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Thermodynamic performance of Pressurized Water Reactor power conversion cycle combined with fossil-fuel superheater

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ABSTRACT

It is known that the Pressurized Water Reactors (PWRs), which are the most common type of nuclear reactor existing today, usually used to provide a base load electricity. In order to be able to compete with other generation types (fossil and renewables), it would be desirable to develop PWRs with flexible load following capabilities to cope with varying electricity demand, especially in deregulated markets.

The thermal efficiency of PWRs can be increased by fitting the power plant with conventional fossil fuel superheaters. This hybrid system has been hypothesised to be able to adjust the power output and the cycle efficiency of PWRs. Such mode of operation would also improve the efficiency of converting the fossil fuel heat because it is applied only at the superheater stage. There are several ways to supply the heat to the superheaters, for example, by using the exhaust gas from the gas turbines and using the conventional gas burner.

In this paper, the thermodynamic performance of the hybrid system (PWR with superheater) is investigated for large reactor and Small Modular Reactor (SMR) application. The thermal efficiency of the AP1000 can be improved from 30.2% to 45.8% (with CCGT), 35.6% (with gas burner), and 36.6% (gas burner with reheating). The thermal efficiency of the SMR can be improved from 33.4% to nearly 45% (with CCGT), 35.5% (with gas burner), and 37.4% (gas burner with reheating). The analysis results show that it is possible for the hybrid system to operate between 65% and the full power load.

1. Introduction

Nuclear power is a favourable source for providing a base load of electricity due to its stable power supply, high capital costs while relatively small fuel costs. However, the electricity demand is not fixed but varies daily, weekly and seasonally. In order to be able to compete economically with other energy sources, especially in deregulated markets, it is desirable for the nuclear power plants to develop flexible load following capabilities [1]. The Pressurized Water Reactor (PWR) is the most common nuclear reactor type. It currently makes up around 70% of nuclear reactor fleet in the world. However, PWRs have relatively low thermal efficiency compared to that of modern fossil fueled power plants. Coal power plant efficiency can reach up to 42% and gas turbine can reach up to 40% and even 60% if it is combined with a bottoming steam cycle (combined cycle). The low thermal efficiency of the PWR is a result of the steam in PWR being generated at a near saturated condition which limits the temperature of heat addition as boiling in the primary coolant has to be avoided.

One way to develop a PWR with an economical load following scheme is to produce superheated steam, which has several benefits in the Rankine cycle [2]. First of all, the use of superheated steam can improve turbine performance. The lifetime of a turbine is limited by water droplet formation which erode the turbine blades. Superheating of steam reduces the steam wetness thus improving the lifetime of steam turbine. Secondly, superheated steam also improves the thermodynamic efficiency of the Rankine cycle as it increases the average temperature of the heat addition.

Superheated steam in a PWR can be produced by further heating the saturated steam with a superheater. This superheater can either be powered by another nuclear reactor or by fossil fuels. By combining a PWR with a conventional superheater, the economics of the system has the potential to be improved. The hybrid system allows full utilization of nuclear heat source, which is a low-operating-cost base-load system, with peak power production using low-capital-cost fossil heat [1]. The nuclear heat is used to generate the saturated steam while the fossil heat is used to superheat the steam, which suggests that the hybrid system use the

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fossil heat more efficiently than the conventional fossil power plant. The load following that can be achieved without affecting the nuclear reactor operation and the additional heat supplied from the fossil fuel would result in improvement of the power conversion efficiency throughout the system operation. The scope of this paper is to further investigate the combination scheme of PWR with fossil-fueled superheater in order to develop a PWR system with flexible load following capability. The thermodynamic performance of the hybrid system (PWR with conventional superheater) is investigated for large reactor and Small Modular Reactor (SMR) application.

2. Superheating and combined cycle concept

The concept of superheating the steam in Light Water Reactor (LWR) is not a new idea. It has been implemented in several nuclear reactors in the past. Indian Point 1 (USA), Garigliano (Italy), and Lingen (Germany) are examples of nuclear power plants with secondary reheating powered by oil. The performance of the combined cycle was questionable due to low load factor and material failures. It is however, quite reasonable to reconsider this concept as the technology of thermal power plants, nuclear and conventional, has become more reliable than it was back in 1960s [3].

Forsberg and Conklin [1] proposed a hybrid power cycle by coupling the Advanced High-Temperature Reactor (AHTR) with the Combined Cycle Gas Turbine (CCGT). During low electricity demand, the nuclear heat from AHTR could provide an adequate supply for base-load electricity with the CCGT. When the demand is high, further heating of the air in the gas turbine could be done by conventional combustor fueled by natural gas. Although the AHTR is a different type of reactor from the LWR, their study shows that nuclear power could be more competitive when it is coupled with a conventional heater as it can produce low-cost base-load electricity and lower-cost peak power relative to the existing combination of base-load nuclear power plant and fossil-fired peak electricity production.

