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Nuclear Hybrid Energy Systems: Molten Salt Energy Storage

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I. Introduction

With growing concerns in reliable energy supply, the next generation in reliable power generation via hybrid energy systems is being developed [1]. A hybrid energy system incorporates multiple energy input sources and multiple energy outputs. The vitality and efficiency of these combined systems resides in the energy storage application. Energy storage is necessary for grid stabilization because stored excess energy is used later to meet peak energy demands. With high thermal energy production of the primary nuclear heat generation source, molten salt energy storage is an intriguing option because of its distinct thermal properties. This paper discusses the criteria for efficient energy storage and molten salt energy storage system options for hybrid systems.

II. Nuclear Hybrid Energy System

A nuclear hybrid energy system (NHES) couples clean energy sources to establish stable electricity output with multiple inputs and outputs. Such a system combines a nuclear reactor, renewable energy source, energy storage device(s), electricity production, and a non-power output stream such as high-temperature steam electrolysis. The hybrid system configuration has a point of common coupling to establish rapid response to fluctuations in grid demand or renewable energy supply, with the nuclear reactor being used for constant base load power. The NHES design enables the nuclear reactor to run at steady state and achieve high capacity factors by allowing load following to be taken up by subsystems (e.g. chemical products or energy storage).

III. Energy Storage Criteria

An efficient and effective energy storage application should adhere to the following criteria: (1) high energy density; (2) rapid response to establish constant energy flow; (3) negligible or low-energy loss through self-leakage; (4) environmentally friendly and safe in application; (5) low cost; and (6) compatible integration within the system [1].

IV. Molten Salt ESS

A molten salt ESS is an intriguing choice for a hybrid energy system because of its high-temperature applications, low viscosity, high-volumetric heat capacity, high-energy density, and compatibility with high-temperature reactors. There are several possible configurations within a molten salt ESS. The overall efficiency of a configuration is determined by the salt choice, system design, and power cycle choice. Fig. 1, shows the NHES with molten salt ESS.

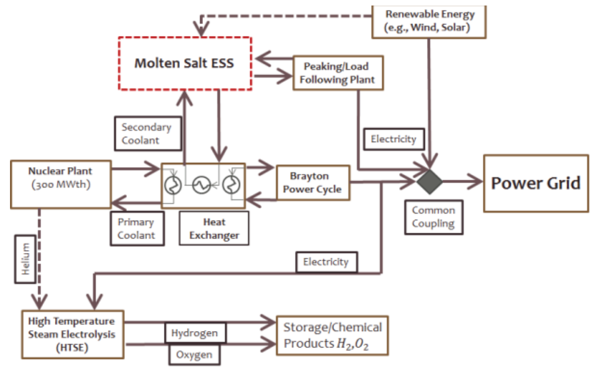

Figure 1. Nuclear hybrid energy system with a molten salt ESS.

A. Salt Choices

The choice of the optimum salt for the system is determined by two main criteria: melting point and volumetric heat capacity. 11 molten salts are compared based on their thermo-physical properties in determining the hybrid system storage salt. The initial determination narrows the molten salt search to three different salts for analysis, $KF\text{-}ZrF_4$, $KCl\text{-}MgCl_2$, and Li-NaF-KF, mainly based on minimum melting point temperature threshold.

B. Design Options (two-tank & thermocline)

The two main designs considered in this paper include a two-tank direct and a thermocline storage system. The two-tank direct system consists of a hot tank and a cold tank with the storage medium being the molten salt itself. The thermocline system is designed for one storage tank with a thermocline separating the hot and cold fluid. An ideal thermocline storage system is considered where the thermal energy is stored within the molten salt only. The power cycle includes an additional make-up water source to maintain constant water volume (supply), if needed. Fig. 2 shows both options attached to a Rankine power cycle.

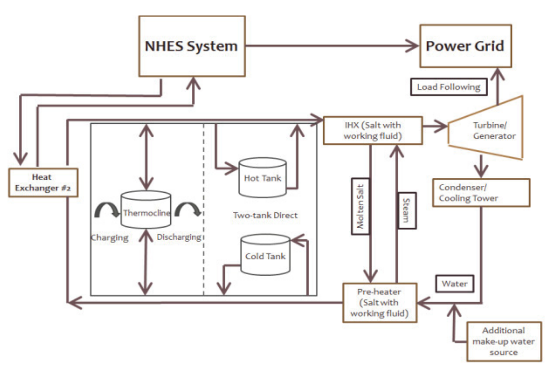

Figure 2. Molten salt ESS options.

