5	in	1.2827	m
	H_outlet	32.56	in	0.827024	m
	D_pool	12.39	in	0.314706	m
	D_UIS	5.5	in	0.1397	m
	D_inlet	0.5	in	0.0127	m
PLOF	Q	6	gpm	0.0003785	m^3/s
	Inlet Velocity	39.2157	in/s	0.99608	m/s
	T_hot	250	C		
	T_cold	200	C		

Simulation Results (PLOF 200 => 250 [C])

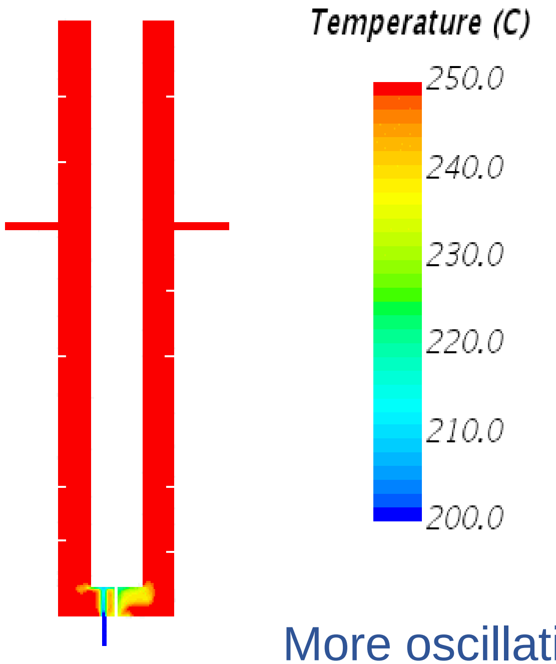
URANS



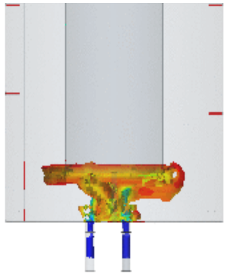
Solution Time 0.504 (s)



Solution Time 0.504 (s)



Solution Time 0.504 (s)



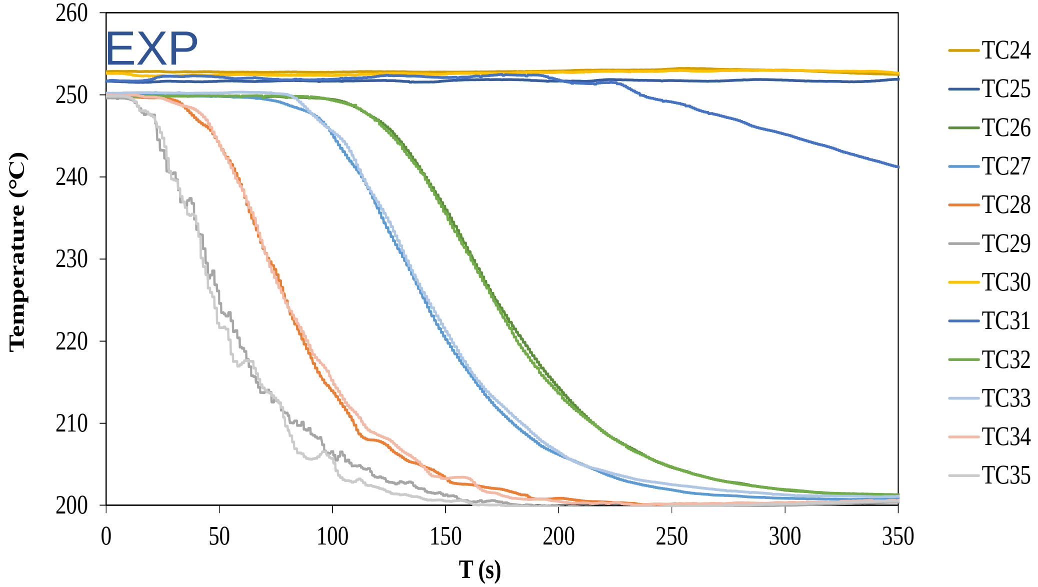
Solution Time 0.504 (s)

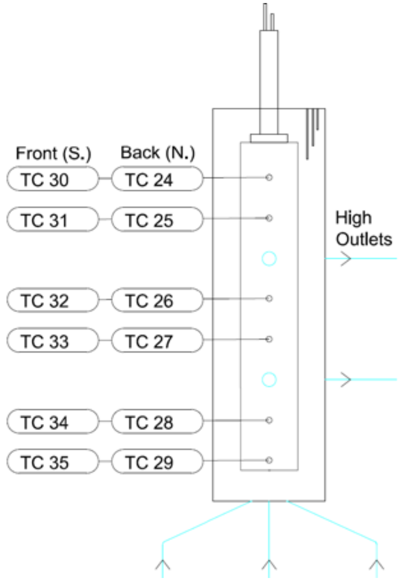
More oscillations In the bottom due to increased resolved turbulence structures

About 5 days for each simulation （till 400s）

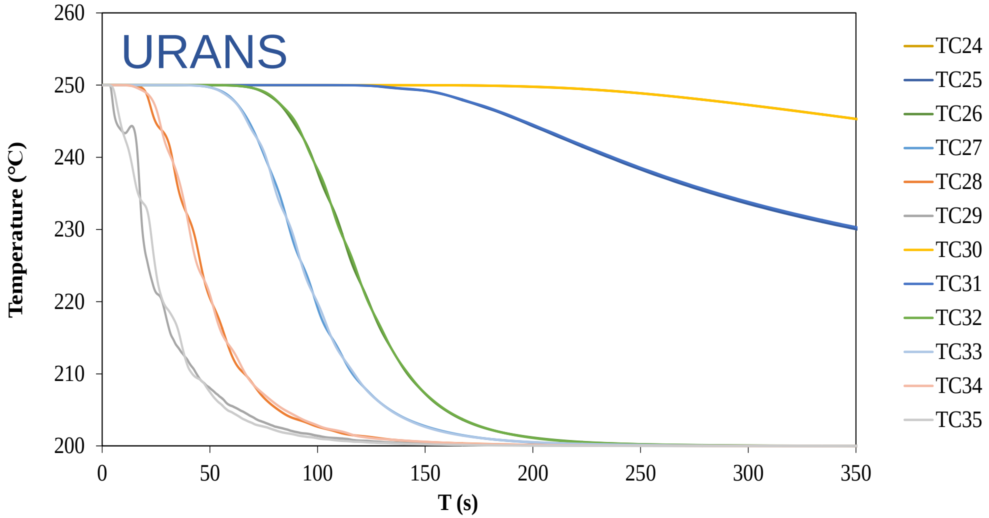
Simulation Results (PLOF 200 => 250 [C])

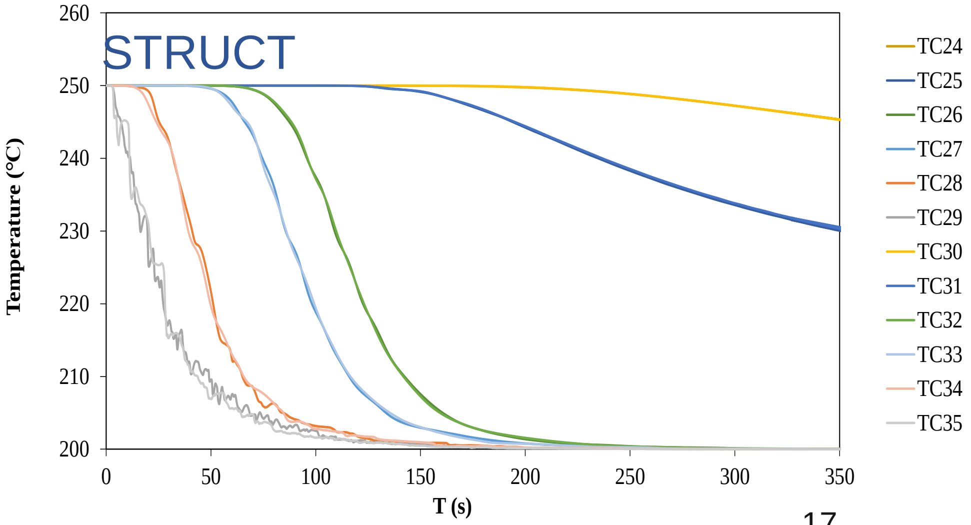
Temperature vs Time Graphs





- The time spent towards isothermal below the outlets predicted by the CFD simulations (around 200 s) is much shorter than the experiment (around 300s).
- Currently exploring the possible reasons, and make changes to the mesh and current settings accordingly.





