Heat Transfer Research in Support of FHRs at the University of New Mexico

"From the MSRE to a New Emerging Class of Reactors 50 Years Later"

Oak Ridge National Laboratory

Workshop on Molten Salt Reactor Technologies

J. Hughes, A. Ali, B. Wallace, M. Liu, and E. Blandford

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FHR Fluoride Salt Cooled High Temperature Reactor

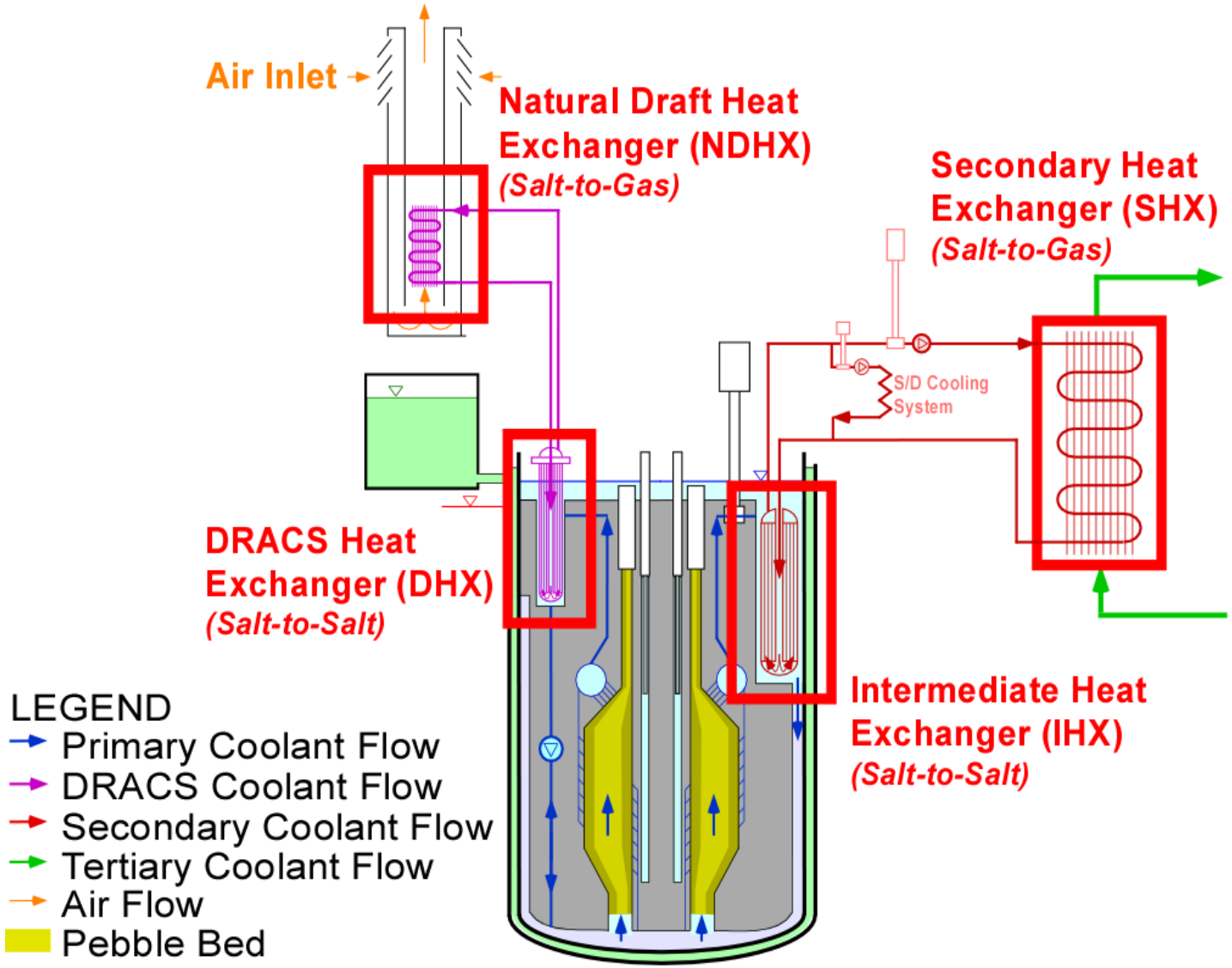
NEUP Nuclear Energy University Program

U.S. Department of Energy

Outline

- Heat Exchanger Challenges in the FHR
- Role of Enhanced Heat Exchangers in FHR Development
- Experimental Heat Transfer Research at UNM
  - Directional Heat Exchanger
  - Twisted Tube Heat Exchangers
- Role of Validation in FHR Development
  - Validation Philosophy
  - NE-KAMS
- Current Status and Future Work

