Citation: Sayma, A. I. (2017). Gas Turbines for Marine Applications. In: J. Carlton, P. Jukes & C-Y. Sang (Eds.), Encyclopedia of Maritime and Offshore Engineering. (pp. 1-10). John Wiley & Sons, Ltd.. ISBN 9781118476406

This is the accepted version of the paper.

This version of the publication may differ from the final published version.

Permanent repository link: http://openaccess.city.ac.uk/17728/

Link to published version: http://dx.doi.org/10.1002/9781118476406.emoe227

Gas Turbines for Marine Applications

Abdulnaser I. Sayma
City University London, London, UK

1 INTRODUCTION

Reciprocating engines have been the dominant machines used for the propulsion and power of merchant ships for over a century. Approximately, 96% of ships used in civilian applications over 100 gross tons are powered by diesel engines. Oil tankers, container ships, and ore carriers are powered by two-stroke reciprocating engines. Cruise ships, ferries, and costal shipping are powered by medium speed engines because these engines are more compact and have a much lower height, which minimizes intrusion into the passenger or cargo space. There are at least three primary reasons for the prevalence of these engines. They feature high efficiency over a wide range of operating conditions and are able to run on, heavy fuel oil manufactured from the residue of the oil-refining process, despite its impurity, and due to its low price. The diesel engine is a well-established technology able to provide marine propulsion and auxiliary power-generation reliably. There are well-established repair and spare part networks around the world, reducing the cost of operation and maintenance. The technology is well understood, and training of skilled work force is well established around the world. However and despite continued design improvements, diesel engines still produce relatively high levels of harmful emissions such as nitric and sulfur oxides (NO_x, SO_x), volatile organic compounds, and particulate matter, which are currently the subject of continuously stricter regulations. Further discussion of marine propulsion systems can be found in **Main Propulsion Arrangement and Power Generation Concepts**.

The basic principles of gas turbines are given in Section 2. A chronological account of the use of gas turbines for marine propulsion can be found in Hunt (2011) and only a brief summary is given here. The first gas turbine used to propel a ship was the *Beryl engine* installed in 1947 on the MGB2009. This was a Metrovick F2 axial flow gas turbine engine. A number of ships were subsequently fitted with gas turbine engines in the following two decades. The world's first ship to be solely propelled by a gas turbine was *HMS Grey Goose* fitted in 1953 by a 4 MW Rolls-Royce PM60 engine. In the United States, the first naval ship to be retrofitted by a gas turbine was the liberty ship *John Sergeant* using a GE FS3 4.5 MW engine in 1955 (McMullen, 1955) and entered service in 1956. A significant milestone was the 1967 decision by the Royal Navy to only use gas turbines for the propulsion of its ships. An Olympus jet engine was installed on HMS Exmouth in 1968. In the United States, the first GE LM2500 aeroderivative entered service with the US Navy in 1969. By the 1980s, all propulsion

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.
This article is © 2017 John Wiley & Sons, Ltd.
DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition)
ISBN: 978-1-118-47635-2

power for *HMS Invincible*, *HMS Illustrious*, and the Royal Aircraft Carrier *HMS Ark Royal* were provided by Olympus engines.

The main driver for their use in naval ships is their ability to support high speed sprint operation because of the high power density and rotational speeds. Gas turbines are also relatively easy to be started and stopped and their power can also be easily modulated. Gas turbines can be used either in purely mechanical propulsion drive configurations or alternatively to generate electricity, which is then used by electric drives to propel the ship. One major disadvantage of gas turbines is their poor specific fuel consumption at part load operation leading to higher operating costs. To maintain the operational advantages of gas turbines and overcome the poor part load performance, several types of combined power plants are used (Saravanamuttoo *et al*., 2009). They can be combined in a steam and gas turbine arrangement (COSAG), combined diesel engines and gas turbines (CODAG), and combined diesel generators and gas turbines (CODLAG). A given combination is tailored to accommodate the varying requirements of a naval ship such as loiter, towed array deployment or cruise, and sprint modes.

The utilization of gas turbines for the propulsion of merchant ships was slower and more gradual when compared to naval applications (RAE, 2013). The first merchant ship to be propelled by a gas turbine was the “Auris,” the Anglo Saxon Petroleum Company Tanker in 1951. An interesting experiment was retrofitting the Clyde paddle steamer *Lucy Ashton* in the early 1950s (after the end of its commercial life in 1949, originally powered by a steam turbine) by four jet engines to perform full-scale hull resistance research experiments. In 1968, the *Admiral W.M. Callaghan* was built and equipped with two aeroderivatives, Pratt and Whitney FT4 gas turbines, to be used as a merchant ship. However, it was later used for military logistic transport instead. The same engines were also fitted to the containership *Euroliner* in 1971, which sailed between the United States and Europe. In 1977, the *Finnjet*, fitted with two Pratt and Whitney gas turbines, was the largest, fastest, and the longest ferry in the world. However, its fuel consumption was too high and thus she was subsequently refitted with more economical diesel-electric propulsion system. More recently, in the early 2000s, cruise ships including the *Millennium Class* and *Queen Mary 2* were designed and powered with combinations of gas turbines and diesel-electric generators in a similar manner to naval ships.

