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BENEFITS, DRAWBACKS AND FUTURE TRENDS OF BRAYTON HELIUM GAS TURBINE CYCLES FOR GFR AND VHTR GENERATION IV NUCLEAR POWER PLANTS

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ABSTRACT

Numerous studies are on-going on to understand the performance of Generation IV (Gen IV) Nuclear Power Plants (NPPs). The objective is to determine optimum operating conditions for efficiency and economic reasons in line with the goals of Gen IV. For Gen IV concepts such as the Gas-cooled Fast Reactors (GFRs) and Very-High Temperature Reactors (VHTRs), the choice of cycle configuration is influenced by component choices, the component configuration and the choice of coolant. The purpose of this paper to present and review current cycles being considered – the Simple Cycle Recuperated (SCR) and the Intercooled Cycle Recuperated (ICR). For both cycles, helium is considered as the coolant in a closed Brayton gas turbine configuration. Comparisons are made for Design Point (DP) and Off-Design Point (ODP) analyses to emphasise the pros and cons of each cycle. This paper also discusses potential future trends, include higher reactor Core Outlet Temperatures (COT) in excess of 1000 degrees Celsius and the simplified cycle configurations.

INTRODUCTION

Generation IV reactors are revolutionary concepts when considering the reactor design, safety and waste management systems and power conversion. A key aspect for the designs is to improve cycle thermal efficiency when compared to the incumbent designs [1]. Furthermore, simplifying the plant design is crucial in enhancing the economics of the life cycle and energy production costs [2]. Complex design configurations derived from complicated arrangements may increase plant capacity but it is not clear whether this will improve the economics. In this case, the overall efficiency of the plant may not substantiate the costs. At present, there are 2 cycle configurations that aim to improve the economics for Gen IV concepts. They are the Simple Cycle Recuperated (SCR) and the Intercooled Cycle Recuperated (ICR). The objective of this paper is to review both cycle configurations by focusing on the design and Off-Design (OD) performance characteristics of the Gas-cooled Fast Reactors (GFR) and Very-High Temperature Reactors, whereby helium is utilised as a coolant and the power conversion is provided by a gas turbine in a closed Brayton cycle.

NOMENCLATURE

Notations

CW	Compressor Work (W)
PR	Pressure Ratio
SW	Specific Work/Power Output (W/Kg/s)
TW	Turbine Work (W)
UW	Useful Work (W)

Abbreviations

C	Compressor
CH	Precooler
COT	Core Outlet Temperature
DP	Design Point
GEN IV	Generation Four
GFR	Gas-Cooled Fast Reactor
HE	Recuperator
HPC	High Pressure Compressor
IC	Intercooled Cycle
ICR	Intercooled Cycle Recuperated

IPC	Inventory Pressure Control
LPC	Low Pressure Compressor
NPP	Nuclear Power Plant
NTU	Number of Transfer Units
OD	Off-Design
ODP	Off-Design Point
OPR	Overall Pressure Ratio
R	Reactor
RPV	Reactor Pressure Vessel
SC	Simple Cycle
SCR	Simple Cycle Recuperated
TET	Turbine Entry Temperature
VHTR	Very High Temperature Reactor

Generation IV (Gen IV) Systems

The Generation IV (Gen IV) concepts that are the focus of this study are the Gas-Cooled Fast Reactor Systems (GFRs) and Very-High-Temperature Reactor Systems (VHTRs). The GFR has the advantage of a high temperature reactor with a core and fast spectrum, which means that the core can be designed to be smaller. The Core Outlet Temperature (COT) is between 850-950°C and utilises an efficient Brayton helium cycle. The pros of using helium as the coolant include it can be used to cool the Reactor Pressure Vessel (RPV), it is chemically inert, single phase cooling in all circumstances of the compression, heating and expansion phases and neutronic transparency [3]. The VHTR is also cooled using helium in the gaseous phase. The high temperature thermal reactor graphite moderation in solid state. Graphite is suitable as a moderator due to retaining good mechanical properties at high temperature. Helium is a stable coolant and is required in this reactor configuration in order not to cause a chemical reaction with the graphite moderator.