Overview of FHR Primary System – Heat Exchangers



FHR Heat Exchanger Summary

	Category	Type	Candidate Working Fluids		Function
			Tubeside	Shellside	
Primary Heat Removal	Intermediate Heat Exchanger (IHX)	Salt-to-salt	FLiBe	LiF-NaF-KF KF-ZrF4 KF-KBF4 KCl-MgCl2	Primary heat removal
Primary Heat Removal	Secondary Heat Exchanger (SHX)	Salt-to-air (Salt-to-gas) (SG)	LiF-NaF-KF KF-ZrF4 KF-KBF4 KCl-MgCl2.	Air SC Steam He SCO_2	Power conversion
Decay Heat Removal	DRACS Heat Exchanger (DHX)	Salt-to-salt	LiF-NaF-KF KF-ZrF4 KF-KBF4 RbF-RbBF4	FLiBe	Passive decay heat removal
Decay Heat Removal	Natural Draft Heat Exchanger (NDHX)	Salt-to-air	LiF-NaF-KF KF-ZrF4 KF-KBF4 RbF-RbBF4	Air	Heat rejection to ultimate sink

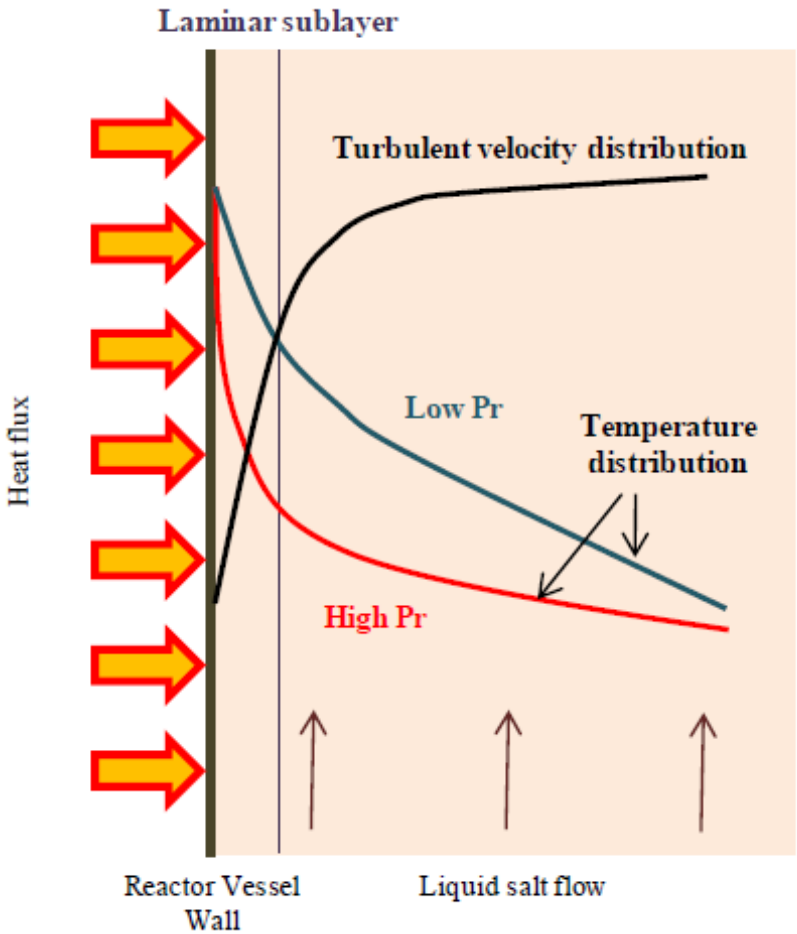
Fluoride salts do have excellent heat transfer capabilities