Two types of prime movers made their appearance in the gas turbine market for merchant ships: the aeroderivative (Section 4) and the industrial gas turbines. The low weight and smaller volume advantage of gas turbines compared to diesel engines of similar power rating allow more flexibility in locating gas turbines within a ship, in particular, when a turboelectric drive is a primary design specification. It is worth noting that while the gas turbine is much smaller than a diesel engine of the same power rating, gas turbines often have larger intake and exhaust ducts compared to diesel engines, reducing their overall volume advantage. Aeroderivatives provide high power density but require the use of high grades of fuel, while industrial gas turbines give more modest levels of power density, but could use lower grades of fuel as well as offer easier maintenance regimes. A typical example of the latter was the *HS1500* high speed catamaran car ferries.

A range of commercially available aeroderivative gas turbines have been designed for the marine market; these include the GE LM2500, the WR21, and the MT30 (Figure 1). Earlier machines included the Olympus (also used for the Concord supersonic airliner) and Tyne gas turbines. The MT30 has a maximum rating of 40 MW and a thermal efficiency of just over 40%. The WR21 was a further development in marine gas turbine technology with variable inlet turbine stator vanes to enhance part-load performance. It also incorporates compressor intercooling and exhaust heat recuperation technologies (Section 3), an arrangement designed to deliver high thermal efficiency, leading to low specific fuel consumption. This engine is used as a source of power for the Type 45 destroyers of the Royal Navy.

Recent drive to reduce emissions, particularly those responsible for green house effect, led calls to rethink

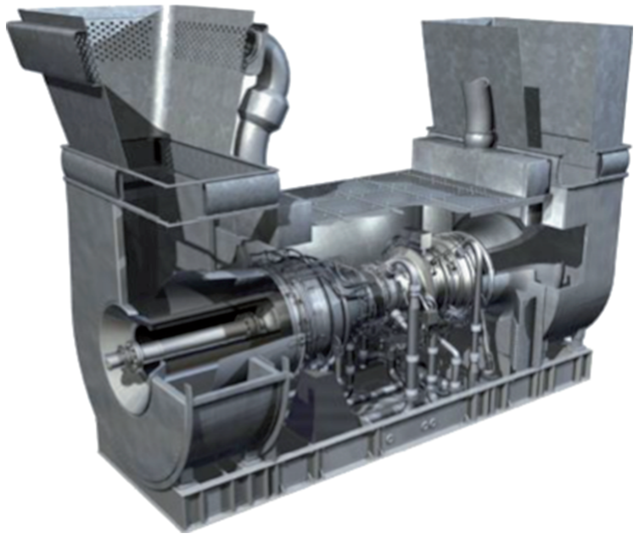

Figure 1. Rolls-Royce MT30 marine gas turbine. Courtesy of Rolls-Royce. (Reproduced with permission from Rolls Royce, 2014. © Rolls Royce, 2014.)

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.
This article is © 2017 John Wiley & Sons, Ltd.
DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2

alternative options for power and propulsion for ships. CO_2 reduction falls within the wider international debate on climate change, resulting in increasing calls for shipping to reduce emissions. International shipping is estimated to contribute about 3% of global emissions of CO_2. Although the industry has reduced its consumption of fossil fuels by employing more thermodynamically efficient diesel engines in recent years, the current total fuel oil consumption is in excess of 350 million tons per annum, and thus other measures should be considered such as carbon capture and storage (CCS) or replacement of propulsion systems with less carbon-intensive engines and fuels. This is likely to open future opportunities for gas turbines, particularly when considering performance-enhancement measures in conjunction with cleaner fuels.

In summary, gas turbines have been established for Naval applications and high speed civilian ships; however, their uses for merchant ships are still very limited. The advantages of gas turbines for marine applications are mainly their proven high power density, low weight allowing for flexibility when locating on a ship, low emissions, and short downtime when maintenance is required because they are relatively easy to be removed and replaced to be taken for maintenance. They are however currently less efficient than their equivalent diesel engines, expensive to operate due to the higher distillate fuel prices and the poor part load performance. However, enhanced performance measures and fuel flexibility may offer new opportunities for gas turbines. Gas turbines can burn gaseous or liquid fuels, including biofuels with minor modifications to the prime mover. They can also be modified to incorporate precapture technologies for carbon dioxide (Section 5).

