Off-Design Analysis of Various Steam Cycles with Different Number of Feed Water Heaters in BANDI-60S

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1. Introduction

The 'BANDI-60S' is a Small Modular Reactor (SMR) currently being developed in KEPCO Engineering & Construction. It is a maritime power reactor with a thermal output of 200 MWth and target electrical output of 60 MWe. According to the disclosed information of BANDI-60S, the power conversion system is equipped with four Feed Water Heaters (FWH). If it becomes necessary to further reduce the size of the BANDI-60S power conversion system to make the marine platform more compact without significantly modifying the existing system, one easily considered design option is to reduce the number of FWHs.

It was confirmed that as the number of FWHs in the BANDI-60S decreases (from 4 > 3 > 2 > 1), the overall cycle efficiency decreases, but the specific work, which refers to the output per unit mass flow rate, actually increases [1]. However, this study only analyzed for the on-design model at the maximum efficiency and was limited to just four of the possible fifteen cycle layouts that could be formed by changing the number of FWHs.

In this paper, all fifteen possible BANDI-60S steam turbine cycle layouts, which can be created by varying the number and combination of FWHs, are designed using the KAIST-CCD to create on-design models. An off-design analysis is then performed by bypassing a portion of the steam flow to the condenser from the turbine inlet and using Stodola's cone equation.

2. BANDI-60S Steam Cycles On-Design Modeling

2.1. Standard Layout Modeling (4 FWH)

The disclosed information regarding BANDI-60S shows that it is assuming to utilize a saturated steam cycle. The cycle consists of steam generator, turbine, condenser, and four FWHs. As the steam passes through the turbine, it splits into four streams, with each stream entering one of the four FWHs to perform the function of heating the feedwater. The standard layout of the BANDI-60S steam cycle is illustrated in Fig. 1 [2]. The key values such as efficiency of the main components in the cycle and the flow rates within the turbine were determined from the available state variables provided in the reference layout. Table 1 presents the key values used in the cycle calculations.

The steam cycle modeling was conducted using the MATLAB-based 'KAIST-CCD' code. KAIST-CCD is an in-house code developed by the KAIST research team for designing thermodynamic cycles. This allows for the calculation of state variables such as enthalpy and pressure at each point, as well as the overall flow rate and efficiency of the cycle. The state data required for these calculations were obtained using REFPROP, developed by NIST [3].

The standard layout cycle of the BANDI-60S, which includes four FWHs, was modeled to achieve the same efficiency and output as the reference. The properties at each station in the designed model closely matched the reference. The standard layout, the most complex layout, has been implemented and validated. This model provides a basis for modeling cycles with fewer FWHs. Fig. 2 shows a T-S diagram comparing the designed cycle with the reference cycle, which shows reasonable match.

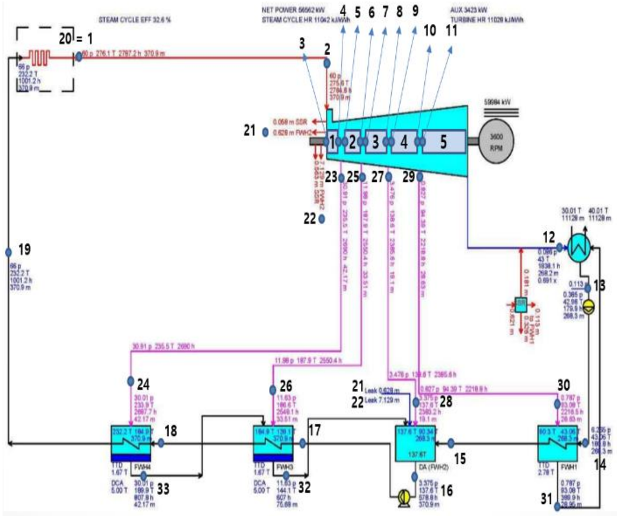

Figure 1. BANDI-60S Steam Cycle [2]

Table 1. Key values for Cycle Calculation

Q_{in} from Steam Generator [MW]		200
Steam Generator Outlet Temperature (˚C)		276.1
Steam Generator Inlet Pressure (bar)		66
Condenser Outlet Temperature (˚C)		42.98
Condenser Outlet Pressure (bar)		0.086
Turbine	Efficiency (%)	75.4 ~ 82.4
	Expansion P Ratio	1.94 ~ 9.62
	Bypass Ratio	0.066 ~ 0.116
Pump	Efficiency (%)	63.5 / 65.6
	Compression P Ratio	19.56 / 72.85
FWH Effectiveness (%)		93 ~ 98

