Molten Salt Reactor Workshop 2017

Key Technology and Safety Issues for MSRs

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Natural Circulation Salt Heat Transfer

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Session 7: Support for Salt Technologies

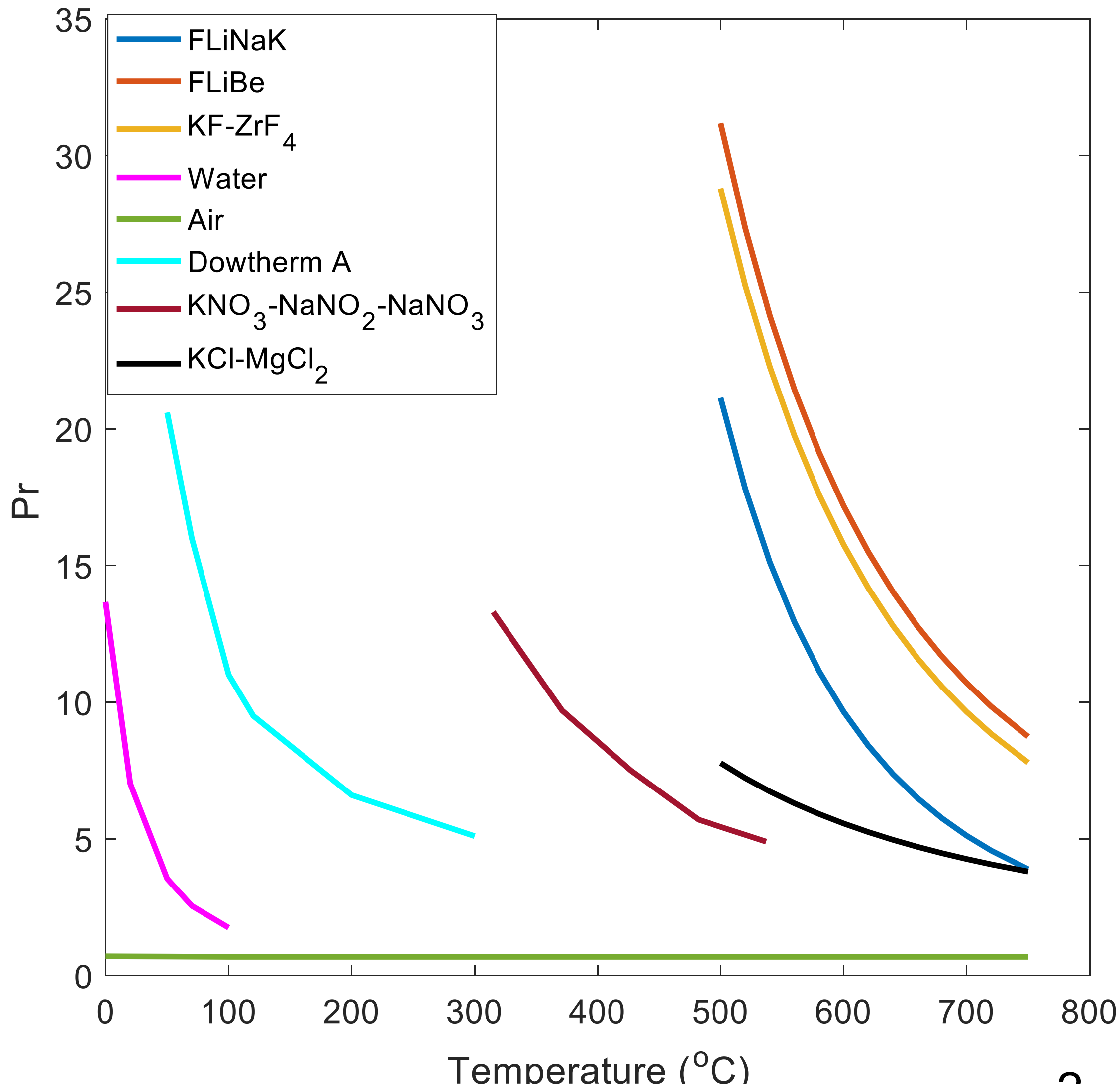
FHR Fluoride Salt Cooled High Temperature Reactor

NEUP Nuclear Energy University Programs

U.S. Department of Energy

Prandtl Number of Different Fluids

- Liquid Salts
  - FLiBe
  - FLiNaK
  - $KF\text{-}ZrF_4$
  - $KCl\text{-}MgCl_2$
  - $KNO_3\text{-}NaNO_2\text{-}NaNO_3$
- Water
- Dowtherm A
- Air



Natural/Forced Convection Heat Transfer Coefficient Correlations

Natural Convection (NC)/Forced Convection (FC)	Correlation	Geometry	Working fluid	Pr range	Ra or Re range	Ref.
NC	$\sqrt{\mathrm{Nu}} = 0.825 + \frac{0.387\mathrm{Ra}^{1/6}}{\left[1+\left(\frac{0.437}{\mathrm{Pr}}\right)^{9/16}\right]^{8/27}}$	Vertical plate	Sodium, mercury, air, water, oil	$0.004 \leq \mathrm{Pr} \leq 300$	$\mathrm{Ra} \leq 10^{12}$	[1]
NC	$\mathrm{Nu} = 0.54\mathrm{Ra}^{1/4}$	Horizontal plate, hot surface facing up	Air	$\mathrm{Pr} = 0.7$	$10^5 \leq \mathrm{Ra} \leq 2\times10^7$	[2]
NC	$\mathrm{Nu} = 0.27\mathrm{Ra}^{1/4}$	Horizontal plate, hot surface facing down	Air	$\mathrm{Pr} = 0.7$	$3\times10^5 \leq \mathrm{Ra} \leq 10^{10}$	
NC	$\mathrm{Nu} = 0.474\mathrm{Ra}^{0.25}Pr^{0.047}$	Horizontal cylinder	Air, water, silicone oils	$0.7 \leq \mathrm{Pr} \leq 3090$	$3\times10^2 \leq \mathrm{Ra} \leq 2\times10^7$	[3]

