NEUP Nuclear Energy University Program
U.S. Department of Energy

Evaluation of Semi-Autonomous Passive Control Systems for HTGR Type Special Purpose Reactors

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Microreactor Program Winter Review 3/09/2023

COLLEGE OF ENGINEERING
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UNIVERSITY OF MICHIGAN

HolosGen™

Argonne NATIONAL LABORATORY

Outline

- Project Overview

- What we said we'd do last year
- What we did last year

- Next Steps

- Backup
    - Retrospective
    - Publications
    - Additional details

Project Overview

Objectives

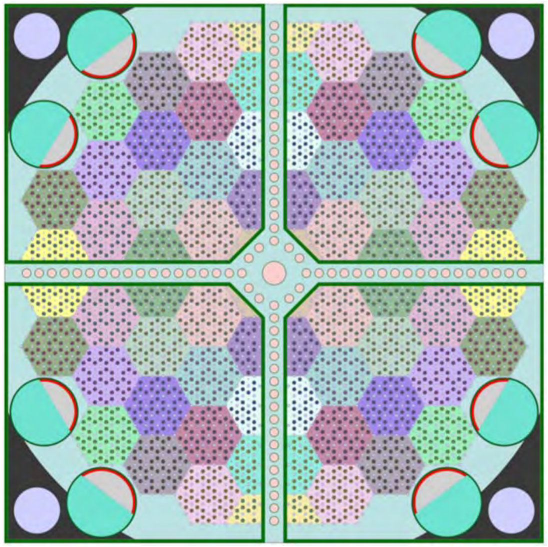
- “The objective of the proposed work here is to ***develop and evaluate new passive autonomous control systems for high temperature gas reactor (HTGR)*** type SPR concepts.”

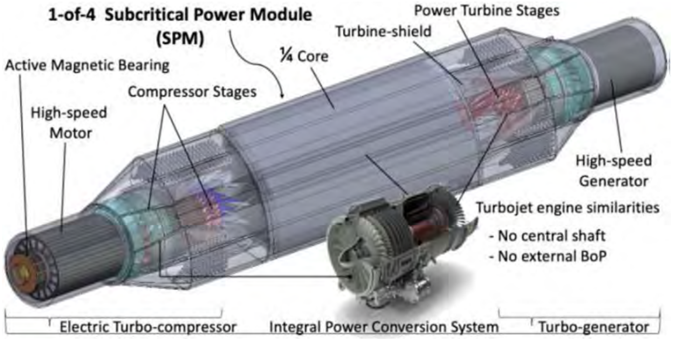
- Investigating Passive Variable Flow Controllers

- Comparing with Control Algorithms for Control Drums
    - Contributed several new methods/capabilities here.

- The value of passive autonomous control systems will be evaluated against transient response to load following.

Cross Section of Core





Automated Control

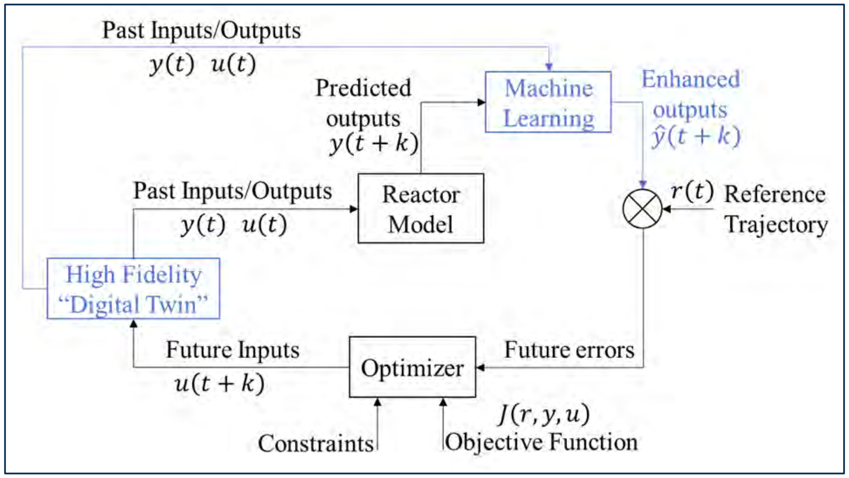
Can reactor components be designed to give a certain dynamic response?

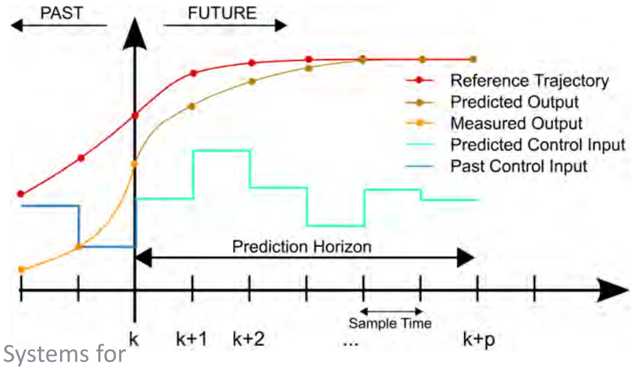
- Reactor Dynamics are well known
  - Point Kinetics and two or three temperature equations
  - Spatial kinetics & high-fidelity

$$\delta\rho(t) = \delta\rho_{cr}(t) + \delta\rho_{T_{inlet}}(t) + \delta\rho_{\dot{m}}(t) + \delta\rho_{Xe}(t) + \alpha_f\left(T_f(t) - T_{f0}\right) + \alpha_m\left(T_m(t) - T_{m0}\right)$$

- Demand More Power → ? → increase reactivity
- Demand Less power → ? → decrease reactivity

How good do model-based controllers have to be, and can they learn?