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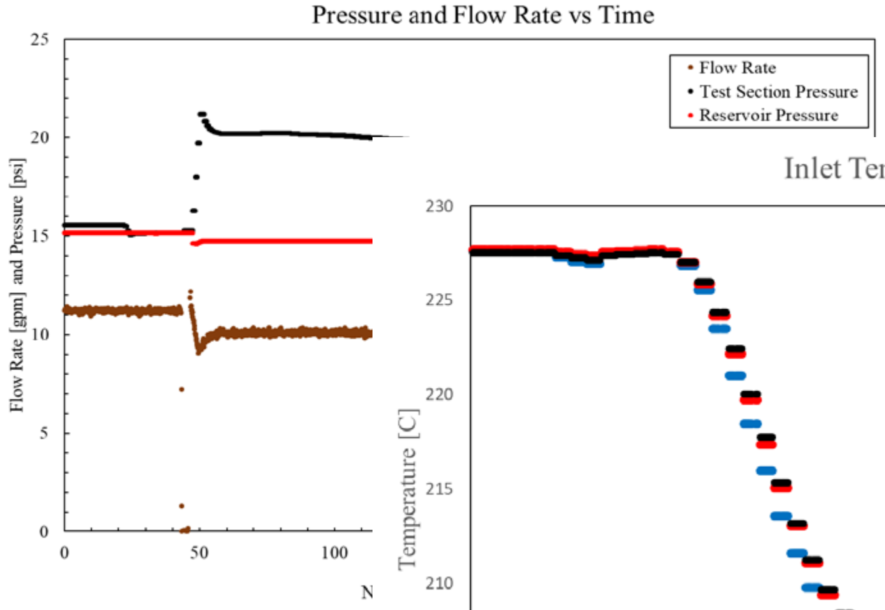
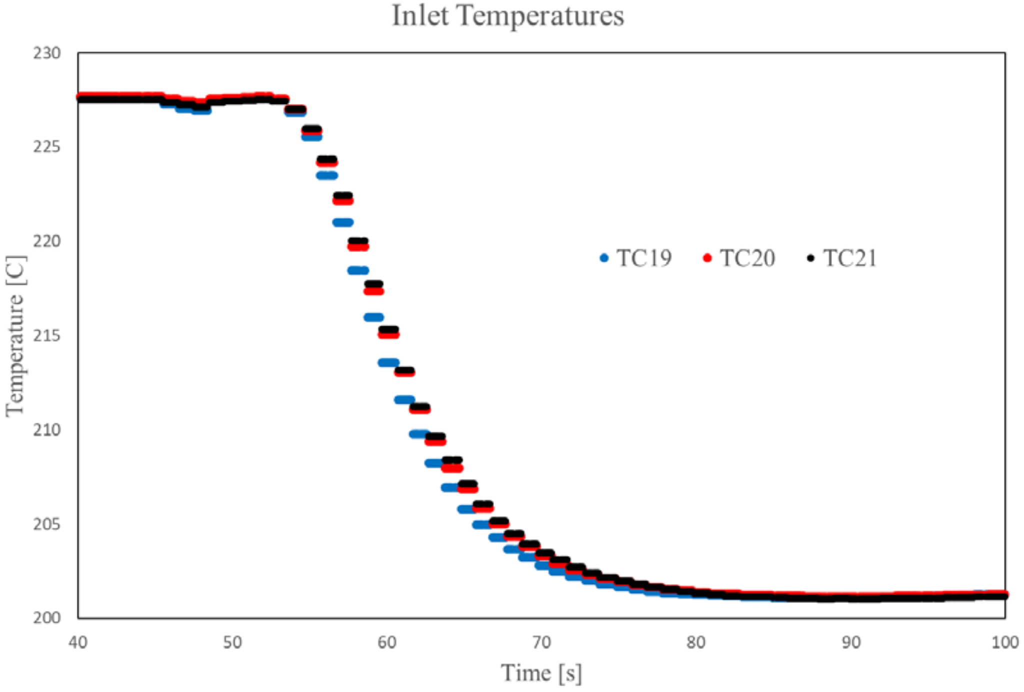
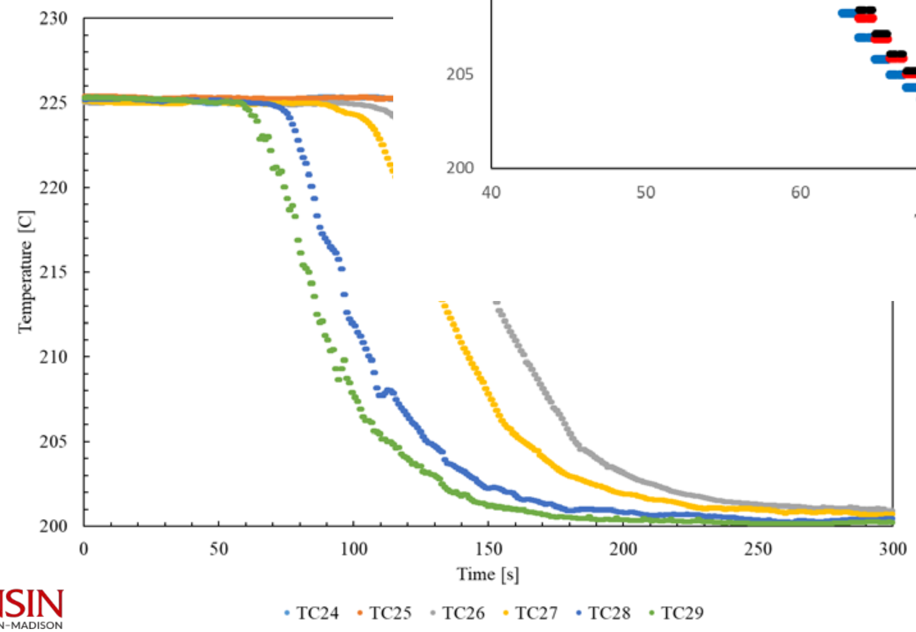
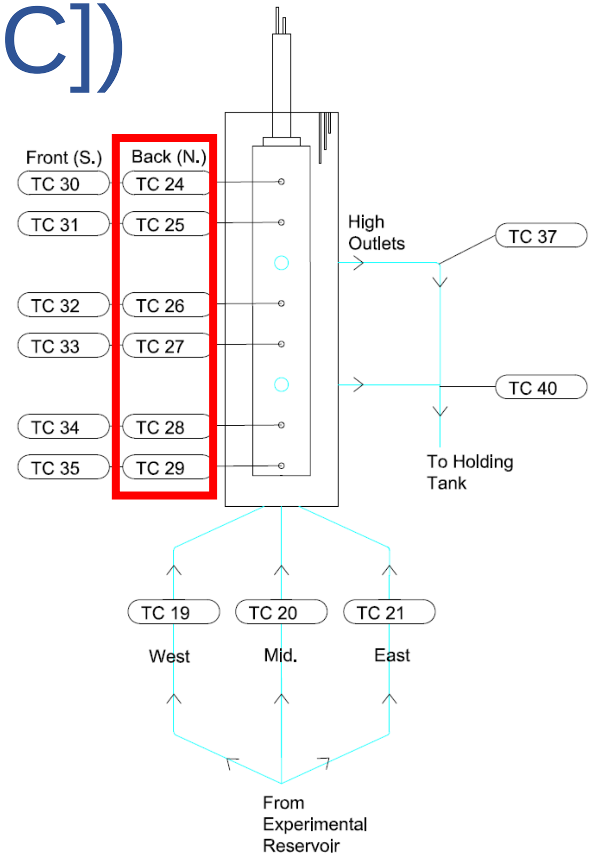
EXP Test Results (PLOF 200 => 225 [C])









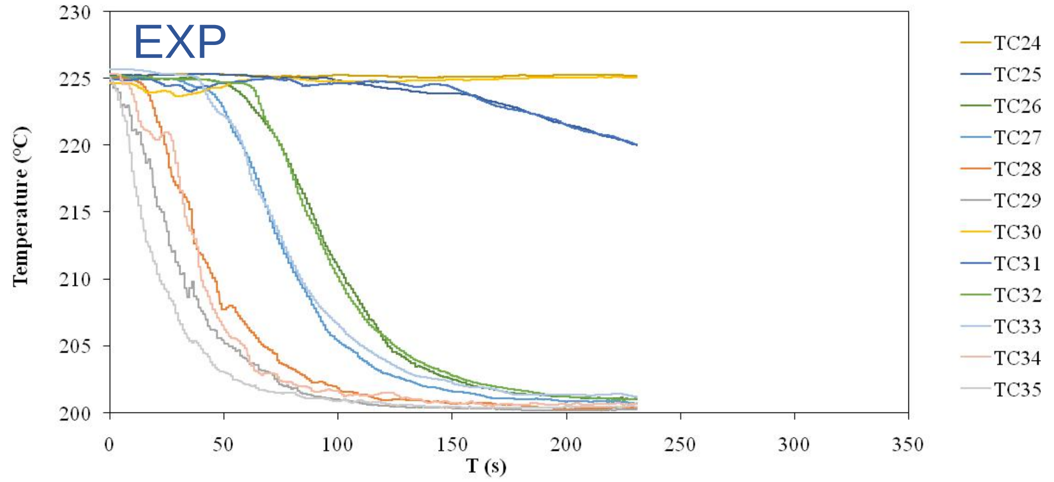
ne test has been repeated with little
iation of flow rate (±0.02 gpm)
ting of loop has proven to be
eatable for flow rates from (5-10 gpm)

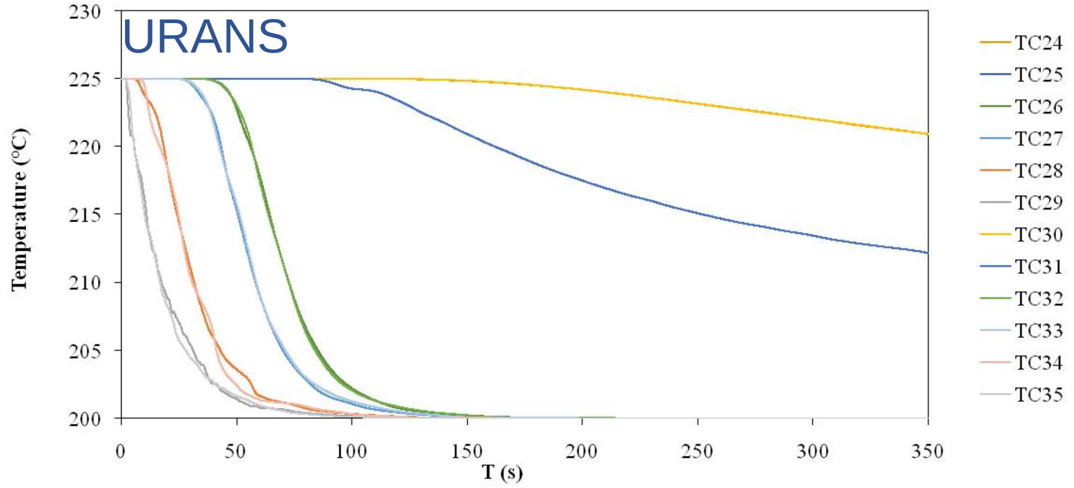
after 200[s]