Material	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	C_p (kJ/kg°C)	ρC_p (kJ/m^3°C)	k (W/m°C)	$\nu \cdot 10^6$ (m^2/s)	$\alpha \cdot 10^6$ (m^2/s)	Pr
$^7Li_2BeF_4$ (flibe)	**459**	**1,430**	**1,940**	**2.34**	**4,540**	**1**	**2.9**	**0.22**	**13.2**
0.58 NaF-0.42 ZrF_4	500	1,290	3,140	1.17	3,670	1	0.53	0.27	1.95
Sodium	97.8	883	790	1.27	1,000	62	0.25	62.1	0.005
Lead	328	1,750	10,540	0.16	1,700	16	0.13	9.41	0.01
Helium (7.5 MPa)	-	-	3.8	5.2	20	0.29	11	14.5	0.76
Water (7.5 MPa)*	0	100	732	5.5	4,040	0.56	0.13	0.14	0.94

*Approximate physical properties at 700°C except the pressurized water data shown at 290°C for comparison.

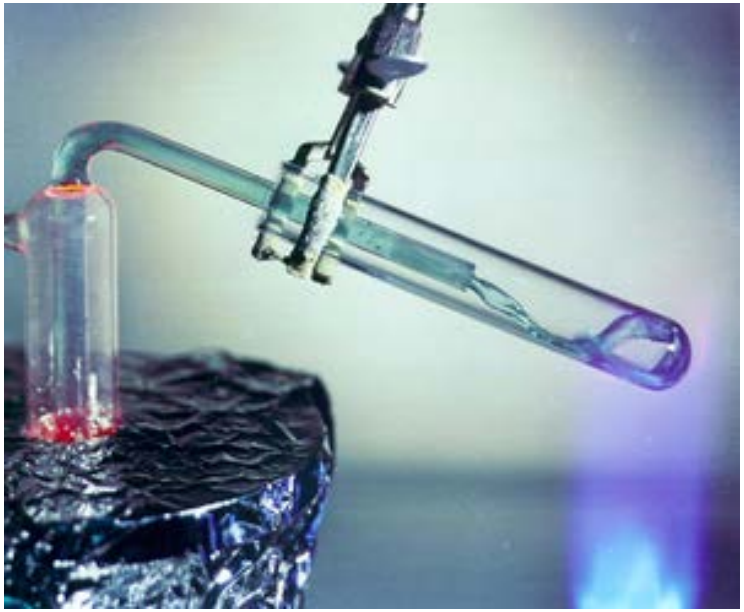
Heat Transfer Challenges

- Due to high salt volumetric heat of capacity and reduced pumping power requirements, flow rates in FHRs are much lower than LWRs
  - Forced-circulation FHR heat transfer commonly occurs at Reynolds number that are barely turbulent or are in the transition regime
  - Natural circulation heat transfer is almost always in the transition or laminar regime
- These conditions could lead to degraded heat transfer in FHRs, leading to large heat exchangers



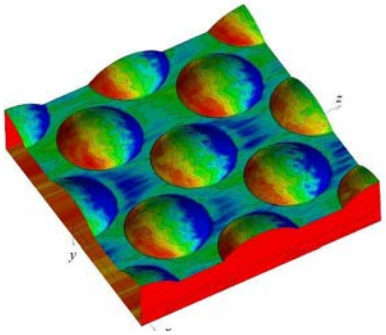
Heat Transfer Challenges (cont.)