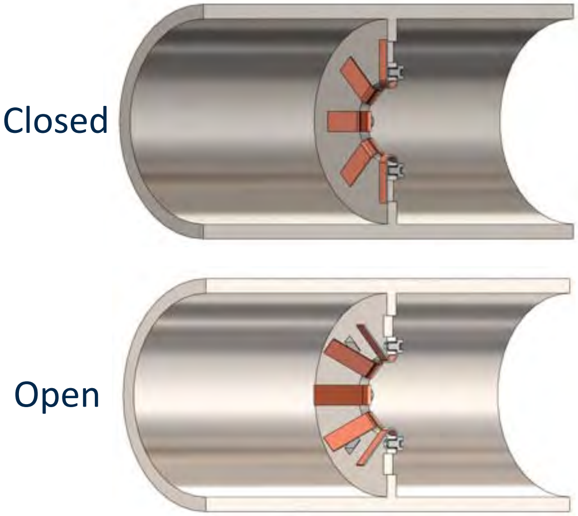




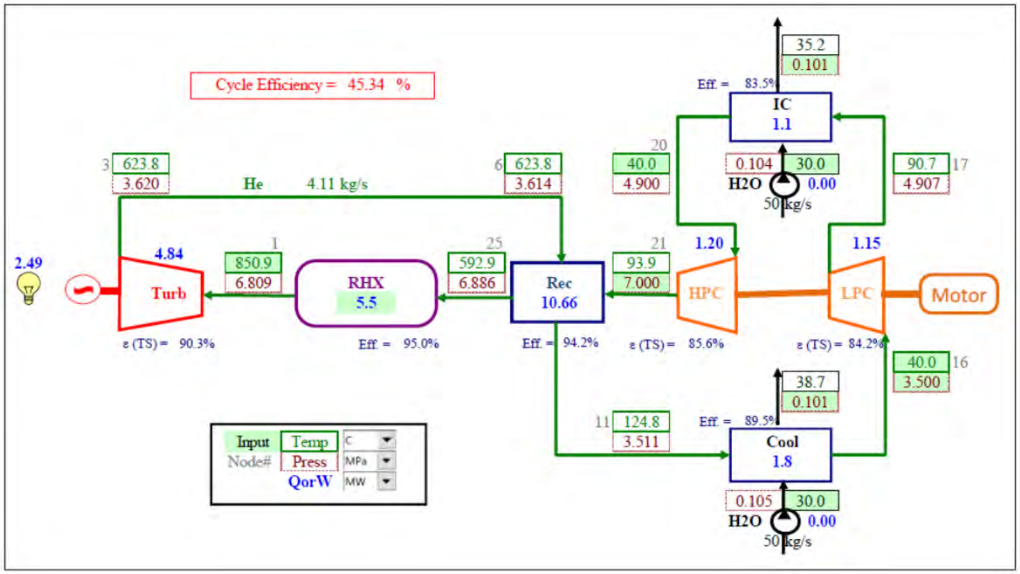
Model Predictive Control

Passive Variable Flow Controllers

- Use bimetallic valve based on thermal expansion
- Temperature increases—flow area increases
- Temperature decreases—flow area decreases