V. Thermodynamic Analysis

The thermodynamic analysis objective is to determine the most efficient molten salt energy storage system by comparing overall system efficiencies. Models for each storage system are developed in the Microsoft program Excel™ to effectively determine the efficiency. The thermodynamic analysis results provide thermal efficiency comparison for the system based on the selected salt and power cycle.

A. Analysis Procedure and Conditions

The analysis involves determining the power required in megawatt thermal (MWth) and the necessary mass flow rates within the systems. With the governing factors of energy balance, heat transfer, and fluid flow, the temperatures in each component of the system are determined. The storage tank(s) require a temperature equation dependent on time, heat transfer coefficients, and mass of salt stored. Assumptions for the analysis include: (1) no heat loss within the pipes, (2) effectiveness for heat exchangers (90%), and (3) a constant atmospheric pressure maintained.

The three power cycles selected for analysis included Rankine, Brayton (helium as working fluid), and Air-Brayton combined cycles. The analysis involves finding inlet and outlet conditions of each component of the power cycle using the NIST Reference Fluid Thermodynamic and Transport Properties (REFPROP). With these values, the overall efficiencies of the system are calculated. Assumptions include isentropic efficiency of 90% in the turbines, isentropic efficiency of 75% in the pumps, isentropic efficiency of 80% in the compressors, inlet and outlet temperatures of specific components, and negligible losses in the condenser.

VI. Economic Analysis

The overall cost for each salt type and base capital cost of the ESS units is first determined using a current economic analysis for a two-tank indirect storage system with the total mass and the cost per unit mass of salt [2]. The cost comparison between the two different molten salt ESS units is determined through comparing the base capital cost of both systems. The cost of each salt is shown in Table 1.

Table 1. Cost of molten salt comparison [3]

Salt Type	Raw Material Cost ($/kg)	Cost/Volume ($/L at 700°C)
LiF-NaF-KF	7.82	15.79
$KF\text{-}ZrF_4$	4.85	13.58
$KCl\text{-}MgCl_2$	0.21	0.35

VII. Results and Discussion

The results indicate that the two-tank direct system is the most thermally efficient system with the Air-Brayton combined cycle. The most economical molten salt choice is $KCl\text{-}MgCl_2$. The most efficient molten salt choice is $KF\text{-}ZrF_4$. The most efficient power cycle is the Air-Brayton combined cycle at over 50%. The thermocline system has the lowest capital costs and is considered the economical choice. From the results, the thermal efficiency of the system is more dependent on power cycle choice than molten salt choice. The base capital cost of the ESS units largely depends on the choice of molten A summary of the results can be seen in Fig. 3.

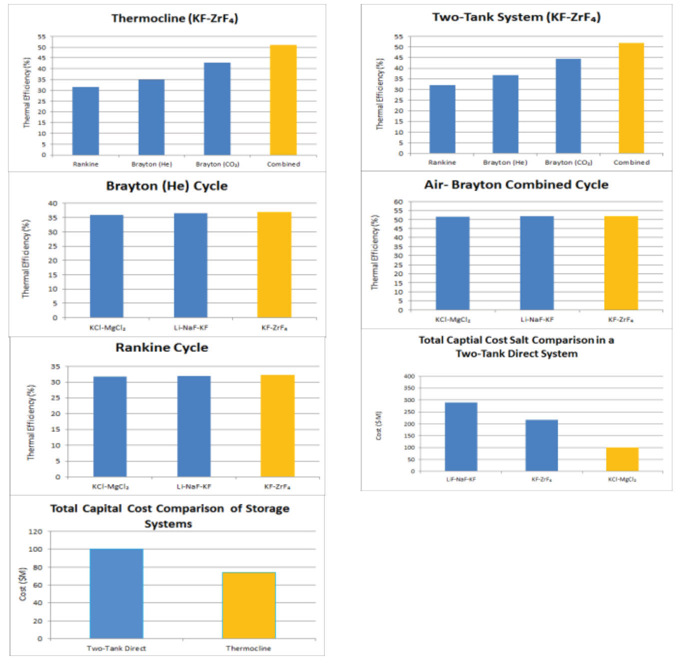

Figure 3. Results for thermodynamic and economic analyses.

VIII. Conclusion

Energy storage is a vital component for successful development of hybrid energy systems. With several types of energy storage available, molten salt is an intriguing option for high-temperature applications because of its high-volumetric heat capacity and high-temperature compatibility. Of the molten salt ESS configurations considered here, the thermocline system with $KCl\text{-}MgCl_2$ as the molten salt and an Air-Brayton combined cycle as the power cycle is expected to be the most economical choice. The two-tank direct system with the same power cycle and $KF\text{-}ZrF_4$ as the molten salt is expected to be the most efficient. Further optimization of an ESS would include exergy analysis and a feasibility study.

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