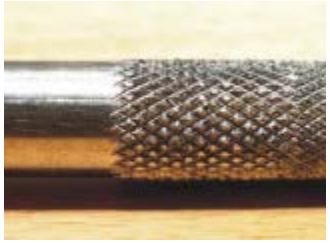
- Flibe is a participating medium where radiative heat transfer can be an important contribution to the overall heat transfer removal mechanism
- Need to develop a better understanding of conjugate natural convection heat transfer with radiation for participating media
  - Transmissivity data for flibe is unavailable
- Radiative heat transfer distortions between simulant fluids and prototypical salts have not been quantified



Enhanced Heat Exchanger Examples

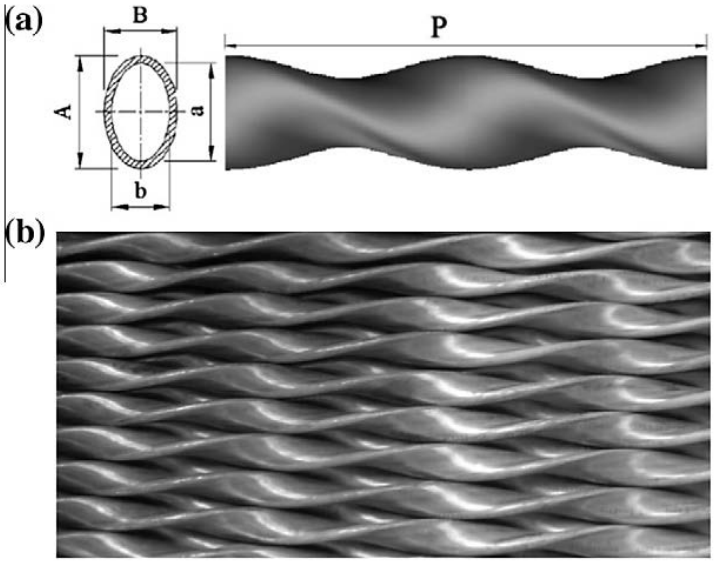
- Enhanced surfaces: fins/ribs/knurling/etc.
- Twisted-tubes
- Double-wall HXRs
- Double-wall twisted-tube HXRs
- Directional HXR

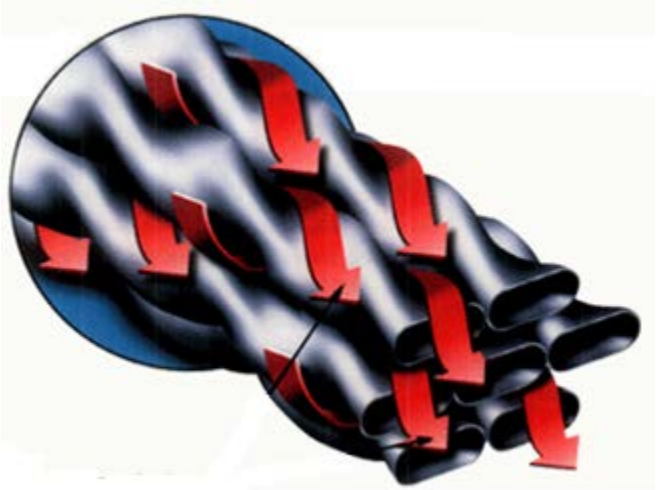




Twisted-tube Heat Exchangers

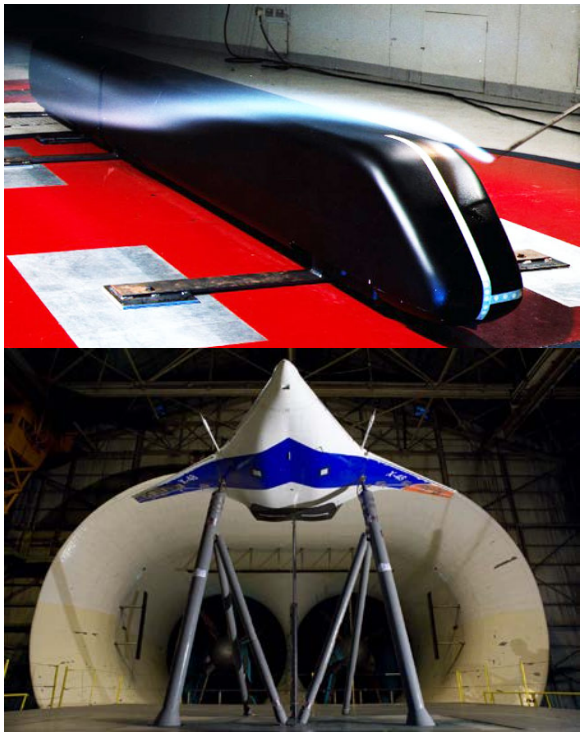
- Used for enhancing heat transfer
- Self-supporting (baffle-less)
- Relatively uniform shell side flow distribution
- Reduced fouling (fewer dead zones)
- Elliptical cross section twisting along axial length
- Induces secondary flow on tube side and swirling flow on shell side