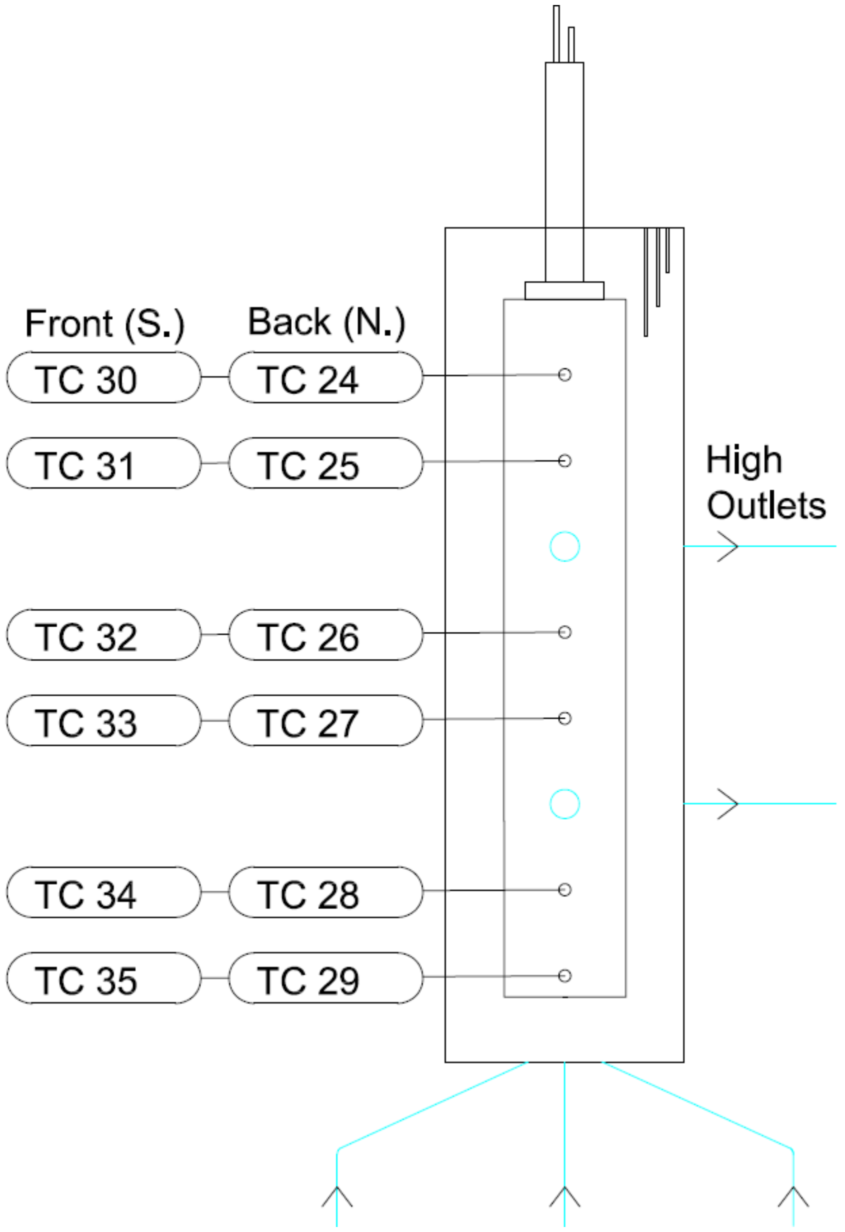
- Wide array of testing parameters

Outlets	# of Inlets	UIS Height	UIS Diameter	DELTA T	Flow Rate
High or Low	2 or 3	0-4.5"	0-5.5"	0-100 (max temp. 300[C])	20 [gpm]
					10 [gpm]
					5 [gpm]
					20-5 [gpm]

Simulation Results (PLOF 200 => 225 [C])







Final Year Plan for Research

- Experimental Data Acquisition Campaign
  - Use fiber optic temperature measurements to create detailed understanding of stratification inside of testing pool
  - Test different parameters: flow rate, scenario, number of inlets, outlet height, UIS configuration

- CFD work
  - Conduct detailed comparison for each experimental campaign conducted. Use validated model to help inform system code analysis

- System Code Development
  - Build physics based 1D model as well as an improved 0D model

- Other Sodium Work
  - Won grant for Isotope transport in gas bubbles in pool of liquid sodium (3 yr.)
  - Won grant for developing a micro-coldtrap for implementation in the VTR sodium test reactor (1 yr.)

Conclusions

- Goal of the project is to obtain high fidelity data for thermal stratification to validate 3D computational fluid dynamic codes, specifically the URANS/STRUCT model
- Use validated CFD codes to inform system code models used analyze nuclear reactor designs

Acknowledgements

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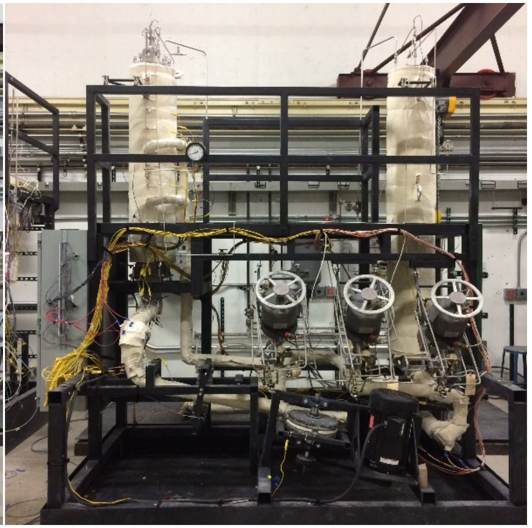
Thank You

Questions?

11/1/2017

11/07/2017

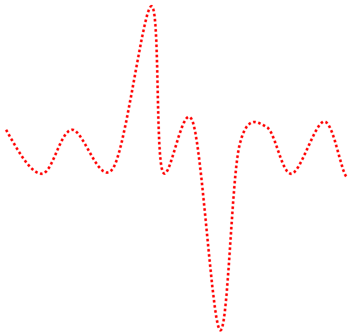
01/08/2018



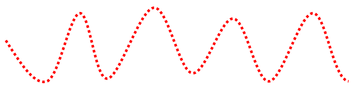
03/30/2018

Original STRUCT model

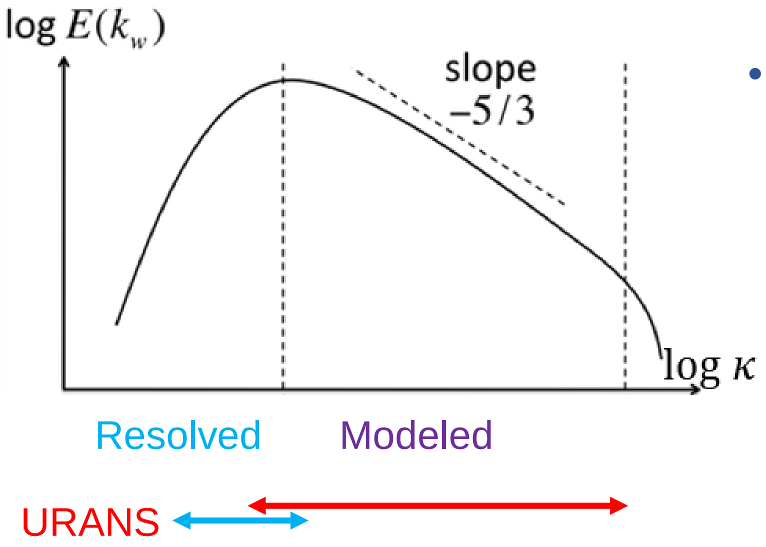
- URANS assumes large scale separation between modeled & resolved scale
- However, this assumption is not valid for complex flows with strong resolved flow deformation, where overlap exists between the large-scale and residual velocity fluctuations.



Large scale separation



Small scale separation



- Idea of the STRUCT model: identify regions where the scale overlap exists and increase the local resolution of turbulence

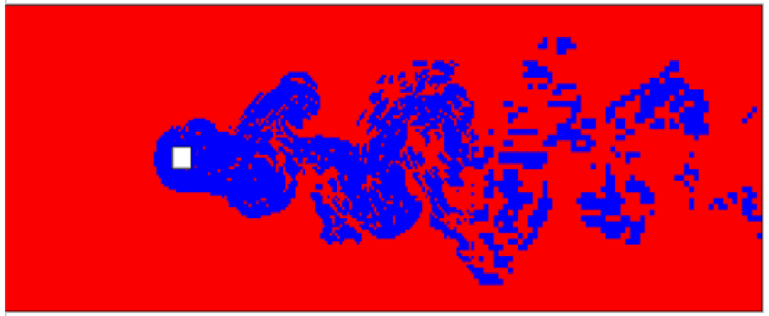
- These regions of high deformation are identified using the second principal invariant of the resolved velocity gradient tensor, $\overline{II}$.

- A simple formulation of STRUCT Model:

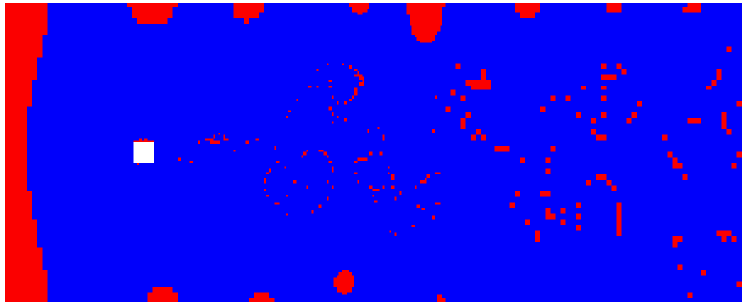
$$\nu_t = \begin{cases} \nu_t & f_r < f_m \\ \phi \nu_t & f_r \geq f_m \end{cases}$$

  - Resolved flow frequency: $f_{\mathrm{r}} = \sqrt{|\overline{II}|}$
  - Modeled flow frequency: $f_m = f(\frac{\varepsilon}{k_{\mathrm{m}}})$
  - Reduction parameter: $\phi \propto \frac{f_m}{f_r}$

Original STRUCT model



Flow past a square cylinder with wall boundaries on the top and bottom, activation regions of the original STRUCT model (blue)



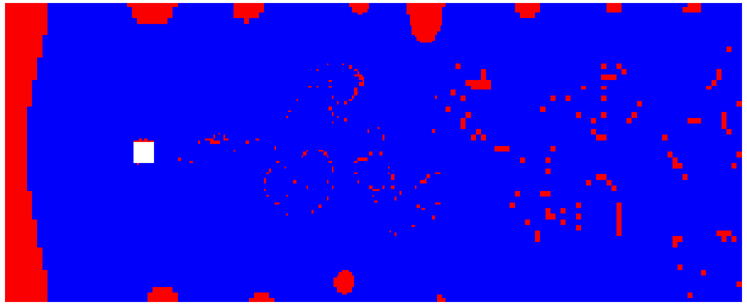
Flow past a square cylinder with symmetry boundaries on the top and bottom, activation regions of the original STRUCT model (in blue)

- STRUCT has demonstrated much improved accuracy in mean and RMS velocity profiles on computational grids typical of URANS simulations.
- STRUCT has been tested on a variety of wall-bounded flow tests including thermal mixing in a T junction, thermal mixing of triple jets, mild separation in asymmetric diffuser, etc.

