Off-design analysis of the LPT branching steam for hydrogen production

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1. Introduction

As environmental regulations are tightened around the world, carbon-free hydrogen is in the spotlight as a future energy. The World Nuclear Association (WNA) announced that countries around the world including United States and Europe have promoted green-hydrogen production through nuclear power generation. Currently, 95% of the world's hydrogen production consists of extracted hydrogen produced by decomposing natural gas into steam and by-product hydrogen produced through petrochemical process [1]. As such, with current technology, greenhouse gas emissions are inevitable during the hydrogen production process. In this context, technologies have been developed to achieve the economic feasibility and eco-friendly nature of hydrogen production in line with global carbon regulations. In order to eliminate carbon emissions during the hydrogen production process, the energy source required for hydrogen production must be eco-friendly energy. If hydrogen is made using renewable energy such as solar and wind power, concerns about carbon emissions will reduce. However, when renewable energy is used for hydrogen production, the production cost is much higher than others at the current technologies.

Nuclear power is considered to be the key to solving the dilemma of hydrogen production [2]. Nuclear power has both economic feasibility and eco-friendliness as the energy source. In particular, if hydrogen production using nuclear power plants (NPPs) during operation is possible, it is expected that the cost of hydrogen production will be greatly reduced. In addition, there is an advantage that energy may be supplied in the form of heat or electric energy according to the type of hydrogen production. If energy is supplied in the form of heat to the hydrogen production facility (HPF), the steam on secondary system of the NPP should be utilized to minimize the effect of the reactor [3]. It becomes a system in which the steam partially branches from the secondary side of the NPP to the HPF, and returns again. It is necessary to conduct detailed research on the secondary system sensitivity analysis according to branch flow, branch point and return point. In this study, an integrated system between a NPP and HPF is first proposed. Second, an off-design analysis of the low-pressure turbine (LPT) is performed, which is expected to be most affected by steam branch. The analysis results may be used to analyze the sensitivity of the steam cycle according to the steam branch.

2. Integration of NPP-HPF

2.1 Hydrogen production using nuclear

The economic feasibility and eco-friendliness of hydrogen energy depend heavily on the production processes. In general, hydrogen production requires binding energy to decompose water. Since the hydrogen binding energy of water is quite large, the energy required for hydrogen production is also significant. To meet the stack temperature of the electrolysis, a considerable amount of energy must be supplied from external energy sources. If NPPs support a part of required energy, the cost of hydrogen production may be expected to reduce.

If nuclear power having low production costs supports energy to hydrogen production in terms of heat and electricity, the cost of hydrogen production may be much lower than alone [4]. That is why we suggest the integrated system between NPP and HPF. In this study, the integrated design is suggested on the based on pressurized light water reactors (PWRs), the most frequently used type in Korea. Before detailed design of hydrogen production using operating NPPs, stability of NPPs applied to the integrated system should be checked. In other words, even if the steam branch from the NPP, the equipment, including turbines, should be evaluated for reasonable performance.

2.2 Conceptual Design

In this study, we evaluate the possibility of applying hydrogen production technology to PWRs. Figure 1 shows the integrated system diagram between the steam cycle of the NPP and the HPF. The steam cycle is designed to secondary side of PWRs. Heat from the NPP is transferred to HPF through intermediate heat transfer loops. The steam branched from inlet of the LPT transfers heat to the intermediate heat transfer loop, and returns to the condenser on the steam cycle. In order to avoid the loss of mass flow on the steam cycle, the branch flow should return again. Although the return point varies depending on the thermodynamic conditions, the return point is generally designated as a condenser considering the operation stability.