Conceptual Illustration

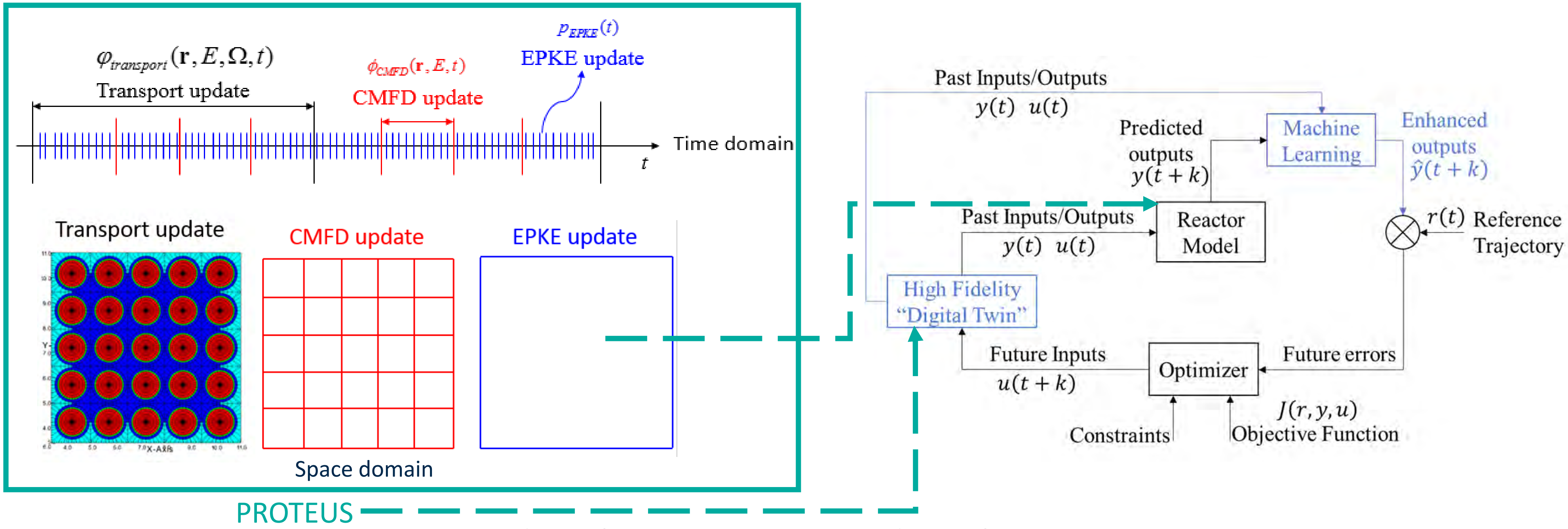


Analogous to turbine throttling
Concept could be implemented for valves for turbine bypass, compressor throttling, maybe inventory control

Next Steps from 3/4/2022

ToDo: PROTEUS Load-Follow Transient

- PROTEUS Transient Methodology based on Transient Multi-Level Method

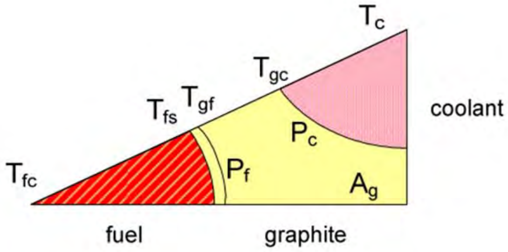


Next Steps—Implementation Plan

- Implement the simplified TH model in Proteus
  - The model is reasonably accurate compared to the results of SAM.
  - Reduce the computational cost from TH part
  - Coolant TH properties solved with assembly-averaged heat rate.

- Implement the control scheme.
  - Implement a PID controller to verify the control scheme.
  - Implement the Model-predictive control (MPC) scheme.
    - MPC will be implemented into Proteus, or externally and called
    - via a wrapper.
  -

- Improve the efficiency of transient simulation
  - Transient process lasts several minutes or even hours.
  - Large time steps are required.
  - Some methods have been developed in MPACT will be used.