The Simple and Intercooled Recuperated Brayton Cycles

The main benefit of utilising a gas turbine for the power conversion is it is able to handle very large mass flow rates at very high operating efficiencies [4]. The combination of higher mass flow rate and higher efficiencies using a Brayton cycle means that the configuration has more superiority over the Rankine cycle in terms of component and cycle efficiencies. The use a precooler upstream of a compressor with a lighter molecular mass coolant such as helium means quicker transfer or rejection of heat. This is a stark contrast to the use of water to raise steam and circulate using lots of pumps and condenser.

The 2 cycles of focus are the Simple Cycle Recuperated (SCR) and the Intercooled Cycle Recuperated (ICR). The SCR includes a compressor and a turbine, which make up the turbomachinery. Focusing is on the turbomachinery and the reactor alone, the work required by the compressor is usually lower than overall work produced by the turbine. After the reactor produces the necessary heat to raise the temperature of the helium, the turbine utilises the power to drive the compressor. The remaining power known as the Useful Work (UW) is then available to drive the generator load. However, component inefficiencies in the cycle means that the compression and expansion phases are not isentropic [5]. This affects the heating and cooling of the cycle because they are not achieved at stable pressures (without considering heat exchangers). This translates into significant losses in the cycle with additional work input required for the compression process. This is as a result of increases in temperature at the inlet of the compressor, resulting in a higher exit temperature [6]. The heat added into the cycle is not isobaric thus, the total gas pressure at the exit is reduced, which also means the total power extracted by the turbine is also reduced due to lower than expected gas exit pressure and reduced component efficiencies [7]. The exit turbine heat is hotter and as a result is redirected to the compressor inlet at unfavourable compression inlet temperatures.

When the precooler and recuperator heat exchangers are added to the cycle, the heat can be directed away from the cycle or to other parts within the plant where it has a positive effect on the efficiency. In the case of the precooler, it ensures the recirculated working fluid can be cooled by a cooling medium (usually seawater) prior at the compressor entry to achieve the necessary cycle inlet temperature [8]. This reduces the Compressor Work (CW) and the compressor exit temperature of the helium, which means that the reactor input thermal power will have to be increased to meet the COT demanded by the cycle [9]. Due to the reactor thermal power being fixed for a given COT, the precooler alone will not yield the Specific Work (SW) required for the NPP, which devalues the economics of the NPP [10]. To mitigate the effects of this in order to improve the performance and economics, the recuperator is introduced, which take the hot gas from the turbine exit low pressure side to the high pressure side of the cycle. The helium is preheated downstream of the compressor prior to entering the reactor. This raises the temperature to reduce the amount of reactor thermal heat input required by the cycle, thereby having a positive impact on cycle efficiency.

With regard to the ICR, the cycle also includes all of the aforementioned components that are part of the SCR. However, it is a bigger cycle, which results in a bigger NPP in comparison to the SCR. However, the difference is that the ICR includes an intercooler and a second compressor, which is downstream of the first compressor. The benefit of the ICR over the SCR is it improves the SW and UW by reducing the CW. The helium downstream of the first compressor is typically reduced to a lower temperature in the intercooler, prior to entry into the second compressor, with negligible reduction in pressure [5]. Figures 1 and 2 show the schematics of the SCR and the ICR respectively.