Role of Scaled Experiments

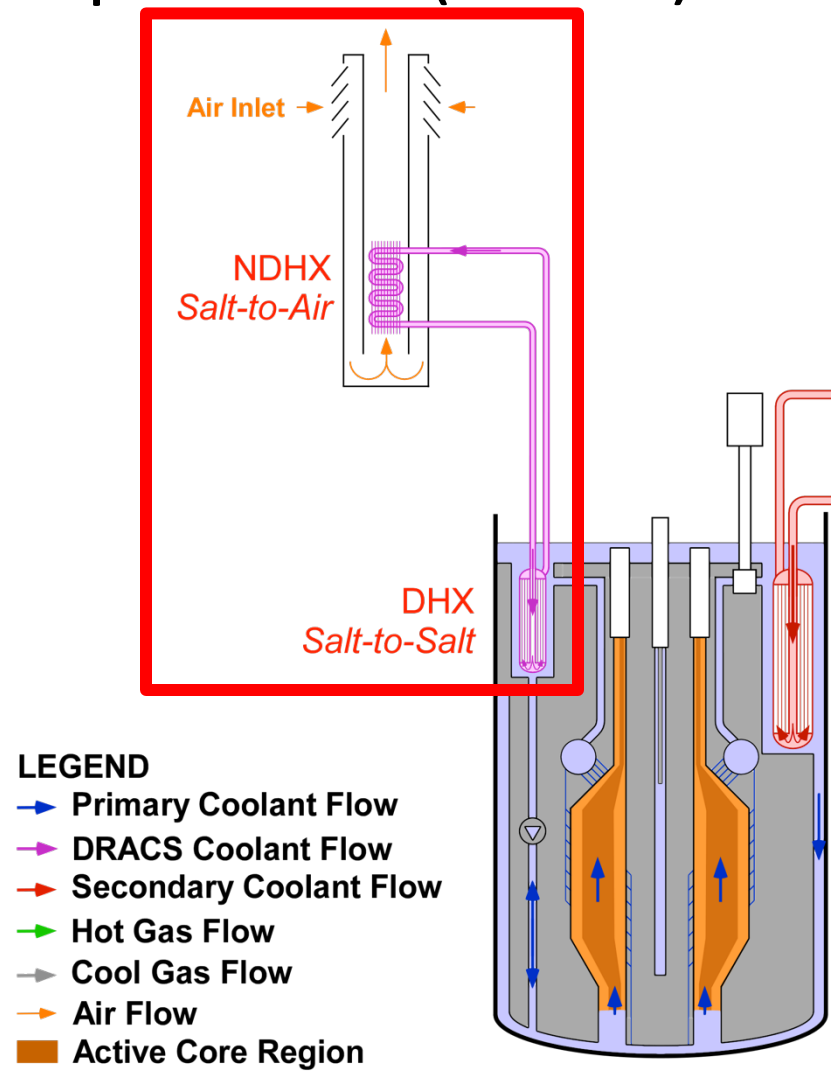
- Unique characteristics of liquid fluoride salt coolant allow for *physically similar* reduced-scale experiments with simulant fluids
- Working with liquid salts is costly and complexity making university research challenging
- Good simulant fluids exist for studying fluoride salt thermal-fluid phenomenology
  - Hydrodynamics – water (Re, SG ratio)
  - Heat transfer – Dowtherm A (Re, Pr, Gr)



High flexibility, low cost, and reveal useful insights

Directional Heat Exchanger Experiment (DirEX^2)

- Multiple DRACS operating (removing heat) passively at all times
- Motivation
  - Reduce parasitic heat losses during normal operation to enhance plant economics (one strategy)
  - Ensure reliable heat removal during accidents involving flow reversal



