Molten Salt Microreactor Controller Design Decisions

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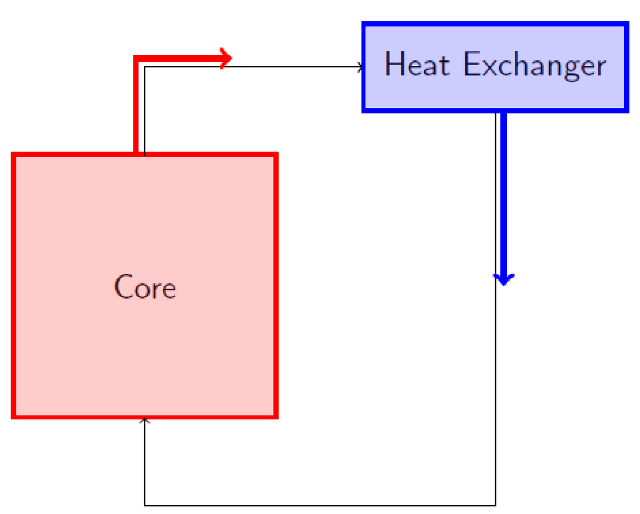
Introduction

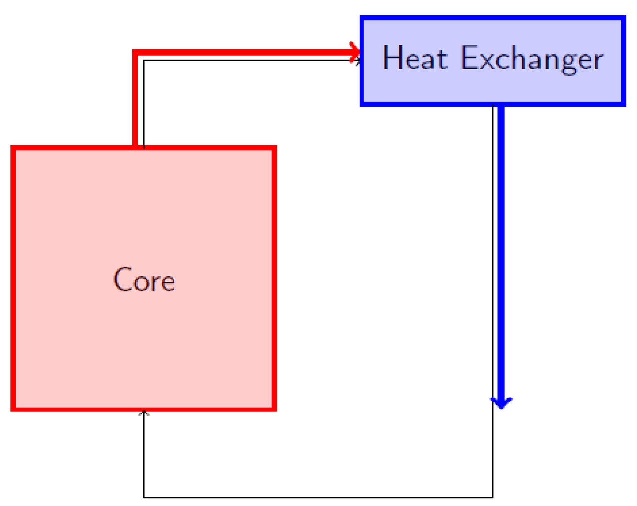
- Natural circulation molten salt reactors have two passive feedback mechanisms that must be considered when designing a controller
- Temperature reactivity caused by heavy-metal thinning and doppler broadening [1]
- Flow reactivity caused by the advection of delayed neutron precursors out of core [2]

Thought Experiment

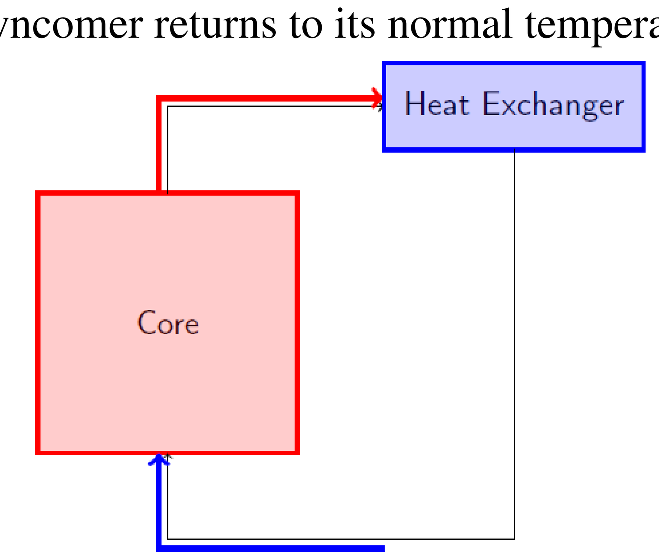
Start design process by investigating dynamics associated with anticipated transients: • Natural circulation flow mode • Passive feedback mechanisms • Transport delays Conduct a thought experiment • Power step increase • Core set-point instantly equal to heat exchanger power demand • Ideal controller which produces rapid load following and disturbance rejection



Immediately, the core produces more power and the heat exchanger rejects more power. This results in a higher flow-rate and a negative flow reactivity insertion