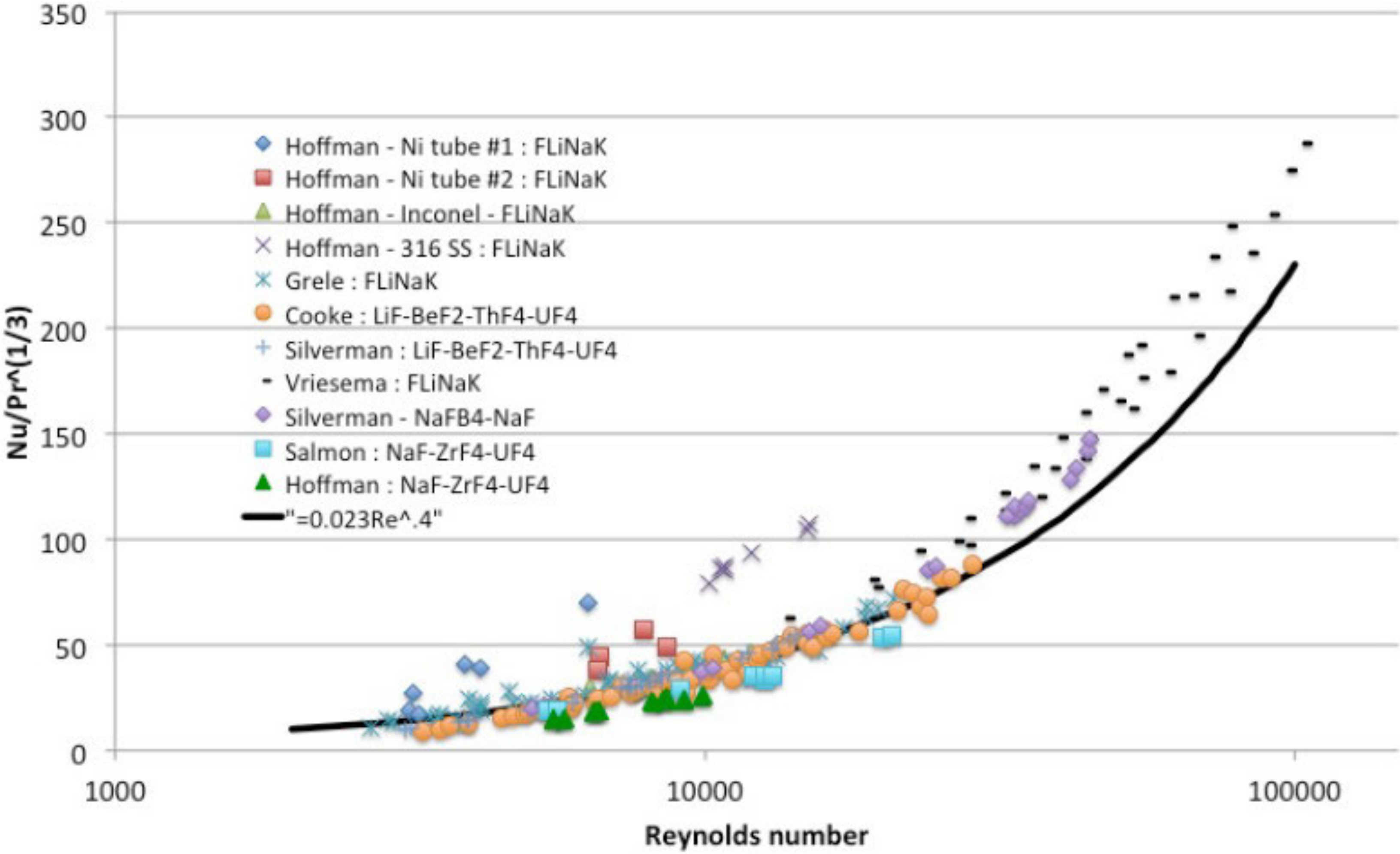
Natural/Forced Convection HTC Correlations (Cont'd)

Natural Convection (NC)/Forced Convection (FC)	Correlation	Geometry	Working fluid	Pr range	Ra or Re range	Ref.
NC	$\mathrm{Nu} = 2 + \frac{0.589\mathrm{Ra}^{1/4}}{\left[1+\left(\frac{0.469}{\mathrm{Pr}}\right)^{9/16}\right]^{4/9}}$	Spheres	air, water, oil	$\mathrm{Pr} \geq 0.7$	$\mathrm{Ra} \leq 10^{11}$	[4]
FC	$\mathrm{Nu} = 0.027\mathrm{Re}^{0.8}\mathrm{Pr}^{1/3}(\mu/\mu_s)^{0.14}$	Pipe	air, water, oil	$0.7 \leq \mathrm{Pr} \leq 16700$	$\mathrm{Re} \geq 10^4$	[5]
FC	$\mathrm{Nu} = 1.86\mathrm{Re}^{1/3}\mathrm{Pr}^{1/3}\left(\frac{D}{L}\right)^{1/3}(\mu/\mu_s)^{0.14}$	Pipe	air, water, oil	$0.7 \leq \mathrm{Pr} \leq 16700$	$\mathrm{Re} \leq 2300$	[6]
FC	$\mathrm{Nu} = 0.116(\mathrm{Re}^{2/3} - 125)\mathrm{Pr}^{1/3}(\mu/\mu_s)^{0.14}$	Pipe	air, water, oil	$0.7 \leq \mathrm{Pr} \leq 3$	$3500 \leq \mathrm{Re} \leq 1.2 \times 10^4$	[7]

Natural/Forced Convection HTC Correlations (Cont'd)

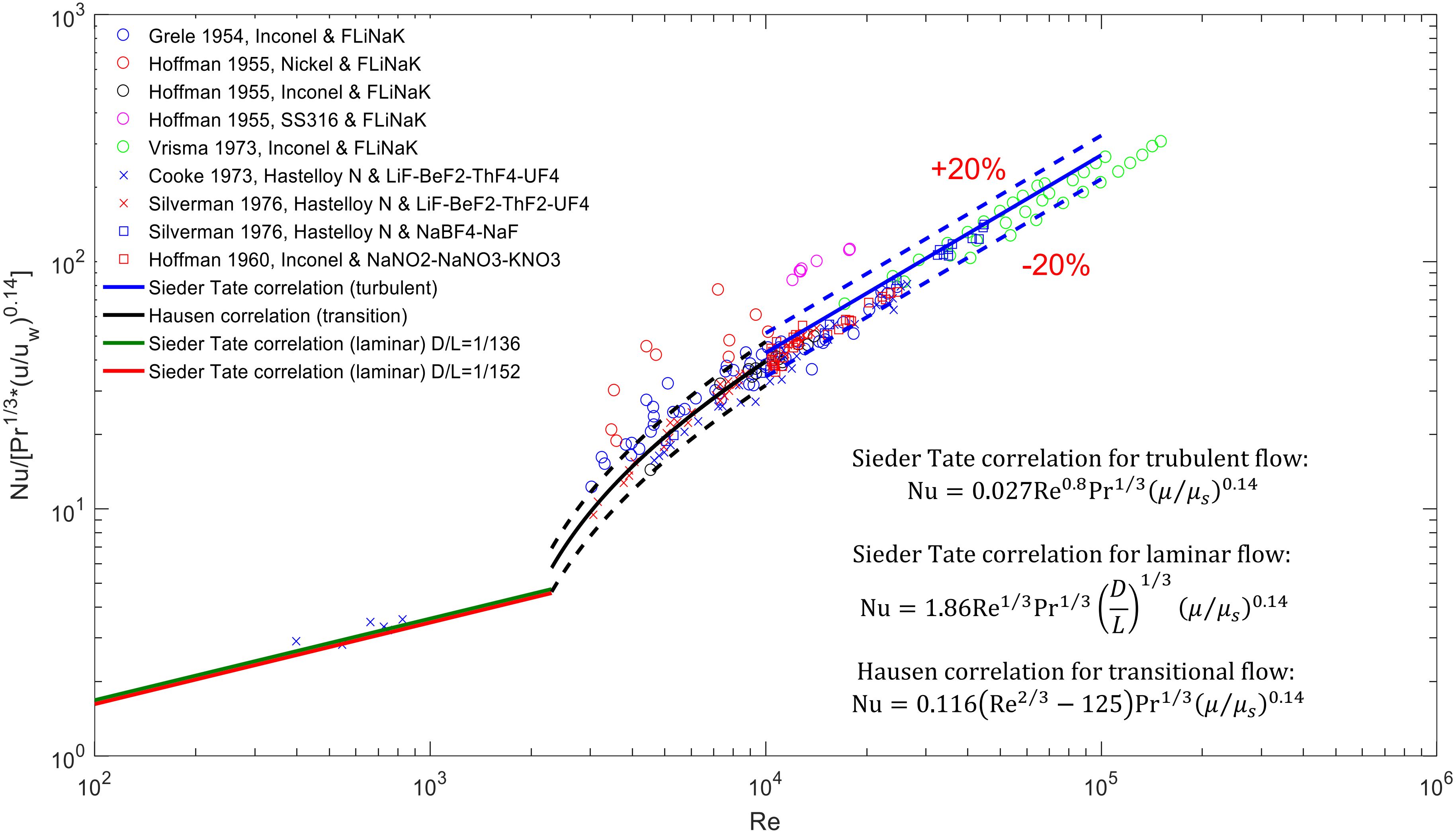
Natural Convection (NC)/Forced Convection (FC)	Correlation	Geometry	Working fluid	Pr range	Ra or Re range	Ref.
FC	$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{P}r^{n}$ $n = 0.4$ if the fluid is heated $n = 0.3$ if the fluid is cooled	Pipe	air, water, oil	$0.7 \leq \mathrm{Pr} \leq 100$	$\mathrm{Re} \geq 10^4$	[8]
FC	$\mathrm{Nu} = 2 + \left(0.4\mathrm{Re}^{0.5} + 0.06\mathrm{Re}^{2/3}\right)\mathrm{Pr}^{0.4}$	Sphere	air, water, oil	$0.7 \leq \mathrm{Pr} \leq 380$	$\mathrm{Re} \leq 7.6{\times}10^4$	[9]
FC	$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{1/3}$	Pipe	air, water, oil	$0.7 \leq \mathrm{Pr} \leq 100$	$\mathrm{Re} \geq 10^4$	[10]

