SUPER CRITICAL CO_2 REGENERATIVE BRAYTON CYCLES BASED WHR AND POWER PLANTS FOR SHIPBOARD APPLICATIONS

Conventional Propulsion and Power Generation Plants which primarily use hydrocarbons are the main prime movers used around the world for various applications ranging from Mobility, Power, Agriculture, Industries etc. The conventional prime movers use the heat generated during chemical reaction on combustion for various applications. The environmental impact of these plants has an adverse impact on the life of humans in a large extant and also impacted the lifestyle of flora and fauna throughout the world. More recently the global warming and increased greenhouse gas (GHG) emissions have driven the industrial revolution towards greener energy solutions and better energy efficiencies of conventional prime movers. Drivers such as increasing carbon and GHG footprints due to fossil fuel economies across the world has resulted in environmental issues such as Global Warming, Ozone Layer Depletion and Climate Change, along with soaring fuel prices are driving the conventional energy systems to be more and more efficient, minimize losses by adopting sustainable, energy efficient and energy recovery technologies. In a typical marine gas turbine engine, at the rated power only about one third of the total chemical energy contained in fuel is converted as useful power, and of the remaining about 70% energy, up to 10% goes as compression work and energy losses, while the remaining major amount (up to about 60%) of energy vents out unutilized as exhaust gases.

The environmental impact has also necessitated a change in regulatory policies governing the Marine Environment and stricter emission norms have forced the Navies around the world to change their approach towards use of hydrocarbons as primary fuel. One of the prime initiatives to improve the efficiency of a power plant used in shipboard applications is to recover the useful energy being let out to atmosphere as exhaust. The present technological developments have enabled research on use of different materials and techniques to trap and utilise the exhaust heat energy to produce useful power. One of the Novel methods under research is to use the exhaust heat energy to drive a bottoming cycle utilising CO_2 as the working medium (working fluid) for power generation or cooling techniques.

The regenerative Brayton cycle, referred to as RBC is basically a closed-loop Brayton cycle with internal regeneration to produce useful work or power. Since the operating parameters (pressure and temperature) throughout RBC are maintained above the critical point of the working fluid (CO_2), it is termed as supercritical carbon dioxide (SC-CO_2) based regenerative Brayton cycle or SC-CO_2 RBC. The supercritical CO_2 regenerative Brayton cycles are emerging as an attractive option due to the simple design, better power density, least volume and smallest footprints than the conventional Brayton cycle equivalents.

The proposed supercritical CO_2 RBC based waste heat recovery system for shipboard application consist of five principal components namely, turbines, compressors, heat exchangers, heat recovery heat exchanger and precooler as shown in Fig.1. RBC is a closed-loop Brayton cycle using supercritical CO_2 as the working fluid, the exhaust of the shipboard gas turbine (topping cycle) at state point g_{in} enters the heat-recovery-heat-exchanger (HRHE) where it transfers the heat to the working fluid (CO_2).