Helium as a Cycle Coolant

Thermodynamically, the presence of entropy in the closed Brayton cycle is ideal in quantifying the reversibilities [11]. Although there are losses in a Brayton cycle due to irreversibilities and component efficiencies, using helium means as a real gas, it has the advantage of behaving like an ideal gas and adheres to the state of reversibility (i.e. no heat is lost to the process or surrounding). To understand this effect, it is worth taking into account coolant properties that are desirable for nuclear power. According to [12], the desirable properties include non-adverse reaction with the components, low radioactivity, dissociation at high temperature during irradiation and good heat transport capabilities. When considering the heat transport capabilities such as specific heat at constant pressure, Helium has ~x5 specific heat than carbon dioxide, nitrogen gas and air. This means it carries x5 more power per unit mass. The consequences of changing from air to helium in a nuclear gas turbine have been extensively covered in [13]. Although the study focuses on off-design, control and transient operational modes of a helium gas turbine, it provided good bases for off-design analyses, which have been demonstrated in [9], [14], [15].

Modelling of the SCR and ICR Nuclear Power Plant and Performance

The Design Point (DP) and Off-Design Point (ODP) performance analyses of the SCR and ICR were carried out with an in-house modelling and simulation tool. With regard to DP performance, the tool calculates the mass flow rate, temperatures and pressures for each component based on known cycle inlet conditions and COTs. It considers the component efficiencies, pressure losses and cooling requirements of the cycle. The tool is also capable of analysing effects on cycle output, capacity and efficiency by investigating the sensitivities of any of the above parameters. When focusing on ODP performance, the tool includes component maps for the turbomachinery, which have been described extensively in [9], [14], [15]. The data generated from the tool was also used to create maps for the reactor, recuperator and intercooler. The tool can calculate the long term optimal conditions for operating the plant. This is particularly useful when reduced power settings are demanded for very long periods or when seasonal changes to ambient conditions away from DP are observed. For short term operation using Inventory Pressure Control (IPC) to regulate the flow, the power can be adjusted for short term requirements. Other requirements for short term operation may include load-following in situations where frequent variation in ambient temperature is observed. The modelling environment and governing equations are described in [7], [9], [10], [16].

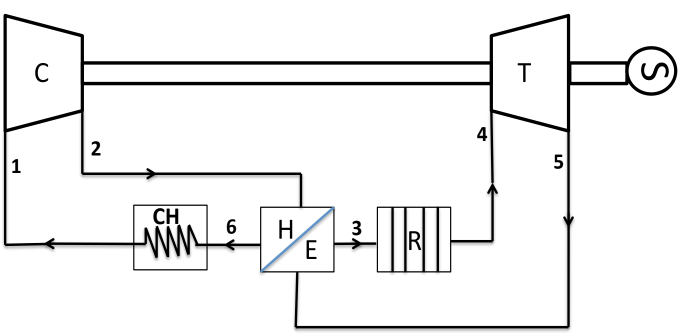

Figure 1 – Typical Simple Cycle with Recuperator [9]

Results and Discussion

<u>*Optimal Design Point Performance*</u>

With regard to DP performance, the ICR takes advantage of the lower compressor exit temperatures when compared to the SCR. This is due to the intercooler and second compressor, which adds 2 extra stages to the cycle denoted as 2a and 2b in Figure 2, in comparison to the SCR in Figure 1. Without accounting for turbine cooling and for a COT of 950°C and a compressor Pressure Ratio (PR) of 2, the effects translate into an increase of ~73% in compressor exit temperature, ~7% average increase in CW and ~3% increase in reactor thermal power for the SCR. The benefit of reduced compressor exit temperature, reduced CW and reactor thermal power equates to a ~1% increase in cycle power and a 2% cycle efficiency benefit for the ICR.