Comparison of Colburn Correlation with Salt Forced Circulation Experiments



(G. Yoder, 2014)

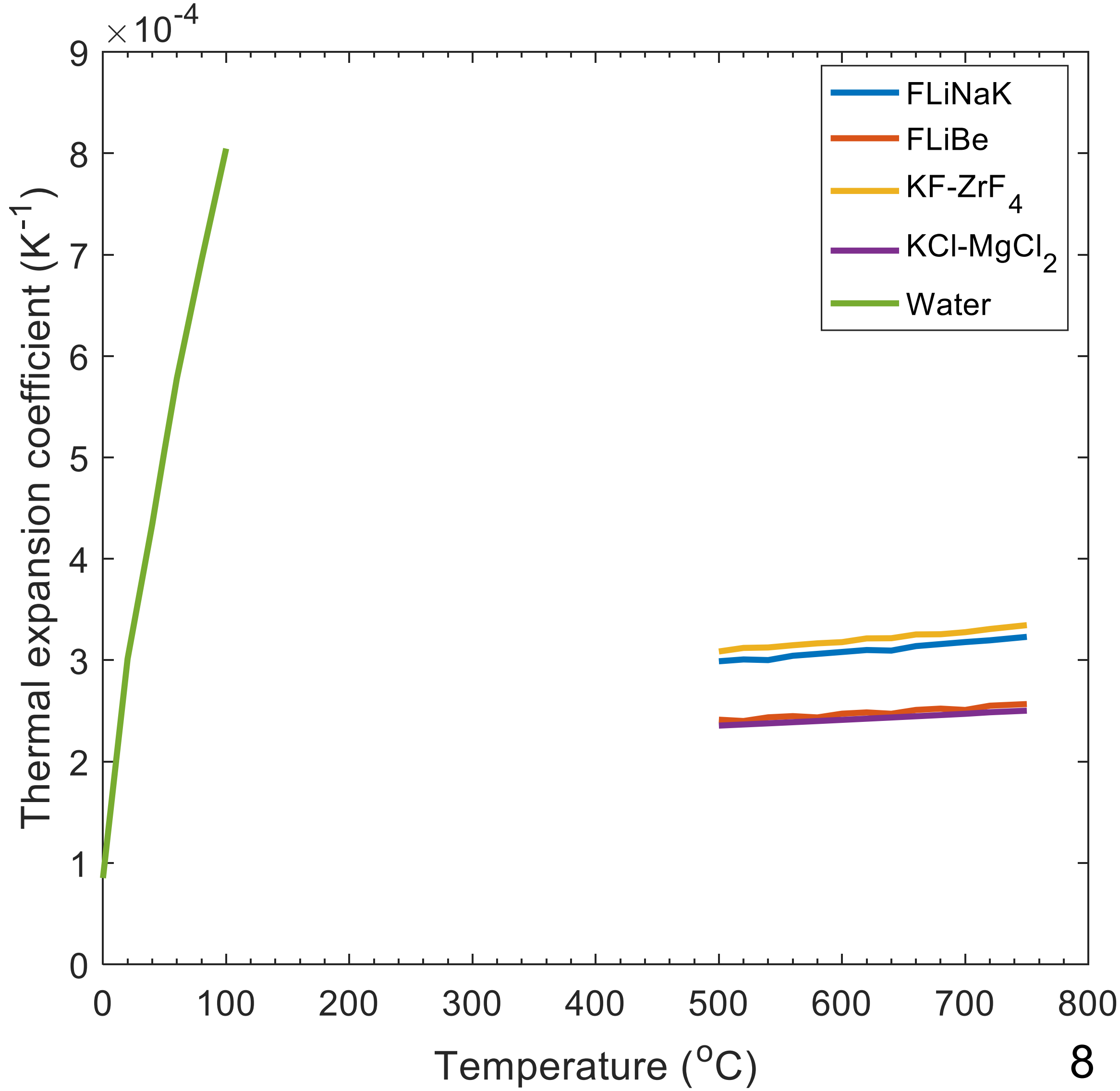
Comparison with Salt Forced Circulation Experiments



Thermal Expansion Coefficient for Different Fluids

- FLiBe
- FLiNaK
- $KF\text{-}ZrF_4$
- $KCl\text{-}MgCl_2$
- H_2O (1 atm)

$$\Delta p = \left(\rho_0 \beta \Delta T\right) g \Delta h$$



Review of Natural/Forced Circulation Loops for MSRs/FHRs

Organization	NC/FC	Experiment Modeling	Objective	Material	Working fluid	Max working temp. (°C)	at max temp. (K^{-1})	Max power (kW)	Ref.
Oak Ridge National Laboratory, USA	NC	Experiment	Preparation for operation of the MSRE	Hastelloy N Single loop	$LiF-BeF_2-ZrF_4-UF_4$,	784	--	30,000	[11]
					$LiF-BeF_2-ZrF_4$	670		8.8	
	NC	Experiment Fluent	a) Determine if the experimental configuration provides sufficient salt velocity for collection of corrosion data; b) Quantify natural circulation salt velocities using a laser Doppler velocimeter;	Nickel crucible	FLiNaK	700	0.00032	0.5	[12] [13]
	FC	Experiment	a) Develop a nonintrusive, inductive heating technique b) Measure heat transfer characteristics	Inconel 600 single loop				200	
The Ohio State University (University of Michigan), USA	NC	Experiment Relap5 MOD 4.0	Examine the couplings among the natural circulation/convection loops and provide experience for high-temperature DRACS loop design	SS 304 coupled loops	Water	76.5	0.00061	2	[14] [15]
	NC	Experiment	Investigate DRACS performance under steady-state and transient conditions, including startup, pump trip test w/o IHX	SS 316 coupled loops	FLiNaK	722	0.00032	70	

Review of Natural/Forced Circulation Loops for MSRs/FHRs (Cont'd)

