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Thermal-Hydraulic Analysis of a Once-Through Steam Generator Considering Performance Degradation

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1. Introduction

A small modular reactor (SMR) has received much attention due to its high flexibility and modularity in design, less on-site construction, short construction time, and high cost-effectiveness [1]. Several countries have entered into a global race for the commercialization of SMRs, and considerable research and development have been implemented. Among the various reactor designs, many SMRs have adopted an integral type pressurized water reactor (PWR) to enhance the nuclear safety and system reliability [2,3].

In the integral reactor design, a single reactor pressure vessel contains primary system components such as fuel and core, steam generators, pumps, and a pressurizer. For the component integration into a reactor vessel, it is important to design each component as small as possible. Thus, it is a common practice to employ a once-through steam generator in the integral reactor design due to its advantages in compactness [4]. Fig. 1 shows the exterior view of a once-through steam generator using helically coiled tubes considered in the present study.

In general, gradual degradation in thermal-hydraulic performance of the steam generator occurs with time, and it changes slowly the operating point of the steam generator during plant lifetime. For long-term operation, therefore, it is necessary to predict the operating points according to the degradation rate. For this performance prediction, the thermal-hydraulic performance of the helically coiled tube once-through steam generator is numerically evaluated in this paper. The intention of this paper is to investigate the operation strategies of the steam generator with degradation in performance.

Fig. 1. Exterior view of the helically coiled tube once-through steam generator.

2. Design Method

Consider a helically coiled tube once-through steam generator under counter flow condition, as sketched in Fig. 1. The primary coolant flows down across the helically coiled tube bundle, and the secondary feedwater flows up through the helically coiled tubes. The primary coolant flows outside the tubes and releases thermal energy into the secondary side. As the feedwater travels through the tubes, it absorbs heat from the primary coolant and begins to evaporate. The superheated steam is then vented out.

To evaluate the thermal-hydraulic performance of such a helically coiled tube once-through steam generator, a well-established numerical code, ONCESG, is used. The ONCESG code was developed in Korea Atomic Energy Research Institute (KAERI) for thermal-hydraulic design and performance analysis of a once-through steam generator using helically coiled tubes [4]. In the present simulation, the friction factors and heat transfer coefficients are calculated by using SKBK correlations for both tube-side and shell-side of the helical tubes.

In the thermal-hydraulic design, a design margin is added on the initial clean design to compensate for uncertainties in design and deterioration in performance due to plugging and fouling [5]. Here, all these margins are taken into account in terms of the heat transfer area by applying an area utilization factor (AUF) in each control volume. For example, AUFs of 1.0 and 0.9 reflect 0% and 10% design margins, respectively. Such a design margin gives an increment in size of the steam generator at a given thermal power output, or deterioration in performance of the steam generator at a given size. When the size of steam generator is fixed, therefore, an AUF decrement results in a reduction in the effective heat transfer area due to plugging or fouling, and consequently the performance degradation occurs.

In the present study, the performance deterioration of the steam generator is investigated in terms of thermal power output and degree of superheat. The parameter ranges are $0.7 \leq \text{AUF} \leq 1.0$ and $45 \text{ kg/s} \leq m_s < 48 \text{ kg/s}$, and the geometrical parameters and the operating conditions given in Table 2 in reference 4 are used.

3. Results and Discussion

The average tube length L of the helically coiled tube once-through steam generator for transferring a constant thermal power output at various AUFs is listed in Table I. As expected, the average tube length increases with the decrease in AUF to compensate for the reduced heat transfer area by fouling, plugging, etc. Here, a helically coiled tube once-through steam generator with the average tube length of $L = 61.59$ m is employed for the performance analysis considering 30% design margin.

The thermal power output variation according to the feed water flow rate is plotted in Fig. 2. It almost linearly increases with the feed water flow rate. It is evident that the thermal power output decreases with the decline in AUF. That means the steam generator performance deteriorates as it experiences the heat transfer area reduction or flow path blockage problems by fouling or plugging.

It is also noticeable that the red square symbol in Fig. 2 represents the design point because the steam generator is originally designed with 30% design margin. When the steam generator begins its first operation with clean flow paths, however, the operating point is located on the green line. Thus, the steam generator will show higher performance compared to the original design at a given feed water flow rate, see the green triangular symbol in Fig. 2. Such unintended steam generator operation is unsuitable for stable operation of the primary system. For this reason, it is required to operate the steam generator with the properly reduced feed water flow rate at the early stage of the plant operation. This initial operation point is presented in Fig. 2 with the green circular symbol. Consequently, the steam generator can maintain the thermal power output during plant lifetime by gradually increasing the feed water flow rate.

