Modeling and Optimizing Molten Salt Thermal Storage for Nuclear Power

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INTRODUCTION

In 2017, renewable energy global capacity increased by 244.7 GW [1]. As electricity generated from these energy sources continues to increase, the demand curve minus wind and solar power generation is drastically changing [2]. This change results in non-renewable resources needing to fluctuate according to demand. While energy sources such as natural gas have the current ability to handle these fluctuations, clean energy sources such as nuclear power plants (NPPs) do not have the same load-following ability [2]. Load-following with an NPP is quite problematic as ramp rates are fixed based upon reactor type. The development of a cost-effective method of load following would ensure the competitiveness of nuclear power in a growing renewable market.

One proposed solution to this problem is that of a molten salt thermal energy storage (TES) system [2]. Molten salts have operating temperatures and heat capacities that fit well for the application of TES systems. Many concentration solar plants make use of a molten salt TES system to store the heat captured from reflecting the sun [3]. One can apply this same technique to nuclear power generation for the use of adding a load-following ability to an NPP.

To optimize the sizing, initial, and operating conditions of a TES system for an NPP, the thermal-hydraulics of the system must be understood. Once a model is generated describing the thermal-hydraulics of a given system, that model can then be used to help optimize the system for grid-scale energy storage. This optimization would help determine what temperatures the salt should operate at, the response time of the system, energy storage capacity, as well as unit sizing.

Reactor Excursion Leak Analysis Program (RELAP) is a thermal-hydraulic series of codes that allows a user to analyze transients in different locations throughout a model. RELAP5-3D is the latest code version of the RELAP5 series and can create multidimensional models using user-defined fluids. Idaho National Laboratory developed RELAP5-3D for the primary purpose of modeling accident behavior and operational transients of light water reactors. In 1981 RELAP5-3D was used to model the TES system at the Barstow concentrated solar plant [4]. In this work, RELAP5-3D was used to model a lab-scale TES unit for the proof of concept of TES modeling.

Description of Actual Work

The Miniature Passive Endothermic Reaction Cooling System (mini-PERCS) is a lab-scale shell and tube heat exchanger created for the study of an endothermic reactor safety measure for nuclear reactors. The same lab unit was designed in RELAP5-3D to use as a basis for a lab-scale TES system. This system contains a tank 56.91cm tall with a diameter of 40.64cm. Through the tank, there are seven evenly spaced pipes, each of 3.175cm diameter. The fluid inside the tank and pipes were both defined as LiF-BeF_2 (FLiBe) with mole fractions of 0.66 LiF and 0.34 BeF_2.

RESULTS

Two-hundred and eight iterations of this model were run while changing initial conditions of the system, such as the initial temperature of the molten salt in the tank, temperature of the flowing molten salt, and flow rate of the molten salt. From each test, a plot of average temperature in the center of the tank versus time was created. Fig. 1. shows an example of one of these plots.

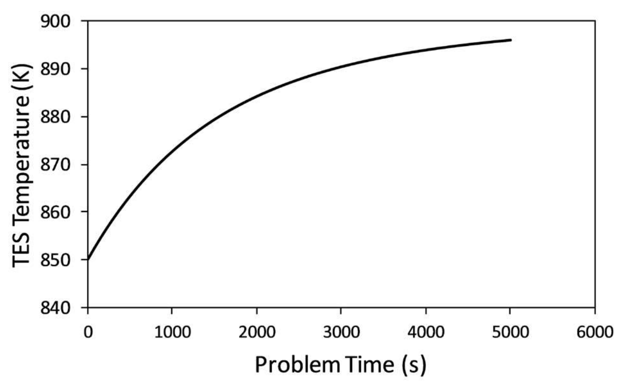

Fig. 1. TES heating over time plot produced by RELAP5-3D.

Once plots for all 208 tests were obtained, the data was placed into Design Expert 11 to create a simplified model. This model takes inputs of initial conditions and time and outputs the amount of energy stored. Fig. 2 shows a surface plot of the model created using this data.

From this data, a model equation showing the relationship of each of the variables to the amount of energy stored was produced. Eqn. 1 shows the reduced-order model while Table I. shows the coefficients for this equation. This equation is specific to the mini-PERCS design while using FLiBe as the heat transfer and thermal storage media. In the future, this methodology can be used to develop similar models for entire reactor systems where different initial and operating conditions can be modeled into a simplified equation. This reduced-order model can then be used in the optimization of the TES system.