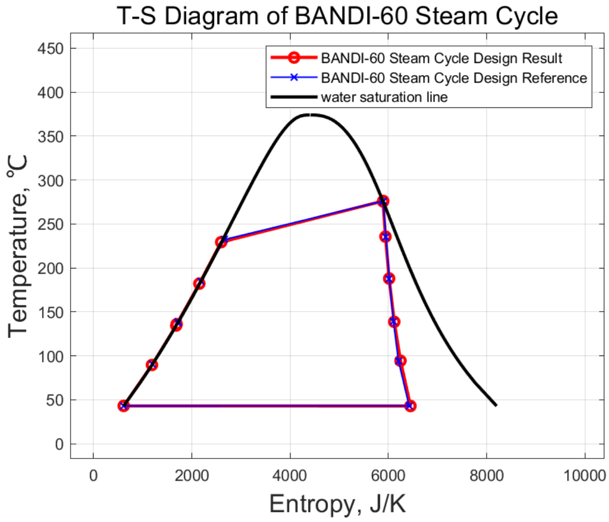

Figure 2. T-S Diagram Comparing the modeled Cycle with the Reference Cycle

2.2. Alternative Layouts (3, 2, 1, 0 FWH)

The FWHs are sequentially named FWH1, FWH2, FWH3, and FWH4, with 1 being the closest to the condenser, and 4 being the closest to the steam generator. A total of fourteen different layouts can be considered, ranging from a layout with all four FWHs to a layout with no FWH. The key values for cycle calculation such as Q_{in} from steam generator and efficiency of the components were kept constant across the various layouts, and the structure of the existing cycle was preserved as much as possible. When an FWH was removed, the pipeline branching off from the turbine to that FWH was also removed. If the flow from the hot side, after heat exchange within the FWH, has no subsequent FWH to enter, it is assumed to flow into the condenser.

The standard layout cycle code of the BANDI-60S was modified to create 15 additional cycle codes, with calculations performed for state quantities at specific points, cycle flow rates, output, and other factors. Fig. 3 presents a diagram showing the overall efficiency and specific work based on the design results for each cycle.

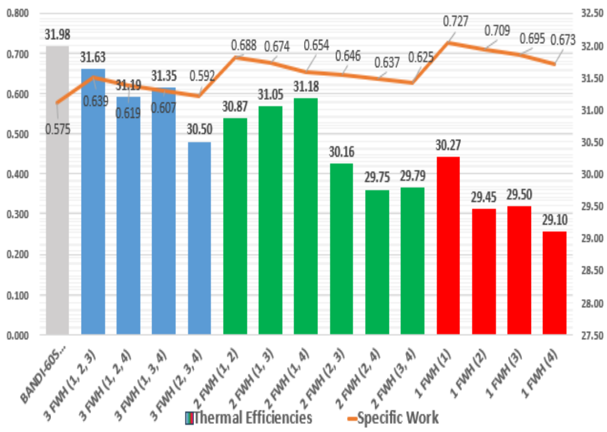

Figure 3. Thermal Efficiencies and Specific Work of Various BANDI-60S Steam Cycles

Upon reviewing the design results of all the cycles, it was observed that there are significant differences in thermal efficiency and specific work even among combinations with the same number of FWHs. Among the 3 FWH configurations, 3 FWH (1, 2, 3) has the highest efficiency and specific work. Similarly, for the 2 FWH configurations, 2 FWH (1, 4) stands out, and for the 1 FWH configurations, 1 FWH (1) has the highest efficiency and specific work.

Interestingly, some results were found to differ from the previous studies. Earlier research suggested that reducing the number of FWHs would generally decrease cycle efficiency while increasing specific work. However, this trend doesn't hold true for some FWH configurations. For instance, in the case of 3 FWH (2, 3, 4), the cycle efficiency is lower than that of 2 FWH (1, 2), despite having more FWHs. Similarly, 1 FWH (4) exhibits lower specific work compared to 2 FWH (1, 2) or 2 FWH (1, 3), which have a greater number of FWHs. Notably, these anomalies are more common in cycles where FWH1 is excluded.