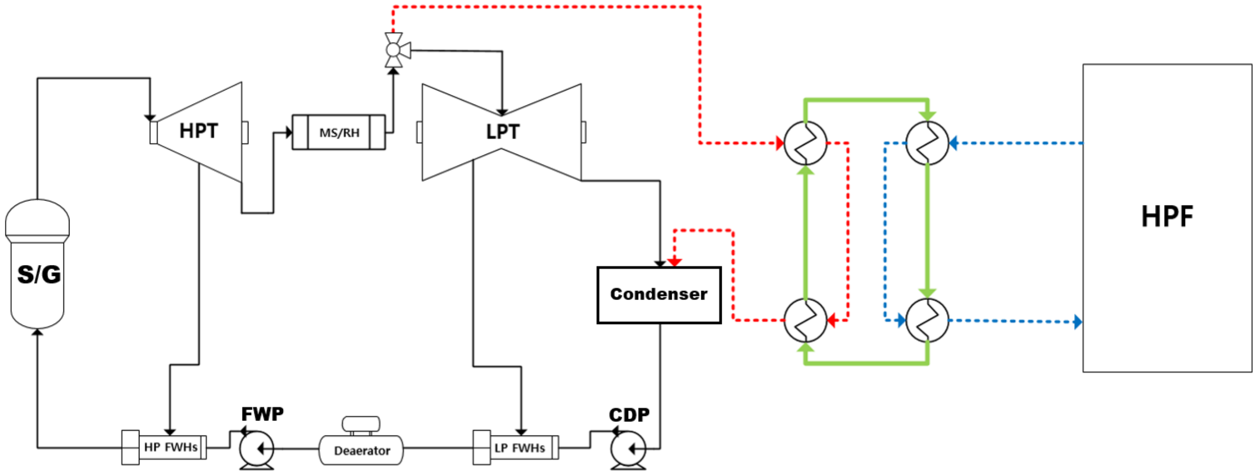

Fig. 1. Conceptual design layout of the NPP-HPF

The selection of the branch and return point on the steam cycle is important. This is because it determines the amount of the transferred energy to the HPF. It is important how high the steam temperature is to ensure heat efficiency. In this paper, the inlet of the LPT is selected as a branch point in consideration of thermodynamic advantages. The main steam line before high-pressure turbine (HPT) may be considered as a candidate for a branch point. However, there are concerns about performance degradation and instability of equipment located after branch point. Therefore, inlet of the LPT, which has the second highest temperature, is selected as the branch point in this paper.

3. Turbine Performance

3.1 Steam branch on LPT

As mentioned earlier, we consider the NPPs on operation for integration of HPF. Therefore, the effects of branch and return of steam flow during operation should be evaluated. As shown in Figure 1, the steam branches from the inlet of the LPT and returns to the condenser. Therefore, as an amount of the branch flow increases, the steam mass which enters the LPT decreased. Since turbine performance is significantly affected by inlet mass flow rate, an off-design analysis of the LPT is required. The off-design performance of the LPT must be verified before the validity of the proposed integration system be verified. Figure 2 shows LPT, whose type is a double-flow turbine. Although LPT in large NPPs actually have much more stages, only 5 stages which have extraction and exit are analyzed in this paper. The steam extractions from each stage enter the hot side of LP feedwater heaters (FWHs) shown in Figure 1.

3.2 Off-design performance

The design conditions of the LPT refer to Shin Kori Units 5 and 6 information but are not stated here to avoid releasing of proprietary information issue. For off-design performance of the LPT, the Stodola's cone law is used as followings [5]. κ may considered as 1.135 for wet steam [5][6]. Turbine efficiency is calculated by eq. (4) [7]. In addition, the amount of the required energy for HPF is unknown since the HPF has no detailed design. The required energy for HPF depends on the type and performance of its stack. In this paper, the feasibility of integrated system is evaluated up to 20% branch of inlet flow of the LPT.

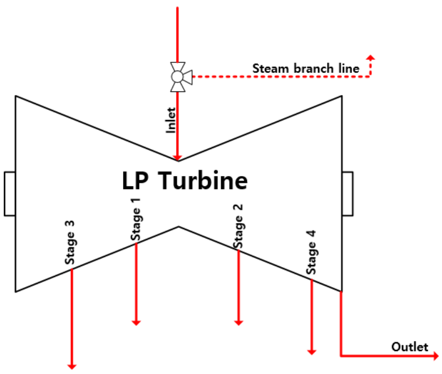

Fig. 2. The steam path of the double-flow LPT

$$\frac{\dot{m}_{off}}{\dot{m}_{on}} = \frac{P_{in,off}/\sqrt{T_{in,off}}}{P_{in,on}/\sqrt{T_{in,on}}}\sqrt{\frac{1-\left(P_{out,off}/P_{in,off}\right)^{\frac{n+1}{n}}}{1-\left(P_{out,on}/P_{in,on}\right)^{\frac{n+1}{n}}}} \quad (1)$$

$$P_{out,off} = P_{in,off}\left[1-\left(\frac{\dot{m}_{off}}{\dot{m}_{on}}\right)^{2}\left(1-\frac{P_{out,on}}{P_{in,on}}^{\frac{n+1}{n}}\right)\right]^{\frac{n}{n+1}} \quad (2)$$

$$n = \frac{\kappa}{1+\frac{\kappa P\left(v_{vapor}-v_{liquid}\right)}{r}\left(1-\eta_{turbine,on}\right)} \cong 1 \quad (3)$$

$$\eta_{turbine,off} = \eta_{turbine,on} - \alpha\left[\frac{N_{on}/\sqrt{\Delta H_{on}}}{N_{off}/\sqrt{\Delta H_{off}}}-1\right]^{2} \quad (4)$$