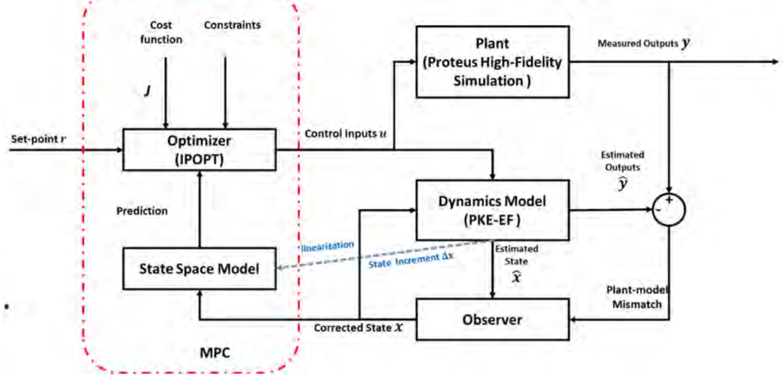


$$T_{gc} = T_c + \frac{q_s''}{h_c}$$

$$T_{gf} = T_{gc} + \frac{2A_g}{P_f + P_c}\frac{q_s''}{k_g}$$

$$T_{fs} = T_{gf} + \frac{q_s''}{h_g}$$

$$T_{fc} = T_{fs} + \frac{r_f}{2}\frac{q_s''}{k_f}$$



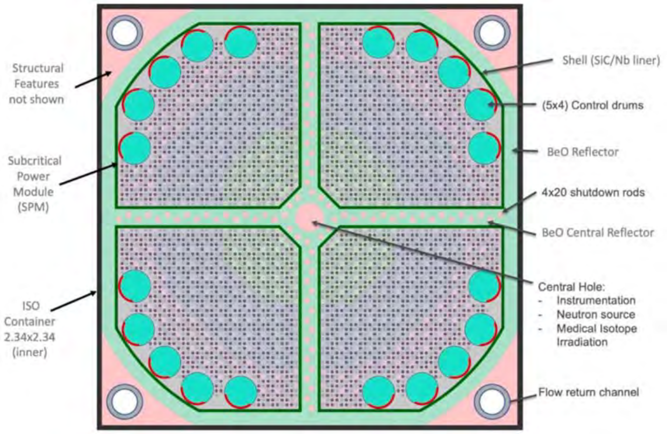
Activities in the Last Year

Short version: we got there, but not the way we planned

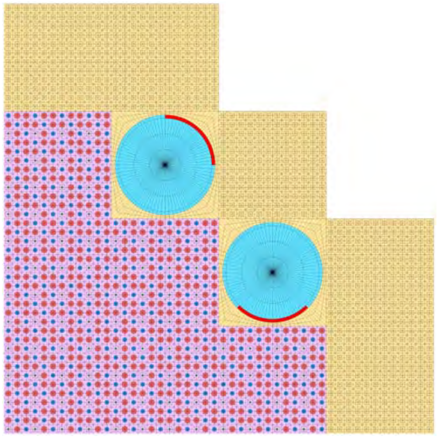
Target Microreactor Model

- Holos-Quad and simplified microreactor

Holos-Quad



Simplified microreactor



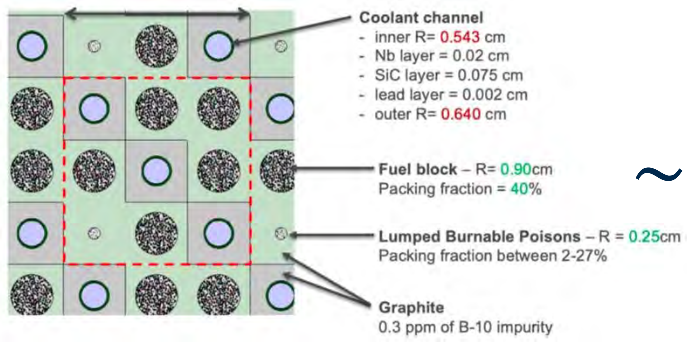
Comparison

Parameter	Holos-Quad (Gen 2+)	Simplified Microreactor
Power (MW)	22.00	2.42
# of fuel compacts	2300	480
Active core height (cm)	380	200
Power density (W/m)	2517	2517
# of coolant channels	1528	288
Core coolant mass flow rate (g/s)	21896	3085
Inlet temperature (K)	863	863
Estimated outlet temperature (K)	1123	1014

Thermal Hydraulics/Fluids Solver

- Simplified Thermal Hydraulics/Fluids (STH) solver for HTGRs
  - PROTEUS/SAM coupling requires significant efforts and computational time
  - The STH solver solves 1D radial conduction and 1D axial convection problems for each unit-cell
    - Geometry correction factors are applied to the heat conduction solver

Holos unit-cell



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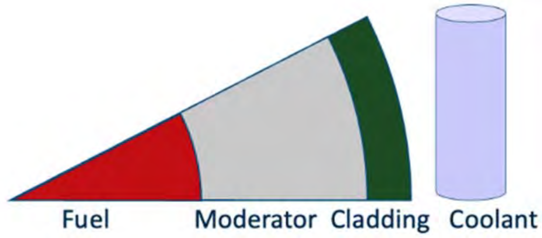
STH solver coordinates



Heat conduction equation

$$q'' = -k\left.\frac{\partial T}{\partial x}\right|_w = h_w(T_w - T_b)$$

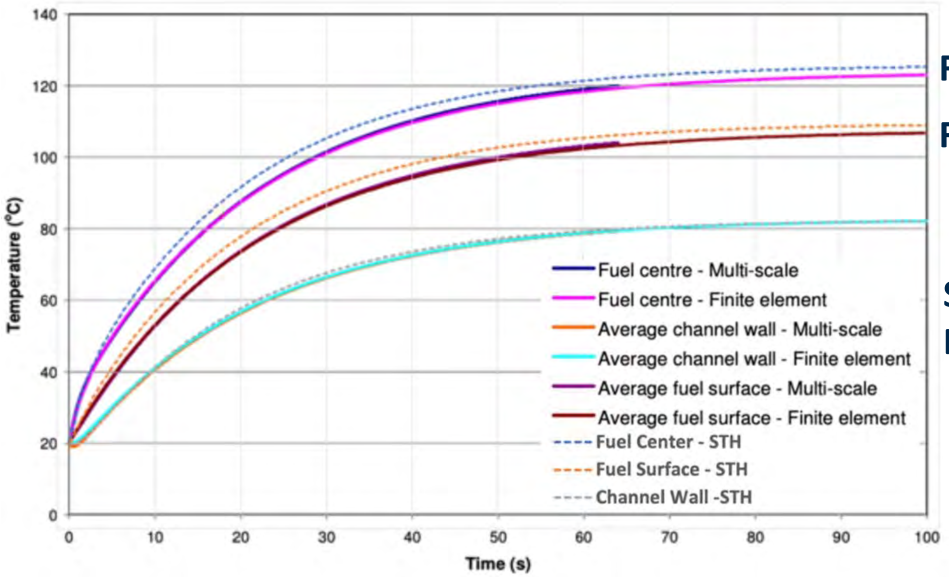
Convection equations

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot k(T)\nabla T + q$$

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} k(T) \frac{\partial T}{\partial x} + q$$

