Development of LMFR Core Thermal-Hydraulic Benchmark for VVUQ of Sub-Channel and CFD Codes

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TH26-Mission Related Research Projects: Preparing for Future Challenges

This presentation discusses the research and development project entitled "*OECD/NRC Liquid Metal Fast Reactor Core Thermal-Hydraulic Benchmark for Verification, Validation, and Uncertainty Quantification of Sub-Channel and Computational Fluid Dynamics Codes*"

– The project is funded through the US NRC's University Leadership Program grant.

– This mission-related project is in line with the US NRC strategy and plan for advanced non-Light Water Reactors (non-LWR) research.

– It is intended to help the US NRC to prepare for upcoming challenges related to developing and validating core thermal-hydraulics modeling and simulation capabilities for confirmatory analysis of LMFRs.

– It would also provide nuclear industry with international standard problem based on high-resolution experimental data for validating tools for LMFR design and safety analysis including quantification of modeling uncertainties.

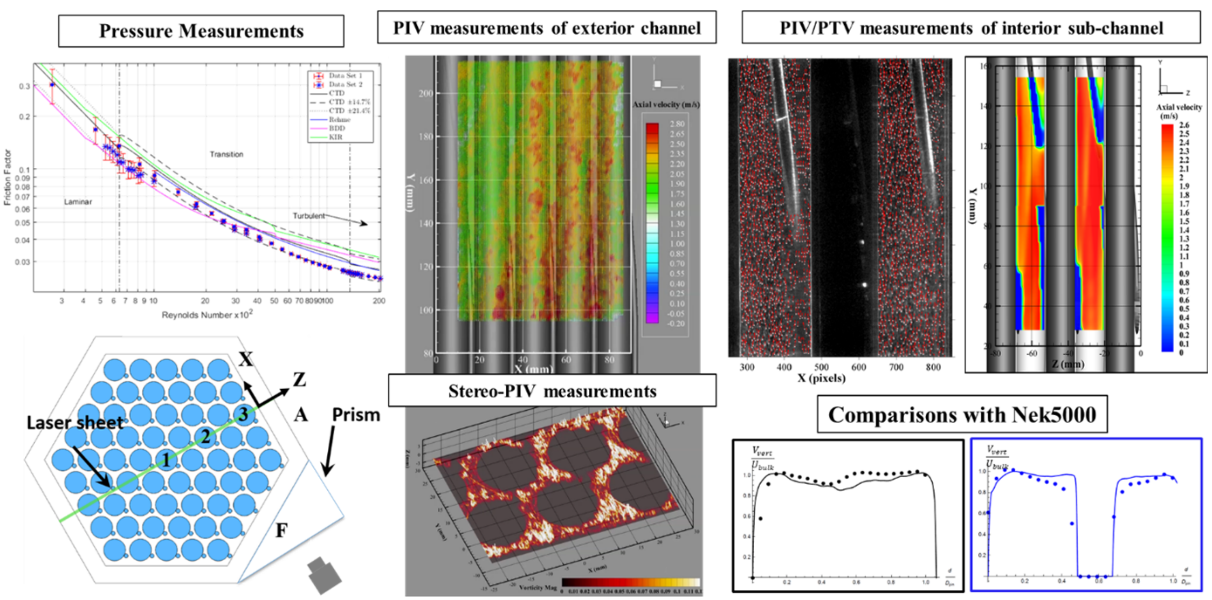
– In summary, this project will contribute to establishing Modeling and Simulation (M&S) tools for licensing and operation of LMFRs.