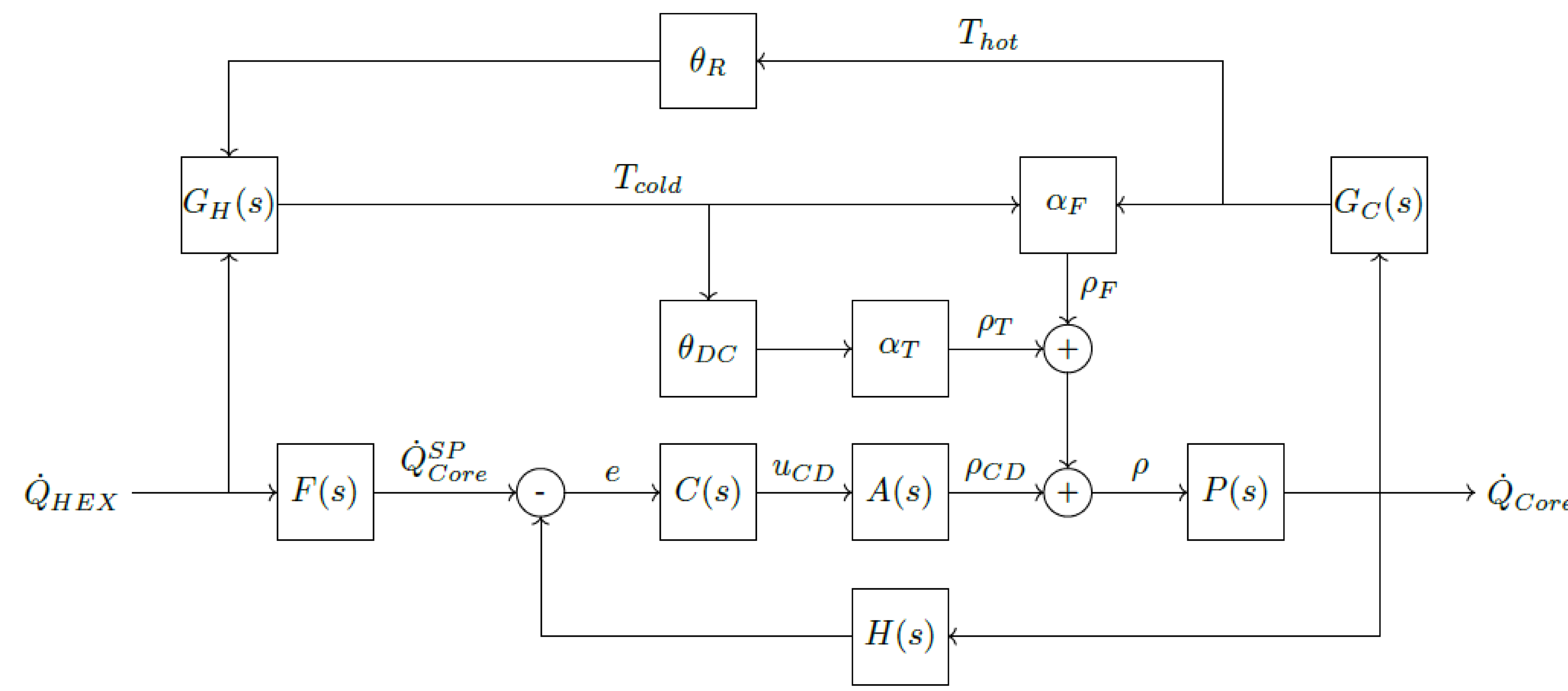


When the hot salt from the core reaches the heat exchanger, the additional power is delivered and the downcomer returns to its normal temperature



When the cold salt from the heat exchanger arrives in the core, this is a positive temperature reactivity insertion, followed by a negative temperature reactivity insertion when the normal temperature salt arrives