Problem of the original STRUCT model:

- Original STRUCT model suffers from a robustness issue when extending to open boundary flow cases: undesirable hybrid activation appear when improper inlet conditions are specified

Problem of original STRUCT model



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  - Modeled flow frequency: $f_m = f\left(\frac{\varepsilon}{k_m}\right)$
  - Reduction parameter: $\phi \propto \frac{f_m}{f_r}$

Problem of the original STRUCT model:

- Original STRUCT model suffers from a robustness issue when extending to open boundary flow cases: undesirable hybrid activation appear when improper inlet conditions are specified

- Recap the STRUCT formulation:
- the hybrid activation is explicitly dependent on the modeled frequency f_m

- In open boundary flows, the user-defined inlet turbulence quantities k_m and ε transport to the whole flow domain, therefore if user defines k_m and ε corresponding to a very low f_m, the activation is almost everywhere

Proposal of improved STRUCT model

$$\nu_t = C_\mu \frac{{k_m}^2}{\varepsilon}$$

$$\frac{\partial k_m}{\partial t} + \bar{u}_i \frac{\partial k_m}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k_m}{\partial x_j}\right] + P_k - \varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} + \bar{u}_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon 1}\frac{\varepsilon}{k_m}P_k - C_{\varepsilon 2}\frac{\varepsilon^2}{k_m} + \boxed{C_{\varepsilon 3} k_m |\overline{II}|}$$

$$P_k = -\overline{u_i u_j}\frac{\partial \bar{u}_i}{\partial x_j}$$

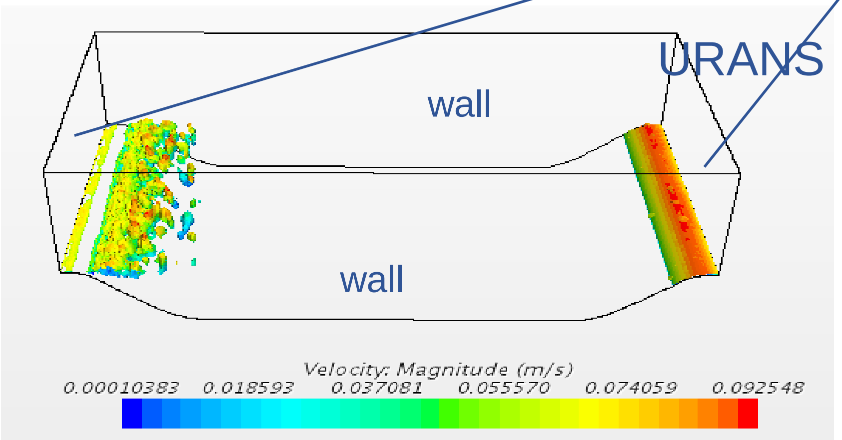
$$C_{\varepsilon 1} = 1.44,\ C_{\varepsilon 2} = 1.92,\ \sigma_k = 1.0,\ \sigma_\varepsilon = 1.30,\ C_{\varepsilon 3} = 1.5$$

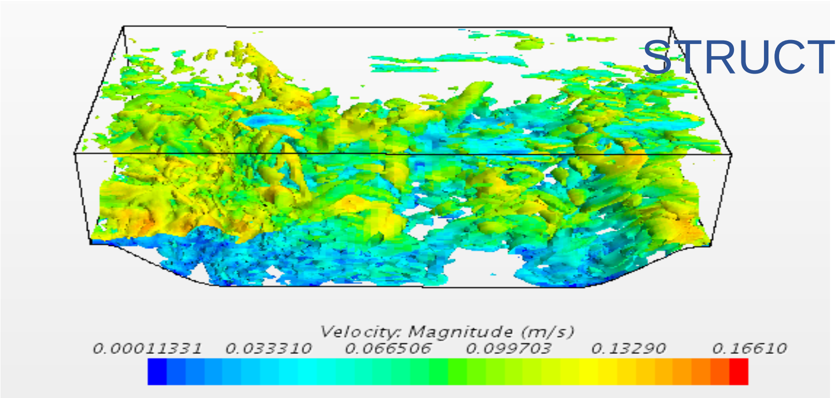
- To address this issue, a new version of STRUCT model has been proposed.
- This improved model reduces the eddy viscosity implicitly by adding a source term $C_{\varepsilon 3} k_m |\overline{II}|$ in the ε transport equation of the standard k- ε model.
- With this new proposed STRUCT model, the hybridization region no longer depends on the user defined inlet turbulence.
- The formulation is also consistent with the original STRUCT idea implying the comparison of $\overline{II}$ and $/k_m$: the modification of the ε equation would only become noticeable when $|\overline{II}|$ is compared larger than ε/k_m.

Tests of the improved STRUCT model

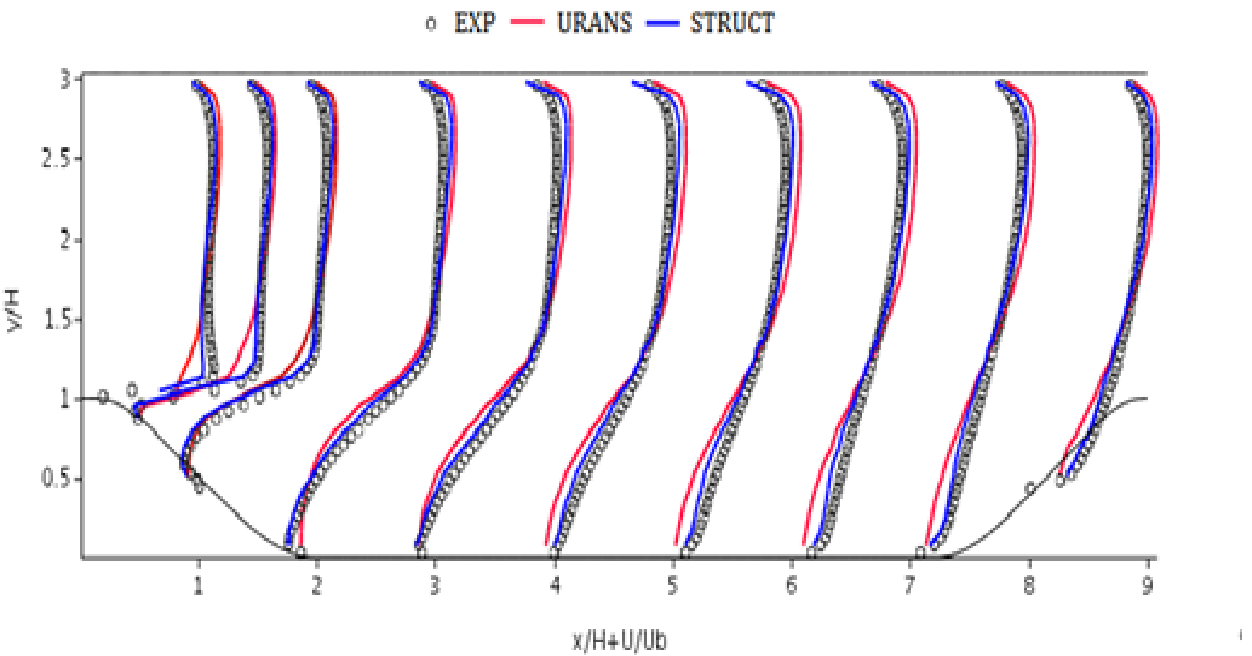
- Periodic hill

Periodic with constant mass flow



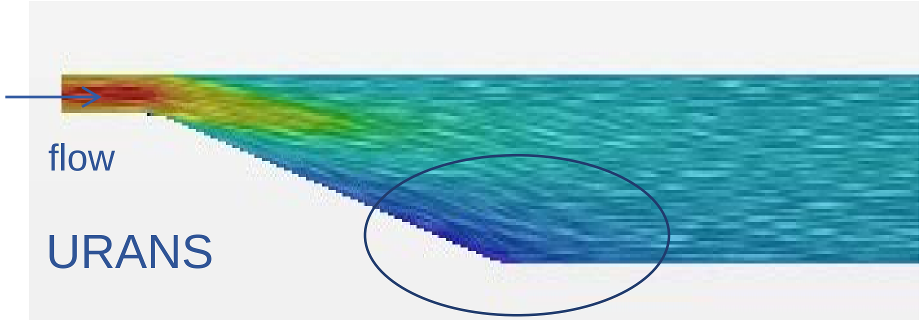


Mean U

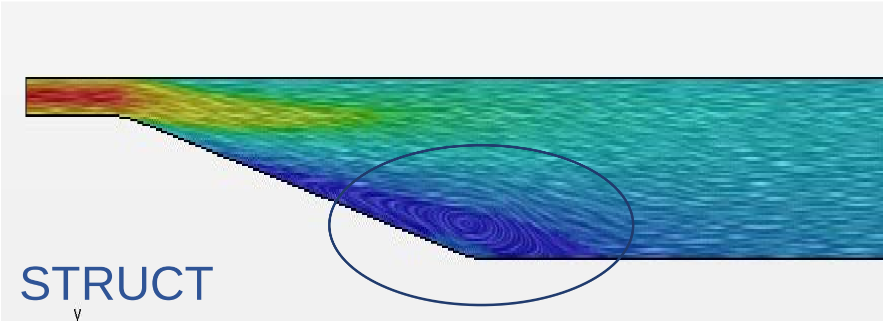


Tests of the improved STRUCT model

- Mild separation in an asymmetric diffuser

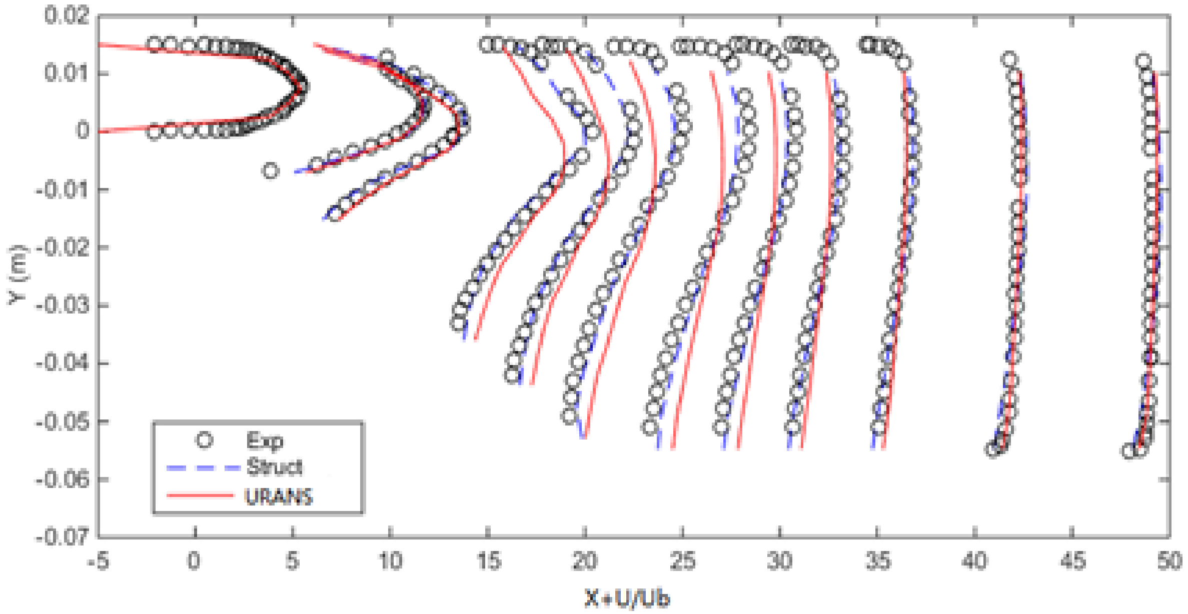


No separation



Mild separation

Mean U

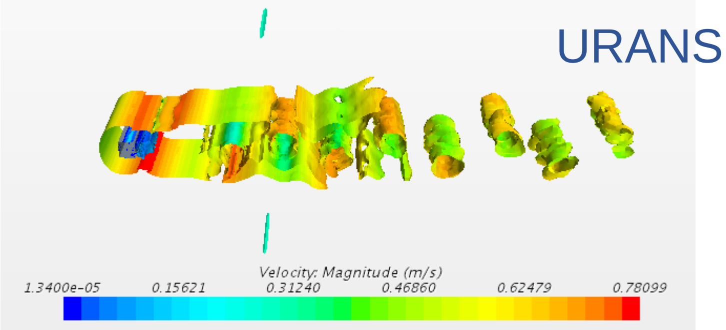


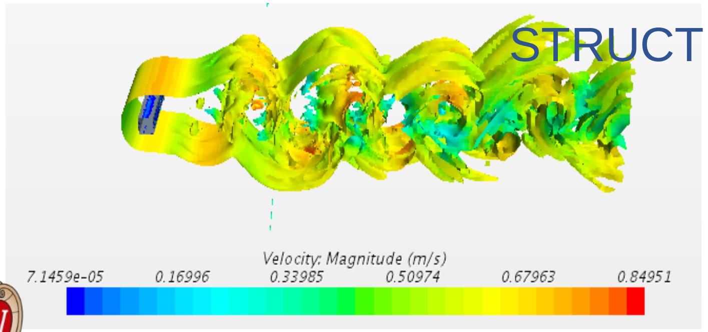
Tests of the improved STRUCT model

- The potential of the improved STRUCT model will be leveraged to assess its accuracy and robustness for thermal striping and stratification analysis through comparison with URANS and experimental results.