Verification of STH transient solver

- Comparison to FEM solution
  - *AMEC NSS Limited, "Investigation of Local Heat Transfer Phenomena in a Prismatic Modular Reactor Core," Technical report NR001/RP/001 R02, 2009*
- Transient scenario – 0 to full power



Fuel Center

Fuel Surface

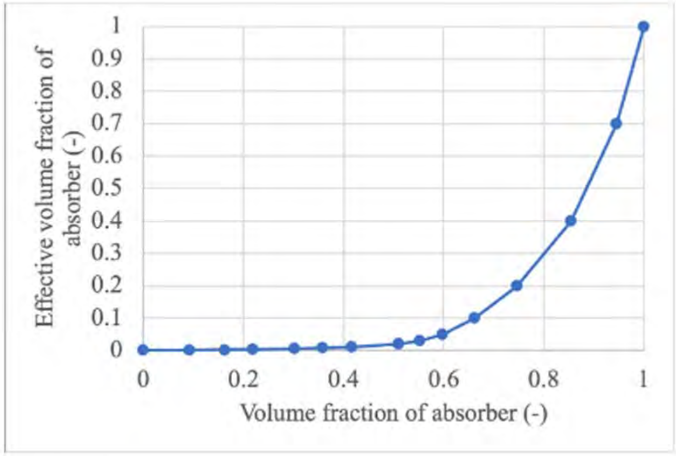
Channel Wall

Solid line: FEM
Dashed line: STH

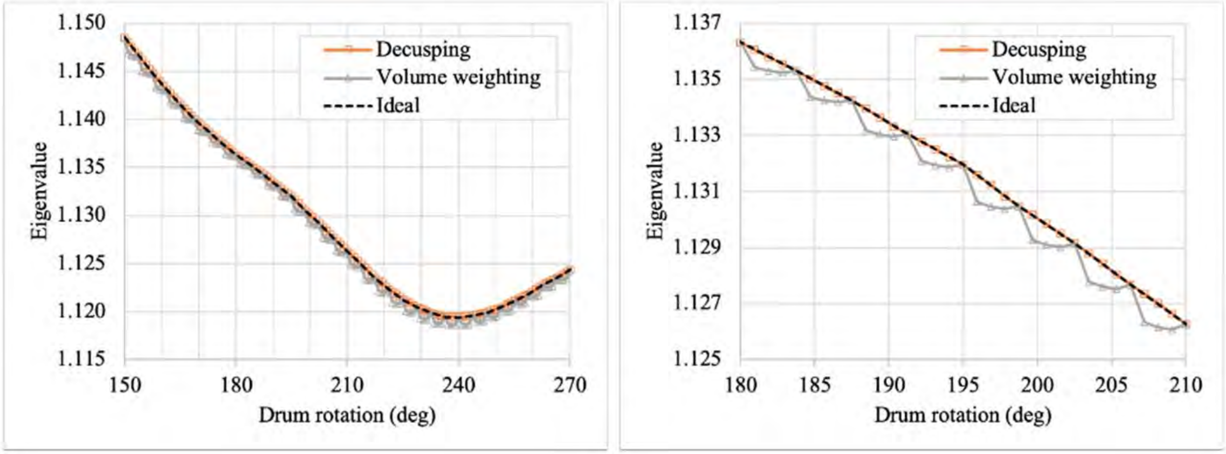
Control Drum Decusping

- Control drum decusping method has been implemented for reliable simulation of drum rotation