Darwish et al. [4] investigated the thermal performance of the PWR nuclear reactor AP600 combined with existing gas turbines in Kuwait. The results of their study show that this combination scheme could increase the nuclear power plant (NPP) power output from 607 MWe to 1151.4 MWe. The power cost of the modified AP600 was predicted to be \$49.83/MWh, which was less by 45.6% than that of Gas Steam Turbine Combine Cycle (GSTCC) power plant (\$91.6/MWh).

Zaryankin et al. [5] studied the hybrid nuclear power plant (WWER-1000) with fossil-fuel superheater (gas combustor technology) and found that the hybrid nuclear power plant could increase the power generation from 1000 MWe to 2050 MWe with an efficiency increase of 8%. The designed external steam superheater enables an increase in steam temperature from 274 °C to 600 °C.

Most previous studies in the area of hybrid nuclear system with fossil fuel superheater [4,5] focused on the improvement of the cycle efficiency. Darwish et al. [4] utilizes the heat from a gas turbine while Zaryankin et al. [5] uses the conventional gas burner. In this paper, both schemes of coupling are considered and compared. In addition, the reheating method was investigated to further improve the cycle efficiency. Finally, the hybrid system heat balance was modified to show that it has the capability of load following without affecting the reactor operation.

3. AP1000 steam cycle

The nuclear power plant used as a reference in this study is the AP1000. It is a PWR designed by Westinghouse which produces about 1100 MWe. A schematic diagram of AP1000 steam cycle based on its plant description [6], is shown in Fig. 1. The heat from the primary loop is used to generate steam in the steam generator (SG). This steam then enters the turbine after some portion is extracted to provide heat for the Moisture Separator & Reheater (MSR). The AP1000 turbine consists of a double-flow, high-pressure (HP) cylinder and three double-flow, low-pressure (LP) cylinders. The steam conditions at the inlet of HP cylinder are 55 bar and 271 °C. Some portion of the steam is extracted from the HP turbine to provide heat to MSR and High Pressure Feedwater Heater. The HP turbine outlet then goes through the MSR to be dried before entering the LP turbine. Some portion of the steam is again extracted from the LP turbine to provide heat to the Low Pressure Feedwater Heaters. The outlet steam from the LP turbine is condensed before being pumped and heated as a feedwater for the steam generator [6]. The conditions at each point in Fig. 1 are reported in Table 1.

The heat produced from the reactor is used for generating the steam in the Steam Generator (SG) by following Eq. (1) while the steam expansion process inside the turbine follows Eq. (2) and Eq. (3). The heat rejection in the condenser can be calculated by Eq. (4).

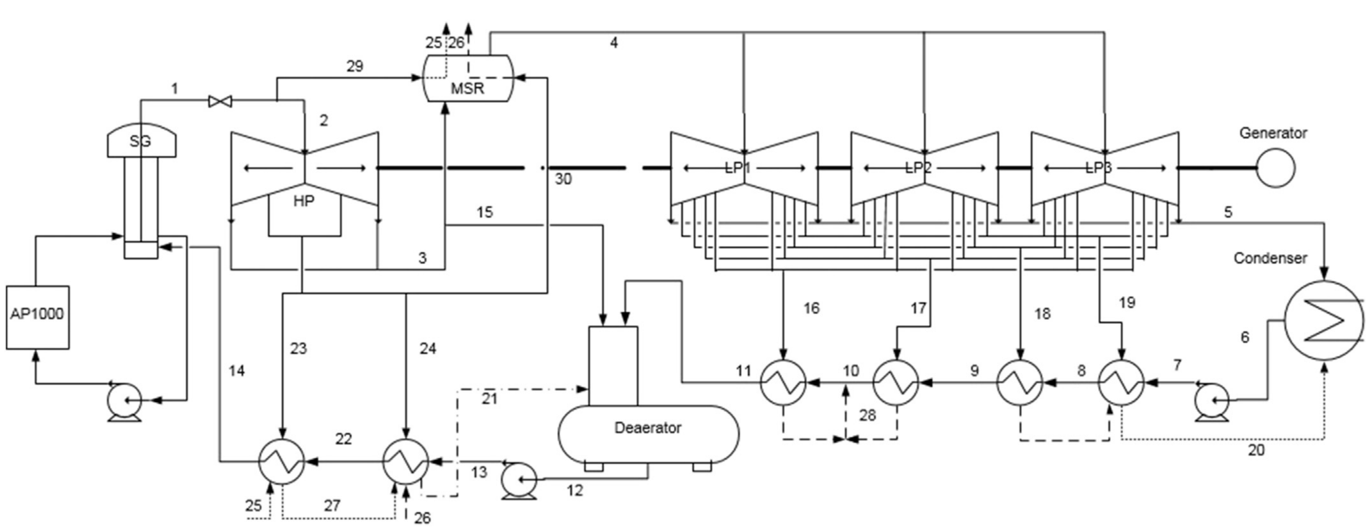

Fig. 1. AP1000 steam cycle flow diagram.