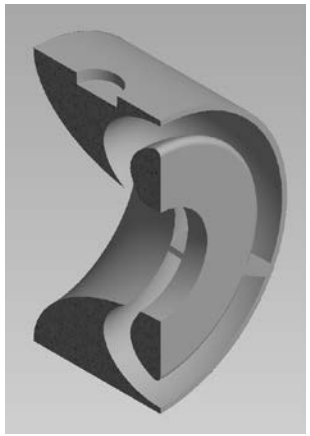
Design Options for Enhancing Directional Performance of DHX

- Goal to enhance heat transfer during accidents and degrade heat transfer during normal operation (i.e., reduce parasitic heat losses)

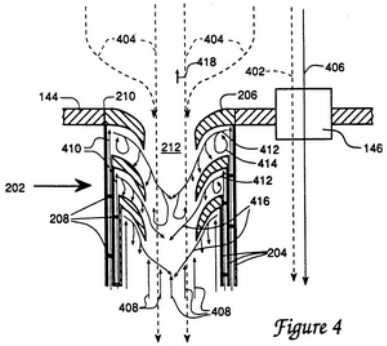
Upper Plenum Options
- Cusp diodes
- Scroll diodes

Tube Options
- Directional surface enhancements – one starting point may be high-efficiency vortex (HEV) static mixer design

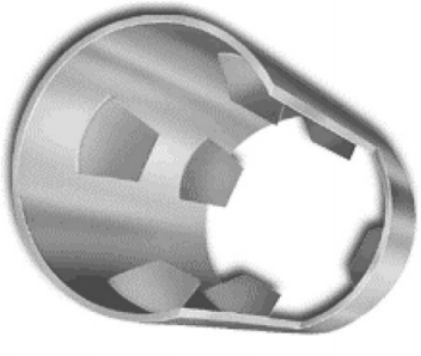
Lower Plenum Options
- Cusp diodes
- Scroll Diodes
- Vortex Diodes



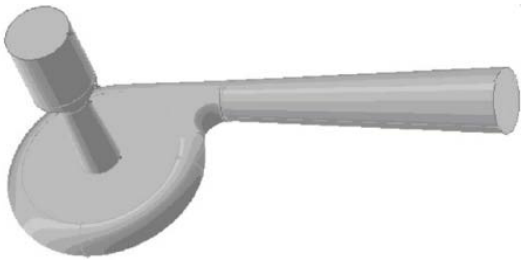
Cusp Diode



Scroll Diode
Patent US 5303275 A



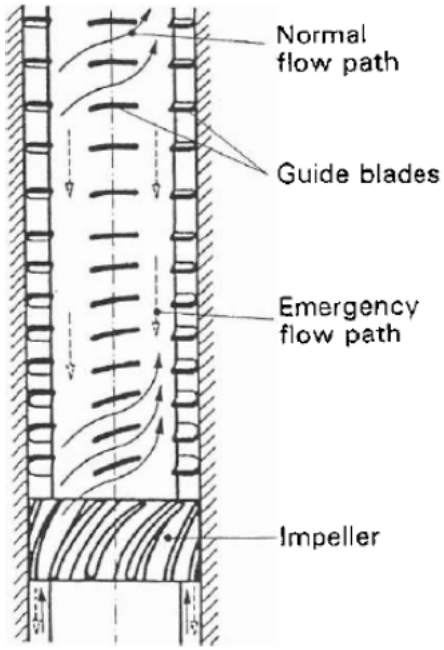
HEV Mixer
(Habchi, C. et al)

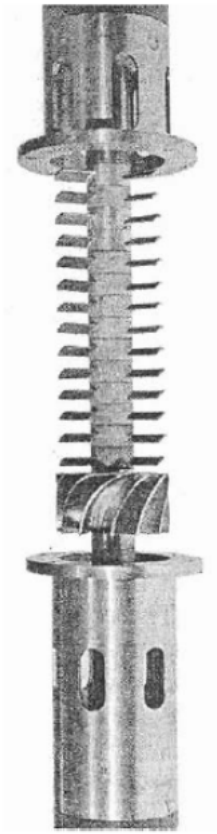


Vortex Diode
(Kulkarni, C. et al)

