Control schemes of S-CO_2 cooled KAIST Micro Modular Reactor as marine propulsion engine to treat rapid load change condition

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1. Introduction

The northern sea route (NSR) is already a valuable channel for the regional export of raw materials and has attracted substantial attention because it saves up to 40% of sailing distance between Yokohama and Rotterdam compared to the typical route through the Suez Canal [1-3]. Even though the sailing distance is reduced about 40%, the absolute distance of NSR is still about 12,700 km. Navigating NSR with conventional fossil fueled engine such as diesel, gas turbine, or steam power system has a few limitations.

Firstly, it has to ship extra fuel tanks because the fossil fuel engine has too low endurance to sail NSR without refueling. For example, a destroyer driven by fossil fuel engine has endurance of 8,046 km at most economical speed and 2,414 km at top speed, even where the voyage is not in ice fields [4]. Secondly, fossil fuel engines emit considerable greenhouse gas to the environment. Due to the regulation of IMO, total emission amount of greenhouse gas in 2012 keeps similar level of 2007 data. However, the report predicts total CO_2 emission of 2050 and the results show that an increase of total CO_2 emission will become 50% at minimum, and 250% at maximum in the period up to 2050 [5].

To resolve these limitations of fossil fuel engines, nuclear marine propulsion system can be a promising option. The World's first nuclear powered icebreaker '*Lenin*' went into service with the Arctic Fleet and has been reported to have journeyed more than 96,560 km, 64,374 km of them through ice fields of the NSR [6]. Also nuclear powered system has been recognized as one of several alternative technological ways to generate electricity and reduce greenhouse gas emissions cost effectively, compared to other renewable energy and efficient fossil fuel system [7]. They demonstrate that nuclear propulsion system can overcome the abovementioned problems of fossil fuel engines.

However, including *Lenin*, the nuclear powered fleets are usually equipped with PWR cores and a steam Rankine cycle. Despite of many advantages of steam Rankine cycle, it has some mediocre aspects such as bulky volume of system, quality control at turbine blade, corrosion of structure material and etc. [4]. Supercritical CO_2 cycles (S-CO_2 cycles) are regarded as a promising alternative to substitute steam Rankine cycle because S-CO_2 cycles offer lots of advantages in a practical application like high thermal efficiency, low volume to power ratio, mild environment for keeping integrity of turbomachinery blade, and so on [8-10]. Thanks to its low volume and high efficiency, S-CO_2 cycles are considered as a candidate of marine propulsion and S-CO_2 cycles as a fleet engine can achieve about 25% saving compared to typical diesel engine. In diverse cycle layouts, Comb et al. concluded that simple recuperated cycle is the most adequate for marine propulsion system because of its high compactness [11].

In KAIST for providing distributed power to a remote region, a fully modularized reactor called KAIST Micro Modular Reactor (MMR) has been developed. The layout of MMR is a simple recuperated cycle in order to minimize its volume and weight to be transported by ships or trailers [12]. After that, modified GAMMA+ code which was originally developed in KAERI has been used to check its autonomous load following characteristics and response of hypothetical accidents [13]. Later, MMR has been taken into account a shipboard propulsion system as well as distributed power source [14] and Bae et al. considered combination of MMR reactor and trans-critical CO_2 cycle as a marine propulsion system [15].

However, nuclear powered shipboards are usually subjected to abrupt load change during its voyage but otherwise ground nuclear systems are not. Therefore, control systems that have fast response against a rapid load change should be designed. For closed Brayton cycles including S-CO_2 cycles, turbine bypass, inventory, turbine throttle and turbine inlet temperature control are conventionally used to follow a load following condition [16-18]. Among these control strategies, inventory control is known as the most efficient control [19, 20] but the inventory control is not expected to be used for rapid load changes because gas transfer from and to the operating inventory is normally a very slow process [21]. To compensate its slow characteristic time, turbine bypass control is operated in case of a drastic load change situation. However, turbine bypass valve makes efficiency of closed Brayton cycles to be inferior as shown in Fig. 1. In this paper, therefore, varied inventory control options will be analyzed with respect to location of discharging and feeding point of gas inventory to enhance response time of inventory control and minimize or exclude turbine bypass control.