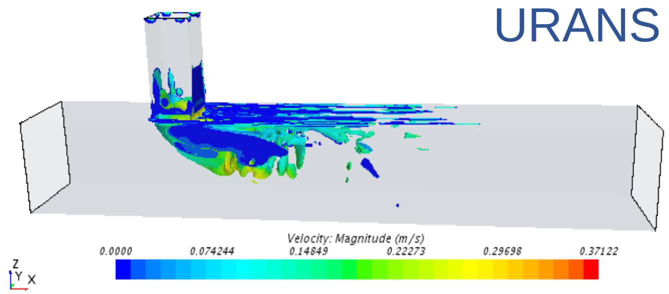
- Other simple tests:

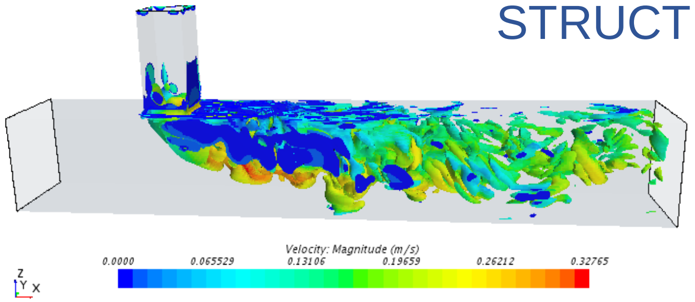
Flow past square cylinder



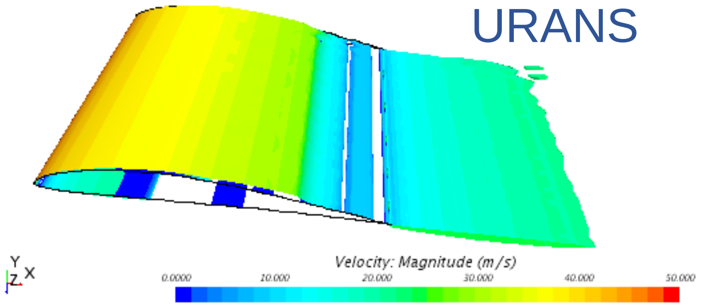


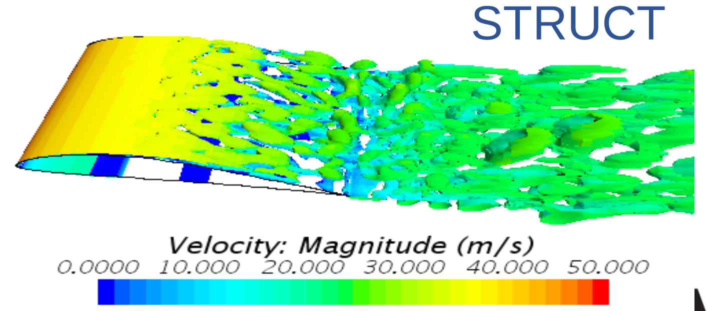
Turbulent mixing in a T-junction





Natural transition of a hydrofoil

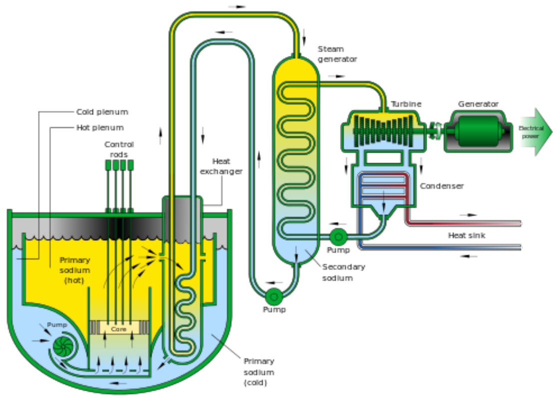




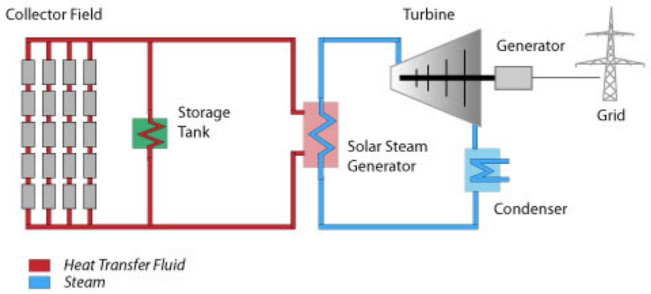
Liquid Sodium Background

- Liquid sodium's desirable properties as a heat transfer fluid
  - High Thermal Conductivity (64.28 W/m-K @ 500[C])
  - Low Prandtl number fluid
  - Similar properties to water (viscosity, density) near melting point (~98 [C])
  - Low melting temperature relative to other coolants
  - Good studies conducted regarding sodium corrosion of stainless steels
  - Neutronics: doesn’t moderate neutrons allowing them to maintain the fast spectrum

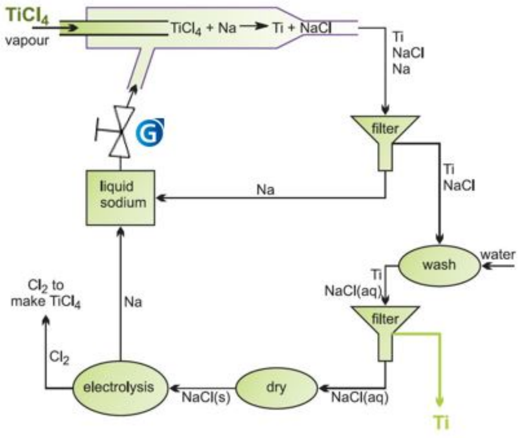
- Liquid Sodium uses:
  - Primary coolant in a nuclear reactor
  - Concentrated solar thermal systems
  - Titanium Manufacturing



[1] Whittle, *The challenges for materials in new reactor designs*



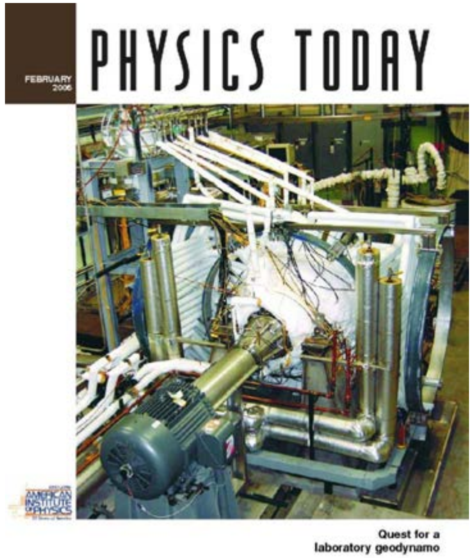
[2] Green Rhino Technology, *Concentrated solar systems*



[3] Guichon Valves, *Guaranteed tightness in a sodium line for a titanium application*

Tantalus Testing Facility

- The Tantalus facility is an 8000 sq-ft underground building operated by the University of Wisconsin-Madison Thermal Hydraulics Laboratory. From 1968-1987 the facility housed one of the first particle accelerators called Tantalus. Tantalus sat dormant until 1997 at which time it was revitalized as a research facility to study safety and special effects of advanced nuclear reactors and fundamental physics. In 2002 a 1 m^3 sodium filled spherical vessel, The Dynamo, was constructed along with a room specially suited for large scale sodium experiments. The Dynamo was removed and in 2012 to make room for a new set of sodium loop facilities. Currently work is being conducted to support the Department of Energy's mission to advance nuclear reactors and conduct testing for commercial reactor vendors.



Sodium Dynamo Experiment

Thermal Stratification Test Facility

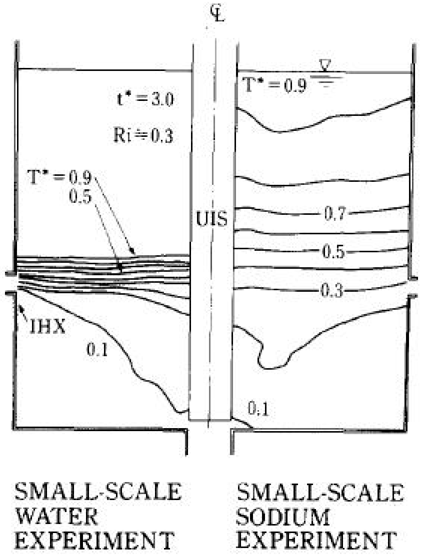
Materials Testing Loop

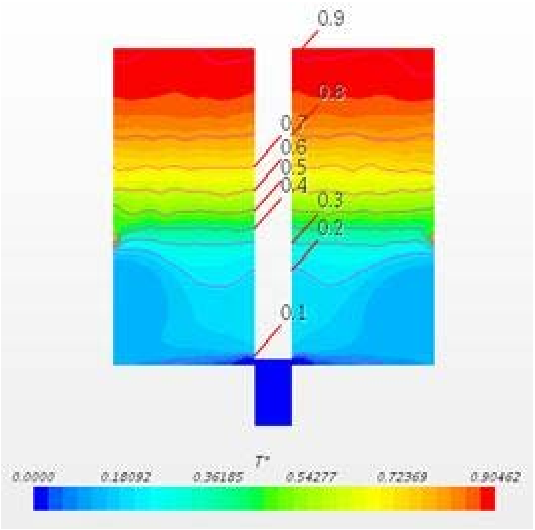
Thermal Stratification Project Overview

- Conduct a series of thermal stratification experiments with advanced temperature and fluid measurement instrumentation. A specific geometry will be considered both experimentally and computationally.(UW, MIT,VCU, ANL)
- Use the STRUCT modeling approach along with URANS methods to analyze the low Prandtl number (sodium) heat transfer, thermal stratification and thermal striping experiments (UW-MIT)
- Development of improved models for thermal stratification and thermal striping to be implemented in system level codes such as SAM and SAS4A/SASSYS-1. (VCU-ANL)
- Train several students in the aspects related to the SFR technology from working with sodium by conducting the experiments to detailed state of the art CFD for the low Prandtl number fluids and ultimately development and implementation of models into relevant systems code (UW, VCU, MIT)