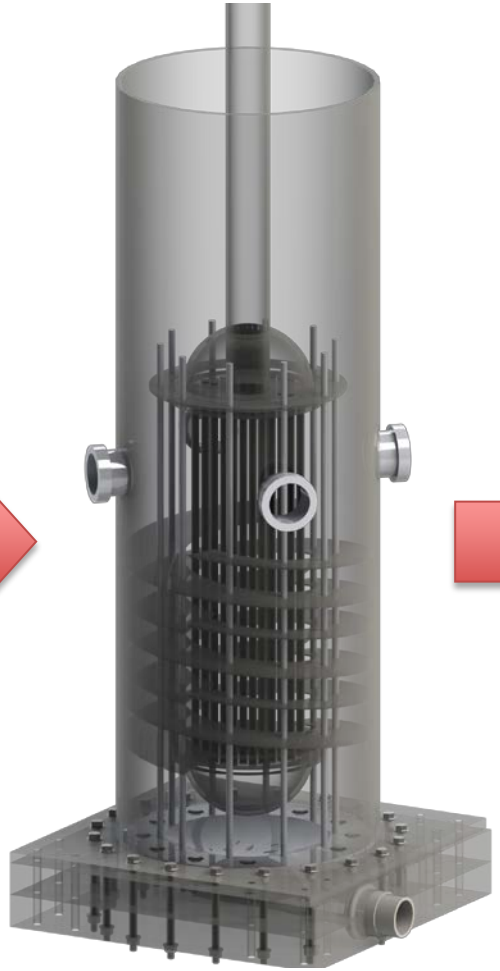
Design Options for Enhancing Directional Performance of DHX

- Re-direct bulk flow





Fluid Rectifier



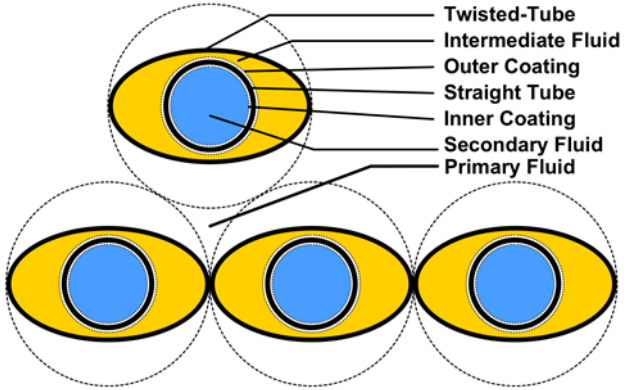
Hydrodynamics Test Loop

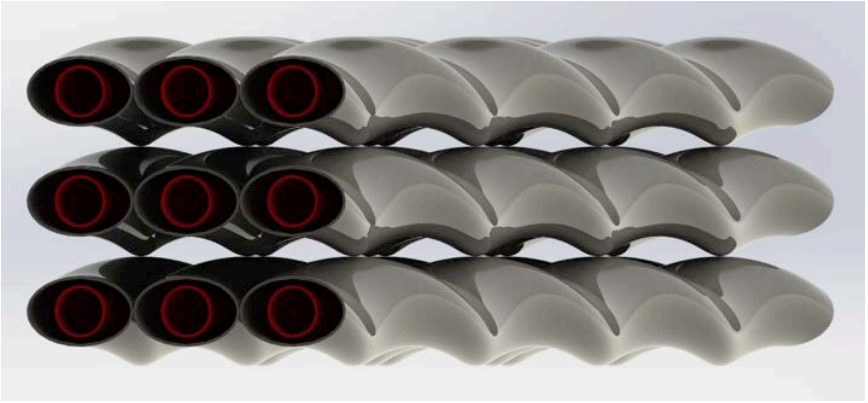
Experimental Heat Transfer Loop

- Heat transfer loop recently constructed
  - 20 kW DC programmable power supply (resistance heating)
  - 13.5 kW chiller
  - Natural circulation and bi-directional forced flow modes over a wide range (~0-3 m^3/hr)
  - Bi-directional ultrasonic transit time flowmeter
- Shakedown tests completed
- ~30-40 operating hours so far (with water – transition to Dowtherm A Spring 2016)