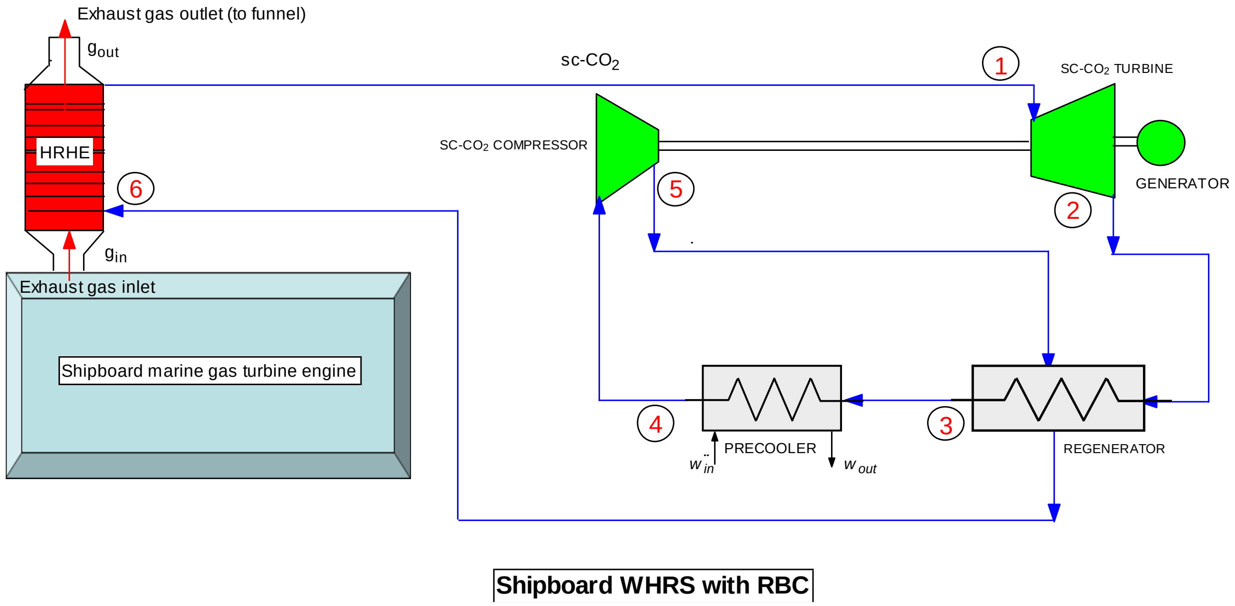

Fig.1 Schematic of SC-CO_2 RBC for shipboard WHR and Power applications

The thermodynamic cycle (T-s diagram) for the proposed system is shown in Fig.2, during the bottoming cycle, during process g_{in}-g_{out}. In the HRHE, the working fluid gets superheated to the state point 1 during the heat addition process 6-1. Thereafter, the superheated CO_2 at state point 1 enters the turbine and expands to state point 2, while delivering power during expansion process 1-2. The exhaust of the turbine enters the regenerator and cools down to state point 3 while transferring the heat to the exhaust of the compressor during process 5-6, as shown in Fig. The working fluid stream at state point 3 enters the precooler where it is precooled to state point 4 before entering the compressor. The discharge of the compressor at state point 5, enters the regenerator and gets heated up to state point 6 and finally enters the heat recovery heat exchanger where it gets superheated to state point 1, thereby, completing the cycle.

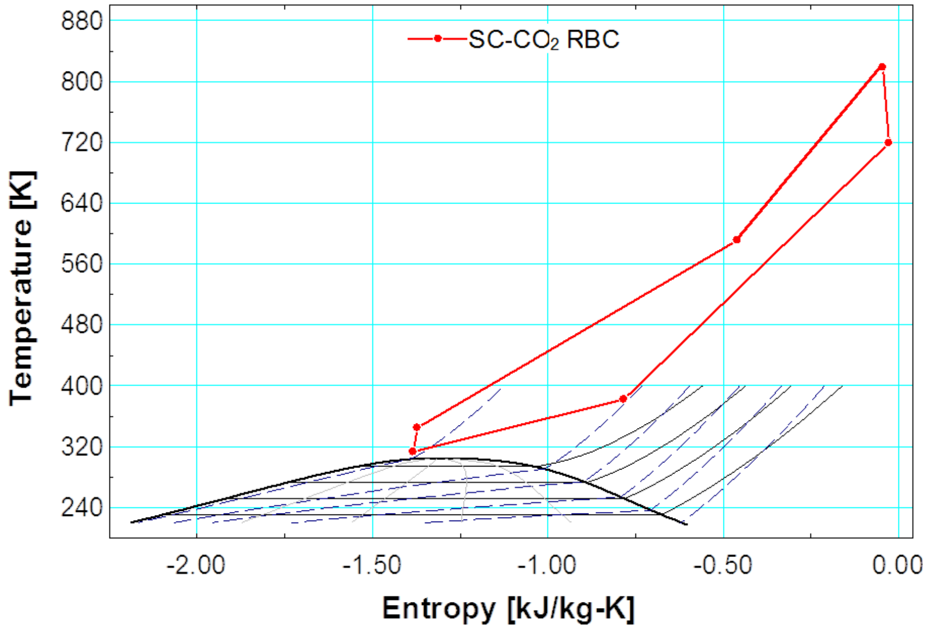

Fig.2 T-s diagram of SC-CO_2 RBC

Another improved but complex variant of RBC is the regenerative recompression Brayton cycle (RRCBC) which consists of seven main components, turbine, compressors (main compressor and recompression compressor), regenerators (high temperature recuperator and low temperature recuperator), heat recovery heat exchanger, precooler or gascooler, etc. as shown in Fig.3.