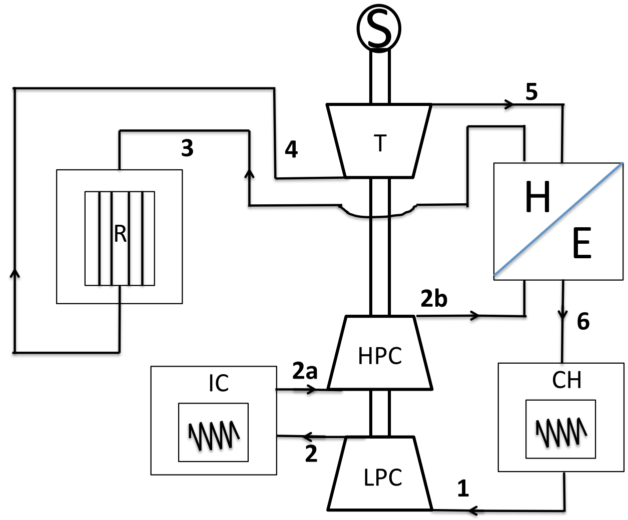

Figure 2 – Typical Intercooled Cycle with Recuperator (ICR) [9]

The achieved cycle efficiencies for the cycles are typically around 51% (SCR) and 53.2% (ICR). The above performance values apply when both cycles have the same inlet conditions including compressor PR. However, when the cycles are optimised to reflect the percentage of coolant mass flow required for turbine cooling and maximum efficiencies, the results change. Figures 3 and 4 denote the efficiency and Specific Work (SW) curves for a range of COTs/TETs (Turbine Entry Temperatures) of the SCR and ICR respectively. Firstly, hot temperature conditions have been made possible due to advancements in turbine cooling technology [7]. Cooling technologies such as film impingement convection, which is adopted for this cycle reduces the temperatures in the turbine. The cooling amount takes into account the blade metal temperature, which is necessary for turbine mechanical integrity and lifing. In addition, achieving optimal efficient cycles require tailored conditions. Apart from the inlet pressure, temperature and mass flow rate, the compressor PRs and amount of turbine cooling demanded are different for both cycles for a given COT. At the same COT of 950°C, the optimum PRs are 2.2 (SCR) and 2.6 (ICR). The SCR parameter figures for the optimised cycle are described follows - compressor exit temperature is higher than the ICR temperature by 54%; 12% decrease in CW and 15% decrease in reactor thermal power in comparison to the ICR. However, optimal running conditions for the ICR and debiting compressor coolant for turbine cooling means that the efficiency of the SCR has dropped to 50%. Furthermore, the ICR uses less percentage of the helium mass flow rate for turbine cooling, meaning the efficiency only dropped by 0.2% from previously quoted. The benefit of optimal conditions means that both cycles observe power output increases but the ICR is greater than the SCR by 26%.

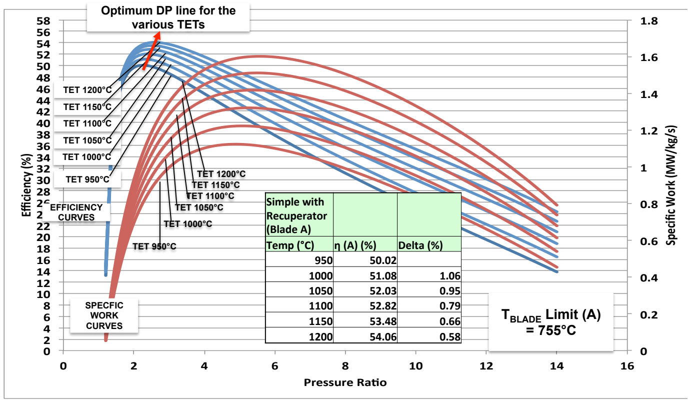

Figure 3 – SCR Optimal Efficiencies and Specific Work (SW) Curves [7]