2 GAS TURBINE FUNDAMENTALS

Although John Barber patented the first concept of a gas turbine in the United Kingdom in 1791, it was not until the early 1900s when the first experimental gas turbines emerged when several unsuccessful tests were conducted. Their development for electric power generation started and accelerated just before World War II. At that time however, they could not compete with steam turbines and diesel engine generators. It is not surprising that their first application was in military jet engines because of their superior power-to-weight ratio. This subsequently propelled them to become the primary power plant for both military and civilian aviation applications within a relatively short period of two to three decades. However, it took longer for gas turbines to make impact on other civilian applications such as power generation and nonair transport. Nowadays, a single industrial gas turbine is capable of providing power of over 300 MW at efficiencies exceeding 40% or exceeding 60% when combined with a waste heat recovery steam cycle. Another main driver to the success of gas turbines is their simplicity in terms of operating principles and the small number of moving parts when compared to reciprocating engines.

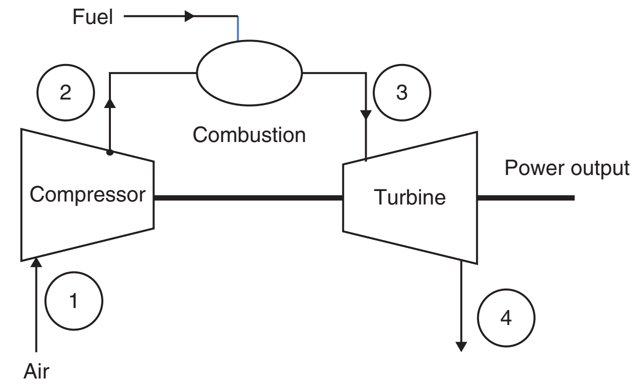

Figure 2. Schematic of a simple cycle gas turbine.

Figure 2 shows schematically the basic components of an open cycle gas turbine used to provide shaft power. In order to produce expansion through a turbine, the working fluid needs to have pressure ratio above unity from turbine inlet to exit. Thus, the working fluid, in this case air, must be compressed in a compressor. Heat is then added in a combustion chamber by burning fuel, the reaction utilizes the oxygen in the compressed air. The hot gases are expanded in the turbine to ambient conditions producing shaft power; part of this power is used to drive the compressor installed at the same shaft of the turbine. Figure 3 shows the ideal thermodynamic (Brayton) cycle on a temperature–entropy (T–S) diagram. Air enters the compressor from ambient at point 1. Process 1–2 is an isentropic compression and the ratio of pressure at point 2 to that at point 1, given the symbol r, is termed the *cycle pressure ratio*. An isentropic process is an ideal process that does not involve heat transfer to or from the working fluid and has no friction losses, the so-called adiabatic and reversible process. Process 2–3 is the heat addition process, typically happens in a combustion chamber at constant pressure. Thus for the ideal cycle, the pressure at turbine inlet, point 3, is the same as the pressure at compressor exit, point 2. Process 3–4 is an isentropic expansion in the turbine. Connecting point 4 to point 1, both having the same pressure although the exhaust gases are not necessarily those that re-enter the compressor, completes the cycle. All components were assumed to have ideal behavior; thus, compressor and turbine have 100% efficiency and combustion chamber and connecting piping have no pressure losses. Analysis of ideal cycles helps to understand the important parameters influencing the gas turbine performance, and

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.

DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2

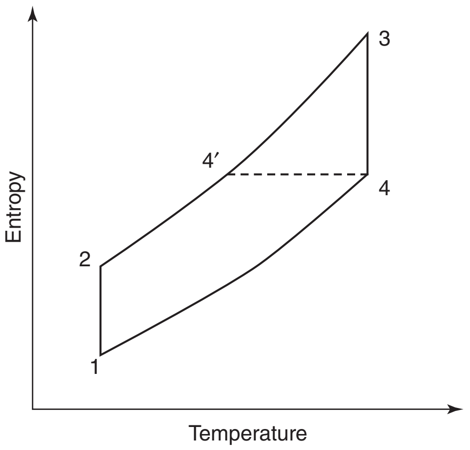

Figure 3. Temperature–entropy diagram of the ideal gas turbine (Brayton) cycle.

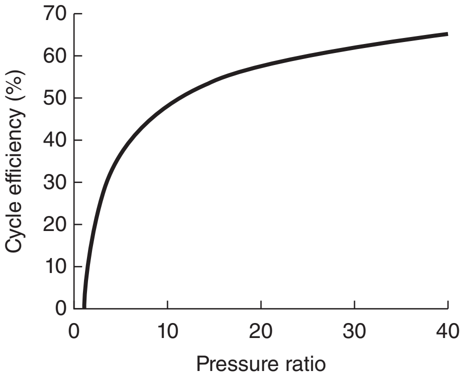

Figure 4. Ideal gas turbine efficiency as a function of pressure ratio. "*t*" is function of pressure ratio and turbine inlet temperature.