Presentation Outline

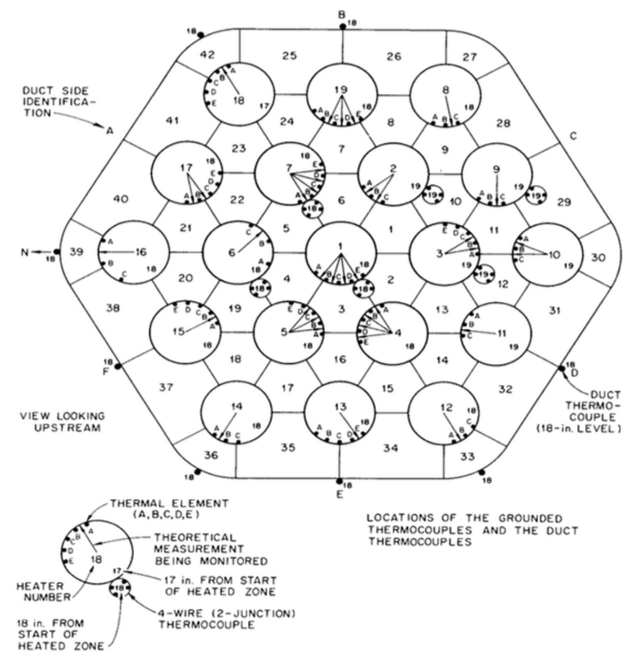
1. LMFR core TH benchmark - overview and status
2. Uncertainty quantification
3. Discussion of benchmark importance for nuclear industry and regulation
4. Conclusions

LMFR Core TH Benchmark employs a series of well-defined problems with complete sets of input specifications and reference experimental data from the THORS experiments (ORNL) and the 61-pin LMFR test facility at TAMU.

TAMU Flow Visualization: Wire Wrapped Bundle [1-4]



THORS Data



Benchmark Team, Sponsorship & Endorsements

Benchmark Team: North Carolina State University and Texas A&M University

NCSU: Prof. Maria Avramova, Dr. David Holler, Mr. Cole Takasugi

TAMU: Prof. Yassin Hassan, Dr. Rodolfo Vaghetto

Funding and Endorsement:

- Sponsored by US Nuclear Regulatory Commission.
- OECD-NEA provides supporting activities (establishing of benchmark website and e-mail distribution list, publication and distribution of benchmark materials, and carrying out the logistics of the benchmark workshops).

  https://www.oecd-nea.org/jcms/pl_32180/liquid-metal-fast-reactor-core-thermal-hydraulics-benchmark-lmfr-t/h
- Cross-linked to Phase II of the on-going OECD/NEA SFR UAM benchmark – LMFR Core TH benchmark will support the development of thermal-hydraulic exercise within SFR UAM.
- Supported and monitored by the OECD/NEA Expert Group on reactor core Thermal-Hydraulics and Mechanics (EGTHM).
- ORNL provides technical guidance on Phase II.

Time frame: Three years (11/30/2020 – 11/29/2023)

