Design of a PID Controller for a Molten Salt Microreactor

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Abstract

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Dedication

To my mother, Tammy, who planted and nurtured my love of science. To my father, Paul, who taught me how to design and build, and showed me that I am an engineer. To my cats, Babe and Bunyan, who stayed up with me all those late nights studying and writing. Thank you for your endless support.

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Acronyms

INL Idaho National Laboratory.

LWR Light Water Reactor.

MSNB Molten Salt Nuclear Battery.

MSR Molten Salt Reactor.

MSRE Molten Salt Reactor Experiment.

NPP Nuclear Power Plant.

NRC Nuclear Regulatory Commission.

NREL National Renewable Energy Laboratory.

ORNL Oak Ridge National Laboratory.

PID Proportional-Integral-Derivative.

Chapter 1

Introduction

The world is working to move away from fossil fuel as its main energy source [1]. National Renewable Energy Laboratory (NREL) has partnered with over 700 organizations, including large manufacturing companies, to de-carbonize supply chains [2]. Nuclear power has been well established as an alternative for base-load electrical generation with 93 facilities in the United States and 435 globally which generate on the order of 1 GWe, but there remains a need for smaller reactors to be deployed in more dynamic applications such as small remote grids, manufacturing, and power-peaking [3]. These small energy utilizers could turn to microreactors to fill their needs; to make this a reality, a robust control system for microreactors must be designed that is capable of ramping production up and down to meet demand.

1.1 Microreactors

Microreactors, as the name suggests, are small nuclear reactors which are designed to be fully assembled when shipped, rather than constructed on site. This is a hot area of research in the private sector as companies are working to capitalize on the growing need for clean and dependable small scale electrical generation [4]. They aim not to replace the utility scale Nuclear Power Plants (NPPs) which handle base-load electrical generation, but the diesel or natural gas engines that are found at countless manufacturing facilities, peaking stations, military bases, islands, and other locations where on-site generation is the primary or only source of electricity.

The goal is to be able to deliver a prefabricated microreactor to a site, integrate it to the necessary power cycles and process heat applications, and meet the needs of the site for a long period of time - up to a decade - without the need for refueling or significant maintenance. This would be quite convenient compared to building a pipeline to deliver fossil fuels to the site or scheduling regular delivery. One of the biggest challenges in implementing microreactors is the transients that these applications often require. Engines handle these quite well, simply adjusting the flow rates of fuel and combustion air. Nuclear reactor load following is a bit more complicated, as the reactor must be made supercritical to ramp up power or subcritical to decrease power. This necessitates valid characterization of the reactor's criticality control & actuation system and reactivity feedback mechanisms, so the controller can be designed and tuned to effectively and safely match power generation to consumption.

1.2 Molten Salt Reactors

Molten salts are highly desirable in high temperature applications due to their excellent thermophysical properties [5]. Salt mixtures have been developed to have very wide liquid temperature ranges (i.e. low melting point and high vaporization point). They also have very high volumetric heat capacities compared to other high temperature coolants (which tend to be gaseous), and are able to operate at or slightly above ambient pressure. These properties combine to make molten salts excellent choices in heat transfer and thermal storage applications. Furthermore, they are extremely strong electrolytes which cn be useful as solvents, catalysts, or reagents in certain chemical reactions including a pyrometallurgical method for reprocessing spent nuclear fuel [6].

Molten Salt Reactors (MSRs) are a family of nuclear reactor in which a fuel salt (containing fissile and/or fertile nuclides) is dissolved in a coolant salt [7]. The concept was proven by the Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory (ORNL) in the 1960s [8]. It has yet to take off beyond the research reactor sector, but it has re-emerged as a Gen-IV reactor concept, with a team at the Shanghai Institute of Applied Physics gaining approval to operate a now fully constructed thorium breeding MSR [9]. Some of the benefits of MSRs over more conventional LWRs include:

- Higher operating temperatures allow for use in applications requiring high-grade process heat, and yield higher thermal efficiency [7];
- Lower pressure operating pressure lends itself to inherent safety, and less expensive (thinner) components [5];
- The ability to burn minor actinides supports the goal of reducing global stockpiles of high-level waste [5];
- Natural circulation of the fuel introduces an additional feedback mechanism that presents the possibility of autonomous load following of certain power demand transients [10];
- There is no concern of core melt-down as the reactor is designed for liquid fuel;
- The liquid state homogenizes nuclides throughout the core, which minimizes burn-up gradient to produce a flatter temperature and power profile within the core [11, 12]. The flowing nature also allows for online reprocessing, removing fission products and poisons during operation;