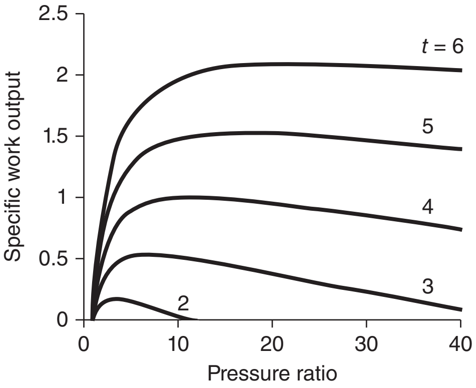

Figure 5. Specific power output as a function of pressure and temperature ratio for an ideal cycle, "*t*" is the ratio of the turbine inlet to the compressor inlet temperatures.

hence drives the technology trends. The cycle efficiency is defined as the useful work divided by the heat input. The useful work is the work delivered by the turbine less that consumed by the compressor. It is possible to show that the ideal cycle efficiency η_{cycle} is a function only of the pressure ratio and the operating fluid properties as shown in Equation 1 (Saravanamuttoo *et al*., 2009).

$$\eta_{\text{cycle}} = 1 - r^{\gamma/(\gamma-1)} \tag{1}$$

where γ is the working fluid's ratio of specific heats.

The specific power output defined as the power output per unit mass flow rate of the working fluid ($W/\dot{m}$) gives an indication of the size of the power plant. This is a function of both the pressure ratio and the temperature ratio, termed t, and defined as the ratio of the turbine entry temperature (TIT) to the compressor inlet temperature, Equation 2, where specific work is expressed in a nondimensional form,

$$\frac{W}{c_p T_1 \dot{m}} = t(1 - r^{\gamma/(\gamma-1)}) - (r^{(\gamma-1)/\gamma-1}) \tag{2}$$

where c_p is the specific heat of air at constant pressure and T_1 the temperature at the compressor entry; both can be considered constant for a given cycle condition.

Figure 4 shows the cycle efficiency for an ideal simple cycle with air as the working fluid. While it is required to obtain higher efficiency as the pressure ratio is increased, it is important to consider the specific power output shown in Figure 5. It is obvious that the specific power increases with increasing the temperature ratio, which is directly related to TIT for a fixed compressor inlet temperature. Cross-referencing the two diagrams illustrates the continuous trend in gas turbine engine technology toward increasing, in tandem, compressor pressure ratio and TIT with the objective of obtaining higher specific power output and cycle efficiency. These however are restricted by metallurgical limitations of the turbine materials and compressor design. With the continuous progress in the design methods for compressors through better understanding of their aerodynamics, it is now possible to achieve pressure ratios over 40 in multistage axial flow compressors. The achievable efficiency has to be matched by improved specific power output through increasing the TIT. This has been made possible by the introduction of turbine cooling technologies by which a proportion of the compressed air is extracted from suitable places in the compressor and channeled to cool turbine discs and blades. Modern high pressure turbine blades are also equipped with small holes where cooling air is ejected forming a thin film of cold air around the blades. Combined with

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.
This article is © 2017 John Wiley & Sons, Ltd.
DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2

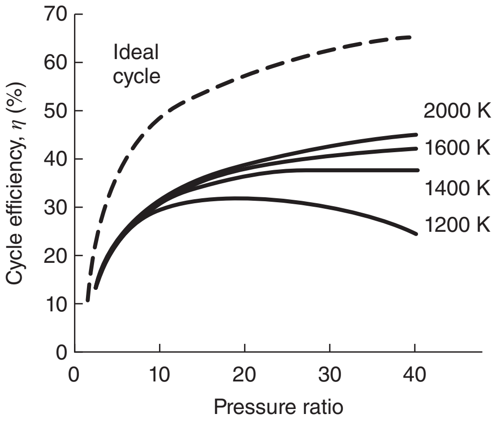

Figure 6. Ideal cycle efficiency compared to cycle for compressor efficiency 87%, turbine efficiency 85%, and turbine inlet temperature as a parameter.

improved ceramic-based thermal barrier coatings, it is possible nowadays to achieve TITs around 1700°C, well beyond the metallurgical limit of the turbine base material, without compromising blade life.