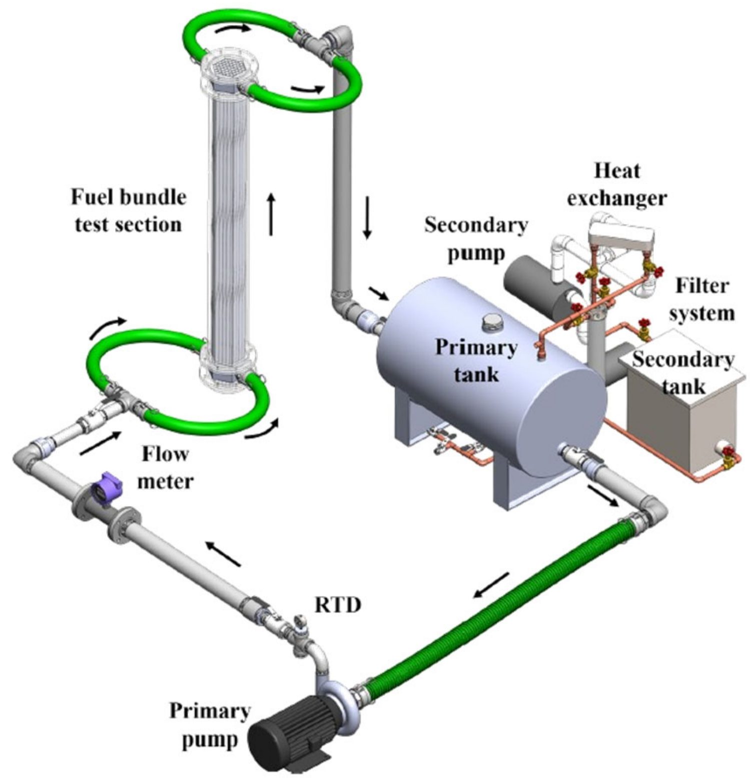
Benchmark Objectives & Phases

Phase I	Numerical predictions of TAMU separate effect tests
Objectives	Provide a high-resolution experimental database of isothermal turbulent flow and pressure drop acquired from a 61-pin wire-wrapped hexagonal fuel bundle (all from TAMU).
	Assess the performance of numerical schemes and turbulent models currently implemented in the state-of-the-art CFD codes.
	Establish best practices for uncertainty quantification of model geometry, initial and boundary conditions, and other associated uncertainties for CFD calculations → link to the SFR UAM Benchmark.

Phase II	Numerical predictions of THORS integral effect tests
Objectives	Provide a sodium turbulent flow and heat transfer database for CFD and sub-channel model validation.
	Emphasize the importance of uncertainty analysis for TH simulations and establish best practices for quantification of geometry modelling, input data, fluid properties, and other uncertainties associated with the complex flows in LMFR bundles→ link to the SFR UAM Benchmark.
	Develop guidance for CFD model/code validation for LMFR fuel bundles that can be used to improve the existing standards.
