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An optimized power conversion system concept of the integral, inherently-safe light water reactor

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ABSTRACT

The integral, inherently safe light water reactor (I^2S-LWR) has been developed to significantly enhance passive safety capabilities while maintaining cost competitiveness relative to the current light water reactor (LWR) fleet. The compact heat exchangers of the I^2S-LWR preclude boiling of the secondary fluid, which decreases the probability of heat exchanger failure, but this requires the addition of a flash drum, which negatively affects the overall plant thermodynamic efficiency. A state of the art Rankine cycle is proposed for the I^2S-LWR to increase the thermodynamic efficiency by utilizing a flash drum with optimized operational parameters. In presenting this option for power conversion in the I^2S-LWR power plant, the key metric used in rating the performance is the overall net thermodynamic efficiency of the cycle. In evaluating the flash-Rankine cycle, three basic industrial concepts are evaluated, one without an intermediate pressure turbine, one with an intermediate turbine and one reheat stream, and one with an intermediate turbine and two reheat streams. For each configuration, a single-path multi-variable optimization is undertaken to maximize the thermal efficiency. The third configuration with an intermediate turbine and 2 reheat streams is the most effective concept, with an optimized efficiency of 35.7%.

1. Introduction

The integral, inherently safe light water reactor (I^2S-LWR) has been developed to significantly enhance passive safety capabilities while maintaining cost competitiveness relative to the current light water reactor (LWR) fleet. These capabilities are made possible through several key safety features that serve to both decrease accident frequency and mitigate accident consequences through passive safety technology. The most significant of these safety features includes the decay heat removal system, the core makeup tanks, and the compact heat exchanger. Each of these systems has innovative design aspects that improve overall plant safety. However, the incorporation of these systems within nuclear power plants has the potential to negatively impact plant economic performance, manifested primarily in alterations to manufacturing, maintenance, and operational methods (Ansolabehere et al., 2003). This is seen clearly in the compact heat exchanger design utilized in the I^2S-LWR. As part of the safe operation of this compact heat exchanger, secondary coolant is pressurized to preclude boiling, which decreases the probability of heat exchanger failure, but this requires further processing, which negatively affects the overall plant thermodynamic efficiency (Memmott and Manera, 2015). Thus, it is of interest to develop a power conversion system (PCS) that meets the requirement of no boiling in the primary heat exchanger while maximizing the thermodynamic efficiency of the overall plant.

In order to offset the negative economic impacts of incorporating passive safety systems, significant focus has been placed on maximizing the thermodynamic efficiency of the I^2S-LWR through modifications or alterations to the PCS. The initial I^2S-LWR PCS design, which was based on a simple Rankine cycle, was able to achieve an efficiency of 33% (Memmott and Manera, 2015). However, this value is on the lower end of the thermodynamic performance spectrum for current nuclear plants, and there is no margin should future alterations in the reactor design further decrease the efficiency.

A state of the art Rankine cycle is proposed for the I^2S-LWR to increase the thermodynamic efficiency. The cycle utilizes a flash drum with optimized operational parameters, which represents the base PCS for the I^2S-LWR. This is the base configuration for the I^2S-LWR primarily because it represents standard, well-known technology, with no deviances in fabrication, maintenance, or operating procedures.

This paper describes the optimization of the base configuration PCS for the I^2S-LWR, which is designed to maximize the economic

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viability of the plant. In presenting this Rankine cycle option for power conversion in the I^2S-LWR power plant, the key metric used in rating the performance is the overall net thermodynamic efficiency of the cycle. Thus, the primary purpose in optimizing the PCS design is the maximization of the overall thermodynamic efficiency of the cycle.

2. Power conversion system performance

The thermodynamic efficiency is the predominant metric that is used to evaluate the effectiveness of a given PCS. The thermodynamic efficiency is a measure of electrical power output relative to the thermal power input for a PCS, and thus indicates the effectiveness of converting thermal energy to electrical energy. The net thermodynamic efficiency represents the thermodynamic efficiency after house loads such as pumps are considered. Currently operating nuclear power stations have efficiencies ranging from 33% to 37% (Honorio and et al., July 2013), and thus any commercially viable plant should maintain a net thermodynamic efficiency of at least 33%. Several studies have been dedicated to achieving even marginal increases in thermodynamic efficiencies (Attia, 2015; Gulen and Smith, 2010; Murugan and Subbarao, 2008; Siviter et al., 2015; Zandian and Ashjaee, 2013). This is because the thermodynamic efficiency of a cycle correlates directly to the economic competitiveness of the power-plant in which it is integrated. Based on simple calculations, for a currently operating nuclear power plant with a 35% thermodynamic efficiency, a 1% increase in the thermodynamic efficiency could translate into at least a $40M increase in annual profits for the plant.