In practice, both compressors and turbines have losses resulting from a number of irreversible processes such as shear work, secondary flows, and other loss mechanisms. These result in efficiencies lower than 100%. In addition, there are pressure losses in the combustion chamber and flow channels. It can be shown that actual cycle efficiency is a function of both pressure ratio and TIT in addition to component efficiencies. Figure 6 shows typical cycle efficiency variation with pressure ratio and TIT for real component efficiencies. It is clear that this is much lower than ideal cycle efficiency, but the trends are similar.

3 EFFICIENCY ENHANCEMENTS SUITABLE FOR MARINE APPLICATIONS

A number of modifications to the simple cycle can be introduced to improve efficiency. Marine applications for gas turbines have a set of unique requirements not necessarily associated with the nominal ground installations. The fundamental issue in meeting the specific requirements of marine gas turbines is to identify the particular known and proven gas turbine performance enhancements that can effectively be incorporated in the gas-turbine-powered ships and produce the desired performance enhancement. The modifications described here have been shown to be either suitable, or has the potential to be, for marine gas turbines. In addition to those mentioned below, other techniques used to augment the power output include steam injection into the combustion chamber, which can also serve the purpose of lowering the combustion temperature and thus reducing NO_x emissions.

As the case for aircraft engine, the volume and weight that can be devoted to the ship's propulsion plant are restricted, though to a lower extent. Gains resulting from the incorporation of particular gas turbine performance enhancements must result in limited or no increase in both parameters. In addition, the maintainability and durability of the enhanced gas turbine plant during operation remote from land is an important consideration compared to the relatively easily accessible support for ground-based power plants. Gas turbine performance gains from proposed enhancements must not be significantly compromised at the expense of their operational complexities. An additional complication results from the requirements by some performance-enhancement measures, such as compressor intercooling, to use high purity water due to heat exchanger designs and materials, and thus alternative solutions should be sought such as the redesign or replacement of the particular equipment without significantly adding to the complexity or initial and maintenance cost of the system.

3.1 The recuperated gas turbine

When the exhaust temperature is reasonably higher than the compressor exit temperature, it is possible to utilize some of the heat remaining in the exhaust gases to reduce the fuel consumption. This is possible for relatively small pressure ratios or high TITs. Inspecting Figure 3, it can be seen that the temperature at point 4 can be higher than that at point 2. It is thus possible, through the use of a heat exchanger, to preheat the air before entering the combustion chamber, theoretically to point 4′ using the heat in the exhaust gases. Thus, the heat added in the combustion chamber will be reduced to that from point 4′ to point 3 instead of that from point 2 to 3, thus reducing fuel consumption and increasing cycle efficiency. The recuperated cycle configuration is shown in Figure 7. Practical constraints on heat exchangers however result in the temperature at point 4′ to be lower than that at 4. Heat exchangers are bulky and heavy and thus recuperated cycles are not used in aeroengines. However, this limitation is not severe for marine applications and improvements in cycle efficiency, and thus the reduction in fuel consumption can be more than compensated by the reduction in fuel carried onboard. It should be noted however that most marine gas turbines are those based on aeroderivatives with relatively high pressure ratios, resulting in turbine exit temperature to be either lower or not much higher than compressor exit temperature and thus are not suitable for recuperated cycles.

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.
This article is © 2017 John Wiley & Sons, Ltd.
DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2

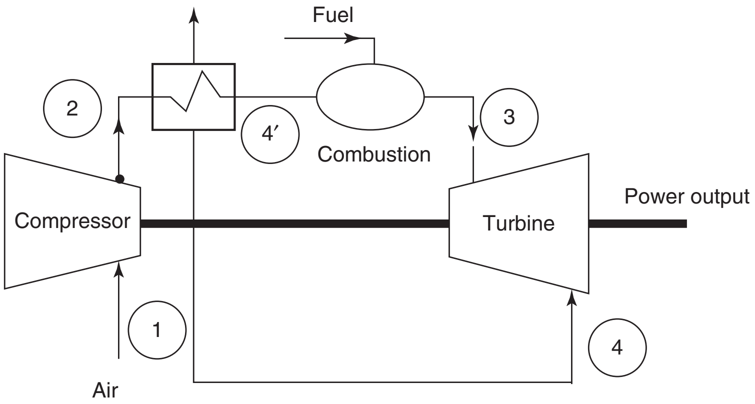

Figure 7. Schematic of a recuperated gas turbine cycle.