	Update the current TH models for pressure drop and inter-channel mixing.
	Develop the hybrid experiment/simulation database necessary to establish and calibrate the low order models with high resolution (both experimental/numerical) data.

Phase I: Experimental Facility & Data

- 61-pin wire-wrapped fuel bundle.
- Completely isothermal at room temperature.
- Solid material = acrylic plastic, working fluid = p-Cymene.
- Constructed <5 years ago and still in operation.
- Located at Texas A&M University THR Lab in College Station, TX, USA.
- Figure adopted from [1-4].



Phase I: Experimental Facility & Data

Dimensions of the main test section & Nominal facility conditions

ITEM	TYPE	VALUE	UNITS
Pin number	Base	61	-
Flat-to-flat distance (FTF)	Base	154	mm
Corner-to-corner distance (CTC)	Base	178	mm
Inner duct side length	Base	88.8	mm
Bundle total length	Base	1857	mm
Main test section length	Base	1666	mm
Pin diameter	Base	15.9	mm
Pin pitch	Base	18.9	mm

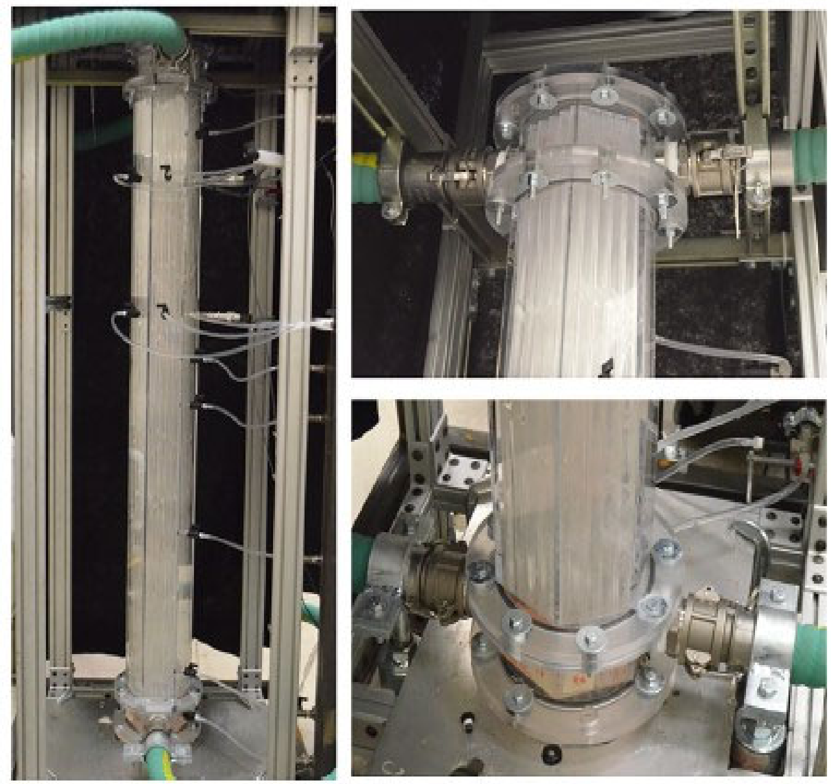
PARAMETER	TYPE	VALUE(S)	UNITS
System pressure	Base	101.325	kPa
Fluid temperature	Base	22.0	°C
Fluid density	Base	855.23 (at 22.5 °C)	kg/m^3
Fluid dynamic viscosity	Base	8.18×10^{-4} (at 22.5 °C)	Pa-s
Fluid kinematic viscosity	Derived	9.47×10^{-7}	m^2/s