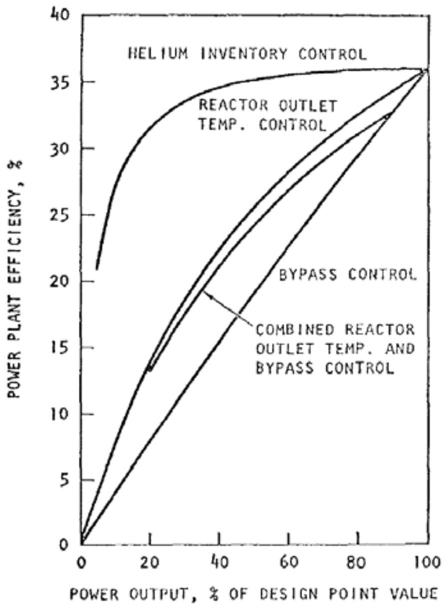


Fig. 1. Part-load efficiency for the various control modes [19]

2. Discussion and Results

2.1. Concept of MMR

With the concept of a long life core, MMR has been designed to be fully modularized reactor including power conversion system, core, and safety features into a double layered steel containment as shown in Fig .2. This module can be utilized for a 10MWe class shipboard engine.

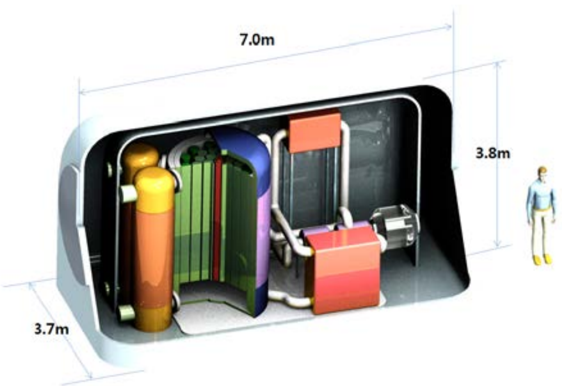
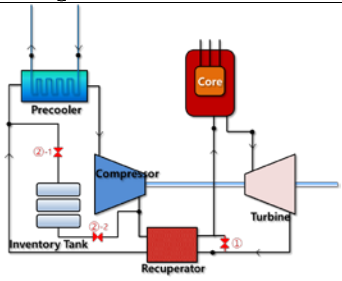
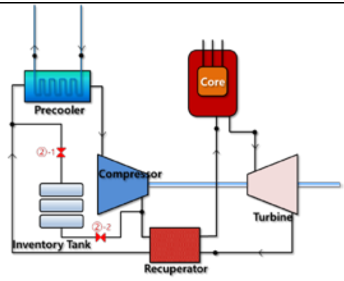
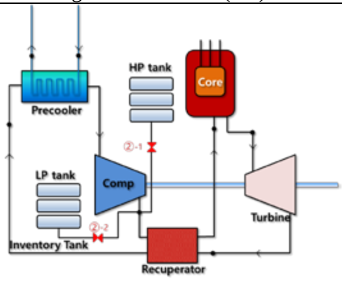
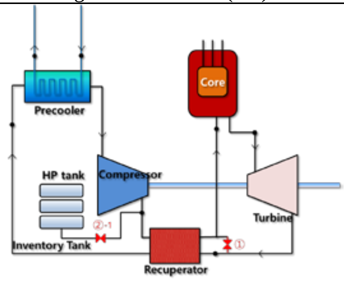


Fig. 2. Concept diagram of MMR

2.2. Control schemes of MMR

To cope with rapid load changes in marine propulsion environment, four control schemes are proposed in Table I.

Table I. control scheme options against rapid load changes.