Effective volume fraction of absorber

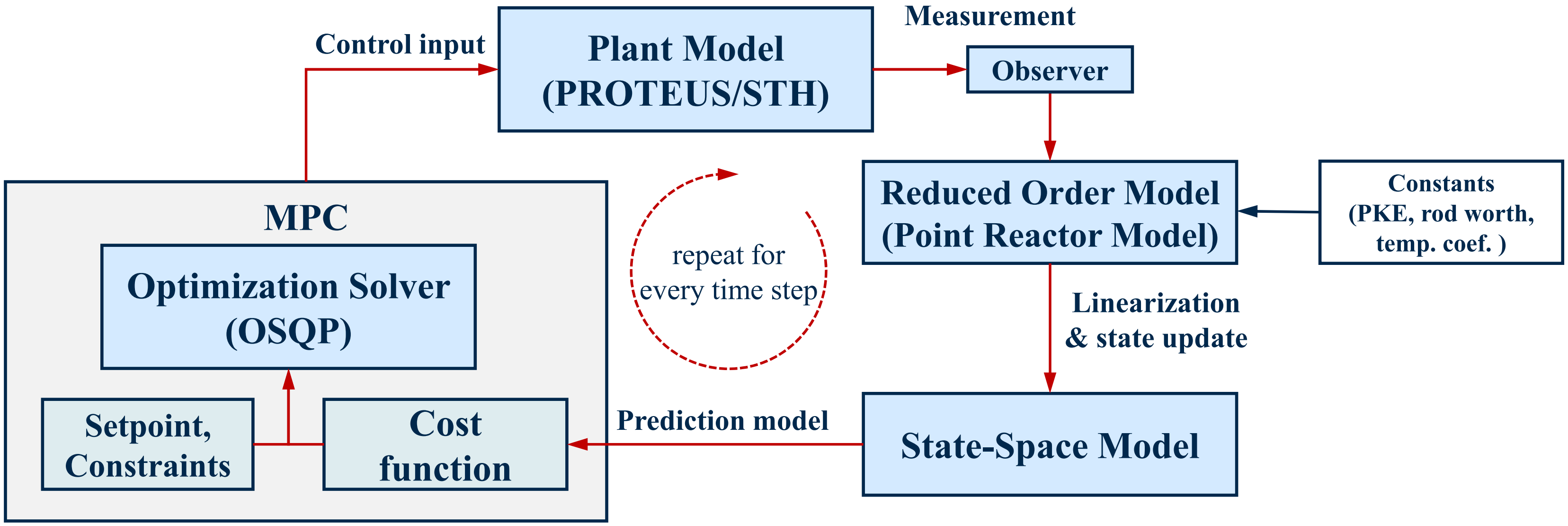


Eigenvalue with and without decusping function



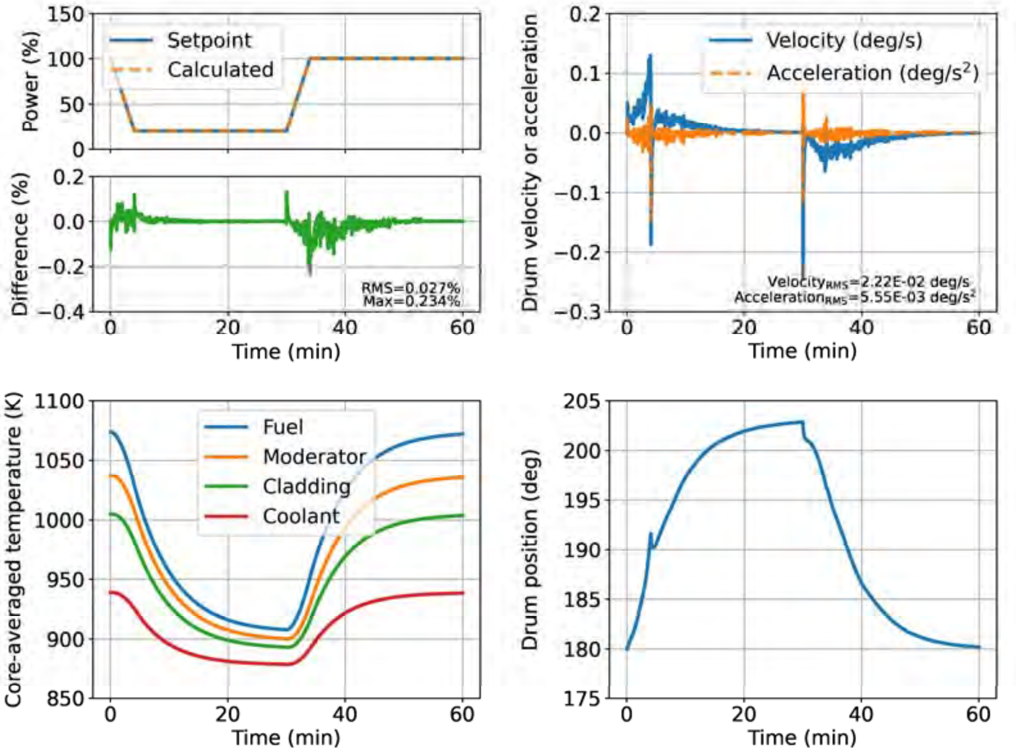
Calculation Flow

- PROTEUS/STH/Adaptive MPC



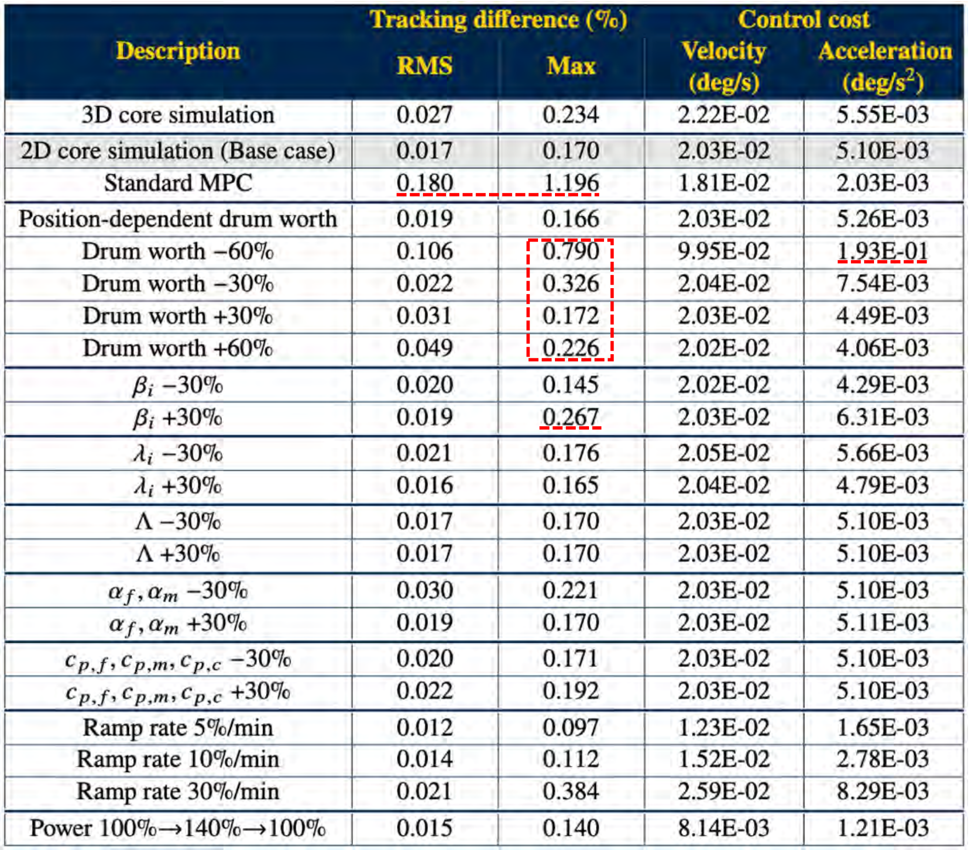
Microreactor Load-follow Simulation Results