ITEM	TYPE	VALUE	UNITS
Wire diameter	Base	3.00	mm
Wire pitch	Base	476	mm
Edge pitch	Derived	19.5	mm
Wall gap size	Derived	0.671	mm
Helical pitch to pin diameter ratio	Derived	30	-
Pin pitch to pin diameter ratio	Derived	1.189	-
Total wetted perimeter	Derived	4.155	m
Total flow area	Derived	79.96	cm^2
Hydraulic diameter	Derived	7.696	mm

Phase I: Experimental Facility & Data

TAMU experimental data

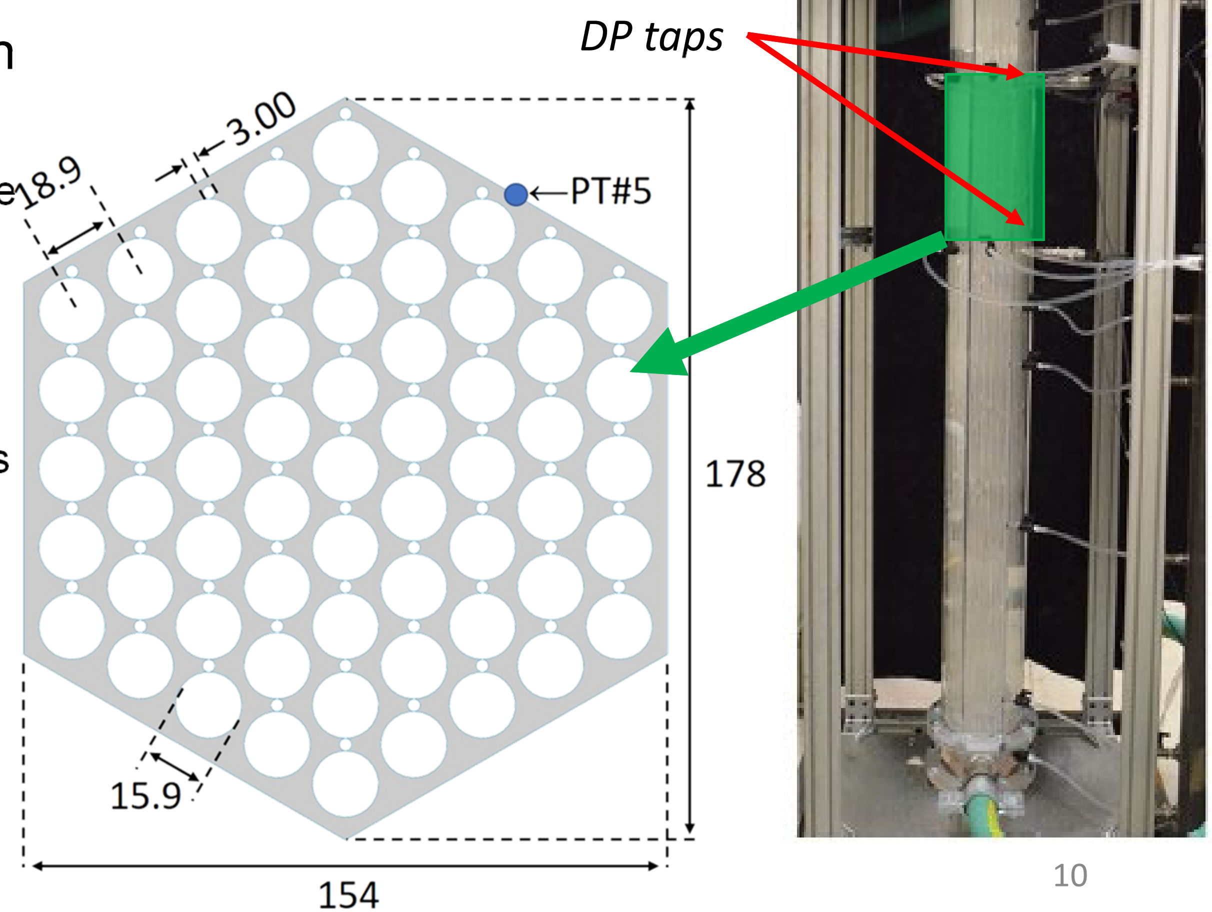
- Facility was built to acquire pressure drop and high-resolution velocity measurements:
  - Particle Image Velocimetry (PIV)
  - Particle Tracking Velocimetry (PTV)
- Both types to be included in separate benchmark tasks:
  - Pressure drop along one axial wire pitch
  - PIV measurements of vertical and axial planes