Organization	FC/NC	Experiment Modeling	Objective	Material	Working fluid	Max working temp. (°C)	at max temp. (K^{-1})	Max power (kW)	Ref.
University of California, Berkeley, USA	NC/FC	Experiment Relap5-3D modeling	Provide experimental validation data for system-level thermal hydraulic codes; Serve as an advanced reactor test bed;	Stainless steel/copper	Dowtherm A	120	0.00075	10	[16] [17]
University of New Mexico, USA	NC/FC	Experiment	System code validation; Heat exchanger testing	Stainless steel single loop	Dowtherm A	--	--	20	[18]
University of Wisconsin, USA	NC	Experiment Fluent	Research in natural circulation stability, salt freezing, etc.	--	FLiBe	800	0.00027	--	[19]
	FC	Experiment	Identify salt corrosion and heat transfer issues	SS 316 Single loop	KCl-$MgCl_2$	600	0.00029	4	[20]
US Industry	NC/FC	Experiment	Gaining operation experience with salts, corrosion, component testing, instrumentation, etc.		Salts				
Ulsan National Institute of Science and Technology, Korea	NC	Experiment MARS code modeling	Understand the thermal-hydraulic characteristics of molten salts using simulants	SS 304 Single loop	Dowtherm RP	80	0.00071	0.3	[21]

Review of Natural/Forced Circulation Loops for MSR/FHR (Cont'd)

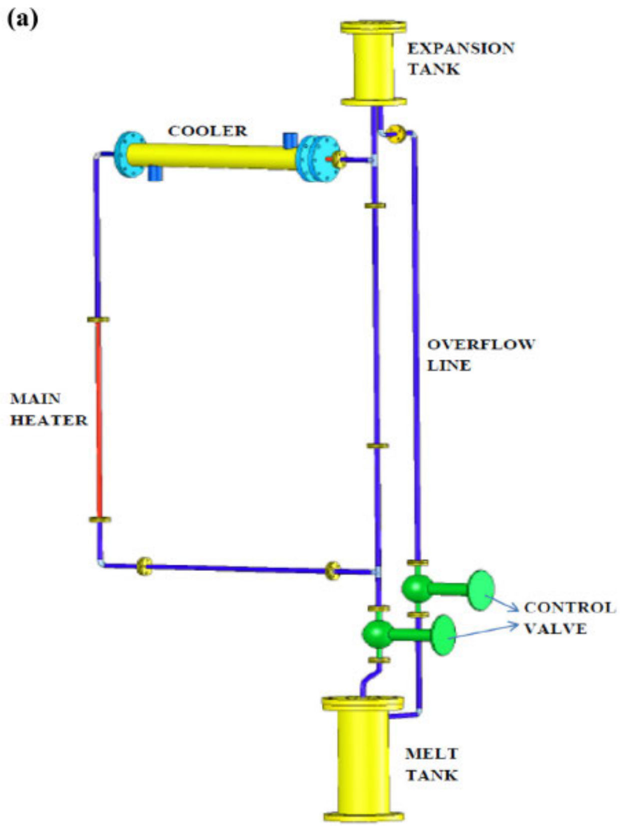
Organization	NC/FC	Experiment Modeling	Objective	Material	Working fluid	Max working temp. (^oC)	at max temp. (K^{-1})	Max power (kW)	Ref.
Shanghai Institute of Applied Physics, China	NC	Experiment	Gather experience on design and validation of passive decay heat removal system for FHRs	SS 316 Single loop	KNO_3-$NaNO_2$-$NaNO_3$	450	0.00075	--	[22]
	FC	Experiment	Validate system design; Develop principle prototypes of molten salt pump, valves, HX, etc.	Hastelloy C276 Single loop	FLiNaK	650	0.00032	150	
Beijing University of Technology, China	NC	Experiment	Investigate natural circulation heat transfer of molten salt in a single energy storage tank	SS 316 tank	$Ca(NO_3)_2$- KNO_3-$NaNO_3$-$LiNO_3$	250	--	0.3	[23]
Bhabha Atomic Research Centre, India	NC	Experiment In-house developed code LeBENC	Investigate thermal hydraulics, instrument development, and material related issues relevant to high-temperature reactor, such as MSBR	Inconel 625 Single loop	KNO_3-$NaNO_3$-$LiNO_3$	580	0.0006	2	[24]
	NC	Experiment OpenFOAM	Experiments: a) Steady-state at different power levels; b) Startup transient; c) Loss of heat sink; d) Heater trip; d) Step change in heater power.	Hastelloy N Single loop	LiF-ThF_4	750	0.00049	1	[25]

Review of Natural/Forced Circulation Loops for MSR/FHR (Cont'd)

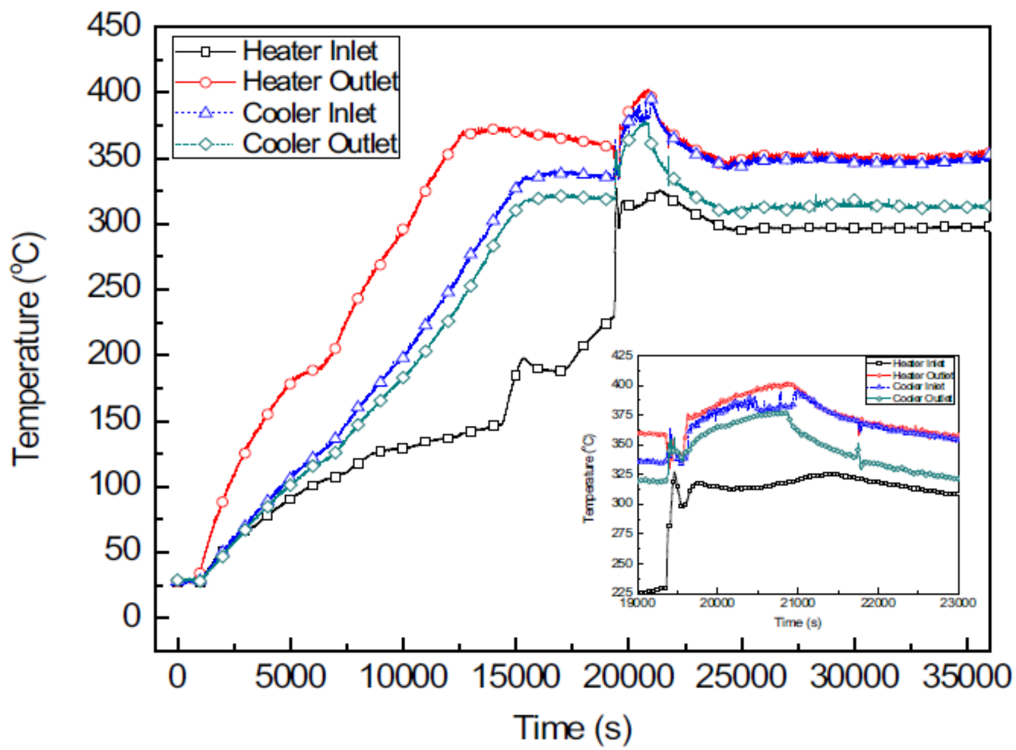
Organization	NC/FC	Experiment Modeling	Objective	Material	Working fluid	Max working temp. (°C)	at max temp. (K^{-1})	Max power (kW)	Ref.
EU project SAMOFAR	FC	Experiment	Preparation for MSFR FFFFER: Forced Fluoride Flow for Experimental Research	--	FLiNaK	700	0.00032	--	[26] [27]
	FC	Experiment	Study the solidification phenomena of a molten salt						
Czech Republic	FC	Experiment	Experimental program in MSR physics and corrosion flow loop	--	FLiBe	--	--	--	[28]