- PROTEUS/STH/MPC simulation
- 1 hour of load follow simulation
  - 100%→20%→100%
  - Ramp rate: 20%/min
- Control every second with MPC controller
- Tracking error
  - RMS 0.027%
  - Max 0.234%
- Run-time: 46 hours with 60 cores



Sensitivities on Reduced Order Model Parameters

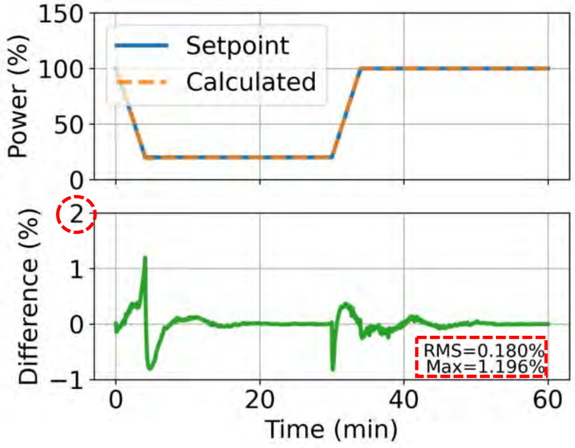
- Even though observer may correct some degree of error, MPC still needs to have a reasonable ROM for accurate and stable simulation results
- Control drum differential worth and β_i have larger sensitivities than other parameters
- ROM parameters may have pretty large margin (30%)
- Standard MPC causes large error since it cannot predict time-varying component

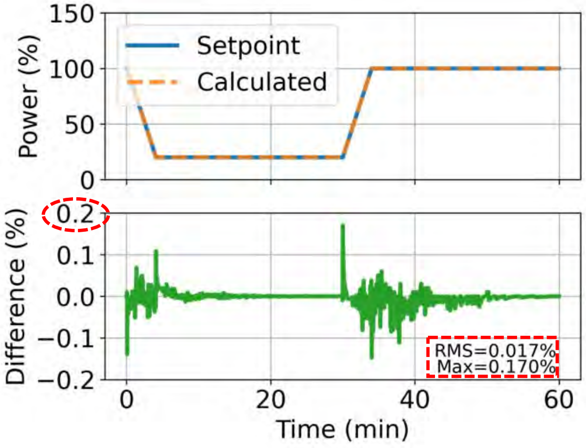


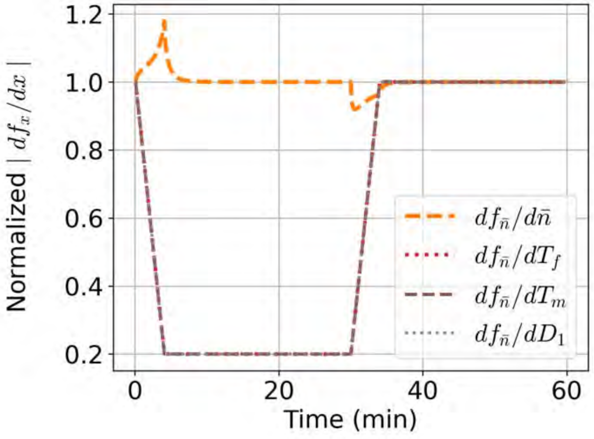
Description	Tracking difference (%)		Control cost	
	RMS	Max	Velocity (deg/s)	Acceleration (deg/s^2)
3D core simulation	0.027	0.234	2.22E-02	5.55E-03
2D core simulation (Base case)	0.017	0.170	2.03E-02	5.10E-03
Standard MPC	0.180	1.196	1.81E-02	2.03E-03
Position-dependent drum worth	0.019	0.166	2.03E-02	5.26E-03
Drum worth −60%	0.106	0.790	9.95E-02	1.93E-01
Drum worth −30%	0.022	0.326	2.04E-02	7.54E-03
Drum worth +30%	0.031	0.172	2.03E-02	4.49E-03
Drum worth +60%	0.049	0.226	2.02E-02	4.06E-03
β_i −30%	0.020	0.145	2.02E-02	4.29E-03
β_i +30%	0.019	0.267	2.03E-02	6.31E-03
λ_i −30%	0.021	0.176	2.05E-02	5.66E-03
λ_i +30%	0.016	0.165	2.04E-02	4.79E-03
Λ −30%	0.017	0.170	2.03E-02	5.10E-03
Λ +30%	0.017	0.170	2.03E-02	5.10E-03
α_f, α_m −30%	0.030	0.221	2.03E-02	5.10E-03
α_f, α_m +30%	0.019	0.170	2.03E-02	5.11E-03
$c_{p,f}, c_{p,m}, c_{p,c}$ −30%	0.020	0.171	2.03E-02	5.10E-03
$c_{p,f}, c_{p,m}, c_{p,c}$ +30%	0.022	0.192	2.03E-02	5.10E-03
Ramp rate 5%/min	0.012	0.097	1.23E-02	1.65E-03
Ramp rate 10%/min	0.014	0.112	1.52E-02	2.78E-03
Ramp rate 30%/min	0.021	0.384	2.59E-02	8.29E-03
Power 100%→140%→100%	0.015	0.140	8.14E-03	1.21E-03