Phase I: Pressure Drop Comparisons

Axial pressure drop for one wire pitch

- Pressure drop measured with two Differential Pressure (DP) taps across one axial wire pitch (476 mm).
- Experimental data will be compared to both CFD and sub-channel predictions.
- Figure on right (dimensions in mm) shows wire clock position at both ends of DP region (dimensions adopted from [1]).



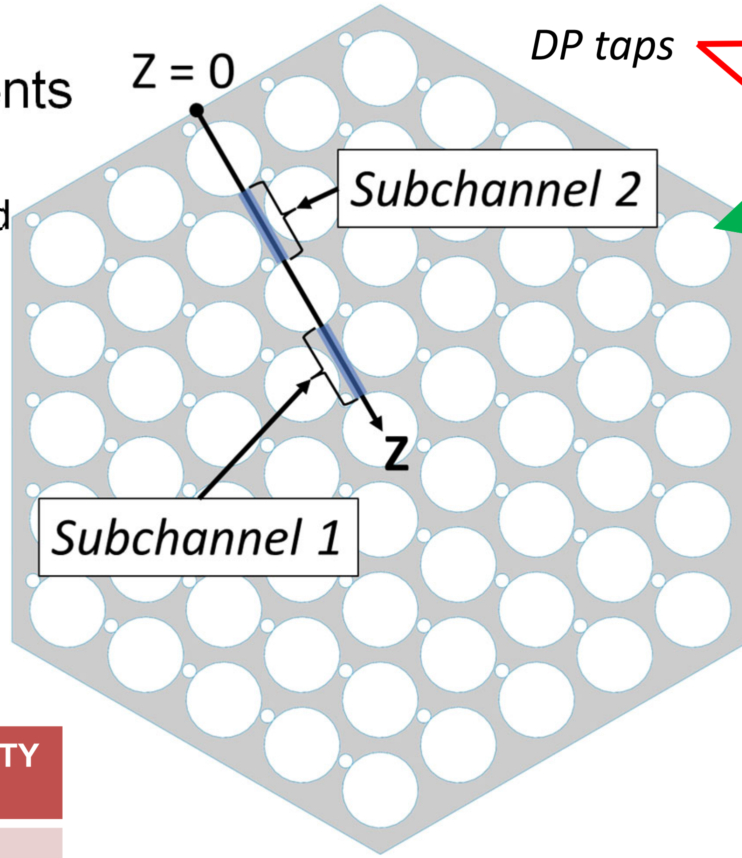
Requested output

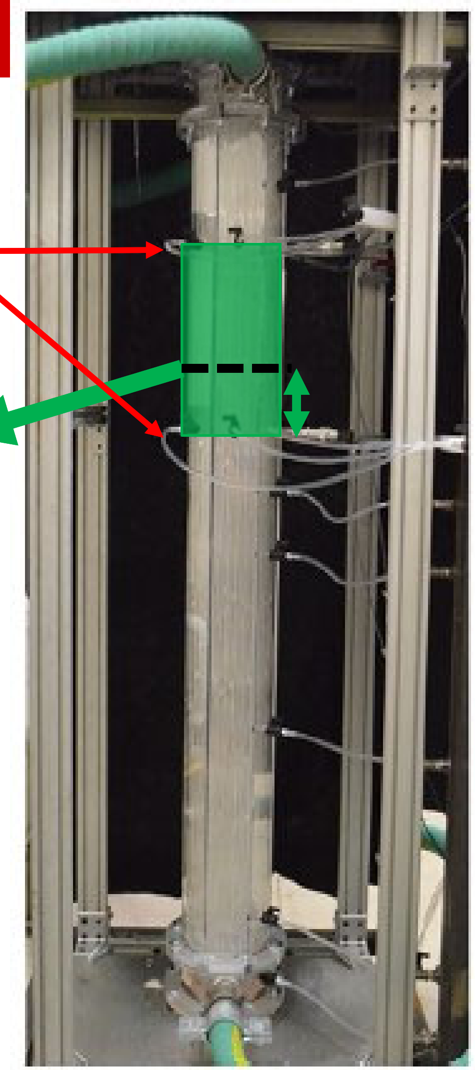
CASE	DP [Pa]	UNCERTAINTY [Pa]
#	xxx.x	xx.x

Phase I: Velocity Comparisons

High-resolution velocity measurements

- Line of velocity data at Re ≈ 19,000
- Velocity data measured in fully-developed region between DP taps
- Figure shows one of two lines under preparation for benchmark
  - 66.05 mm into DP region
  - Second line is at 152.9 mm





Requested output

SUBCHANNEL	POINT	VELOCITY [m/s]	UNCERTAINTY [%]
...	...	x.xxx	x

Phase II: Integral Effects Comparisons

- Comparisons to select data from the Thermal Hydraulic Out of Reactor Safety (THORS) experimental campaign.
  - Experimental facility was originally built in 1970 as the Fuel Failure Mockup (FFM) facility.
  - Name was changed in 1976.
  - Table on next slide shows the experiment campaign progression.
- Targeted data are from Bundles 3C, 6A, and 9.
  - Select data from Bundles 3C and 6A are public.
  - Bundle 3C (19 central pins + 12 guard pins) involved steady state with blockage and transient conditions.
  - Bundle 6A (19 pins) involved natural circulation and boiling.
  - Bundle 9 (61 pins) was used to thoroughly investigate behavior on a larger bundle in both steady and transient conditions.
- See [5] for more information.

Phase II: Integral Effects Comparisons

THORS experimental campaign

BUNDLE ID	NUMBER OF PINS	BLOCKAGE CONFIGURATION	HEATED LENGTH	TOTAL OPERATING TIME [hr]
1A, 2A	19	None	24 in (614 mm)	1,500
2B	19	13 and 14-channel inlet	21 in (538 mm)	3,480
1B	19	None	24 in (614 mm)	1,244
3A	19	6-channel in heated zone	21 in (538 mm)	3,190
3B[a,b]	19	6-channel in heated zone	21 in (538 mm)	588
5A, 5B, 5C	19	12-channel in edge gap	18 in (461 mm)	3,643
5D[a,b]	19	None	18 in (461 mm)	2,924
6A	19	None	36 in (922 mm)	8,244
3C	31[c]	6-channel in heated zone	21 in (538 mm)	3,856
9	61	None	36 in (922 mm)	5,836

[a] Boiling tests.
[b] Boiling tests with gas injection.
[c] Nineteen central pins with twelve surrounding bent pins.

