ABSTRACT
The most effective way to improve economic competitiveness of NPPs is to enhance its efficiency which has remained static at around 33% since the first commercial LWR came into operation. New generation reactor designs including the six Gen-IV reactor concepts aim to increase the NPPs efficiency to almost 50%. This is proposed to be achieved by high temperature designs using Brayton cycle based power conversion systems. World over, Super-critical Carbon dioxide Brayton Cycle (SCBC) for power generation is an important R&D area. High efficiency SCBC power conversion system is proposed as power conversion system for Indian Molten Salt Breeder Reactor (IMSBR) and Innovative High Temperature Reactor (IHTR). This section provides the details regarding design and development of SCBC for these reactors.

BACKGROUND
Enhancing the economic competitiveness of Nuclear Power Plants (NPPs) is a major objective of the advanced reactor designs. In the past, most of the work and efforts had been directed towards simplification and cost reduction of the nuclear island. Similar efforts are required towards redesign and reduction of turbine island cost as it constitutes ~30 % of the total cost of NPPs, Dostal (1). Besides, the most effective way to improve economic competitiveness of NPPs is to enhance its efficiency which has remained static at around 33% since the first commercial LWR came into operation. In order to achieve the high efficiency of electricity generation, let us consider closed cycle power generation systems. Closed cycle power generation systems most commonly use Rankine cycle and recuperated Brayton cycle. Both of these thermodynamic cycles involve two constant pressure and two isentropic processes. The Rankine Cycle operates mainly in the saturated region of its working fluid, whereas the Brayton Cycle operates entirely in the superheat or gas region. Rankine Cycle is inherently efficient, since the heat is added and rejected isothermally and the pressure rise in the cycle is accomplished by pumping a liquid, which is also an efficient process requiring small energy input. Therefore, the ideal Rankine cycle can achieve over 90% of Carnot cycle efficiency between the same temperatures. The ratio of net work output to gross work in Rankine cycle is large. But the temperature range of Rankine cycle is severely limited by characteristics of working fluid. To avoid this, if superheating is employed, it departs the cycle from isothermal heat addition. In addition, if temperature range is increased without superheat, it leads to excessive moisture content in the turbines and results in blade erosion. The expansion ratio of this cycle is usually large and in some cases, requires in more than 30 turbine stages. On the other hand, the recuperated Brayton Cycle adds heat at constant pressure over a temperature range. The temperature level in this cycle, is independent of the pressure level. Since this cycle operates in gas region, no blade erosion occurs in the turbine. The pressure ratio is low, therefore one or two turbine stages are adequate. The compression process requires more energy input in comparison to Rankine cycle and therefore the net work to gross work ratio is small. The cycle is very sensitive to compressor efficiency and pressure drop. The thermodynamic power cycle, which avoids most of above stated problems of these cycles and yet retains many of their advantages, is the supercritical cycle.
SUPERCRITICAL CARBON DIOXIDE BRAYTON CYCLE (SCBC)

A recuperated brayton cycle has mainly five components namely compressor, heat source, gas cooler, recuperator and turbine to produce work. Figure-1 (a) shows the schematic of recuperated brayton cycle, while figure-1(b) shows the corresponding T-S diagram for this cycle.

In Ideal brayton cycle, the heat is added and rejected at constant pressures in this cycle. Isentropic expansion and compression of working fluid occurs in turbine and compressor respectively. In ideal case efficiency of brayton cycle depends only on pressure ratio. Like any other power cycle, the efficiency of brayton cycle may be improved by employing reheat, inter cooling and recompression. These options have been studied by Dostal(1) and he concluded that the recompression cycle resulted in highest efficiency, while re-heating was found good option mainly for indirect cycles and Inter-cooling offered modest efficiency improvement.

The supercritical cycle offers the characteristics, which are desirable in a practical application such as high thermal efficiency, low volume to power ratio, no blade erosion in the turbine, no cavitation in the pump, single stage turbine and pump, single phase fluid in the heat rejection process, and insensitivity to compression efficiency. With carbon dioxide as the working fluid and a nuclear reactor as the heat source, the supercritical power cycle can be a compact and portable electric power generator.

In fact, the idea of using Supercritical CO2 (S-CO2) in power systems is not new one. The S-CO2 based brayton cycle has very long history, which dates back to 1948, when Sulzer Bros. filed patent for partial condensation brayton cycle. The advantages of CO2 fluid were quickly realized and investigations on supercritical CO2 cycles were carried out in many countries including Russian Federation, Italy, United States, and Switzerland among others. The design and development of Supercritical Carbon dioxide Brayton Cycle (SCBC) gained momentum two decades later when E. G. Feher(2) and Gianfranco Angelino (3) rediscovered the idea and thoroughly described the systems.

