FHR and MSR Thermal Hydraulics Research at UC Berkeley

ORNL MSR Workshop
Per Peterson, UC Berkeley
October 5, 2016
Overview: Simulant fluid TH experiments

- Thermal hydraulics experiments with simulant fluids have important advantages.
  - Low temperatures and ability to use transparent structural materials allows very high fidelity experimental measurements with simulant fluids
  - Experiments can be constructed rapidly and at low cost
  - Key issues involve validating principals of similitude and identifying/quantifying sources of distortion

- Examples presented here:
  - Granular flows of pebble beds: Pebble Recirculation Experiments (PREX)
  - Separate effect tests for convective heat transfer: PB-HTX
  - Integral effect tests: Compact Integral Effects Test (CIET)
Pebble Recirculation Experiments (PREX)
Early scaled experiments in 2006 confirmed ability to recirculate pebbles in FHRs

2006: UCB Pebble Recirculation Experiment (PREX)

2014: Model for SINAP 10-MW TMSR-SF1 Test Reactor
PREX-1 studied key issues for pebble recirculation

Scaled defueling chute

Pebbles injected and carried downward in cold leg

Pebble bed bottom

PREX-1, 8300 pebbles
Validating similitude of friction coefficients required testing with molten salt.

Friction coefficient measurement with flinak (simulant for flibe)
Credit: Patrick Purcell, 2009 NE 170 senior design class
Graphite pebble friction measurement results

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Normal Mass (kg)</th>
<th>$\mu_d$</th>
<th>$\mu_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>492</td>
<td>.915</td>
<td>.237</td>
<td>.273</td>
</tr>
<tr>
<td></td>
<td>1.39</td>
<td>.190</td>
<td>.256</td>
</tr>
<tr>
<td></td>
<td>1.86</td>
<td>.180</td>
<td>.253</td>
</tr>
<tr>
<td>525</td>
<td>.915</td>
<td>.224</td>
<td>.260</td>
</tr>
<tr>
<td></td>
<td>1.39</td>
<td>.189</td>
<td>.253</td>
</tr>
<tr>
<td></td>
<td>1.86</td>
<td>.182</td>
<td>.255</td>
</tr>
<tr>
<td>559</td>
<td>.915</td>
<td>.215</td>
<td>.251</td>
</tr>
<tr>
<td></td>
<td>1.39</td>
<td>.187</td>
<td>.251</td>
</tr>
<tr>
<td></td>
<td>1.86</td>
<td>.177</td>
<td>.250</td>
</tr>
</tbody>
</table>

- Friction coefficients are reduced to less than half that measured for dry helium operating conditions prior to flinak addition
- Compare to friction coefficient for HDPE on acrylic with water lubrication, ~0.3
PREX-2 (dry) confirmed radial zoning capability

- 15° sector PREX-2 experiment simulating 900-MWth annular core
  - 129,840 colored 1.28-cm diameter HDPE pebbles in 15° sector
  - Average of 9460 + 1260 pebbles in each axial layer
- For simplicity PREX-2 was a dry experiment (unlike PREX-1), so pebbles are added to the top of the core and removed from the bottom
  - Hydrodynamic forces on pebbles neglected; were studied in PREX 3.1
PREX 3.0

Dry experimental/simulation demonstration for radially-zoned pebble motion

PREX 3.1

Wet experiment scaled to match Re and Fr

Suction

Pebble injection

Blowing
X-PREX now enables x-ray tomography for granular flow of packed sphere beds

- X-Ray Pebble Bed Recirculation Experiment (X-PREX) research objective:
  - Generate validation data for discrete element simulations (DEM) for slow, dense granular flow
- Instrumented polypropylene pebbles with tungsten wire inserts
- Digital x-ray tomography will generate translation and rotation motion data for ALL pebbles
Example X-PREX results
FHR Separate Effects Tests

A few examples
The similitude of convective heat transfer in oil and molten salts was discovered in 2005

- Reynolds, Froude, Prandtl, and Grashof numbers can be matched simultaneously.
- Mechanical pumping power and heat input reduced to 1 to 2% of prototype power inputs.
PS-HT²: Experimental facility for capturing heat transfer data in pebble beds