Bhabha Atomic Research Centre's NC Experiments

- Startup



(A.K. Srivastava, et al., 2016)



Startup of natural circulation at 1200 W
(A.K. Srivastava, et al., 2016)

Heat Transfer Correlations (HTC) in RELAP5

- Define the geometry of heat structure
- For single phase liquid, RELAP5 calculate three heat transfer coefficients
  - find the maximum heat transfer coefficient
  - $h = max(h_{laminar}, h_{turbulent}, h_{natural})$

<table>
<tr><th>User defined geometries</th><th>Laminar</th><th>Turbulent</th><th>Natural</th></tr>
<tr><td>Standard</td><td rowspan="5">Nu
= 4.36</td><td>Dittus-Boelter</td><td>Churchill-Chu or McAdams</td></tr>
<tr><td>Horizontal annuli, flow in plate
and single tube</td><td>Dittus-Boelter</td><td>McAdams</td></tr>
<tr><td>Parallel flow in vertical bundle
with in-line and staggered rods</td><td>Dittus-Boelter-
Inayatov</td><td>Churchill-Chu or McAdams</td></tr>
<tr><td>Crossflow in vertical bundle with
in-line and staggered rods</td><td>Dittus-Boelter
Inayatov-Shah</td><td>Churchill-Chu or McAdams</td></tr>
<tr><td>Parallel flow and crossflow in horizontal bundle
with in-line and staggered rods</td><td>Dittus-Boelter</td><td>Churchill-Chu</td></tr>
</table>

HTC for Flow in Circular Tubes in RELAP5 (Cont'd)

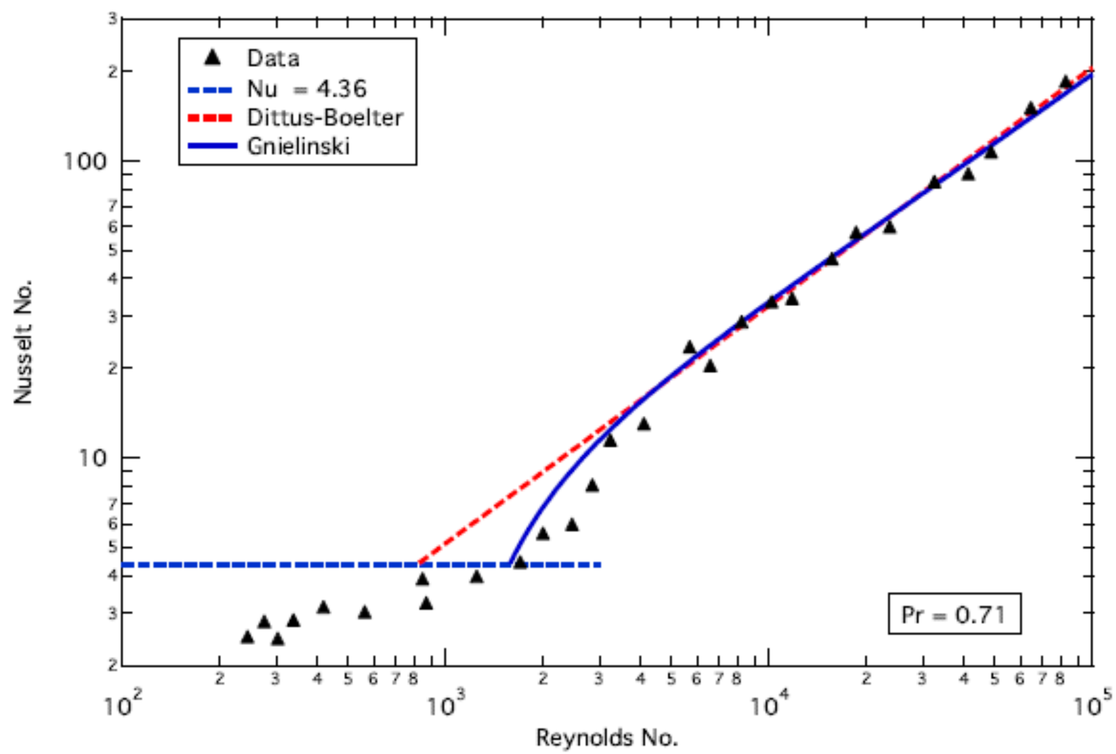
- Laminar forced convection (Sallers)
  - $Nu = 4.36$
- Turbulent forced convection (Dittus-Boelter)
  - $Nu = 0.023Re^{0.8}Pr^{0.4}$
- Natural convection (Churchill-Chu)
  - $Nu = \left\{0.825 + \frac{0.387Ra^{\frac{1}{6}}}{\left[1+\left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2$
  - $Ra = Gr \cdot \mathrm{Pr} \qquad Gr = \frac{\rho^2 g\beta(T_w - T_b)L^3}{\mu^2}$
- Natural convection (McAdams)
  - $Nu = 0.27Ra^{0.25}$

HTC in TRACE

- For single-phase liquid , also take maximum values among laminar and turbulent forced convection and natural convection (NC).
  - $h = max(h_{laminar}, h_{turbulent}, h_{laminar\ NC}, h_{turbulent\ NC})$
- Geometries
  - Tube
  - Rod bundle
  - Helical Coil
  - Cross Flow

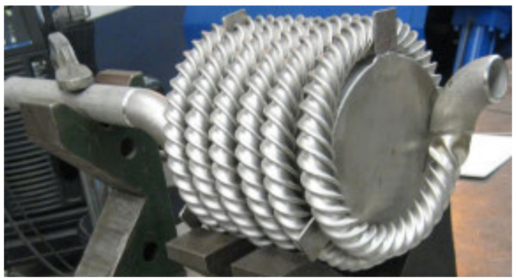
HTC for Flow in Circular Tube in TRACE

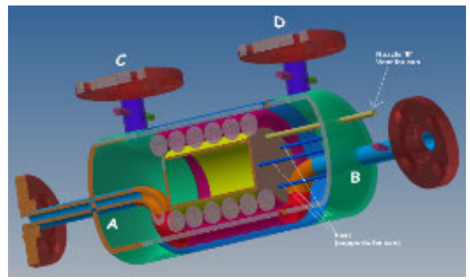
- Turbulent forced convection (Gnielinski)
  - $Nu = \frac{(f/2)(Re-1000)Pr}{1+12.7(f/2)^{0.5}(Pr^{2/3}-1)}$ $f = [1.58ln(Re) - 3.28]^{-2}$
- Laminar forced convection (Sallers)
  - $Nu = 4.36$
- Laminar NC
  - $Nu = 0.59Ra^{0.25}$
  - $Ra = Gr \cdot Pr$
  - $Gr = \frac{\rho^2 g\beta(T_w-T_b)L^3}{\mu^2}$
- Turbulent NC
  - $Nu = 0.1Ra^{1/3}$