3.2 Compressor intercooling

The compressor absorbs large proportion of the turbine work to provide the necessary cycle pressure ratio. High pressure ratio compressors within gas turbine engines are typically made of a number of axial flow stages, each achieving part of the required pressure rise. It can be theoretically shown that the compression work required for certain pressure ratio increases as the entry temperature to the stage rises (Saravanamuttoo *et al*., 2009). Hence, cooling the air before entering each stage would result in reduction in compression work requirements. Axial flow compressors for a typical marine gas turbine comprised more than 10 stages. This makes it impractical to introduce a heat exchanger for each stage. A typical arrangement is to divide the compressor to two or three parts and use one heat exchanger to cool the air in-between them. This improves the efficiency of the compression process, thus reducing the otherwise useful turbine power absorbed by the compressor. For marine applications, seawater can be used as the cooling fluid in the heat exchanger, but requires designs that can withstand fouling and corrosion. Similar to recuperated cycle, this modification is impractical for airborne applications. The Rolls-Royce WR-21 engine was designed to power the latest naval surface combatants. It was the first aeroderivative to incorporate gas compressor intercooling and exhaust gas heat recovery.

3.3 Reheat cycles

The TIT is restricted by metallurgical limitations of the turbine material and allowable cooling technology. It is however possible to increase the heat input to the engine through a process known as *reheat*. In this case, the combustion process is broken down into two stages. In the first stage, the heat added allows the gas temperature to reach the maximum permitted by the turbine materials. This is then followed by a first-stage expansion in a turbine that is usually used to power the compressor. The second combustion chamber then reheats the working fluid before it enters the low pressure power turbine. Reheat can significantly improve some cycle characteristics. For example, it can not only increase the specific power in simple cycles but also increase the overall efficiency in combined cycle operation (Millsaps and Rodman, 2004).

3.4 Gas turbine combined cycle (GCC)

Several investigations in the past few years have advocated the use of gas turbine combined cycles to provide propulsion and electric power for ships in addition to other heating requirements. Combined cycle power plants are common in the power-generating industry where one or more gas turbines are operated in coordination with a steam turbine, which is powered by a waste heat recovery steam generator (WHRSG) utilizing the hot exhaust gases of the gas turbines. Land-based gas turbine combined cycle (GCC) plants in the power range of hundreds of megawatts are currently able to achieve thermal efficiencies just over 60% that can be enhanced further if the remaining heat after the WHRSG is used for heating purposes, commonly known as *district heating*. Various analyses have shown that the use of GCC power plants to power ships would deliver efficiencies comparable to diesel engines. GCC plants would be much smaller and produce lower harmful emissions. The achieved efficiency is obviously lower than land-based GCC plants because weight restrictions on ships dictate the use of less-powerful turbines that also have lower heat output. Figure 8 shows a schematic diagram of an integrated

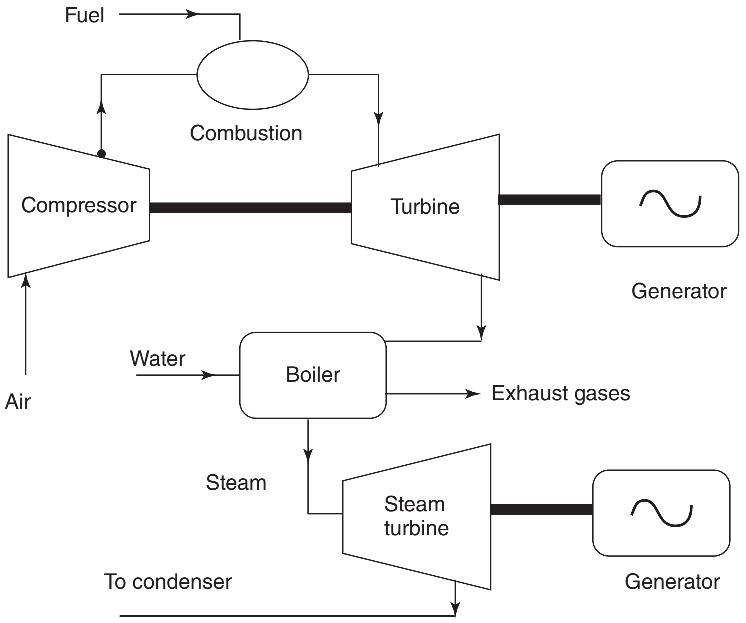

Figure 8. A schematic of a combined cycle gas and steam turbines (GCC) with one gas turbine.

gasification combine cycle (IGCC) plant consisting of one gas turbine and one steam turbine. There are several ship designs for GCC power plants that are either currently in use, or under consideration for future use in Navy ships. A number of options may be used ranging from conventional direct mechanical propulsion to hybrid mechanical and electric options, to fully integrate all electric systems (Emmanuel-Douglass, 2008).

