

Sizing and Economic Assessment of Very-High Temperature Reactor Type Small Modular Reactor–Coupled Open-Air Brayton Cycles

Joohyung Jung^a, Taejun Song^a, Seongmin Son^a *

Department of Convergence & Fusion System Engineering, Kyungpook National Univ., Daegu, 41566, Republic of Korea

*Corresponding Author: seongminson@knu.ac.kr

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1. Introduction

Nuclear power has long played a central role in the global low-carbon electricity generation portfolio and has been widely recognized as a practical option for mitigating climate change. Previous studies have consistently highlighted that nuclear energy functions as a strategic energy resource by enabling large-scale, continuous power generation while minimizing greenhouse gas emissions during operation [1]. Despite these advantages, the widespread deployment of nuclear power has been constrained primarily by economic factors rather than technical performance. High upfront capital costs and complex infrastructure requirements remain the dominant barriers. A comprehensive analysis of global nuclear construction costs reported that the overnight construction cost of nuclear power plants spans a wide range from 1,914 US\$/kW to 12,600 US\$/kW, with an average value of approximately 5,430 US\$/kW [2].

As a potential alternative to conventional large light-water reactors (LWRs), small modular reactors (SMRs) have attracted increasing attention. Unlike large-scale nuclear plants that require substantial initial capital investment, SMRs mitigate financial risk by limiting unit output and allow for incremental capacity expansion in response to electricity demand. These characteristics make SMRs particularly suitable for power markets with high uncertainty and evolving demand structures. In parallel with the growing interest in SMRs, power conversion cycles that can accommodate flexible operation and simplified system architectures have gained attention. Among such options, the Open-Air Brayton Cycle (OABC) employs air as the working fluid and features a structurally simplified configuration, enabling ease of fluid supply and reduced system complexity. The relatively small number of components also facilitates maintenance and operational flexibility, making OABC an attractive power conversion cycle, particularly for high-temperature nuclear applications [3]. However, OABC is inherently designed to operate with a lower expansion ratio than conventional steam cycles. Consequently, for the same electrical output, OABC requires larger turbomachinery. This characteristic leads to a rapid increase in turbine diameter with increasing power output, imposing a structural limitation on scalability and creating a potential bottleneck for application in large-scale nuclear power plants. While

extensive research has been conducted on steam cycles for various heat sources, studies that integrate OABC into nuclear power systems and systematically link turbomachinery sizing with economic assessment remain limited. In particular, the tendency for turbomachinery size to increase significantly under low expansion ratios represents a critical challenge for the practical deployment of OABC. Given these considerations, the applicability of OABC as a nuclear power conversion system should not be evaluated based on arbitrarily large output assumptions. Instead, a design-oriented approach is required in which the physically feasible power range is first identified from a turbomachinery sizing perspective. Accordingly, this study establishes a physically realizable output range for OABC-based power systems by applying turbomachinery sizing constraints and subsequently performs a quantitative cost assessment based on the derived operating and design conditions. As a reference system, the AP-1000 large light-water reactor is selected due to its extensive commercial operating experience and well-documented economic data. Through this comparison, the impact of OABC on power system cost is examined, and the output range over which OABC-based power systems can be economically competitive with mature large-scale nuclear power plants is evaluated.

2. Heat Source Specifications and Determination of Optimal Operating Point

Fig. 1 illustrates the power generation process of an SMR coupled with an Open-Air Brayton Cycle (OABC). The system consists of a compressor, a heat source (SMR), a turbine, and a recuperator. Ambient air is first compressed in the compressor. The compressed air then receives thermal energy from the heat source and expands through the turbine, producing mechanical power. Because the turbine expansion ratio is relatively low, the turbine exhaust air remains at a comparatively high temperature. Before being discharged to the atmosphere, this exhaust air passes through a recuperator, where its thermal energy is transferred to the compressed air exiting the compressor. This heat recovery process contributes to an improvement in the overall thermodynamic efficiency of the cycle.

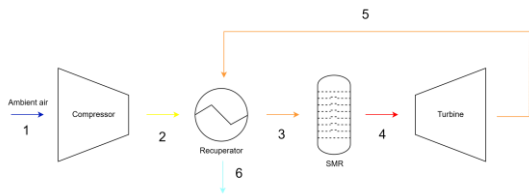


Fig. 1. SMR – OABC combined cycle

Table I summarizes the input conditions and key performance parameters of the integrated OABC–SMR system considered in this study. The table includes both the operating conditions of the OABC power conversion cycle and the thermal power and outlet temperature of the SMR serving as the heat source.