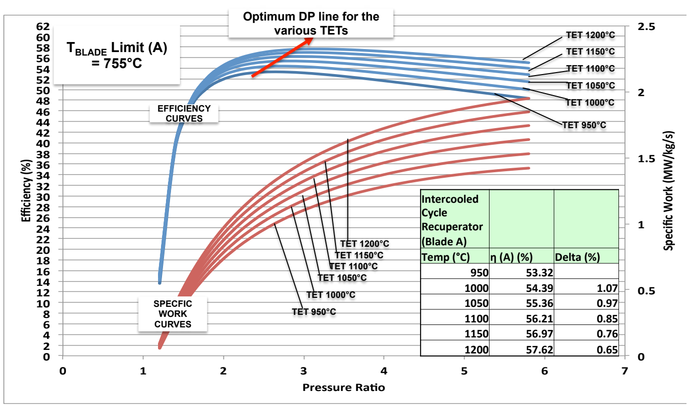

Figure 4 – ICR Optimal Efficiencies and Specific Work (SW) Curves [11]

Long Term Off-Design Point Performance

The NPP compressor inlet is influenced by ambient conditions in most cases. A change from the DP temperature of 28°C or in the power output demanded, will result in the and off-design operation, which will need to be optimised to run it in OD mode. An un-optimised off-design operation is not economical advantageous for the plant especially for a long period unless it runs at the designated ODPs where equilibrium of all component characteristics are guaranteed. Assessments have been performed in [9] for an inlet temperature range of -35 to 50°C and at COTs between 750 to 1000°C. The ODP low temperature inlet conditions of between 9°C to -9°C yielded cycle efficiencies that are 10% to 18% lower for the ICR, when compared to the DP cycle efficiency. Typically it is expected that the efficiency and power output increases with decreasing temperature as the case is with the SCR. A study in [8] indicated that there were notable changes in CW, although the ICR aims to reduce the CW, which indicated non-linearity. This level of non-linearity is dependent on the increased level of complexity (additional components) during matching. For the ICR, the 2 additional components especially the intercooler are judged to have the bigger influence on this phenomenon. This is further analysed in [14], [15].

When the COT is varied to modulate the power, the results are slightly better for the ICR. The ICR has 12% more power output than the SCR at a COT of 750°C. However, this is significantly reduced to 3% at 900°C. This indicates that the ODP performance at lower COT is better suited to the ICR. This is a noticeable difference between both cycles, which is less favourable for the ICR and affects changes in the mass flow rate. The change at 750°C translates into an increase of 0.26% for the ICR when compared to the SCR (0.20%). At 1000°C, the reduction in mass flow rate is greater for the ICR than the SCR by a factor 3. This impacts the control methods for short term operation of the power plant and demands a sizeable inventory for the ICR in comparison to the SCR.

Short Term Off-Design Point Performance

The Inventory Pressure Control (IPC) method is crucial in regulating the power when sudden changes to ambient conditions or a demand for immediate adjustment of power settings. Figure 5 shows a typical arrangement for the SCR, which can also be applied to the ICR. For comparison purposes and without changes in inlet or ambient conditions, Figure 6 illustrates the transient performances of the SCR and the ICR. The helium inventory is withdrawn during at an average flow rate of 0.13kg/s based on studies conducted in [17], with the aim of reducing the power output to 50%. The results show that the SCR took 9 minutes 27 seconds with the ICR achieving 19 minutes 8 seconds. This indicates that the ICR has a volumetric inventory requirement that is 102% larger than the SCR. This is the size difference in inventory storage as documented in [10] and takes into account the complete removal of the inventory from the cycle in emergency conditions. The percentage reduction in CW and TW are matched for both cycles. Typical limitation of the use of the IPC method is expected to be no less than 50% of full power operation.