CFD Validation for Experimental Design

- Initial validation of STRUCT model with experimental data
  - STRUCT model is a 2G-URANS model recently developed at MIT[5]
  - Validations of STRUCT model include thermal mixing in T-junction, flow past object, asymmetric diffuser, etc.
  - Computational recreation of experiment run by Tanaka[6] in 1990
  - Data comparison and validation of codes

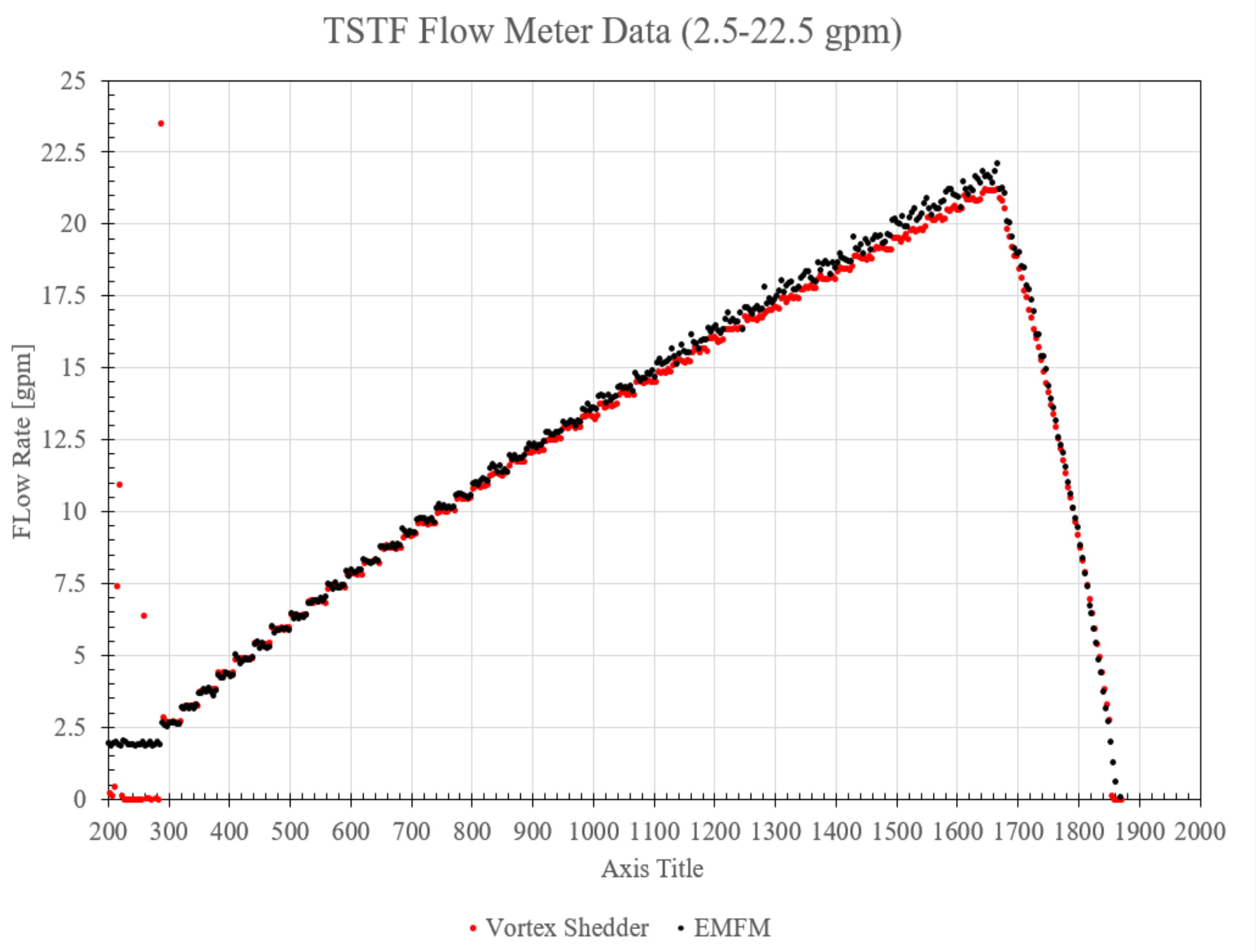




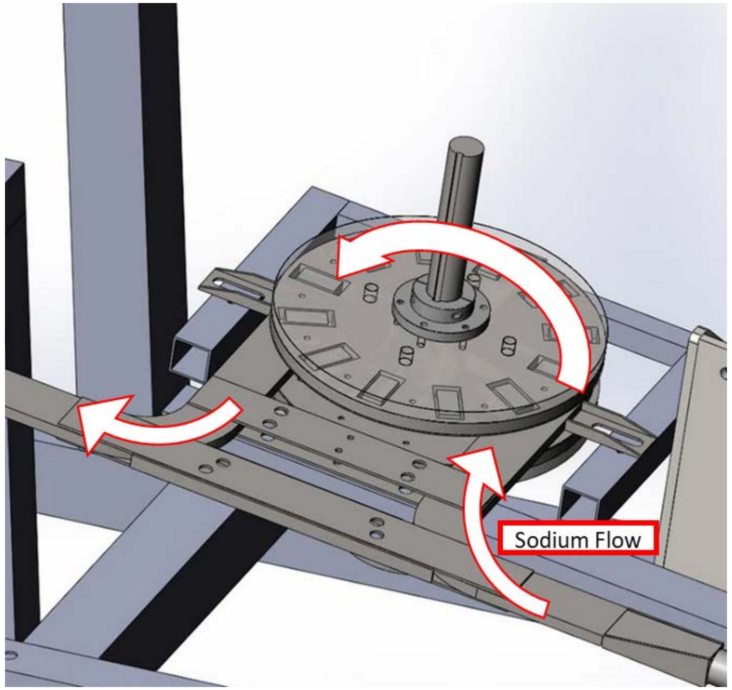
[5] Lenci, Giancarlo, and Emilio Baglietto. "A Structure-Based Approach for Topological Resolution of Coherent Turbulence: Overview and Demonstration." *16th Int. Top. Meet. Nucl. React. Therm. Hydraul* (2015): 1-14.

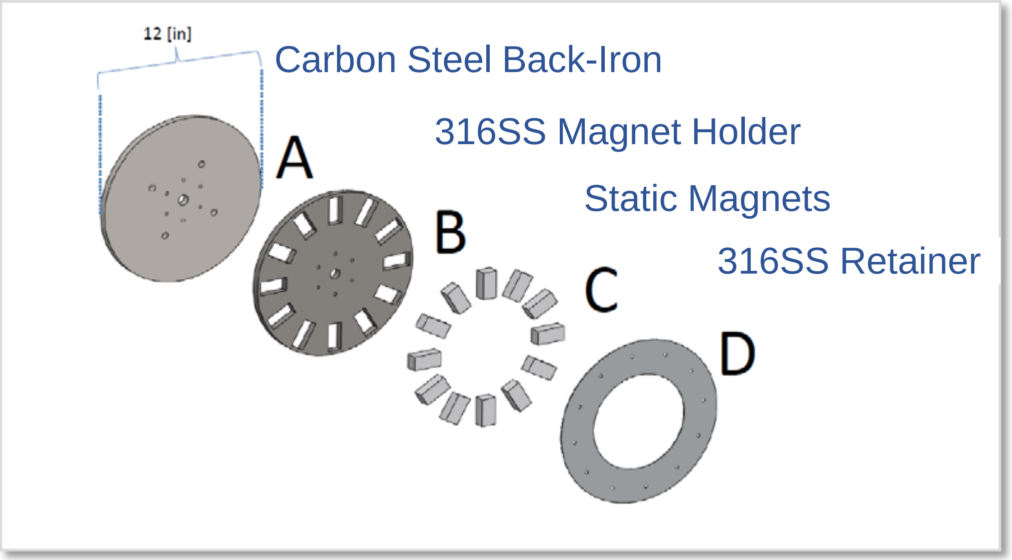
[6] Tanaka, Nobukazu, et al. "Prediction method for thermal stratification in a reactor vessel." *Nuclear engineering and design* 120.2-3 (1990): 395-402.

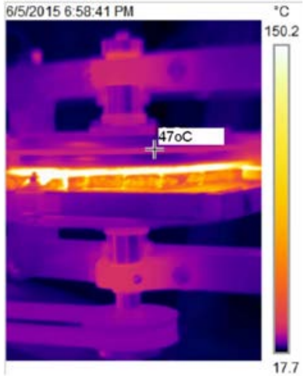
Flow Rate Comparison

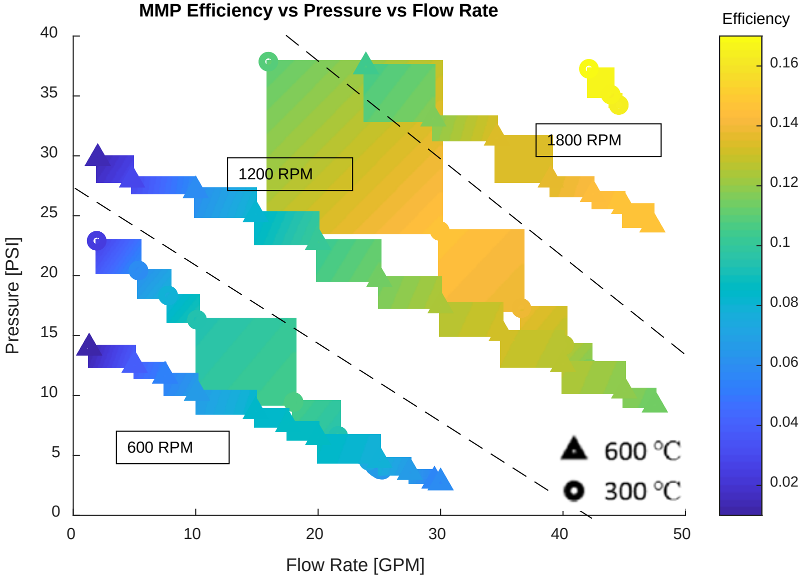


Moving Magnet Pump









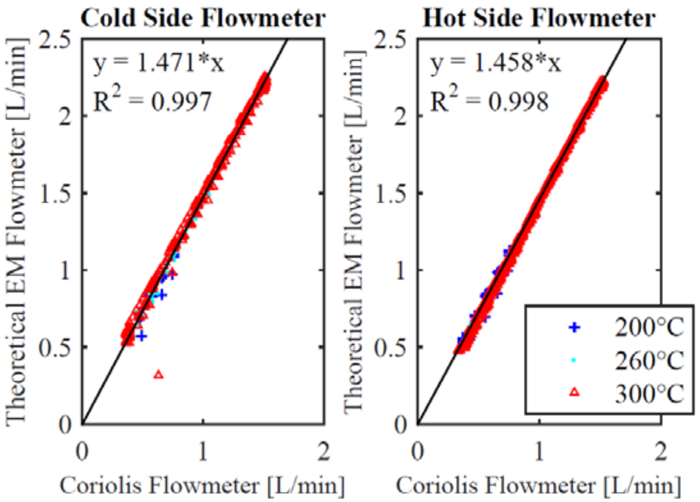
[1] M. Hvasta, *Designing & Optimizing a Moving Magnet Pump for Liquid Sodium Systems*, University of Wisconsin PhD Thesis