Table I: Input condition of OABC-SMR cycle [4][5][6]

Component	Spec
Recuperator effectiveness	95%
Recuperator P ratio	99%
Turbine Eff	90%
Turbine inlet temperature(K)	838.75
Compressor Eff	90%
Compressor P ratio	Calculated
Atmosphere pressure	1 atm
Atmosphere temperature(K)	288
Ratio of exhaust pressure to atmosphere pressure	98%
Reactor power (MWth / MWe)	200 / 80

Figure 2 illustrates the variation of system thermal efficiency as a function of the compressor pressure ratio for the OABC–SMR system. As the pressure ratio increases, the system efficiency rises rapidly in the low-pressure region and reaches a maximum value of 40.11% at an optimal pressure ratio of 2.11. Beyond this point, further increases in pressure ratio lead to a gradual reduction in efficiency due to the increased compression work.

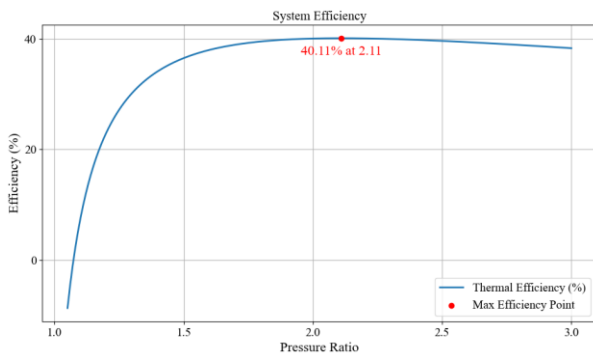


Fig. 2. Optimal pressure ratio & system efficiency

3. Turbomachinery Sizing Methodology

The Smith chart is a representative turbomachinery performance map that employs the flow coefficient and load coefficient of a single-stage turbine or compressor as its principal axes, with iso-efficiency contours

presented in the form of contour lines [7]. Such performance maps enable the systematic derivation of feasible rotational speed and diameter ranges under given power conditions and are particularly useful for quantitatively comparing multiple design alternatives during the early conceptual design stage. Due to its characteristic operation in a relatively low optimal pressure ratio regime, the OABC tends to require larger turbomachinery diameters than a steam cycle delivering the same power output. However, the size of turbomachinery is inherently constrained by physical limitations, rendering unrestricted increases in diameter impractical. Accordingly, this study establishes a realistic upper bound on turbomachinery size by referencing currently deployed aircraft turbomachinery and utility-scale gas turbines.

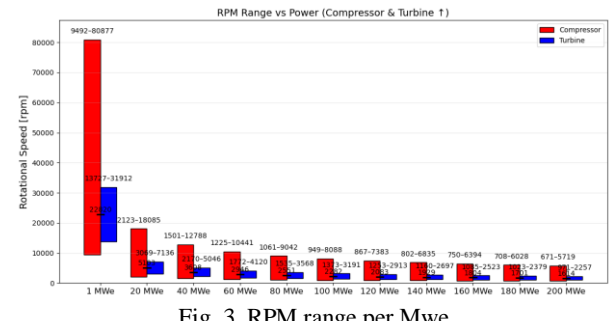


Fig. 3. RPM range per Mwe

Fig. 3 presents the rotational speed ranges of the turbine and compressor derived based on the Smith chart. For each power level, the minimum and maximum rotational speeds satisfying the allowable ranges of flow coefficient and load coefficient were determined. The results indicate that the required rotational speed decreases as the power output increases.

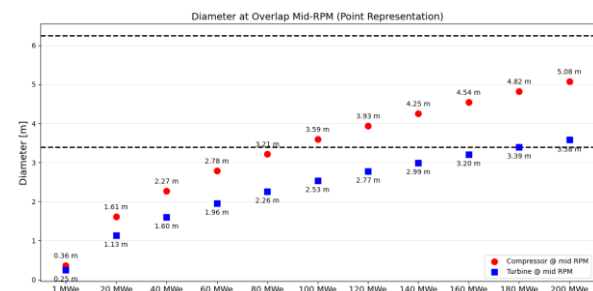


Fig. 4. Diameter at mid-rpm

Fig. 4 illustrates the turbomachinery diameter evaluated at the mid-RPM condition within the overlapping operating region of the turbine and compressor derived from the RPM ranges shown in Fig. 3. The results in Fig. 3 indicate that the turbomachinery diameter does not exceed the predefined upper bound even at a power level of 200 MWe, suggesting that physically realistic turbomachinery sizing is achievable from a mechanical feasibility perspective.

4. Economic evaluation

The economic evaluation was conducted based on component-wise cost estimation correlations for the turbomachinery and heat exchanger. The total CAPEX of the OABC power block was calculated by summing the costs of the compressor, turbine, and recuperator, with the cost of each component estimated using empirical correlations reported in previous studies [6][8][9]. For comparison, the power block CAPEX of the AP-1000 was assumed to account for 17% of the total plant CAPEX, as reported in the literature. Two reference cases were considered: the initial announced budget of the AP-1000 and the initial announced budget of the MIGHTR-1 [6][10][11]. These assumptions resulted in estimated power block CAPEX values of 731 k\$ and 1,239 k\$, respectively, which are indicated as dashed reference lines in Fig. 5.