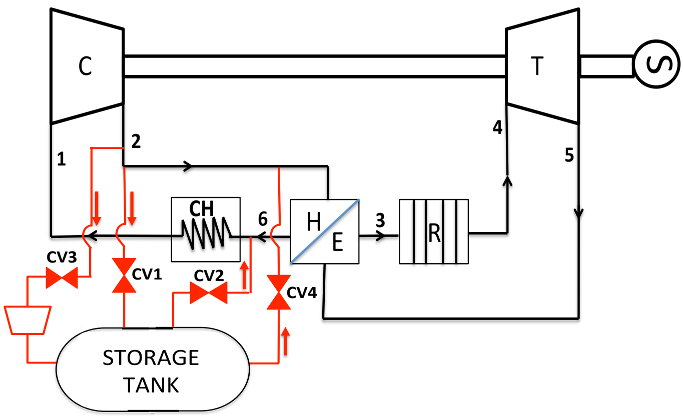

Figure 5 –Simple Cycle with Recuperator (SCR) with Inventory Pressure Control Schematic [16]

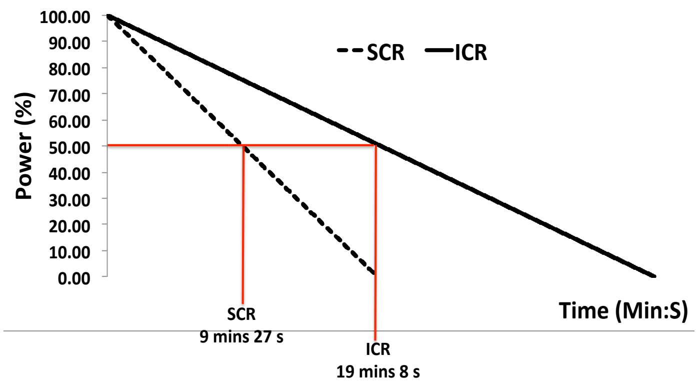

Figure 6 – Transient Part Power Performance (T_1 @ DP) [10]

For load-following operations, both cycles can be used to match the requirements to regulate power output in order to maintain reactor thermal power. This is very useful when there are varying changes in ambient temperature. The SCR is able to regulate the flow to within 2 seconds, whilst the ICR is able to regulate the flow to within 3 seconds. However, the SCR loses more power output (between 3-5% drop in power output) than the ICR (1-3% drop in power output) in order to maintain reactor power at high inlet temperature. Nonetheless, both cycles gain the same level of increase in power output at lower cycle inlet temperatures. This is typically an increase of ~3% per 10°C drop in cycle inlet temperature.

Reactor Technology Status

The development of the High-Temperature Gas-cooled Reactors has influenced the GEN IV VHTR designs. The pedigree and technology from the last half a century of development from the first reactor (Dragon) that was built to use the TRISO tri-isotropic coated particle field, is still the standard form of fuel today. Today, Asia pioneers the latest VHTR designs; the High-Temperature Engineering Test Reactor (HTTR) in Japan and the High-Temperature Test reactor (HTR-10) in China. Although the COT of the HTR-10 (~700°C) is not the same as the HTTR (950°C), it shares the design and passive safe philosophies of the VHTR objective [18]. The VHTR is a near-term deployment and suitable for electricity generation as well as hydrogen production due to the high temperature COT and is able to accommodate other service such as seawater desalination. The VHTR is typically of a prismatic cylindrical core (HTTR) or annular core (GTGTR300) or a pebble bed core. The prismatic core gives a modularity advantage in design. It has the benefit of being able to optimize the number of enrichments in the core, which will minimise the power peaking and peak fuel temperature throughout the core burnup period [18]. The pebble bed core has the fuel in the form of pebbles, stacked together. It can be controlled as proposed in the PMBR design as the control rods will be inserted at close proximity to the surrounding graphite reflector and control achieved by using neutral absorbers contained within the pebbles.

With regard to the Gas-cooled Fast Reactors (GFR), their biggest potential in addition to its high temperature capapbility for process heat, is as a high breeder reactor which make for shorter doubling times, higher power densities and burner capabilities to minimise waste. The economic advantage is to have the high power density in the design, without intermediate loops, minimise spent fuel inventory and uranium resources [19]. However, the safe concerns relating to high core neutronic leak, which led to high fissile loading also challenges the proliferation resistance characteristics. The design challenges of GFRs have meant that near term deployment is still far away in comparison to the VHTR. Nonetheless, the analysis in this paper is applicable to both due to potential COTs (850-950°C), the favourable benefits of helium, the pressures within the circuit (up to 7MPa) and the capacity to utilise IPC for both designs.