Haglind (2008c) studied analytically the use of GCC to power large ships such as tanker and bulk carriers and container ships. The main argument is that for GCC plant to have sufficiently high efficiency, they need to be fairly large. He also argued that for such power plants to be competitive, their performance over a wide range of load conditions should be comparable with the slow two-stroke diesel engines. The study concluded that for a configuration using turboelectric transmission, it is possible to achieve high part load performance. In this configuration, the gas turbine and steam turbine power is converted to electricity and an electric motor is used to drive the ship propeller. This improved part load performance results from the ability to shut down one or more of the power units during part load operation. Haglind (2008a) performed further studies on energy management of GCC plants for marine applications and in his study (Haglind, 2008b) he performed full analysis of emissions in comparison with other forms of ship propulsion.

4 AERODERIVATIVES

Modern aeroderivative gas turbines are designed to operate with commercially available distillate fuels, which meet current legislation on emissions. However, these fuels are significantly more expensive than the conventional heavy fuel oil burnt in diesel engines used by merchant ships by a factor of about 1.5. For this reason they are not currently favored in the merchant marine industry. Despite this, nowadays, about 7% of the gas turbine market is for marine propulsion and power generation (Hunt, 2011). The majority of this proportion is gas turbines used in naval applications. These are mostly of the type known as *aeroderivatives*.

Aeroderivatives are adaptations of gas turbines, originally designed and built for aviation applications, to serve land-based applications such as power generation and sea transport. This type of gas turbines appeared in the late 1960s as a result of vast investments in the development of gas turbine for airborne applications, particularly for military aircraft. This has led to significant technological advances in terms of performance and reliability. It became apparent that if some design modifications were introduced, they would be suitable for industrial applications offering a number of advantages over purpose-built industrial gas turbines. These include the ability to start and reach peak load quickly, the large power density, and light weight (Doom, 2013). This allowed them to find widespread use

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.
This article is © 2017 John Wiley & Sons, Ltd.
DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2

for peak load and emergency energy purposes, pumping applications for gas and oil transmission pipelines and offshore oil platforms among other similar applications and naval applications (Saravanamuttoo *et al*., 2009). All main gas turbine companies nowadays have a range of aeroderivatives on offer with some dedicated for marine propulsion and power generation. Examples are GE LM2500 series, Rolls-Royce MT7 and MT30 (Figure 1), and the Pratt and Whitney GG4.

5 FUTURE TECHNOLOGIES

It is conceivable that the change of marine power plants from the current conventional systems relying on heavy fuel oil with the associated environmental penalties will be a slow process and it can only be modestly accelerated through concerted international efforts on legislation and technology development. However, the move to alternative more efficient and less-polluting systems can be considered a short to medium term solutions. In the long term, marine power plants should comply with other drivers in the power-generation sector, but less so in the aviation sector, to significantly decarbonize power systems. A number of technologies are under development for land-based applications, some have been more developed than others. This section briefly discusses some of these options and comments on future viability for marine power needs.

5.1 Carbon capture and storage

CCS has emerged in the past few years as a potential medium term tool for decarbonization of the power generation. The idea is to collect carbon dioxide from power plants, compress it, and store it either in depleted oil wells or nonporous caverns underground or below the seabed. It can also be used for enhanced oil recovery. Numerous studies have concluded that vast amounts of CO_2 could be stored for a very long time without major risk of leaking. Several technologies have been suggested for the carbon capture, some rely on what is known as *precapture*, that is, before the combustion process and others postcapture. Research is showing that both solutions may have similar levels of difficulty and added cost to the price of electricity generated despite the different technologies used. A number of small-scale demonstration plants have been built to test the technology, but so far there is no full-scale power plants operating with CCS. For gas-turbine-based power plants, there are several concepts being proposed and researched including what is known as *oxy-fuel cycles* (Anderson *et al*., 2008). The general concept is to remove nitrogen from air before entering the gas turbine, thus the fuel can be burned with the presence of oxygen only. Recycled exhaust gases are used to moderate the combustion process and increase the CO_2 concentration at the gas turbine outlet to make it easier to capture.

There are several barriers preventing the progress in this direction. These include cost and the absence of international legislation mandating the carbon free power generation and the ineffectiveness of the emissions trading schemes. Public concern about CO_2 leaks is also a factor. Although currently there is no known interest to use CCS technology onboard ships, it is conceivable, as emissions regulations get stricter, that these options may be considered. However, not withstanding the additional complications for marine applications, it is more than likely that the consideration of this option will await their success in land-based applications.

5.2 Biofuels

Aviation industry has been considering the use of biofuels as a long-term alternative to fossil fuels, and several of flight tests have been conducted in the past few years with varying degrees of the proportion of biofuels used. Biofuels have lower calorific value than kerosene, and hence the amount of fuel carried onboard for a particular mission has to increase and hence will have considerable consequences on the overall operation including the payload. The technology is still evolving and it is anticipated that such limitations will be reduced in the future generations of biofuels. Past experience shows that technological advances in gas turbine engine technology will mostly be led by the air transport sector and it can be perceived that success would lead to some penetration into the marine sector.