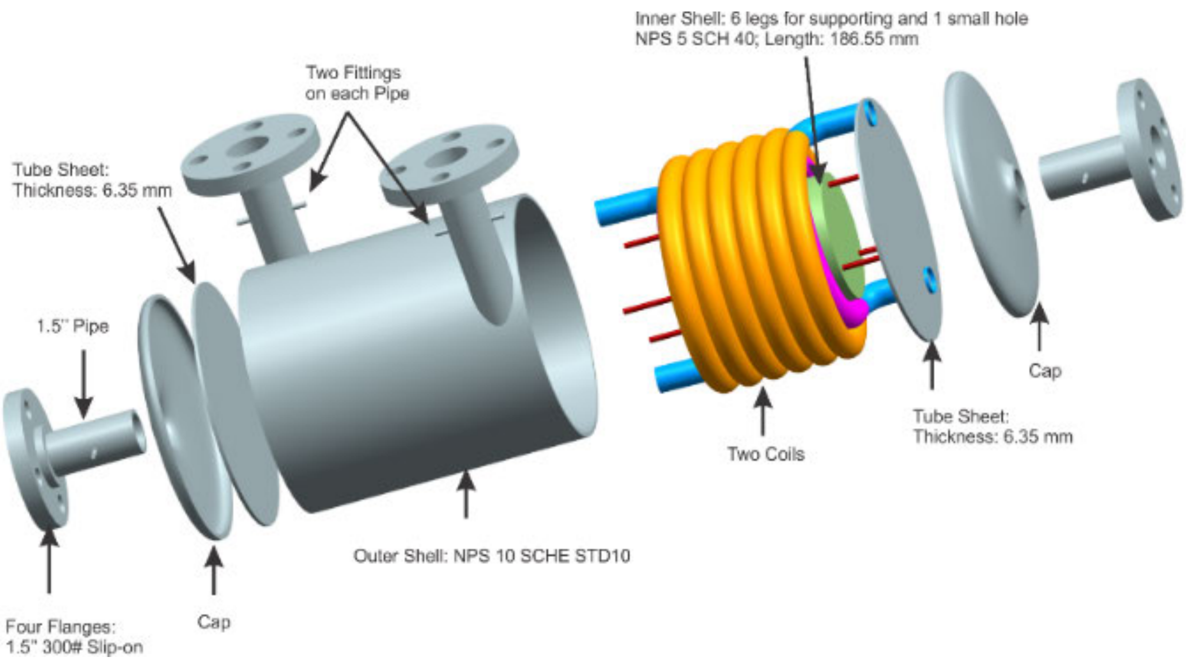


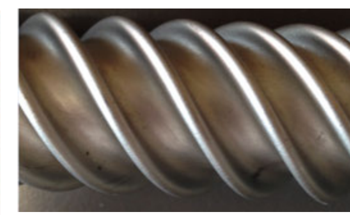
Natural Circulation Heat Transfer in Fluted Tube Heat Exchangers

- Helically-Coiled Fluted Tube Heat Exchangers



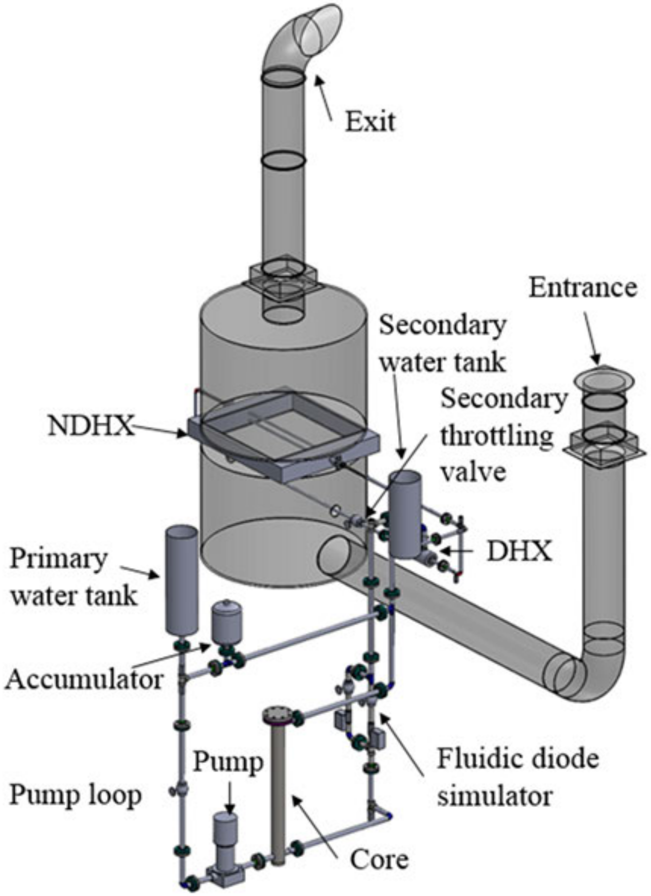






Low-temperature DRACS Test Facility (LTDF)