They also carry some demerits:

- Molten salts are very corrosive [13];
- The chemistry of the coolant (not only the fuel) is constantly changing due to fission, transmutation, and impurities from corrosion;
- Lithium is commonplace in molten salts, so tritium production is unavoidable (Rxn. 1.1). Off-gas systems need to be robust to handle tritium as well as radionuclide noble gasses, halides, and inter-halides [14];

$$^{6}Li + n \rightarrow {}^{3}H + \alpha \qquad \text{(Rxn. 1.1)}$$

1.3 Molten Salt Nuclear Battery

The Molten Salt Nuclear Battery (MSNB) is a self contained design for a liquid fueled molten salt microreactor [15, 4]. It is fueled by an inorganic form of uranium, UF_4, dissolved in a coolant salt such as $FLiNaK$ (a eutectic mixture of three alkali fluorides) or $FLiBe$ (a mixture of LiF and BeF_2) [7]. Heat is generated in the core by fission, is transported by the natural circulation of the coolant/fuel salt, and rejected to a secondary working fluid in an integrated heat exchanger. Criticality is manipulated using axial control drums, which may be rotated to aim either a neutron reflecting material or a neutron absorbing material towards the core. The design studied in this work is intended to produce up to 1 MWth, although larger designs of up to 50 MWth also exist.

1.4 Scope

As a developing design, work has been done on neutronics [4], thermal-hydraulics and autonomous load following [15], and corrosion concerns [16]. However, until now, little to no work has been done on the control system. First and foremost, this work details a multiphysics characterization of the MSNB required to design a feedback controller capable of matching the core power generation to the secondary power demand. In addition to the main control mode of following power transients during normal operation, specific discussion is centered around more dynamic time periods, namely: 1) initial start-up; 2) shutdown, both planned and emergency; and 3) restart;

1.5 Outline

This report will begin by discussing the field of process control engineering, specifically the control methods which are most useful in the design of a controller for the MSNB, and the challenges inherent to a controlling a nuclear chain reaction, both in normal operational modes and special cases. The reactor will then be characterized, using a combination of stochastic neutron transport code to define the reactivity curve of the control drums and finite element process simulation to understand the reactivity feedback effects intrinsic to the design. The resulting model of the reactor will then be used to design and tune the controller, which will then be tested against the reactor's autonomous response to load demand changes. Finally, after the results of the simulation are analyzed, the limitations of this method, as well as future work that will be required to implement a Molten Salt Nuclear Battery will be discussed.

Chapter 2

Process Control Engineering

There are two main goals in process control engineering: 1) Reference tracking, where a process variable is matched to a set-point which may be changed over time; and 2) Disturbance rejection, where the process variable is held to the set-point despite outside influence upsetting it; This is usually achieved by a controller which detects the process variable using a sensor/transmitter and controls the process variable by manipulating an actuator.

2.1 Feedback

The most common type of controller is a feedback controller. The controller takes action based on the 'error' (e) between the set-point (SP) and process-variable (PV) (Eqn. 2.1).

$$e(t) = PV(t) - SP(t) \qquad \text{(Eqn. 2.1)}$$

The action, or controller output (u) is often determined by a Proportional-Integral-Derivative (PID) equation (Eqn. 2.2), which considers the instantaneous, cumulative, and predictive error in determining the proper actuation [17].

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \qquad \text{(Eqn. 2.2)}$$

The first term is the proportional control term. The control output is manipulated in proportion to the error defined by the proportional gain constant (K_P). A high gain yields an aggressive controller that is prone to overshooting the set-point, while a low gain may result in steady-state offset.

The second term is the integral control term, which considers the historical cumulative error (calculated by taking the time integral of the 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.

The third term is the derivative control term, which estimates the time rate of change of the error to dampen overshoot. This mechanism, sometimes referred to as anticipatory control, slightly reduces the proportional response to the error when the error is changing rapidly. This results in reducing the peak overshoot. A wel tuned anticipatory gain can allow a more aggressive proportional gain to be used without the large overshoot.