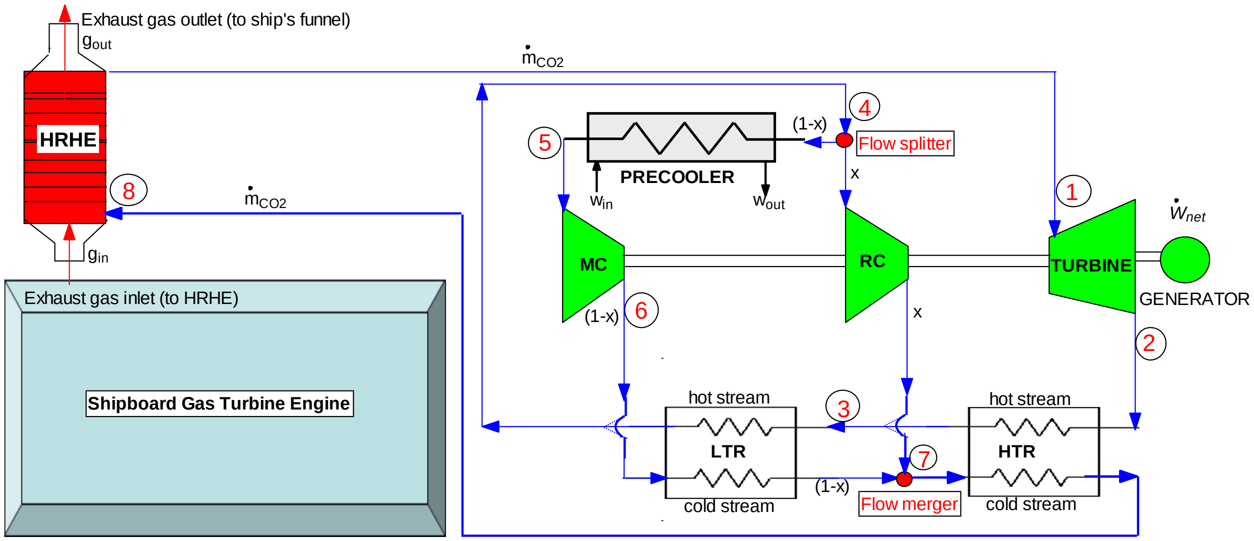

Fig.3. Schematic of SC-CO_2 RRCBC for shipboard WHR and Power applications

The exhaust of the topping cycle gas turbine at state point gin enters the heat-recovery-heat-exchanger (HRHE) and transfers the heat during process gin-gout to the supercritical CO2 as the working fluid (bottoming cycle) which gets heated to state point 1 during the heat addition process 8-1. The superheated CO2 at state point 1 enters the turbine and expands to state point 2, while delivering power during expansion process 1-2. Further, the exhaust of the turbine enters the high temperature regenerator (HTR) and cools down to state point 3, while transferring the heat to the exhaust of the recompression compressor (RC) during process 7-8, as shown in Fig.4. Subsequently, the remaining excess heat of the hot stream of CO_2 is utilised in the low temperature regenerator (LTR) during process 3-4, while this heat is taken away by the exhaust of the main compressor (MC) during process 6-7. The stream at state point 4 is split via a flow-splitter and a small fraction (x) of the stream enters the recompression compressor (RC) and remaining (1-x) of the stream is precooled in a precooler (also called as gascooler) to state point 5. At state point 7, both these streams get mixed and together enter the high temperature regenerator (HTR) and get internally heated to state point 8 before entering the heat recovery heat exchanger (HRHE) where the CO2 stream finally, gets superheated to state point 1 thereby, completing the cycle.