Phase II: Integral Effects Comparisons

- Current effort in Phase II is focused on data recovery.
  - Plots available in public documents have been digitized with a web service [6].
  - Most THORS reports are still export-controlled documents.
  - The Gateway for Advanced Innovation in Nuclear (GAIN) office is assisting with THORS data release.

Uncertainty Quantification

- Considered Uncertainties in LMFR-TH benchmark:
  - Fluid properties
  - Boundary condition
  - Manufacturing tolerances
  - Experimental measurement uncertainty
    - Pressure drop and velocity measurement uncertainty (previously analyzed by TAMU)
    - Unique facility and working fluid pose challenges (availability of uncertainties are in progress)

- Participants are encouraged to use the best UQ methods available.
- Coupling to UQ codes is possible.
  - CTF-DAKOTA coupling complete and demonstrated.
  - CFD coupling more expensive but possible.

Benchmark Discussion & Guidelines for Analysis

- Output format can be adjusted if needed.
- Manufacturing tolerances and fluid property uncertainty investigation is in progress.
- Reference subchannel and CFD analyses are in progress.
- Participants' code(s) selection is welcome.
- The NEA international benchmark framework will broaden participation and benefit the benchmark comparative analysis.

- Many CFD studies have been performed on wire-wrapped fuel bundles:
  - Pin-wire contact
  - Wire shape
  - Recent application: Versatile Test Reactor (VTR)
- Reference team can provide guidance on most CFD codes:
  - Reference calculations to be performed with Nek5000 (LES turbulence model)
  - NCSU team has experience in other common CFD codes (Star-CCM+, OpenFOAM, Fluent)
- Sub-channel expertise is available and evaluation guidelines are forthcoming.

Benchmark Contributions

1. The benchmark will provide a LMFR turbulent flow and heat transfer database for high resolution (CFD and Sub-channel) model validation.

2. The benchmark will emphasize the importance of uncertainty analysis for TH simulations and will establish best practices for Quantification of geometry modelling, input data, fluid properties, and other associated uncertainties.

3. The benchmark will develop guidances for sub-channel and CFD model/code validation for LMFR fuel bundles that can be used to improve the existing standards e.g., ASME V&V 20.

4. The benchmark will update the current generation TH models for pressure drop and inter-channel mixing.

5. The benchmark develop the hybrid experiment/simulation database necessary to establish and calibrate the low order models with high resolution (both experimental/numerical) data, e.g., Hi2Lo model information.

Benchmark Mission and Status

- This benchmark will provide a unique and official comparison between many LMFR-type TH analyses:
  - Phase I will provide the opportunity to benchmark separate effects.
  - Phase II will benchmark more integral effects.
  - Phase I specifications has been released; Phase II specification to be released for review soon.
  - Benchmark workshops are regularly conducted on yearly basis.
  - Benchmark progress is supported and monitored by the NRC Office of Research and NEA EGTHM.

- The deliverables to US NRC on this project include:
  - Quarterly progress reports and a final project report.
  - Benchmark specification reports.
  - Benchmark comparison reports.
  - Workshop summary records.
  - Reports on CTF and CFD modeling and validation using the LMFR Core T-H benchmark database.

Conclusions

– The benchmark serves to address LMFR TH modeling challenges by assembling teams of experts whose work accelerates research towards this topic.

– This benchmark aims to bring together participants from various institutions to contribute towards the validation of LMFR core TH prediction methods.

– Previous numerical and experimental studies that have been performed on LMFR core geometry lack appropriate high-resolution experimental data supplemented by uncertainties and structured set of techniques for proper comparison.

– This benchmark provides the necessary structure and through the OECD/NEA and NRC collaboration an extensive framework for a unique and official comparative analysis between many LMFR-type TH analyses.

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