Future Trends – Smaller High Pressure Ratio Cycle Configuration

One of the future trends include the simplification of the cycle and plant design. This is a key requirement under the Gen IV framework, which ensures improved life cycle and cost of energy production [1]. The Intercooled Cycle (IC) has undergone technological advancements with gas turbines such as the General Electric LMS100 achieving 46% efficiency with air in a gas-fired plant. This prompted studies to explore the potential of this cycle for VHTR and GFRs as documented in [20]. Incorporating this cycle configuration without a recuperator before now has not been fully explored, due to the perceived economics of a nuclear gas turbine cycle without a recuperator to capture the exhaust heat and transfer back into cycle [6]. Nonetheless, its performance potential was analysed in [6]–[8], [16], [21] for DP and ODP. Figure 7 illustrates the IC configuration.

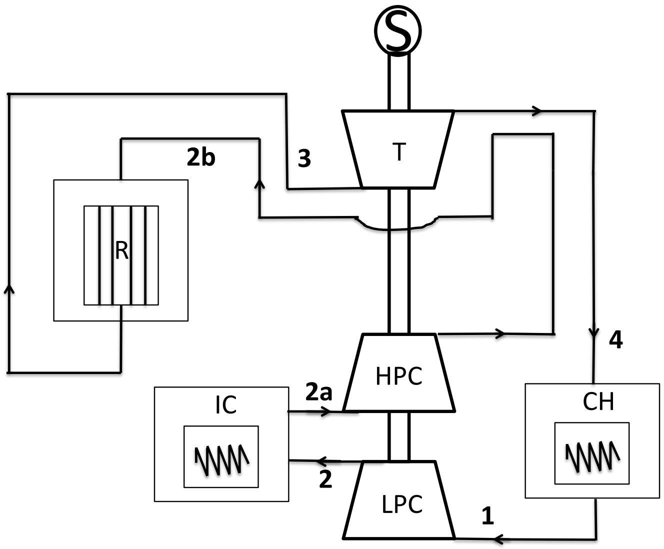

Figure 7 – Typical Intercooled Cycle without Recuperator (IC) [7]

Future Trends – Higher Core Outlet Temperatures >1000°C

Figure 8 shows the cycle efficiencies for the SCR and ICR including the IC and a Simple Cycle (SC), which is neither intercooled nor recuperated. For this study, which is documented in [7], two turbine blades were used with different maximum blade metal temperatures. Blade A had a lower metal temperature of 13% less than blade B. This was important for 2 reasons - the first is the amount of helium cooling demanded by the turbine was dependent on the COT/TET and the blade metal temperature. The second was to demonstrate the performance benefits of improved turbine blade materials. The study reviewed COTs/TETs in excess of 1200°C and considered the viability of such temperatures. The reason being that the proposal was novel and would require improvements in materials for components such as the recuperators. As such, the study concluded on immediate to near term goals which limited the SCR and the ICR to 950°C, until improvements in high temperature recuperators have been conceived. The caveat was that the economic studies had to show a real benefit.

Current reactor development aim to deliver temperatures in excess of 1200°C for Gen IV applications [22], [23], which will be beneficial for increasing the efficiency of the cycle. Judging by the advantage of the ICR and the SCR as illustrated in figure 8, it is evident that cycle efficiency gains could offer competitive savings against other generating sources. Current economic studies as documented in [24] concluded that there was no real economic advantage of COTs in excess of 1000°C for electricity generation alone. According to [18], industries that would benefit from COTs in excess of 1000°C included iron and steel production, which will eliminate the need to improve the recuperator design. Future economic studies would need to consider the overall price ($/MWh) of higher nuclear heat generation for this purpose. With regard to the IC; its economics will need to offer similar prices to the SCR and ICR to make it a viable configuration concept.