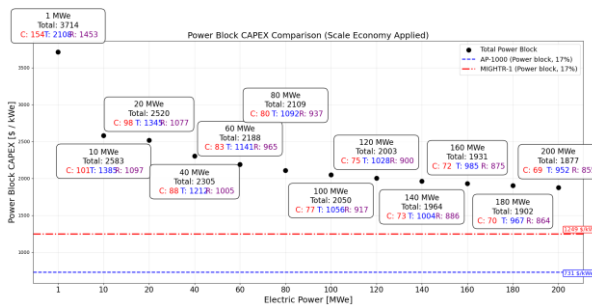


Fig. 5. CAPEX comparison

According to the results presented in Fig. 5, the power block CAPEX of the OABC system, expressed on a \$/kWe basis, exhibits a clear decreasing trend as the electric power output increases. This behavior reflects the incorporation of economies of scale in the cost estimation of the turbine, compressor, and heat exchanger, such that while the total CAPEX increases with power output, the cost per unit electric capacity continuously decreases [12]. In particular, in the low-power range of 1–20 MWe, the power block CAPEX remains relatively high, at approximately 2,500–3,700 \$/kWe. However, as the power output increases, the CAPEX per unit capacity decreases rapidly, reaching approximately 2,100–2,050 \$/kWe in the range of 80–100 MWe. Beyond this range, a more gradual decreasing trend is observed, with the power block CAPEX further declining to approximately 1,880 \$/kWe at an output level of 200 MWe.

5. Conclusion

This study presents an integrated assessment of the technical and economic characteristics of an OABC power conversion system coupled with an SMR, combining Smith chart-based turbomachinery sizing with cost evaluation. The turbomachinery sizing results indicate that, as the electric power output increases, the required rotational speeds of the compressor and turbine

decrease, while the corresponding diameters increase. When the mid-RPM condition identified within the overlapping operating region is adopted as the sizing criterion, the turbomachinery diameters are confirmed to remain within realistic upper bounds even at the maximum output level of 200 MWe. Based on the results referenced to the initial announced budget, the OABC power block exhibits a pronounced reduction in unit CAPEX (\$/kWe) in the output range of approximately 80–100 MWe, clearly reflecting the effect of economies of scale associated with increasing power output. However, in terms of absolute cost levels, the OABC power block maintains higher CAPEX values than the AP-1000 power block across the entire output range considered. Furthermore, when compared with the power block of MIGHTR-1, the OABC power block does not demonstrate a clear cost advantage. Nevertheless, as the electric power output increases, a gradual reduction in the unit CAPEX gap is observed, indicating a tendency toward cost convergence. This suggests that the OABC power conversion system should not be interpreted as a primary power block option for large-scale nuclear power plants, but rather as an alternative system whose cost structure becomes increasingly comparable when coupled with high-temperature reactors in the small- to medium-power range. Future work should extend the sizing and cost evaluation framework proposed in this study to a broader range of SMR–OABC configurations. In addition, a more comprehensive economic assessment incorporating steam cost, operation and maintenance expenses, and LCOE-based metrics is required to quantitatively evaluate the long-term competitiveness of OABC power conversion systems.

6. Discussion

The turbomachinery sizing in this study is based on a single-stage assumption, which is effective for estimating feasible diameter and rotational speed ranges during the early design stage. However, as the power output increases, the required loading may exceed the allowable limits of a single stage, necessitating a transition to multistage configurations. While multistage turbomachinery can mitigate the increase in overall machine size by distributing the load across multiple stages, it may lead to an increase in required piping diameter due to higher mass flow rates. In particular, at higher power levels, the piping size may become a bottleneck in the overall system configuration. Therefore, the results of this study represent the physically feasible range under a single-stage assumption, and further analysis incorporating multistage design along with piping constraints is required to more accurately evaluate the scalability and economic performance of the system at medium- to large-scale power outputs.

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Table II: Capital expenditure of the Xe-100 - OABC power block

Electric Power (MWe)	Compressor (\$/kWe)	Turbine (\$/kWe)	Recuperator (\$/kWe)	Total (\$/kWe)
1	154	2108	1453	3714
10	101	1385	1097	2583
20	98	1345	1077	2520
40	88	1212	1005	2305
60	83	1141	965	2188
80	80	1092	937	2109
100	77	1056	917	2050
120	75	1028	900	2003
140	73	1004	886	1964
160	72	985	875	1931
180	70	967	864	1902
200	69	952	855	1877