In addition to indicating power plant economic performance, the thermodynamic efficiency is an extremely useful metric that allows the performance of various power generation systems to be easily compared and contrasted with respect to fuel utilization. Therefore, this metric will be utilized as the primary basis for comparison regarding the Rankine cycle design options for generating electricity with the I^2S-LWR. As stated by the I^2S-LWR design team (Nuclear Association, 2016), one of the primary design basis goals was to design a PCS that is capable of reaching thermodynamic efficiencies of greater than 33%. In addition, a stretch-goal of 36% was established to further enhance economics; at this efficiency, the economics of the I^2S-LWR would be comparable to efficiencies that one would see in current Gen II or Gen III light water reactor power conversion systems (Nuclear Association, 2016; Todreas and Kazimi, 2011).

For each Rankine cycle design option introduced in this paper, dozens of design, performance, and state variables can be altered which modify the thermodynamic efficiency. Therefore, a simple, single-approach multivariable sensitivity analysis was conducted for the key variables that impact the thermodynamic efficiency of the overall cycle. The optimum thermodynamic efficiency based on these sensitivity studies was used to compare the flash drum Rankine cycle design options, such that each efficiency reported here indicates the idealized efficiency for the given thermodynamic power conversion system design.

3. Additional PCS considerations

In addition to thermodynamic efficiency, there are other performance metrics that should be considered in selecting a given power conversion system for use with the I^2S-LWR. These performance metrics include:

1. Capital Costs
2. Operations and Maintenance
3. Safety

The capital costs of a PCS are the first significant metric that must be considered in the system design in addition to the thermodynamic efficiency. Thermodynamic efficiency can be asymptotically increased by increasing the turbine stages, reheaters, exchangers, and other complex components. However, the marginal increase in efficiency decreases with each subsequent component added to the system, and there exists a point at which the increased capital cost incurred by adding an additional component cannot be offset by the lifetime net profit increase provided by that component. In other words, the return on investment for the added component is greater than the life of the plant, and thus is an unwise investment. Further, first of a kind concepts have large uncertainties associated with capital cost relative to performance. Thus, this metric precluded the use of exotic and largely unproven power cycles with the I^2S-LWR concept.

The cost of operation and maintenance (O&M) components and systems within a PCS must also be considered, in order to ensure that the increase in profit realized from thermodynamic efficiency increases is not parasitically consumed in additional O&M costs. Changes in steady state flow rates or heat requirements, water chemistry maintenance, or corrosion susceptibility are some of the many factors that are considered in determining changes to the O&M costs. For the I^2S-LWR, this metric precluded the use of highly expensive and specialized equipment for individual components in the I^2S-LWR. Thus, proven technology components such as the flash drum, even if novel in utilization, were selected whenever possible over untested components and systems to simplify operation and maintenance.

Finally, the safety of a nuclear power plant is the highest priority and consideration in any design effort. In order to successfully implement an alternative power conversion system, it must be verified that the impact on the safety performance of the reactor is negligible or in the direction of improved safety. If this is not true, then significant licensing risk must be assumed in order to adopt the new technology. As this course of action represents high costs and low probabilities of success, the I^2S-LWR power conversion system must not contribute any negative factors to the safety of the plant. Thus, parallel to the optimization studies conducted here, safety analyses for the power conversion system are being conducted to determine the impact to nuclear plant safety. A full plant model was developed to investigate the safety of the I^2S-LWR using the base design. These studies consist of the development of a full plant model for each of the power conversion systems proposed in this paper, and the implementation of a series of abnormal operational transients. The results of these transients are then compared and contrasted to each other and to similar transients analyzed for current plants. Any situations where safety impacts are introduced due to the power conversion system implementation are carefully considered, and design alterations or solutions are proposed in order to prevent such an impact to the safety of the I^2S-LWR.

4. Optimized Rankine cycle

The concept explored in this paper is an industrial quality modified Rankine cycle (Siviter et al., Feb 2015). with optimized operation parameters. This concept, which is depicted in Fig. 1, consists of microchannel heat exchangers (Memmott and Manera, 2015) (MCHX) which consist of millimeter scale flow channels etched in metal plates that are stacked vertically at alternating orientations to facilitate hot and cold flow through the channels. The primary role of the MCHX is to transfer heat from the primary loop to the power conversion system followed by flash drums which generate steam that is sent to the turbomachinery. This steam is then expanded in a high pressure turbine, and the