From the observations, when considering a reduction in the number of FWHs to minimize the volume of the BANDI-60S power conversion system based on the on-design model, it would be more advantageous to opt for a layout that includes FWH1 among the various layout options in terms of efficiency and specific work.

3. BANDI-60S Steam Cycles Off-Design Analysis

3.1. Method

'Off-Design Analysis' refers to the evaluation performed under operating conditions different from the original design conditions. An On-Design model represents conditions under which the power output is at 100% level. However, in real-world operation, a power conversion system does not always run at full power. Depending on the power requirements, the output generated by the turbine may need to be reduced. In such cases, the steam cycle can use a bypass method to redirect flow from the turbine inlet to the condenser. Changes in turbine inlet flow affect the expansion ratio and efficiency at each turbine stage. Additionally, the properties of steam, such as temperature and pressure at various stations, may also change, impacting the entire cycle. As a result, the outcomes differ from those observed under On-Design conditions.

The off-design analysis for the BANDI-60S steam cycle was performed using the turbine bypass control method. Flow rates were adjusted from 0% to 40% of the layout's design flow rate with 0.05% increments, and a throttling valve was installed at the turbine inlet to account for density changes corresponding to the bypassed flow. The turbine bypass and throttling valve for Off-Design analysis are illustrated in Fig. 4.

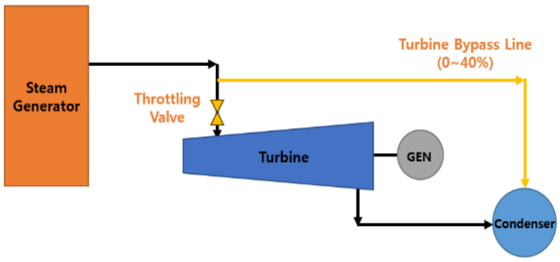

Figure 4. Turbine bypass concept for Off-Design in steam cycle

It was assumed that installing a throttling valve would maintain volumetric flow rate at the design condition and keeping the stage efficiency at constant, even while flow is being split. To calculate each stage outlet pressure and expansion ratio, which vary with flow rate within the turbine stages, the 'Stodola cone equation' was applied. The Stodola cone equation is as follows [4].

$$\frac{\dot{m}_{off}}{\dot{m}_{on}} = \frac{\sqrt{T_{on,in}}}{\sqrt{T_{off,in}}}\sqrt{\frac{(P_{off,in}-P_{off,out})^2}{(P_{on,in}-P_{on,out})^2}} \quad (1)$$

3.2. Analysis Results

Fig. 5. presents the overall cycle efficiency outcomes based on the Off-Design analysis for each layout. While 15 different layouts were analyzed, not all of them were plotted. For layouts with the same number of FWHs, only those that consistently maintained the highest efficiency throughout the entire bypass flow rate range were included. Since the layouts with 2 FWHs do not show consistent efficiency trend with respect to the turbine bypass flow, multiple 2 FWHs layouts are shown.

It was observed that the efficiencies of different layouts, which are established from the On-Design condition with 0% bypass flow, do not remain consistent as the bypass flow increases. In the case of the standard layout, it began to exhibit the lowest efficiency compared to other layouts when the flow was bypassed by approximately 16%. For the layout with the fewest FWHs (1 FWH), it started to achieve the highest efficiency among all layouts when the bypass flow reached around 28%. Additionally, it was generally observed that layouts with fewer FWHs tend to have higher efficiency than those with more FWHs in regions with higher bypass flow rates.

However, it is important to note that the same bypass percentage does not imply that the same amount of energy is discarded in the condenser for each layout. Therefore, it is difficult to determine which layout is more effective solely based on the overall cycle efficiency for each layout. Since the energy received from the steam generator of the reactor is directly discarded in the condenser, it is important to determine how much energy is being wasted in the condenser for each layout.