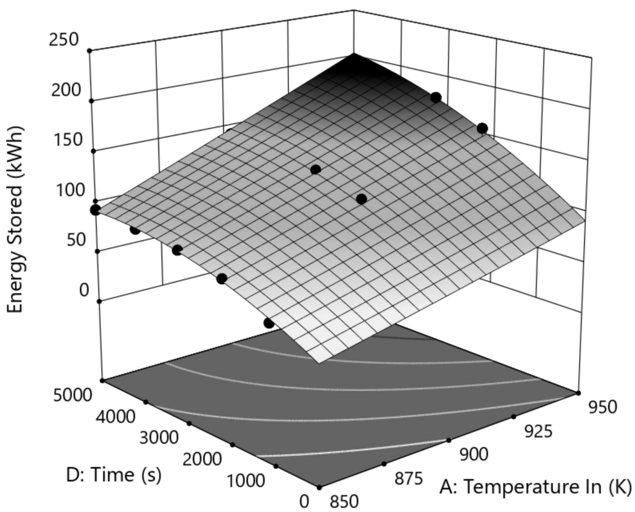

Fig. 2. Energy stored model with an initial tank temperature of 750 K and a flow rate of 100 kg/s.

The equation below can be used for more complex systems, but the individual coefficients should be regressed for each system design. These coefficients will change based upon TES sizing, TES geometric configuration, and thermal storage medium.

$$\varepsilon = A + BT_1 + CT_o + D\dot{Q} + Et + FT_1T_o + GT_1\dot{Q} + HT_1t + IT_o\dot{Q} + JT_ot + K\dot{Q}t + LT_1^2 + MT_o^2 + N\dot{Q}^2 + Ot^2 \quad (1)$$

TABLE I. Coefficients of TES Model

Coefficient	Value	Coefficient	Value
A	-9.84E1	I	-2.90E-3
B	7.05E-2	J	-1.05E-4
C	6.41E-2	K	-1.42E-5
D	3.97	L	2.95E-4
E	1.96E-2	M	9.32E-6
F	-3.75E-4	N	5.08E-4
G	2.94E-3	O	4.72E-6
H	1.01E-4		

Once a representative mathematical model of the TES system is in place, it can be used as part of a digital twin for design optimization. First, a full digital twin of a nuclear-renewable hybrid energy system (NHES) containing the TES unit will be modeled as a function of various design parameters, including those required in the TES model. This digital twin can then be optimized using a variety of optimization techniques including robust optimization, stochastic optimization, economic optimization, and dispatch optimization in order to determine optimal NHES design parameters for the model, thus allowing effective NHES design.

Conclusion

Carefully designed TES systems may allow NPPs to accommodate changing grid demand while maintaining the steady-state operation of the reactor core. With the constant growth of renewable energy capacity, the need for NPPs to have load-following ability is vital. This research demonstrates the ability to create reduced-order models for a TES system that can then be used in optimal NHES design.

Future work will include a lab-scale validation of this model created for the mini-PERCS. Once validated, new thermal-hydraulic models, derived from this model, can be used for research and optimization of future NHES designs.

NOMENCLATURE

ε = Energy Stored (MWh)
T_1 = Temperature of Thermal Storage Inlet (K)
T_o = Temperature of Thermal Storage Medium (K)
$\dot{Q}$ = Flow Rate (kg/s)
t = Problem Time (s)

REFERENCES

1. D. GIELEN, F. BOSHELL, D. SAYGIN, M. D. BAZILIAN, N. WAGNER, "The Role of Renewable Energy in the Global Energy Transformation," *Energy Strategy Reviews*, **24**, 38 (2019).
2. P. DENHOLM, J. C. KING, C. F. KUTCHER, P. P. H. WILSON, "Decarbonizing the Electric Sector: Combining Renewable and Nuclear Energy Using Thermal Storage," *Energy Policy*, **44**, 301 (2012).
3. E. GONZÁLEZ-ROUBAUD, D. PÉREZ-OSORIO, C. PRIETO, "Review of Commercial Thermal Energy Storage in Concentrated Solar Power Plants: Steam vs. Molten Salts," *Renewable and Sustainable Energy Reviews*, **80**, 133 (2017).
4. R. K. BYERS, L. N. KMETYK, "Development of a RELAP Model for the Barstow Thermal-Storage Subsystem," SAND81-1831, Sandia National Laboratories (1981).