On the other hand, the SC is not recommended as a cycle because it was included for comparative reasons, which is to demonstrate the efficiency benefits of the recupertor to the SCR and the ICR.

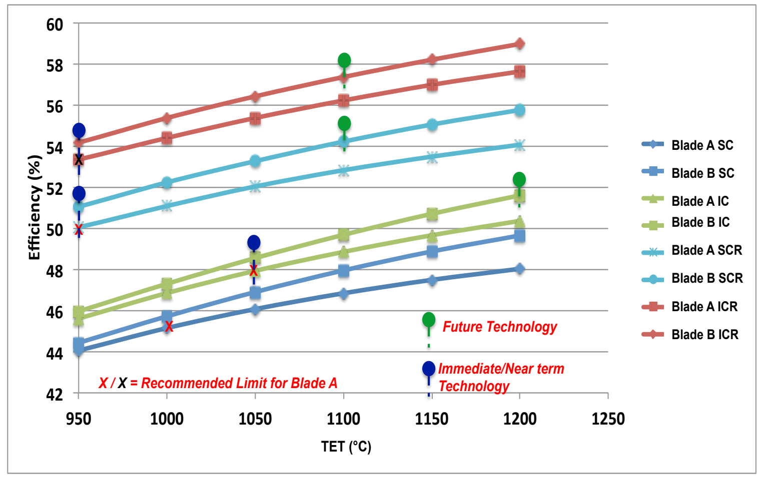

Figure 8 – Technological Assessment [7]

Future Trends – Improved Helium Compressors

Helium as a coolant is very hard to compress when compared to air. This is due to the thermophysical properties. This results in helium requiring more stages to achieve the level of compression required by the cycle. Helium compressor designs have followed the approach of traditional air compressor design philosophy. However, the flow features of helium such as higher speed of sound and lower Mach number in comparison to air means a different approach to helium compressor design will need to be investigated. This is required in order to understand how the design activities can reduce the number of stages by increasing the stage loading and how this affects the aerodynamic losses.

Conclusion

In summary, this paper aimed to describe the benefits, drawbacks and future trends of Brayton helium gas turbine cycles for Gas-cooled Fast Reactors (GFRs) and Very High-Temperature Reactors (VHTRs). The cycles of focus was the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR). The main conclusions are:

- The key advantage of utilising a gas turbine is to handle very high mass flow rates at high temperature and high operating efficiencies. This makes the Brayton cycle more superior to the Rankine cycle in terms of component and cycle efficiencies.
- When focusing on helium heat transport capabilities (specific heat at constant pressure), Helium has ~5 times the specific heat than carbon dioxide, nitrogen gas and air. This means it carries 5 times more power per unit mass.

- For similar inlet conditions, the ICR has a greater power output of 26% in comparison to the SCR. The ICR efficiency is 53% when pitched against the SCR, which is 50%.
- The ODPs enable the NPP to be operated at conditions for long periods, which are not favourable in terms of the NPP ambient temperature and power demanded. Operating the NPP at set ODPs improves the economics.
- For short term Off-Design Point (ODP) operations, the Inventory Pressure Control (IPC) method is key to regulating the power. The ICR has a larger volumetric inventory requirement that is 102% greater than the SCR. This also adds to the fact that without considering IPC, the ICR requires 2 additional components, which will increase the size and complexity of the plant, in contrast to the SCR.
- Future trends include simplifying the cycles to make the NPP smaller, increasing Core Outlet Temperature up to 1200°C, which could benefit high energy intensive process and manufacturing industries. The other future trend include sreduced stages in the helium compressor design, which are currently based on methodologies meaning that the compressor requires more stages to compress the helium. Fututrework will look into increasing the stage loading and understanding the effects on the aerodynamic losses.

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