- Test section filled with 0.00635 mm (1/4“) diameter copper spheres
- 7 instrumented pebbles and 4 thermocouples measuring bulk fluid temperature
- Drakesol 260AT working fluid
- Measure heat transfer coefficient using transient temperature method
CTAH Test bundle experiments are validating THEEM simulation results

- Transverse Heat Exchange Effectiveness Model (THEEM)
  - 2-D Finite Volume Simulation
  - Calculates
    » Effectiveness
    » Heat Transfer
    » Temperature Distribution of Liquid and Gas
    » Pressure drop of Liquid and Gas
FHR Integral Effects Tests
Reduced height, reduced area, integral effect test (IET) facilities have played a central role in passive safety system licensing.

- **PUMA IET facility**, Purdue University, Reduced height (1/4), reduced area (1/400 volume), 0.45 MW (SBWR/ESBWR)
- **APEX IET facility**, Oregon State University, Reduced height (1/4), reduced area (1/192 volume), 1.0 MW (AP1000)
- **MASLWR IET facility**, Oregon State University, Reduced height (1/3), reduced area (1/255 volume), 0.60 MW (NuScale)
The CIET Facility

Research objectives:
- Predict the transient thermal hydraulic response of liquid-salt-cooled reactor systems, including integral transient response for forced and natural circulation operation (two coupled loops)
- Use experimental data to validate numerical models

Experimental configuration:
- Coupled square loops (primary and DRACS) with pump, vertical heater, “fluidic diode”, heat exchangers
- All branches equipped with needle valves to vary friction factor
- Shell-in-tube oil-to-oil DHX, with modularity to switch to twisted tubes heat exchanger

All CIET research falls under the facility-specific quality assurance program.
The UCB Compact Integral Effects Test (CIET) facility scaling matches the Mk1 reactor design

**UC Berkeley CIET**
(50% Height)

- DRACS Head Tank
- DRACS Loop
- Primary Head Tank
- Core bypass
- DHX flow diode
- Primary Pump
- TCHX (Thermosyphon Cooled Heat Exchanger)
- CTAH/IHX (Coiled Tube Air Heater or Intermediate Heat Exchanger)
- DHX (DRACS Heat Exchanger)
- Heater/Core

**Mk1 PB-FHR**
(100% Height)

CIET/Mk1 heat sources and sinks

UCB Nuclear Engineering Thermal Hydraulics Lab

FHR and MSR Thermal Hydraulics Research at UC Berkeley
CIET is validating FHR transient models

CIET In Operation

CIET Front View

Nodalization for CIET/FHR simulation
Example: Calibration of Friction Number Correlation--Static Mixers

Static mixer pressure losses - from manometers M-11 and M-12

K + fL/D = 21 + 4000/Re

From vendor's chart (K = 2.7)

Measured friction losses are higher than vendor’s chart. Potentially due to flow inlet conditions.
Example: Friction Number Correlation Validation—Heater

Heater friction number - from manometers M-10 and M-11

Theoretical correlation for annular channels is valid for the CIET electrical heater. This confirms that as-built geometry is identical to design geometry.
Steady-State, Coupled Natural Circulation Results

RELAP5-3D predicts steady-state mass flow rates in primary and DRACS loops within 5%
The current CIET test program is now studying response to dynamic forcing

- Power oscillation in CIET is enabling study of transient thermal response of heat structures
- Future work will add power feedback to mimic core reactivity feedback phenomena, and will study the design of FHR control systems
Key next steps for simulant fluid IETs for FHRs/MSRs involves scaling methodology

- Three-step scaling methodology to systematically identify and quantify
  - Sources of scaling distortion-study using SETs
  - Sources of measurement uncertainty-quantify uncertainty distributions
- Major steps:
  1) Design hypothetical molten salt (HMS) IET
     » Conventional reduced area, reduced height, electrically heated IET scaling (similar to APEX, PUMA, MASLWR)
     » Identify HMS-specific sources of scaling distortion
  2) Design scaled simulant fluid IET
     » Scaled to match HMS IET forced and natural circulation
     » Identify simulant-fluid-specific sources of scaling distortion
  3) Assess and characterize measurement uncertainty
     » Credit higher measurement accuracy for low-temperature simulant fluids
Questions?

For more info: http://fhr.nuc.berkeley.edu