 <Control scheme 1>	 <Control scheme 2>
- Turbine bypass (1) - Discharging: Compressor outlet (2-2) - Feeding: Precooler inlet (2-1)	- Turbine bypass (X) - Discharging: Compressor outlet (2-2) - Feeding: Precooler inlet (2-1)
 <Control scheme 3>	 <Control scheme 4>
- Turbine bypass (X) - Discharging: Compressor outlet (2-2) - Feeding: Compressor outlet (2-1)	- Turbine bypass (1) - Discharging (X) - Feeding: Compressor outlet (2-1)

Commonly, a single inventory tank, whose pressure is in between maximum and minimum pressures of a cycle, is located between the compressor outlet and the precooler inlet. The layout is shown in control scheme 1 which is the most general control scheme of closed gas Brayton cycles. Since mass transfer can occur naturally due to pressure difference between inventory tank and the cycle, control scheme 1 is advantageous in aspect of simplicity and fast response when load is decreased. However, control scheme 1 leads to a delayed response in case of increase in load. The reason is that the system inventory should also increase when the load is increased. In control scheme 1, inventory is increased at the compressor inlet which can cause an instantaneous rise of compressor mass flow rate compared to the turbine. Consequently, compressor work exceeds turbine work at the beginning of inventory charging [22]. If charging rate is slow enough, turbine and compressor gradually reach the balance and the cycle will approach to a new stable state but if not the system will be unstable so that the system can shut down. Hence, applications of control scheme 1 to marine propulsion system are not proper in order to have fast response control system for both increase and decrease in power. Fig. 3 shows the turbine rotational speed and the produced work when applying control scheme 1 for the 100%-50%-100% load condition. As mentioned earlier, the system becomes unstable when load is again increased.

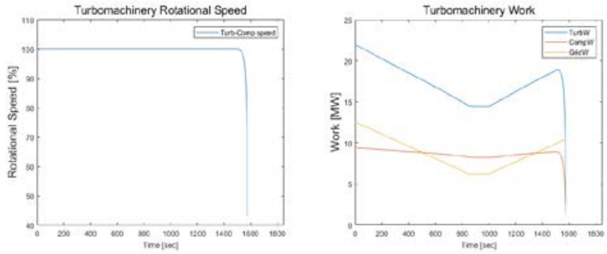


Fig. 3. Application of control scheme 1 to the cycle in the 100%-50%-100% load condition

Control scheme 2 is identical with control scheme 1 except there is no turbine bypass control. In case of control scheme 1, turbine bypass control compensates slow response of inventory charging but control scheme 2 does not have turbine bypass control at all. As a result, control scheme 2 makes MMR system to be very unstable even at 10% load reduction as shown in Fig. 4.

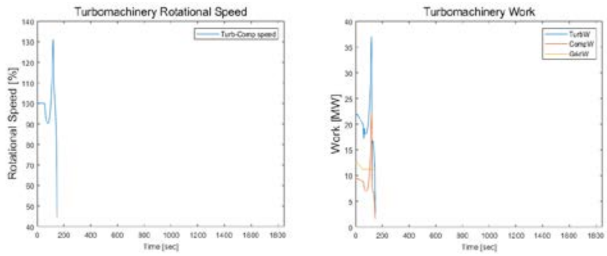


Fig. 4. Application of control scheme 2 to the cycle in the 100%-50%-100% load condition

Control scheme 3 requires two inventory tanks and both tanks are located at compressor outlet. One tank is pressurized more than the compressor outlet pressure to charge inventory through compressor outlet line and the other is pressurized less than compressor outlet pressure to discharge inventory. When this scheme is applied, delayed response problem which occurs in case of load increase can be resolved. Since inventory charging and discharging are conducted at the compressor outlet, compressor work does not exceed turbine work during inventory control. Especially, the response time of this control scheme is quick enough to regulate turbine rotational speed with only inventory control so that the turbine bypass control can be eliminated in the control scheme. This control scheme was firstly devised by Salzmann et al. [23]. As shown in Fig. 5, control scheme 3 shows superior performance compared to control schemes 1 or 2.