Table 1. Parameters description

P	*Pressure*
T	*Temperature*
H	*Enthalpy*
n	*Polytrophic exponent*
κ	*Isentropic exponent*
v	*Specific volume*
r	*Evaporation enthalpy*
η	*Turbine efficiency*
N	*Turbine speed*
α	*Positive constant*

The pressure ratio and efficiency of the LPT are estimated as the steam branches up to 20% of the on-design mass flow rate of the LPT. Branching to 20% of steam flow means that the inlet mass flow of the LPT is reduced by 20%. The steam mass flow at each stage of the LPT is also reduced by 20% as the ratio of the extraction mass is kept constant. Figure 3 and 4 show the reduction in pressure ratio and efficiency of the LPT according to the branch flow. When the branch flow is 20% of the on-design condition of the LPT, the efficiency of the LPT decreases by about 6.5%, and the pressure ratio decreases by 1.4. These pressure ratios and efficiency reductions affects the total output of the steam cycle.

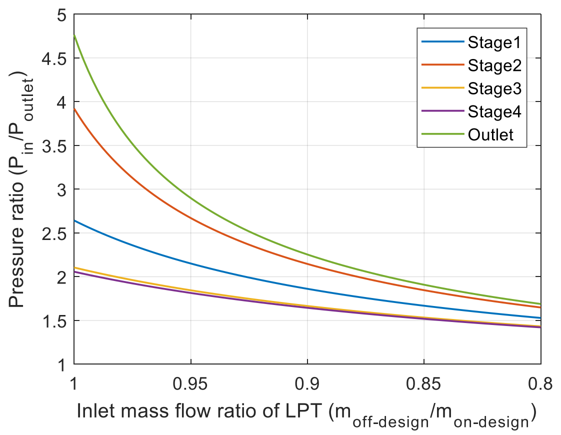

Fig. 3. The off-design pressure ratio with inlet mass flow rate of the LPT

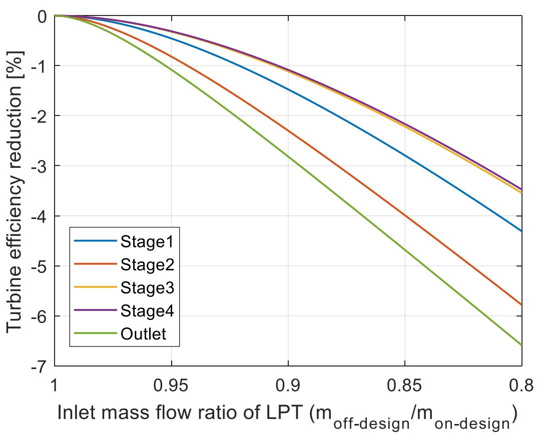

Fig. 4. The off-design turbine efficiency reduction with inlet mass flow rate of the LPT

4. Conclusions

The recent research has reviewed the integration between hydrogen production technology and nuclear power. Hydrogen production requires a lot of energy and accompanies the greenhouse gas emission with current technology. Nuclear power, cheap and eco-friendly, is a key for solving these issues. In this paper, the conceptual design layout is suggested. The integrated design describes that the steam branches from a NPP to the HPF through intermediate heat transfer loop. The branch point is inlet of the LPT and return point is the condenser. In other words, the mass flow rate into LPT decreases as the branch flow increases to HPF. This reduction in inlet mass flow rate may result in the performance degradation of the LPT. This is because the pressure ratio and efficiency reduction heavily depend on inlet mass flow rate of LPT. The equipment of the steam cycle should operate on reasonable performance even when steam branches to verify feasibility of the integrated system. Therefore, an off-design performance of the LPT is evaluated based on the law of ellipse. This is because the performance of the LPT is most affected as the steam branches. In the results, the an off-design map of the LPT is obtained. In the future, the integrated system suggested in this paper will be designed in detail. And the other equipment of the steam cycle will be analyzed on the off-design condition.

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