Adaptive MPC vs. Standard MPC

- Ignoring time-varying elements in standard MPC may degrade accuracy
- Successive linearization in adaptive MPC can consider these nonlinearity in ROM


Standard


Adaptive


Time-varying elements from Adatpvie MPC

Next Steps

Next Steps

- Write-up work on recent simulations
- Complete planned and in-progress journal articles
- Complete calculations of passive variable flow controllers
  - and write milestone report
- Compare MPC with passive flow controllers
  - and milestone report
- Write project final report

Publications (1)

1. S. Choi, S. Kinast, V. Seker, C. Filippone, and B. Kochunas, "Preliminary Study of Model Predictive Control for Load Follow Operation of Holos Reactor," ***Trans. Am. Nucl. Soc***., vol. 122, pp. 660–663, 2020, doi: 10.13182/T122-32327.
2. D. Sivan *et al.*, "Linear Stability Analysis of HTR-like Micro-reactors," ***Trans. Am. Nucl. Soc.***, vol. 122, pp. 664–667, 2020, doi: 10.13182/T122-32399.
3. V. Seker and B. Kochunas, "Assessment of Variable Reflector Reactivity Envelope in Multi-Module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-002-00, Ann Arbor, MI, Apr. 2020.
4. B. Kochunas, K. Barr, and S. Kinast, "Assessment of Variable Reflector Reactivity Envelope in Multi-Module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-003-00, Ann Arbor, MI, Jul. 2020.
5. B. Kochunas, K. Barr, S. Kinast, and S. Choi, "Global and Local Reactivity Assessments for Passive Control Systems of Multi-module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-005-00, Ann Arbor, MI, Sept. 2020.
6. S. Choi, S. Kinast, and B. Kochunas, "Point Kinetics Model Development with Predictive Control for Multi-Module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-006-00, Ann Arbor, MI, Dec. 2020.
7. S. Kinast, D. Sivan, S. Choi, C. Filippone, and B. Kochunas, "Frequency Domain Analysis of HTR-Like Microreactors," **Proc. M&C 2021**, pp. 1517-1527. doi: 10.13182/M&C21-33807
8. S. Choi, S. Kinast, K. Barr, C. Filippone, and B. Kochunas, "Comparative Study of Control Algorithms for Load-Follow Operations of the Holos Microreactor," **Proc. of M&C 2021**, pp. 728-737. doi: 10.13182/M&C21-33733

Publications (2)

9. Q. Shen and B. Kochunas, “Preliminary Passive Feedback Model Development and Integration,” **Tech. Report**, NURAM-2021-004-00, Ann Arbor, MI, June. 2021.
10. D. Price, et. al, “A Perturbation-Based Hybrid Methodology for Control Drum Worth Prediction Applied to the HOLOS-Quad Microreactor Concept,” ***Ann. Nucl. Energy***.
11. D. Price, S. Kinast, B. Kochunas, “Monte Carlo Error Analysis for a Hybrid Control Drum Worth Model,” ***PHYSOR 2022***.
12. S. Kinast, B. Kochunas, “Stability Margin Analysis of Holos-Quad Microreactor Design,” ***PHYSOR 2022***,
13. D. Price, M. Radaideh, and B. Kochunas, “Multi-objective Optimization of Nuclear Microreactor Control System Operation with Swarm and Evolutionary Algorithms,” ***Nucl. Eng. Des.***
14. (Drafting) journal article on stability analysis, frequency domain analysis, and stability margins.
15. (Drafting) journal article on design of passive variable flow controllers
16. (Planned) journal article on the MPC with point reactor model
17. (Planned) journal article on High-Fidelity Transient Simulation with MPC

Thank You