Instead of using three different gain constants, it is common for controllers to be tuned in terms of a single controller gain (K_C) plus two time constants: 1) The integral time constant (τ_I); and 2) The derivative time constant (τ_D); In this case, Eqn. 2.2 is rewritten as:

$$u(t) = K_C \left(e(t) + \tau_I^{-1} \int_0^t e(t)dt + \tau_D \frac{de(t)}{dt} \right) \qquad \text{(Eqn. 2.3)}$$

2.2 Feedforward

The term 'Feedforward' can be used to refer to any element in the control block diagram that exists outside of the feedback loop. In process control, feedforward controllers are almost always implemented alongside, not instead of feedback controllers because a standalone feedforward controller is not guaranteed to reach the set-point.

Disturbance Feedforward

In many processes, the process variable is effected by phenomena other than the actuator. These other phenomena are defined as disturbances. A well-tuned feedback controller is capable of disturbance rejection, but only after the disturbance causes error. In some cases, a disturbance feedforward controller may be added to the feedback controller to cause the actuator to counteract the effect of the disturbance before it occurs [17].

The most prevalent disturbances that would effect the power output of the core of a MSNB are the temperature reactivity feedback effect common to all nuclear reactors and the flow reactivity specific to natural circulation driven liquid fueled MSRs [10]. Temperature reactivity feedback is dominated by Doppler Broadening, where the microscopic radiative capture cross section resonance peaks of nuclides such as ^{238}U are depressed to cover a wider epithermal neutron spectrum [18]. This results in a smaller core neutron population and less fission events, so there is a negative correlation between fuel temperature and fuel reactivity. Flow reactivity is driven by the advection of delayed neutron precursors. Not all fission neutrons are released promptly; sometimes an unstable nuclide which decays by neutron emission produced instead. These unstable nuclides are called delayed neutron precursors and have half-lives ranging from less than a second to over a minute [11]. Since the fuel in a MSNB is flowing, there is a statistical probability that a delayed neutron precursor may leave the core by advection before the neutron is emitted in a much less reactive part of the reactor. When the temperature differential between the thermal center of the core and primary heat exchanger is increased, so too does the natural circulation flow rate. This decreases the likelihood of delayed neutrons being emitted in the core, and negatively contributes to core reactivity. Devices meant to elongate the in-core flow path may minimize delayed neutron losses [15].

Disturbance feedforward will not be utilized in the design of the controller outlined in this work. When the outlet temperature of the heat exchanger is decreased, it takes time for the cooler salt to reach the core. The disturbance transport delay is on the order of minutes. Contrastly, Doppler Broadening has a nearly instantaneous effect, so disturbance dynamics are on the order of milliseconds, governed by the mean neutron lifetime [18, 11]. The effect of control actuation are similarly prompt. Even with a temperature sensor just at the inlet of the core it would be nearly impossible to reliably predict the exact moment that control reactivity would be need to be inserted to counteract the temperature reactivity.

Pre-Filter

This could be electronic (less ideal) or physically realized by decoupling

2.3 Time Variance

Fissile depletion - time function parameters or look-up table to gain-schedule and turn the time variant system into a shift invariant system.

In addition to the relatively slow time variance of fissile fuel depletion during steady-state critical operation, there are specific times in a MSNB's expected operational life-cycle that exhibit a higher degree of time variance: 1) Start-up; 2) Shut-down; and 3) Re-start.

Start-up

Black-start may need to deal with thawing salt - main concern is fission product neutron poison build-up (discuss the burnable poison stuff)

Shut-down

Planned shut-down

Emergency Shutdown/SCRAM(must be passive)

Decay heat and keeping the salt liquid for restart

Re-start

^{135}Xe stripper

Chapter 3

Reactor Characterization

3.1 Reactor Design selection

3.2 Neutronics Modeling

3.3 Process Simulation

Chapter 4

Controller Design

4.1 Reactor Transfer Function

4.2 Tuning Methodology

Chapter 5

Results and Analysis

Chapter 6

Conclusions

6.1 Limitations

6.2 Future Work

6.3 Summary Remarks

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Appendix A

Test

Code 1: Hello!

```
    print("Hello World") #comment
    try:
        a=2/x
    except ZeroDivisionError:
        print('undefined')
```

Inline codes like `import numpy`

Code 2: F strings

```
x = 4
print(f"The numeral four: {x}")
#comment
```

Appendix B

What

Straight Cash Homie