Double-wall Twisted-tube HXR

- Twisted outer tube
  - Good tube support
  - Enhanced turbulence and heat transfer
- Circular inner tube
  - Uniform stresses under high pressure differentials
- Annulus liquid filler
  - Potential tritium getter
  - Could be flowing or stagnant
  - Outer twisted tube enhances heat transfer
  - Options may include lithium

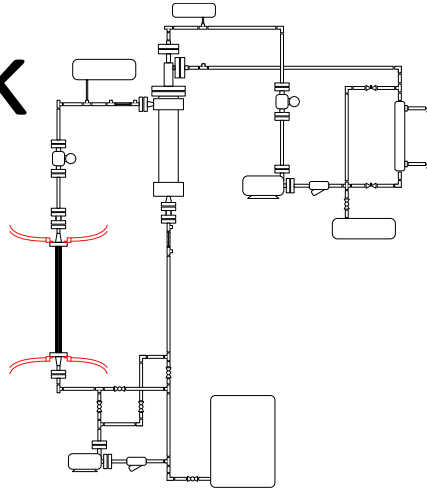




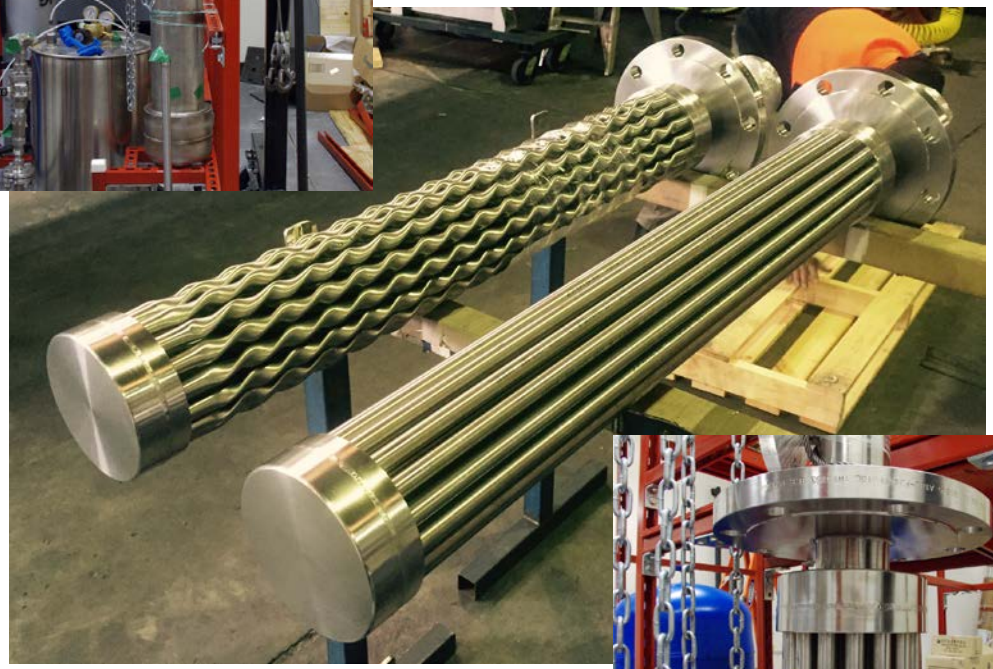
Role of Validation

- "The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model."
  - Oberkampf, W. et al – "Measures of Agreement between Computation and Experiment: Validation Metrics"
- Nuclear Energy Knowledgebase for Advanced Modeling and Simulation (NE-KAMS)
  - Repository for validation data under development at ORNL
  - Structure adopted from materials science community
    - Structured but flexible to allow data input from different fields
    - Allows storage of large amount of metadata
    - Philosophy to allow understanding of data and experiment without ambiguity by posterity

Status and Future Work



- All four heat exchangers are fabricated and ready for testing
  - Two bayonet style
  - Two double wall style
- Baseline shell design at fabrication shop
- Adding intermediate loop between primary loop and chiller for fine secondary side temperature and flow rate control
- Directional heat exchanger testing
- Double wall heat exchanger testing



Questions or comments?