KNS 2021 Autumn Meeting, 2021. 10. 21 – 22,
21A-189

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

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Table of Contents

1. Introduction

<u>Environmental regulations and Hydrogen Production</u>

- As environmental regulations are tightened around the world, a carbon-free hydrogen is in the spotlight as a energy source in the future.
- 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 produced using renewable energy, environmental concerns reduce.
- However, with renewable energy, 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. Nuclear power has both economic feasibility and eco-friendliness as the energy source.

1. Introduction

Nuclear power for Hydrogen Production

- The World Nuclear Association (WNA) announced that countries around the world have promoted green-hydrogen production through nuclear power generation.
- Nuclear power is considered to be the key to lower the production cost. Also, a nuclear has an eco-friendliness as the energy source.
- 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 2nd system of the NPP may be utilized to minimize the reactor effects. 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.

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. 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. Therefore, 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. That is why the integrated system between NPP and HPF is suggested in this paper.
- The integrated design is based on pressurized light water reactors (PWRs), the most frequently used type in Korea. Before detailed design of hydrogen production using operating NPPs, the stability of NPPs applied to the integrated system should be reviewed.
- In other words, even if the steam branch from the NPP, the equipment including steam turbines should be evaluated for reasonable performance.

2. Integration of NPP-HPF

2.2 Conceptual Design

- The possibility of applying hydrogen production technology to PWRs is evaluated.
- The analysis results may be used to analyze the sensitivity of the steam cycle according to the steam branch.

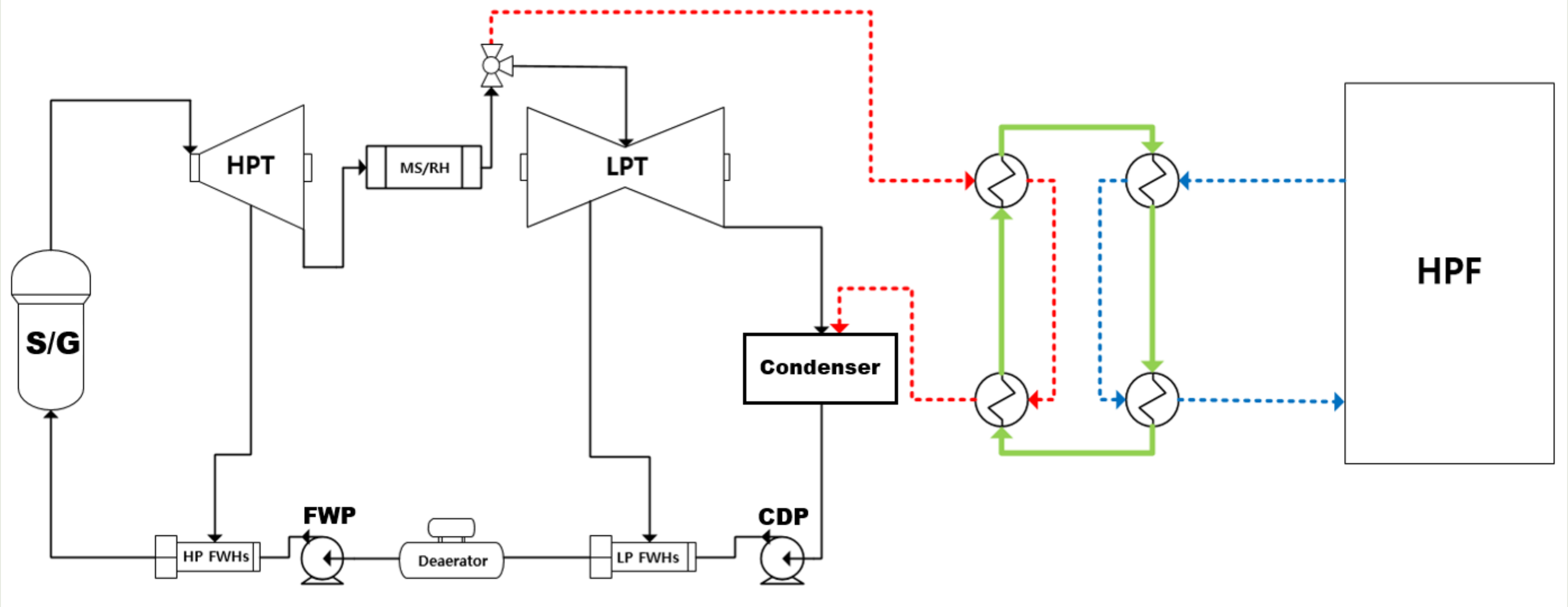

Fig. 1. Conceptual design layout of the NPP-HPF

2. Integration of NPP-HPF

2.2 Conceptual Design

- 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 flow rate on the steam cycle, the branch flow must return again. Although the return point varies depending on the thermodynamic conditions, the return point is generally designated as a condenser.
- The selection of the branch and return point 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.