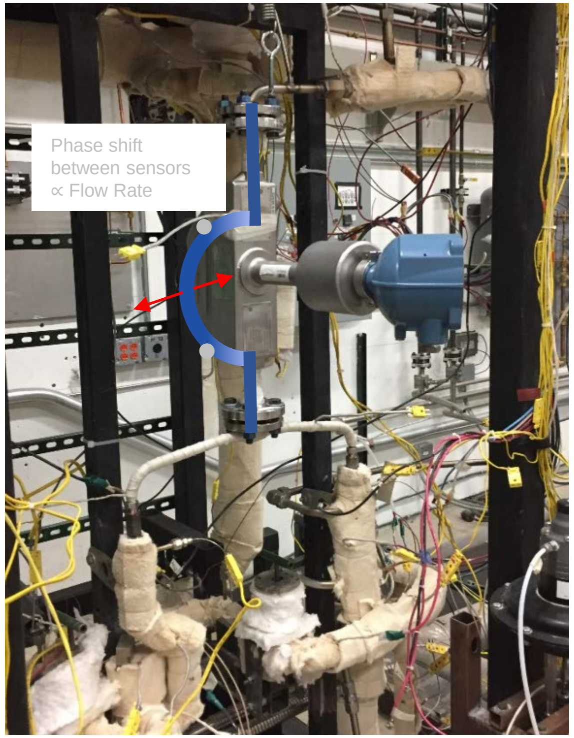
Electromagnetic Flowmeters

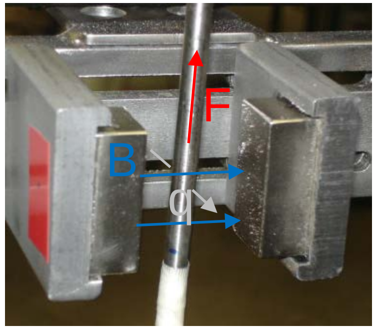
- Permanent magnet flowmeters induce a voltage via Lorentz force which correlates to flow rate
- Theoretical equation predicts flowrate as a function of hydraulic diameter, magnetic field, induced voltage and a series of temperature and geometric scaling functions (K1, K2, K3).

$$Q = \frac{\pi D_H}{4B} = \frac{V_m}{K_1 K_2 K_3}$$

- Micromotion F025A Coriolis flowmeter used to find a fit for theoretical to actual flow rate



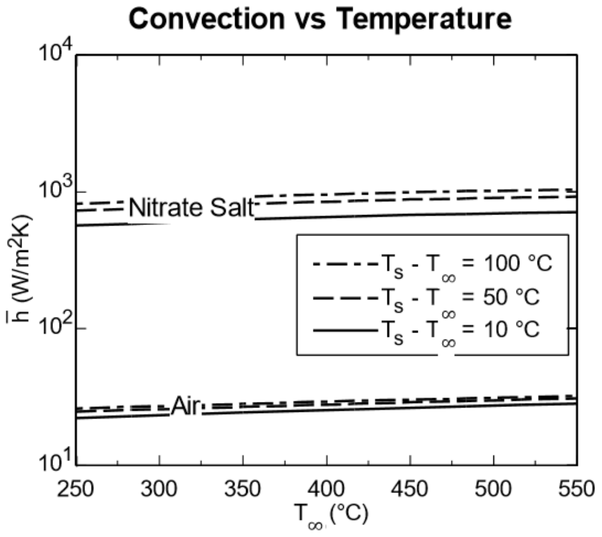


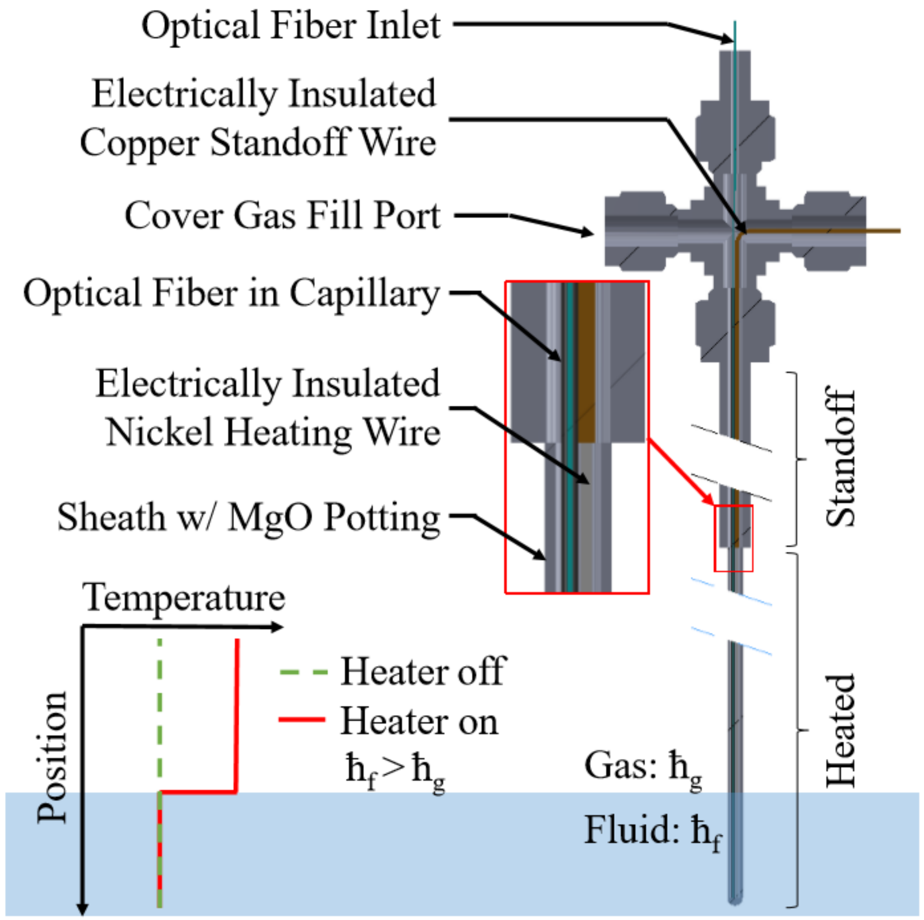


$$\vec{F} = q\vec{v} \times \vec{B}$$

Optical Fiber Level Sensor Overview

- Continuous level sensor consisting of high resolution optical fiber temperature sensor in-line with heater
- Local convection coefficient of fluid surrounding probe dictates temperature profile with heater on
- Tested successfully in nitrate salt (60/40% $NaNO_3$,KNO_3) up to 400°C
- Obtained provisional patent and journal article accepted for publication





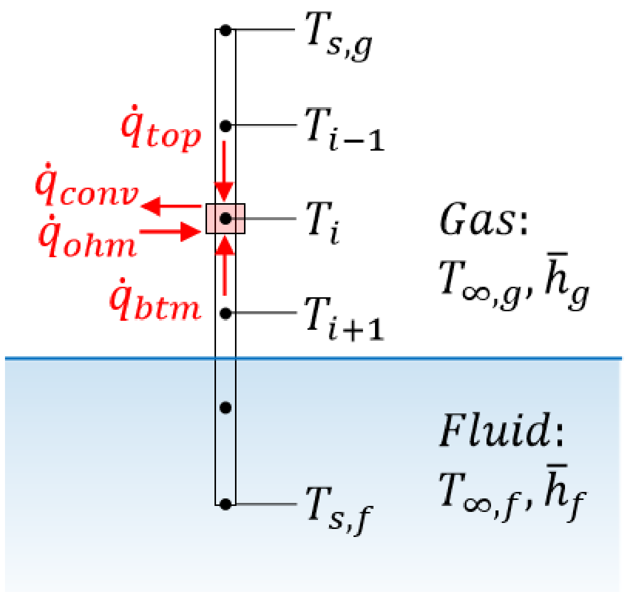
Optical Fiber Level Sensor capillary tensioning system

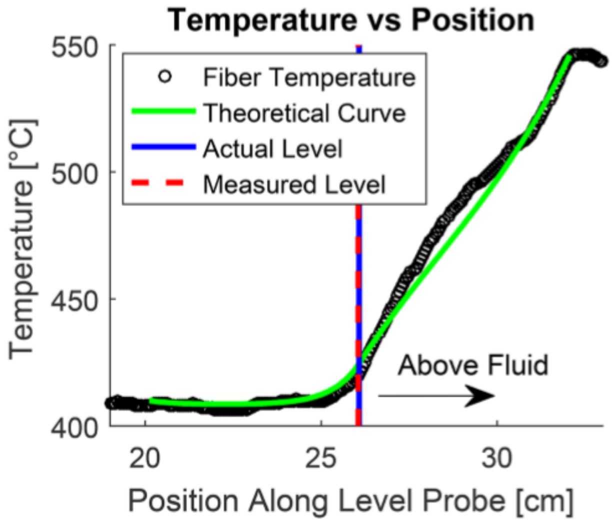
Optical Fiber Level Sensor Theory of Operation

- Computer algorithm continuously acquires temperature data from heated probe.
- Numerical solutions for theoretical probe temperature given gas and fluid temperature and power input to heater solved. Correlations for heated cylinder used to find convection coefficient.

$$Ra_L = \frac{gL^3\beta(T_s - T_\infty)}{\nu\alpha} \qquad \bar{N}u_{L,nc} = \frac{\bar{h}L}{k}$$

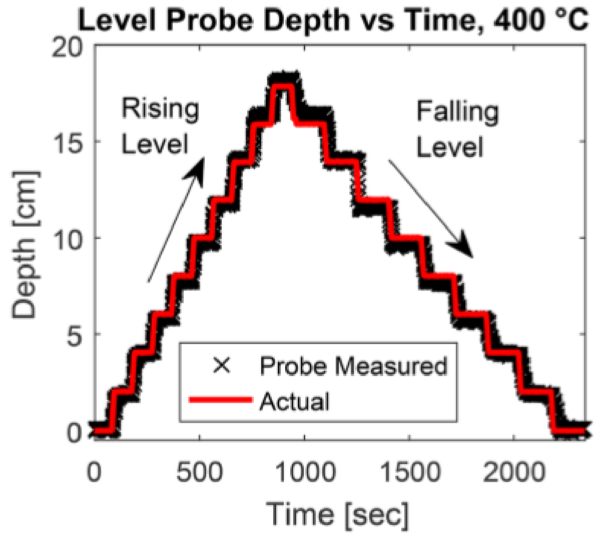
- Theoretical 1D temperature profile fit to optical fiber data by finding least squared residuals