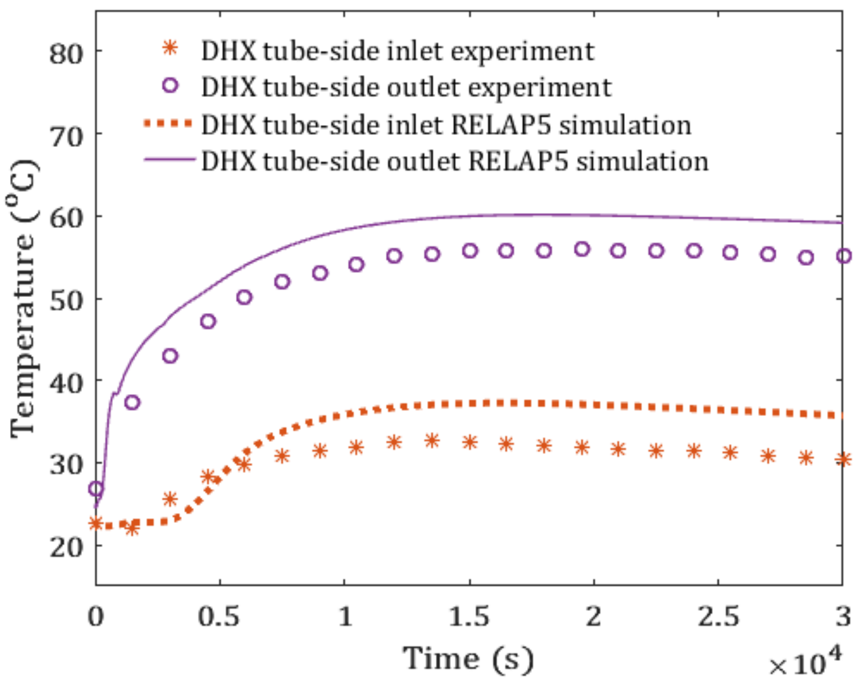
- LTDF Design



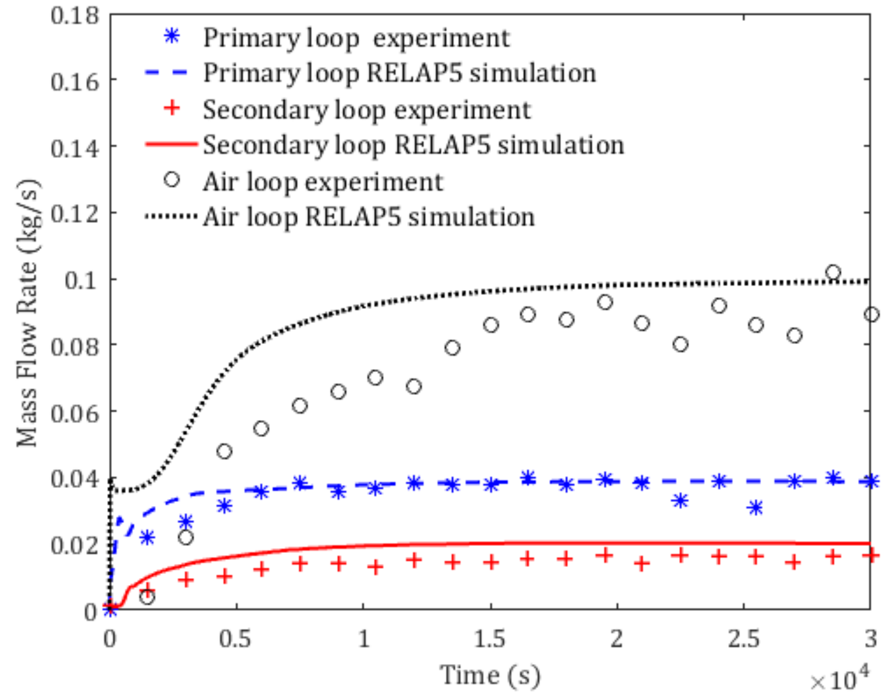
	Primary Water (10 bar)	Secondary Water (1 bar)	Air
T_{hot} (°C)	76.5	65.2	40
T_{cold} (°C)	63.7	34.8	20
ΔT (°C)	12.8	30.4	20
$\dot{m}$ (kg/s)	0.038	0.016	0.102
Loop Height (m)	1.71	0.42	2.1
Pipe ID (cm)	3.7	2.0	35.6

Benchmark RELAP5 Simulation

- DRACS Startup Transient
  - 2 kW from the heater
  - Natural circulation established



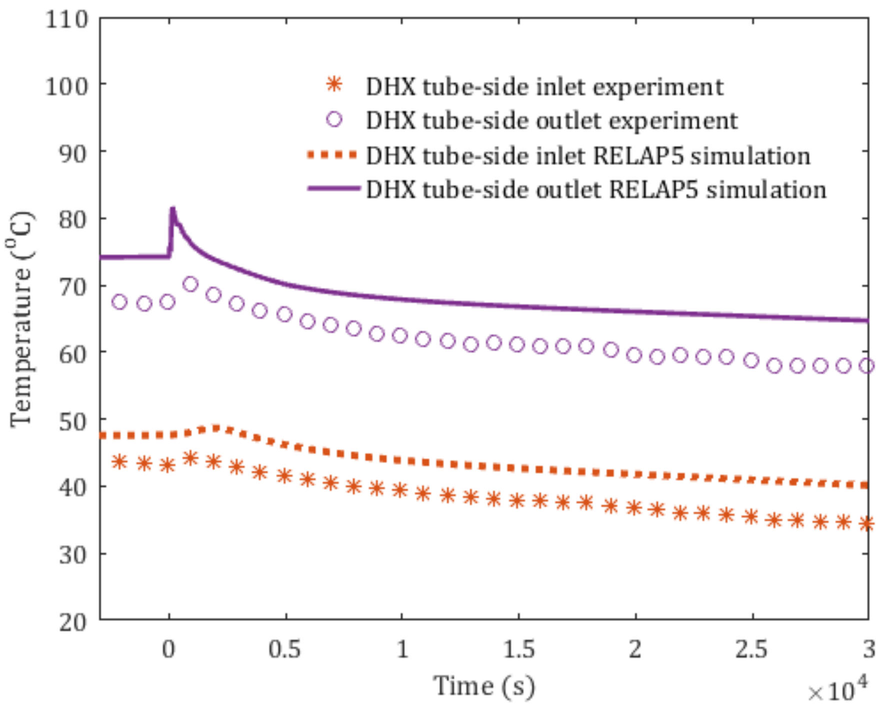
DHX tube-side inlet and outlet temperatures



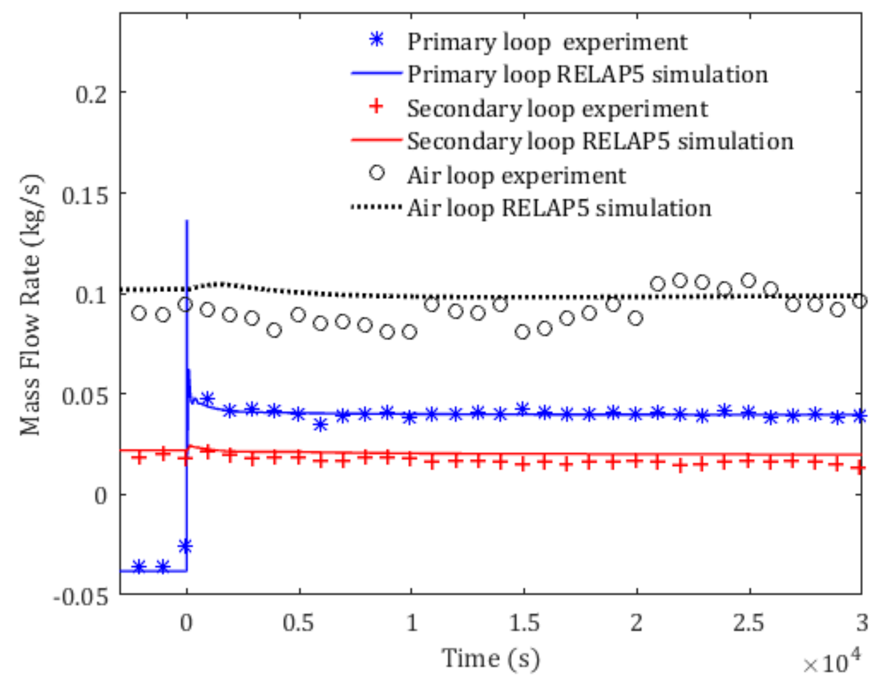
Mass flow rates of three loops

Benchmark RELAP5 Simulation (Cont'd)

- Pump Trip Transient
  - Pump tripped when transient initiated
  - After pump trip, primary flow reversed and natural circulation flow established