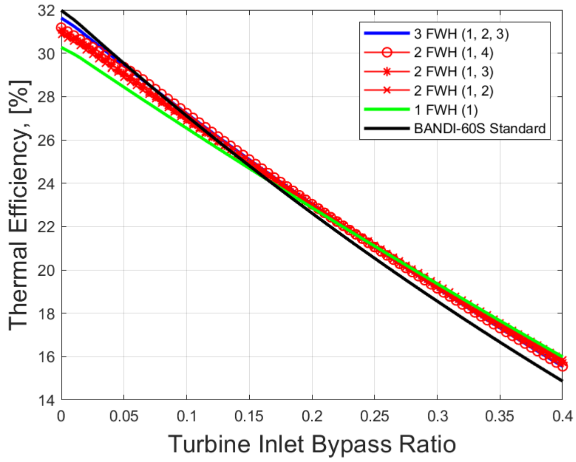

Figure 5. Thermal Efficiencies of BANDI-60 Steam Cycles Off-Design Analysis

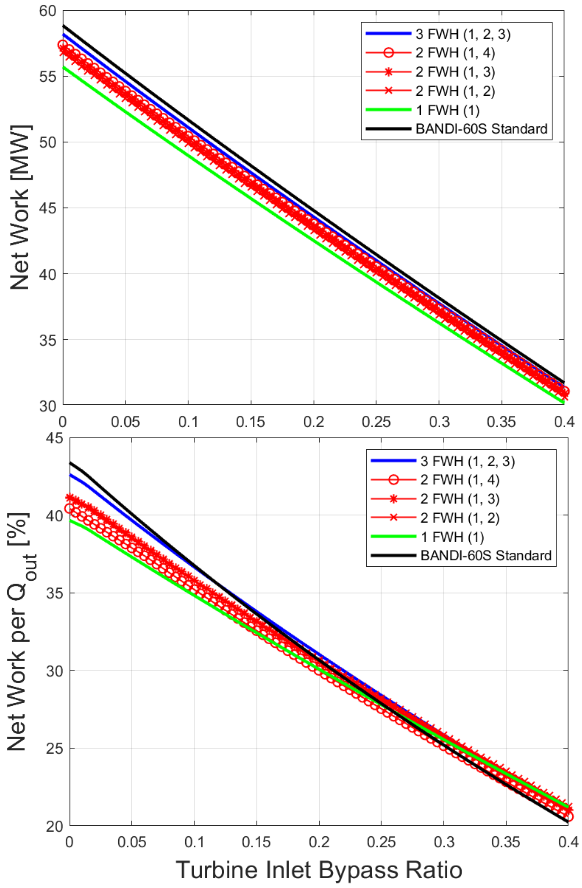

Figure 6. Net Work and Net Work per Q_{out} of BANDI-60 Steam Cycles Off-Design Analysis

In Figure 6, both Net Work and Net Work per Q_{out} are presented for different layouts. Layouts with a greater number of FWHs consistently exhibit higher Net Work than those with fewer FWHs. However, from the point where the bypass flow exceeds approximately 15%, the Net Work per Q_{out} shows a different trend. Layouts with 3 FWHs, 2 FWHs, and 1 FWH sequentially surpass the standard layout.

This indicates that as the bypass flow increases, layouts with more FWHs tend to waste more energy. Therefore, even though the Net Work remains consistently high across the entire bypass ratio range, the Net Work per Q_{out} shows a decreasing trend. In conclusion, when operating in lower power output ranges, choosing a layout with fewer FWHs becomes more effective. For example, when considering efficiency graphs, if the bypass flow is around 20%—requiring about 22~23% efficiency (44~46 MW out of 200 MW)—a layout with only one FWH would be more efficient than the existing BANDI-60S layout.

4. Summary and Conclusions

The previous studies on adjusting the number of FWHs in the BANDI-60S cycle layouts generalized conclusions based on results from only four layouts: the BANDI-60S Standard layout and layouts with 3 FWHs (2, 3, 4), 2 FWHs (3, 4), and 1 FWH (4). However, this study has further confirmed through On-Design analysis of all possible layouts that the generalized conclusion is not always true. Specifically, it was found that layouts which do not remove FWH1, the FWH closest to the condenser, even when the number of FWHs is reduced, are more efficient. Off-Design analysis revealed that as the bypass flow from the turbine increases, layouts with fewer FWHs waste less energy and produce more output compared to layouts with more FWHs.

Reducing the number of FWHs in the existing BANDI-60S layout is effective in terms of reducing the size of the power conversion system and would also be significantly advantageous in terms of efficiency if the BANDI-60S is frequently operating in 40 MW range.

Although the BANDI-60S is currently being developed with offshore power generation in mind, the findings of this study could be useful if the power conversion system needs to be adapted for other applications.

ACKNOWLEDGEMENT

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