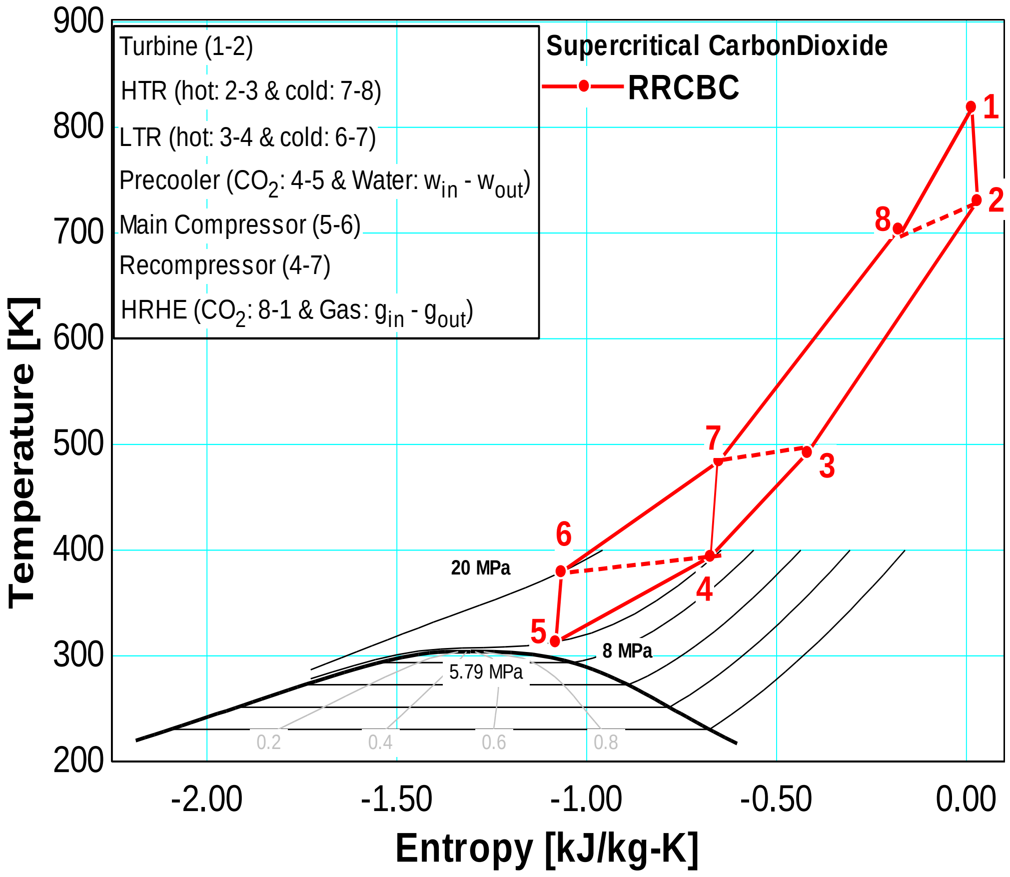

Fig.4 T-s diagram of SC-CO_2 RRCBC

This technology has an immense potential for future power plant applications in navies owing to the added advantage in significant gains in net power output of shipboard gas turbine (up to ~27% of the rated power) in case of RBC, and up to ~25% of rated power in case of RRCBC are possible.

Under low or part-load operating conditions, more amount of waste heat can be recovered for the same amount of exhaust gas input. This leads to enhanced energy conservation with improved waste heat recovery especially with low relative loads. The thermo-economic cost decreases as the material of heat exchanger is changed from costlier hastealloy to cheaper stainless steel. However, the performance is observed to be lower for stainless steel as the rational efficiency decreases and the entropy generation number increases.

The influence of variation in CO_2 properties on cycle is significant for cycle performance. The cycle is very sensitive to the pressure ratio and that even a slight departure from the optimum pressure ratio will cause a significant reduction in cycle performance. The turbine isentropic efficiency has a more pronounced effect on the second law efficiency than the compressor isentropic efficiency. For the given range of study, the second law efficiency increases by 12% in case of turbine isentropic efficiency whereas only 4.5% in case of compressor isentropic efficiency.

It is found through experimental studies in labs that the RRCBC is relatively less sensitive to pressure ratio than the RBC. Further, the optimum cycle pressure ratio that maximises the cycle efficiency is found to be lower in case of RRCBC than that of RBC, across entire range of load conditions.

In addition to significant gain in overall power, it is estimated that with the RBC system significant amount of carbon credits can also be earned annually, that may vary from about INR 71 Lakhs at the 100% relative GT load (design point) to about INR 50 Lakhs at 60% relative GT load. Whereas, with the RRCBC system carbon credits that can be earned vary from about INR 65.4 Lakhs at design point to about INR 47.2 Lakhs at 60% relative load.

The super critical CO_2 based advanced compact power generation systems due to their distinct advantages can be implemented for next generation marine vessel developments to reap the benefits in fuel economy, operational cost reduction, material management, effective utilization of fossil fuels and better space management. Presently, such systems are undergoing extensive experimental investigations at research labs worldwide including select academic institutes such as IISc Bangalore in collaboration with the USA and it would be prudent on part of the Navy to fund collaborative R&D in these technology for reaping early benefits and maturisation of nascent technology for shipboard applications.