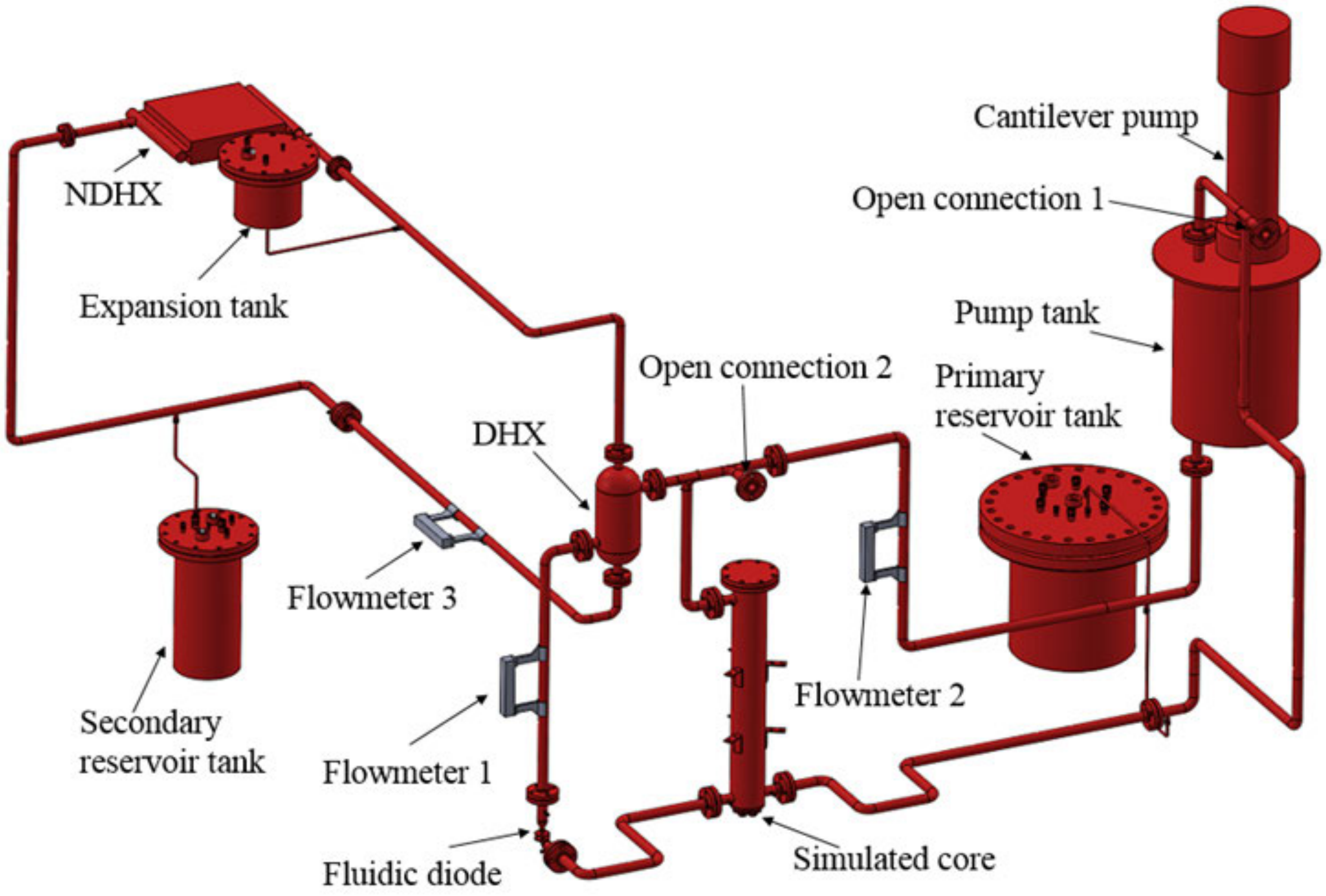


DHX tube-side inlet and outlet temperature



Mass flow rates of three loops

High-temperature DRACS Facility (HTDF)



High-temperature DRACS Facility (Cont'd)

Summary of HTDF Design

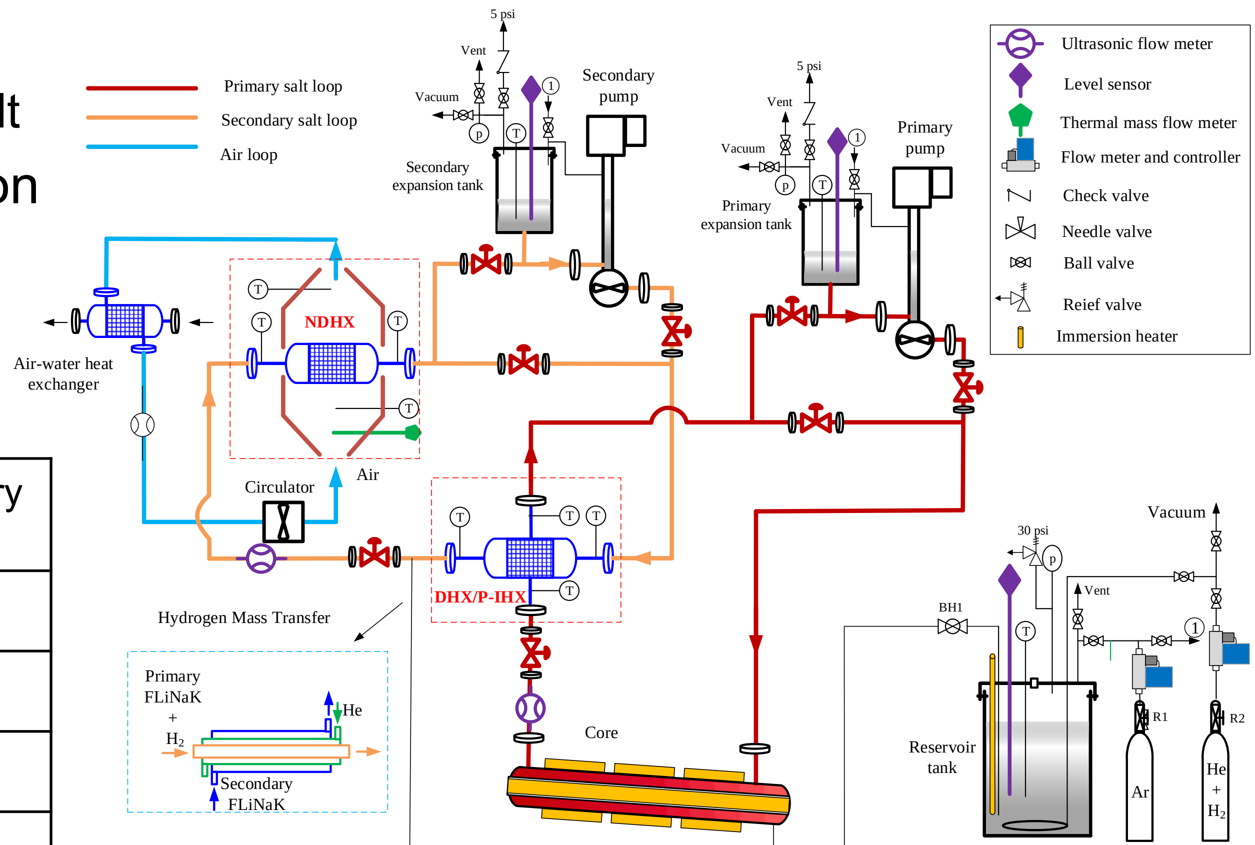
- Nominal power: 10 kW

	Primary Fluid (FLiNaK, 0.1 MPa)	Secondary Fluid (KF and ZrF_4, 0.1 MPa)	Air
T_{hot} (°C)	722	666	110
T_{cold} (°C)	678	590	40
$\dot{m}$ (kg/s)	0.120	0.127	0.142
Loop Height (m)	1.14	1.08	3.43

- Core: Simulated by 7 cartridge heaters (Max.: 70 kW)
- DHX: Shell-and-tube heat exchanger
  - Shell ID: 211 mm; 80 tubes (5/8”) with length: 325 mm; 4 baffles
  - SS 316 as the structure material
- NDHX: Plain-tube heat exchanger
  - 30 tubes (5/8”) in 2 rows; tube length: 438 mm
  - SS 316 as the structure material

High-temperature Fluoride Salt Test Facility

- High-temperature Fluoride Salt Test Facility
  - Natural/Forced circulation
    - Primary salt
    - Secondary salt
  - Forced circulation
    - Air



Item	Primary salt	Secondary salt
Salt	FLiNaK	FLiNaK
T_{hot} (°C)	700	587
T_{cold} (°C)	682.7	550
$\dot{m}$ (kg/s)	0.23	0.11
Loop height	1.15	1.22

Summary

- Heat transfer coefficient for salt forced convection: Existing correlations/models seem to have reasonable accuracy

- Natural circulation salt heat transfer
  - Strongly geometry dependent
  - Thermal radiation effect
  - Experiments for salt natural convection heat transfer
  - Experiments for salt natural circulation

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