The carbon dioxide was selected because of the moderate value of its critical pressure, its stability and relative inertness, sufficient knowledge of its thermodynamic properties, non-toxicity, abundance and low cost. Moreover, low critical temperature leads to lower temperature of heat rejection, thus CO2 in non-condensing cycles has the greatest potential for high efficiency. The
specific advantage of supercritical CO2 is its high density, which is comparable to liquids resulting in low compressor work and component sizes. The sizes of SCBC components are considerably lesser than that of traditional Rankine cycle, helium Brayton cycle and gas turbine power plants. To sum up, SCBC is simple, compact, less expensive and have shorter construction periods, thus improves overall economics.

The SCBC offers comparable efficiency as helium Brayton cycle i.e. 45%-48%, at significantly lower temperature i.e. 500 °C instead of 900 °C. Thus, SCBC is well suited to any type of nuclear reactor with core outlet temperature above 500 °C. Figure-2 shows the efficiencies of the power cycles as a function of source temperature, Wright (4).

The advantages of SCBC have been recognised globally. Many countries have started their dedicated research program for development of SCBC. High efficiency SCBC based power conversion system is being considered for power generation in many of the advanced reactors, including Indian Molten Salt Breeder Reactor (MSR), Innovative High Temperature Reactor (IHTR).

SCBC FOR MOLTEN SALT AND HIGH TEMPERATURE REACTORS

Considering the advantages of SCBC, India has taken up the development of SCBC based power conversion system with specific application in its proposed IMSBR and IHTR as well as solar power plants. Several programmes were initiated for the development of SCBC in the country. A 3-stage roadmap was drawn up for the development of SCBC to minimize the cost. The first stage is the development of a kW range SCBC for use in solar power plants as well as the Compact High Temperature Reactor (CHTR). In the 2nd stage it will be scaled up to MW range for application in solar plants as well as the 5 MWth molten salt demonstration reactor (MSRD), under development. The third stage will be a scale up to 850 MWe commercial Indian reactors e.g. IMSBR and IHTR.

Molten Salt Breeder Reactors (MSBRs), self sustaining with thorium, are anticipated for large scale deployment during the 3rd stage of Indian Nuclear Power Programme. To achieve this objective, design and development work has been initiated on two molten salt reactors, a low power 5 MWth, technology demonstrator, which is capable of generating 2 MWe using high efficiency Brayton cycle turbine. With the recent commissioning of Power Reactor Thoria Reprocessing Facility (PRTRF), it is possible to setup the demonstration plant by 2025, which will use 2 MWe SCBC for power conversion. In addition, an 850 MWe commercial IMSBR is also under development. The construction of commercial IMSBR is planned in mid thirties (~2035).

IHTR is a 233U-Th fuelled, molten salt cooled pebble bed high temperature reactor. It is being developed to operate at 1000 °C. It is planned to build an IHTR technology demonstrator (20 MWth), which will operate at 750 °C, for development and demonstration of technologies associated with high temperature pebble bed reactors. Whereas, the rated power of IMSBR is 850 MWe and it is proposed to operate at 800 °C. As discussed above, SCBC is well suited for this temperature range. Thus, a simple recuperated SCBC was analysed for IMSBR and IHTR technology demonstrator to optimise the process parameters and efficiency. The scoping studies were carried out with different parametric conditions like compressor inlet pressure, pressure ratio and turbine inlet temperature. The properties of super-critical CO2 were taken from NIST database, Lemmon et. al. (5). The results of the analysis are shown in figure-4.
Fig. 4(a): $\eta$ v/s. Pressure ratio (Pr) for IMSBR

Fig. 4(b): $\eta$ v/s. Pr for HTTR technology demonstrator
Fig. 5(a): SCBC for IMSBR

Fig. 5(b): SCBC for IHTR technology demonstrator
The results of these analyses indicated that cycle efficiency around 50% is achievable for turbine inlet temperatures in the range of 800 °C to 900 °C, hence S-CO2 based Brayton cycle is a promising and efficient option of power generation for upcoming IHTRs as well IMSBRs.

CONCLUSIONS

SCBC is a promising and efficient power conversion cycle is for upcoming Indian high temperature reactors as well IMSBRs, which can significantly alter the competitiveness of NPPs compared to fossil fuelled power plants. In view of this, India has formulated a 3-stage roadmap involving development of kW range, MW range and a large commercial size SCBC power conversion system.

REFERENCES