Molten Salt Microreactor Control Loop

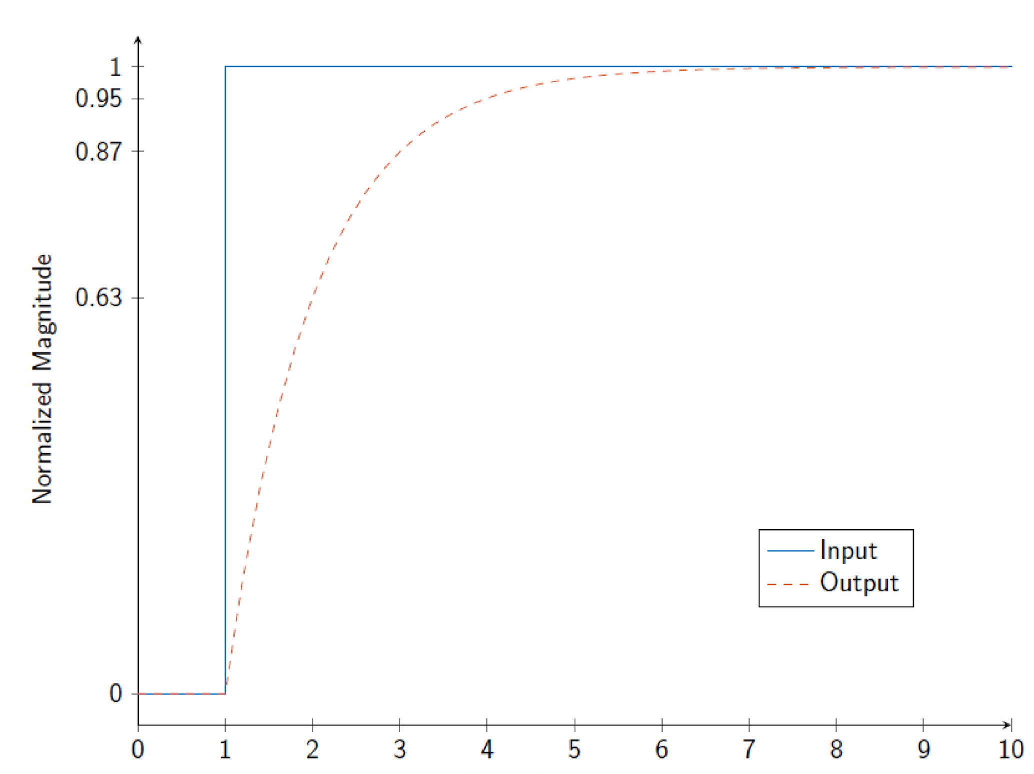


Typical feedback loop with a pre-filter, with the addition of the passive feedback mechanisms. The core ($\dot{Q}_{Core}$) and heat exchanger ($\dot{Q}_{HEX}$) powers go through the respective temperature dynamics (G_C and G_H) and time delays for the riser (θ_R) and downcomer (θ_{DC}) before being converted to reactivity by the temperature(α_T) and flow (α_F) feedback mechanisms. The passive reactivity feedback is combined with the control drum reactivity (ρ_{CD}) and fed into the reactor dynamics ($P(s)$).

Pre-Filter

$$F(s) = \frac{1}{\tau_F s + 1}$$

Pre-filters are unity gain transfer functions that provide inertia against rapid changes. A pre-filter that reshapes the core set-point after a change to heat exchanger demand will make the initial hot edge more gradual. This will allow the temperature profile to equilibrate more quickly rather than settling into bi-stable resonance. Proper tuning of the pre-filter time-constant will allow the reactivity oscillations to decay more quickly.



Dead-band

A dead-band is a type of piecewise function where the output is null for inputs surrounding zero ($\pm\delta$) but has some other value for inputs with greater magnitude. It is common in thermostatic controls (where the furnace in a home only turns on when the temperature inside is sufficiently far from the setpoint). In process control, it is common for a controller gain (K_C) to be dead-banded to avoid swift periodic actuation.

$$K_C = \begin{cases} K_C & \text{if } e < -\delta \\ 0 & \text{if } -\delta < e < \delta \\ K_C & \text{if } e > \delta \end{cases}$$

Previous work [2] has shown that the passive feedback mechanisms (temperature and flow reactivity) are capable of autonomous load following for small transient, though not at the level of performance that may be required in certain applications. Still, this provides the opportunity to minimize fine and rapid actuation while dampening oscillations by using a dead-band; the 'ringing out' of minor perturbations could be left to the passive feedback mechanisms after the active feedback controls the bulk of the power change.

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PID Controller

The controller output (u) is often determined by a PID equation, which considers the instantaneous, cumulative, and predictive error. This equation has three terms:

1. Proportional control term. The control output is manipulated in proportion to the error defined by the proportional gain constant (K_P).
2. Integral control term, which considers the historical cumulative error in an effort to eliminate steady-state offset that a P-Only controller may exhibit. As the process variable settles around the set-point, the cumulative error approaches a constant value and the effect of the integral controller diminishes.
3. Derivative control term, which estimates the time rate of change of the error to dampen overshoot. This mechanism is sometimes referred to as anticipatory control.

A nuclear reactor is controlled by manipulating the criticality of the core, making it supercritical to increase the power, and subcritical to decrease. This is a highly time dependant exponential control mechanism. The derivative controller time constant will need to be carefully tuned to minimize the likelihood of significant overshoot following a power transient

$$u(t) = \underbrace{K_P e(t)}_{\text{Proportional}} + \underbrace{K_I \int_0^t e(t)dt}_{\text{Integral}} + \underbrace{K_D \frac{de(t)}{dt}}_{\text{Derivative}}$$

Future Work

- Neutronics modeling will be conducted to characterize the actuator-control reactivity curve ($A(s)$)
- Finite-element process simulation will be conducted to characterize the heat exchanger ($G_H(s)$), core ($G_C(s)$), and overall reactor ($P(s)$) dynamics
- A gain/bias schedule will be developed to account for the fact that more control reactivity is required to make the reactor go critical later in the fuel lifetime
- Poison reactivity from the build-up of xenon-135 may be accounted for using a Bode-Step controller [3]

References

[1] Peterson, John, 2019 8. An Analysis of the Nuclear Characteristics of a Molten Salt Microreactor. Master's thesis, University of Idaho.

[2] Carter, John P., 2022. Multi-Physics Investigation of a Natural Circulation Molten Salt Micro-Reactor that Utilizes an Experimental In-pile Device to Improve Core Physics and System Thermal-Hydraulic Performance. Ph.D. thesis, University of Idaho.

[3] Al Rashdan, Ahmad, Roberson, Dakota, 2019. A frequency domain control perspective on xenon resistance for load following of thermal nuclear reactors. IEEE Transactions on Nuclear Science 66(9), 2034. doi: 10.1109/TNS.2019.2934171.