3. Turbine Performance

3.1 Steam branch on LPT

- As an amount of the branch mass flow rate 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.
- Fig. 2 shows a LPT, double-flow turbine. Although LPT in large NPPs actually have much more stages, only 5 stages which have extraction and exit are analyzed. The steam extractions from each stage enter the hot side of LP feedwater heaters (FWHs).

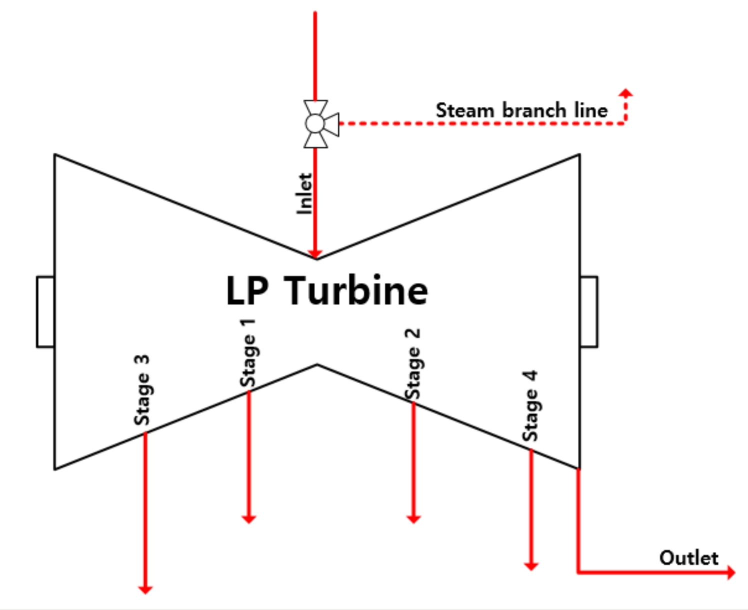

Fig. 2. The steam path of the double-flow LPT

3. Turbine Performance

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. κ may considered as 1.135 for wet steam. Turbine efficiency is calculated as below.
- 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.
- The feasibility of integrated system is evaluated up to 20% branch of inlet flow of the LPT.

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

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

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

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

3. Turbine Performance

3.2 Off-design performance

- 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.
- 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.
- 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.

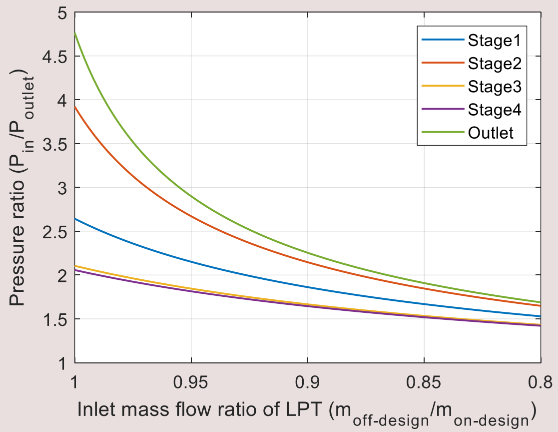

Fig. 3. The off-design pressure ratio with inlet mass flow rate of the LPT

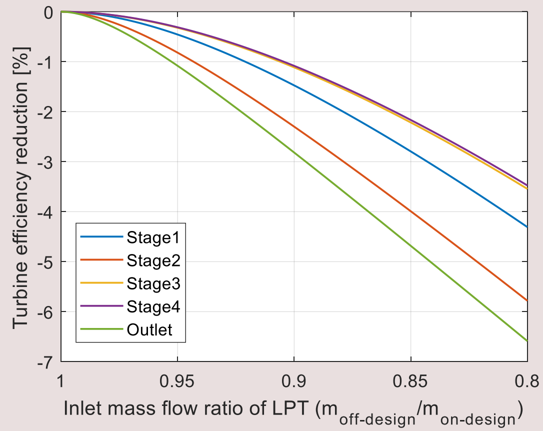

Fig. 4. The off-design turbine efficiency reduction with inlet mass flow rate of the LPT

4. Conclusions

- 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. The conceptual design suggested in this paper 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.
- This reduction in inlet mass flow rate may result in the performance degradation of the LPT, because the pressure ratio and efficiency reduction heavily depend on inlet mass flow rate of LPT.
- Therefore, an off-design performance of the LPT is evaluated based on the law of ellipse. In the results, the an off-design map of the LPT is obtained.
- The equipment of the steam cycle should operate on reasonable performance even when steam branches to verify feasibility of the integrated system.
- In the future, the integrated system will be designed in detail. The other equipment of the steam cycle will be analyzed on the off-design condition.

Thank you