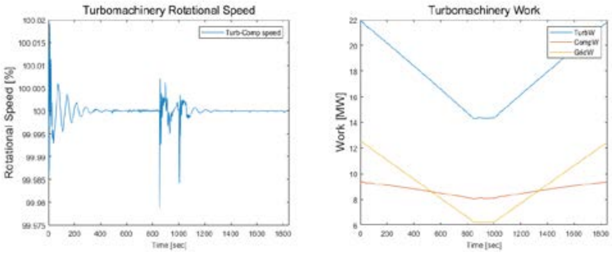


Fig. 5. Application of control scheme 3 to the cycle in the 100%-50%-100% load condition

Control scheme 4 was also invented by Salzmann el al. [23]. In this control scheme, inventory discharging is replaced with turbine bypass control and inventory feeding is implemented from high pressure inventory tank to compressor outlet section. Similarly, delayed response does not appear in control scheme 4. Among four control schemes, control scheme 4 has the fastest response time in case of load increase compared to other schemes. The left plot of Fig. 6 is the turbine rotational speed. After load is increased again from 1,000 sec, control scheme 4 shows the least error against the desired value compared to other left plots of Figs. 3-5.

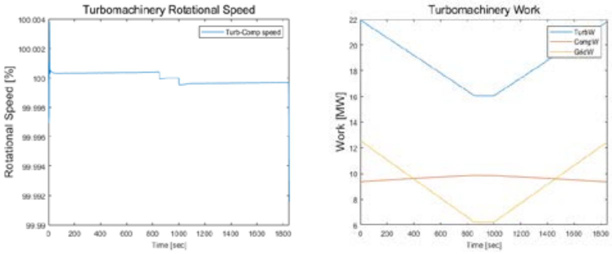


Fig. 6. Application of control scheme 4 to the cycle in the 100%-50%-100% load condition

2.3. Discussion

To evaluate which control scheme is the most suitable one in an abrupt load change condition, robustness (Response time) and performance (Cycle efficiency) should be viewed as key performance parameters. Fig. 7 shows the cycle efficiency during part load condition with respect to four control schemes. In the figure, control schemes 1 and 2 are unfit for marine propulsion control system because system can become easily unstable in case of load increase. Even though control scheme 4 showed the good robustness compared to other schemes, cycle efficiency during part load condition is much lower than control scheme 3. Consequently, control scheme 3 has slight slow response time than control scheme 4 but the gap of response time between schemes 3 and 4 is about a few milliseconds which are ignorable. On the other hand, deviation of cycle efficiency between schemes 3 and 4 is about 7% at 50% load which is substantial discrepancy. As a consequence, control scheme 3 is decided as the most suitable control scheme for a dramatic load change scenario.

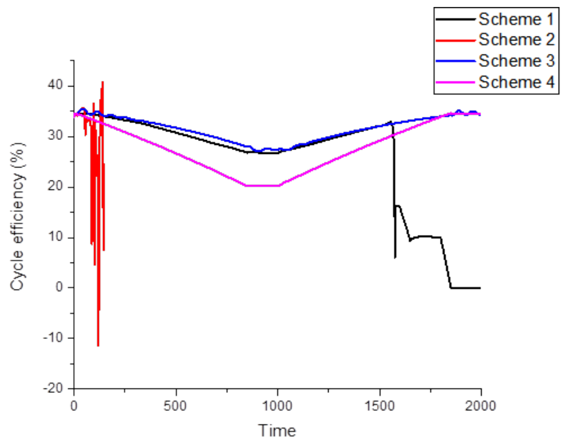


Fig. 7. Comparison of cycle efficiency with respect to four control schemes

3. Conclusion and further works

As a marine propulsion system, various power systems were considered such as diesel engine, gas turbine, steam Rankine with fossil fuel or nuclear power. Among the considered system, a combination of nuclear and S-CO_2 cycle was the most efficient and capable of enduring long journey in the northern sea route. However, most of research has focused on the development of on-shore system, and dramatic load changing scenario is often neglected for the system. In contrast, for the marine propulsion system, rapid load changes frequently occur and more robust control scheme is needed. Thus, a control scheme which has fast response and high efficiency during part load conditions should be developed. Preliminarily, the pre-designed MMR was tested to confirm whether nuclear powered S-CO_2 cycle is robust enough for a rapid change of load. A new inventory control scheme showed satisfying result from a preliminary results. More research works will be followed to test various control schemes under more severe conditions.

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