Table I: Average tube length according to AUF
($Q_{th} = 100$ MW)

AUF [-]	0.7	0.8	0.9	1.0
L [m]	61.59	50.88	43.38	37.82

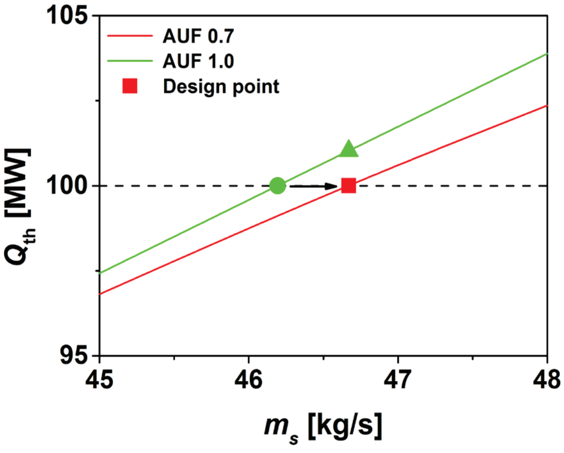

Fig. 2. Thermal power output versus the feed water flow rate.

Fig. 3 exhibits the variation in the superheat degree of steam according to the feed water flow rate. The degree of superheat decreases by increasing the feedwater flow rate. The high AUF results in a gentle decline of the degree of superheat, while it diminishes drastically to the lower value when the AUF dwindles. It is attributed to the fact that the steam generator with high AUF has great potential to transfer heat energy. Thus, it is possible to still maintain the steam temperature close to the primary coolant inlet temperature even when the feedwater flow rate is elevated. From the long-term operation point of view, the superheat degree of steam dwindles during plant lifetime if the feed water flow rate is controlled for constant thermal power output, as pointed out in Fig. 3.

The feed water flow rate and superheat degree curves for the constant thermal power operation are presented in Fig 4. As is evident, the feed water flow rate required for the constant power output is augmented as AUF decreases. This indicates that the gradual augmentation

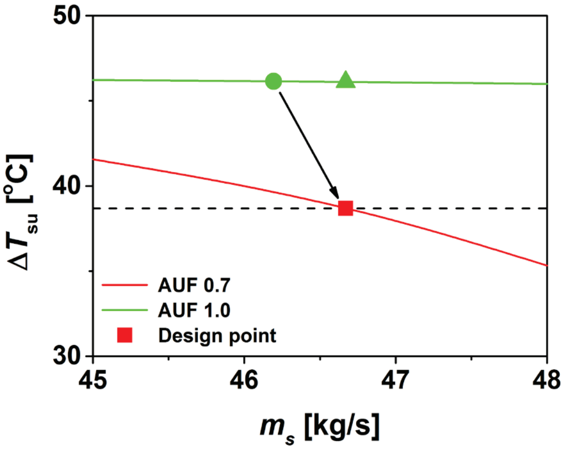

Fig. 3. Degree of superheat versus the feed water flow rate.

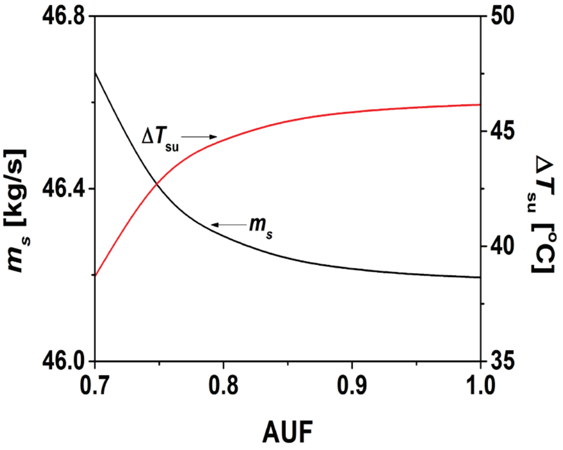

Fig. 4. Feed water flow rate and superheat degree curves for the constant thermal power operation.

of the feed water flow rate is required for the long-term constant power operation as the operating point moves from initial stage of AUF = 1.0 to end stage AUF = 0.7. The degree of superheat, on the other hand, dwindles with the decrease in AUF due to the increase of the feed water flow rate. This means the constant thermal power output is maintained by increasing the feed water flow rate with an expense of the low degree of superheat as AUF decreases.

4. Conclusions

The constant thermal power operation strategy of a helically coiled tube once-through steam generator has been investigated. Numerical solutions are acquired to evaluate the thermal-hydraulic performance of the steam generator at various AUFs. The design results obtained show that the average tube length of the steam generator is augmented with the increase of design margin to compensate for the design uncertainties and heat transfer area reduction by plugging, fouling, etc.

A helically coiled tube once-through steam generator with 30% design margin is considered for comparison of thermal-hydraulic performances according to the degradation rate. The feed water flow rate and superheat degree curves for the constant power operation reveals that the long-term constant thermal power operation becomes possible by properly elevating the feed water flow rate with an expense of the low degree of superheat as the steam generator experiences gradual deterioration in thermal-hydraulic performance.

ACKNOWLEDGEMENT

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