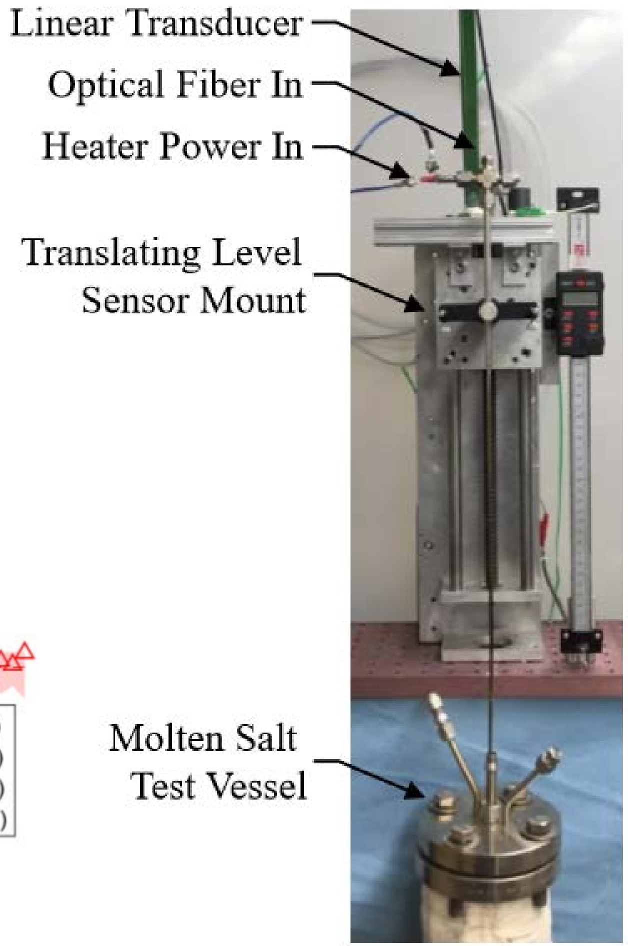


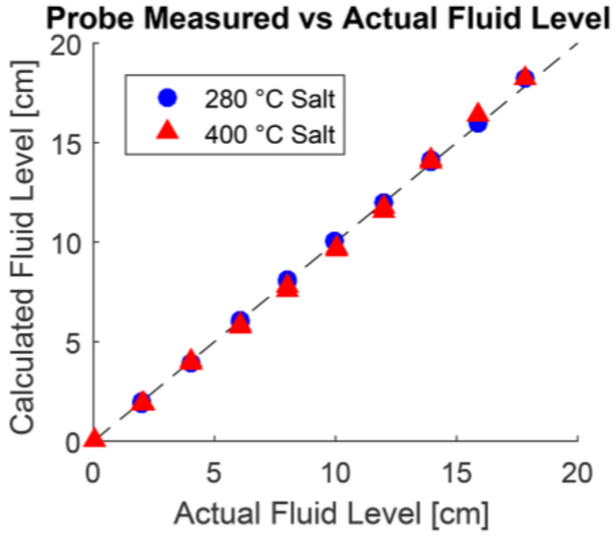


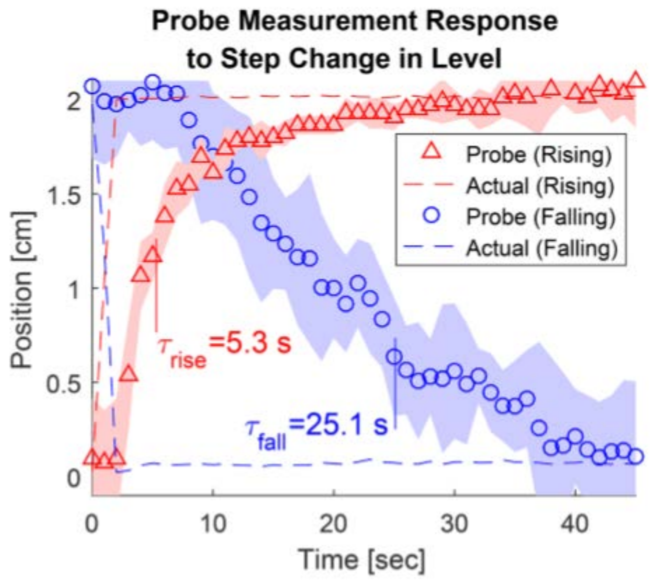
Optical Fiber Level Sensor

- Test results for optical fiber temperature sensor in nitrate salt at 280°C and 400°C with 20 watt heater
- Accuracy of ±1.7 mm*
- Response time as low as 5.3 s









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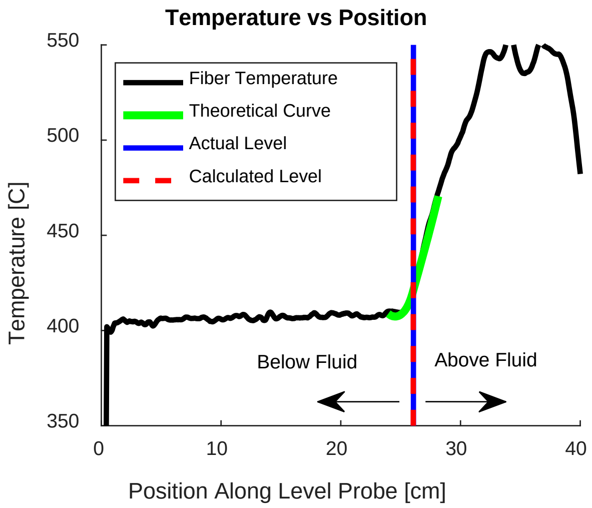
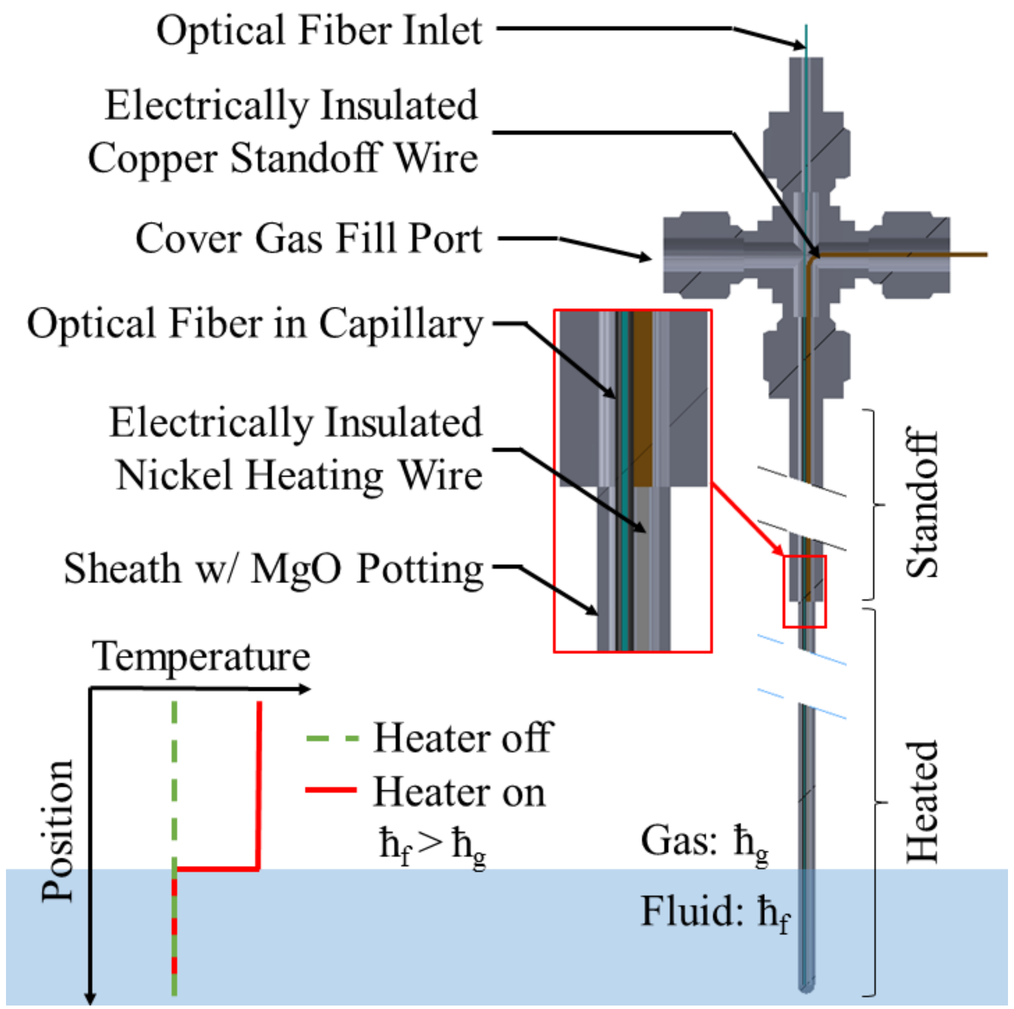
Continuous precision level sensing

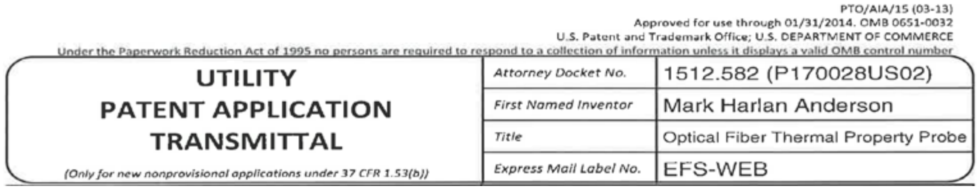
- Continuous level sensing or thermal conductivity in high temperature fluid/solid use of optical fiber level sensor
- Optical fiber temperature sensor running tangential to heating wire may diagnose convection coefficient at level sensor surface.
- Free convection coefficient may be theoretically determined by calculating Rayleigh number and using correlations provided in literature to find Nusselt number[1]

$$Ra = \frac{gL^3\beta(T_s - T_\infty)}{\nu \cdot \alpha} \qquad Nu = \frac{\bar{h}L}{k}$$

- Using heater power and calculated free convection coefficient a theoretical temperature profile may be determined numerically and fit to actual fiber data to determine level position







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UTILITY PATENT APPLICATION TRANSMITTAL	Attorney Docket No.	1512.582 (P170028US02)
	First Named Inventor	Mark Harlan Anderson
	Title	Optical Fiber Thermal Property Probe
(Only for new nonprovisional applications under 37 CFR 1.53(b))	Express Mail Label No.	EFS-WEB

worked with WARF to file patent

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1. Nellis, Klein, Heat Transfer, 2009

ANS

Optical Fiber Level Sensor, Results in Molten Salt