5.3 Energy storage

There has been a significant interest in large-scale storage of energy due to the increased share of renewables in the power-generation sector, in particular, the intermittent solar and wind power. Here, only two concepts that, in principle, may be suitable for implementation in gas turbines for the sea transport sector will be considered.

One possible technology is the storage of electrical energy by electrolyzing water. Hydrogen as energy carrier can be stored under high pressure. It is possible, in principle, to burn hydrogen in gas-turbines-powering ships. Considerable research has been conducted to achieve the utilization of hydrogen-rich fuels in gas turbines. These have been primarily based on IGCC power plants by which

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.
This article is © 2017 John Wiley & Sons, Ltd.
DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2

hydrogen-rich syngas is generated by the gasification of solid fuels such as coal, wood, or solid waste. The EU FP7 funded project, H2-IGCC (www.h2-igcc.eu), is an example where research has been conducted in all aspects of the gas turbine technology to allow the use of syngas containing up to 80% hydrogen. Modifications were required to the combustion system turbomachinery aerothermal design and turbine materials to withstand the use of the low calorific value fuel with high water vapor content in exhaust gases and fast flame propagation among other issues (Cerri and Chennaoui, 2013).

If hydrogen is to become a considerable future energy-storage medium, significant advances are still required in the safety and economy of its storage and transport, which may include specific measures for the sea transport sector.

Another technology suitable for gas turbines is compressed air storage. In this technology, air is compressed using either renewable sources or off-peak electricity and stored in heavy vessels or in the case of large-scale power generation, in underground caverns. When needed, air is released into a turbine to produce mechanical power requiring thermal energy input before it enters the turbine. The basic components of the system are a compressor, a combustor, and a turbine, which is essentially a gas turbine where the turbine and compressor are run separately. There is significant interest currently in this field, and two demonstration power plants have been running for several years (Schulte *et al*., 2012). It is possible in the future that air can be compressed onshore using renewable energy sources, stored in high pressure vessels onboard ships, and used to power the ship. However, the amount of space available for high pressure storage may limit the range of the vessel.

6 CONCLUDING REMARKS

Gas turbines have successfully been used in niche areas of the marine market and represent a proven high power density propulsion technology. In particular, their low weight gives considerable flexibility when locating them in a ship in the context of turboelectric designs. The high grades of fuel for aeroderivative gas turbines are expensive when compared to conventional marine fuels and their thermal efficiencies are lower than slow speed diesel engines of similar power. The increased pressure in introducing legislation to control emissions may reduce the cost gap between the two options. These can be enhanced, however, in combined cycle installations where the exhaust heat is used to develop additional power. A number of promising systems based on gas turbine technologies may offer alternative clean ship propulsion driven by some success in land-based applications. These include the use of hydrogen, compressed air storage, biofuels, and CCS.

NOMENCLATURE

Symbols

$\dot{m}$	air mass flow rate (kg/s)
r	cycle pressure ratio
T_1	compressor entry temperature
t	cycle temperature ratio
W	gas turbine power output
γ	specific heat ratio
η_{cycle}	cycle thermodynamic efficiency

ABBREVIATIONS

CODLAG	combined diesel generator and gas turbine
GCC	gas turbine combined cycle
IGCC	integrated gasification combine cycle
SGT	simple cycle gas turbine
TIT	turbine entry temperature
WHRSG	waste heat recovery steam generator

GLOSSARY

Aeroderivatives	Gas turbines that are originally designed for aircraft propulsion and have been modified for propulsion of ships or power generation.
Combined Cycle Gas turbines	A power plant containing a gas turbine with the exhaust gases heat is used to raise steam that can be expanded in a steam turbine to provide additional shaft power.
Combined diesel engine and gas turbine	A power plant for ship propulsion containing a gas turbine for cruise while a diesel engine is used for part load operation.
Combined steam and gas turbine	A power plant containing a gas turbine for cruise conditions and a steam turbine for part load operation.
Gas Turbines	Combustion engines based on the Brayton cycle with continuous flow.
Marine propulsion	Providing power to propel ships.

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.
This article is © 2017 John Wiley & Sons, Ltd.
DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2

RELATED ARTICLES

Dynamic Positioning
Electrical Propulsion
Ship Performance Prediction
Slow-Speed Two-Stroke Engines
Medium Speed Diesel Engines for Maritime Applications
Gas Engines and Their Fuels

REFERENCES

Anderson, R.E., MacAdam, S., Viteri, F., Davies, D.O., Downs, J.E., and Paliszweski, A. (2008) *Adapting Gas Turbines to Zero Emissions Oxy-Fuel Power Plants*. ASME Turbo Expo, GT2008-51377, Berlin, Germany.

Cerri, G. and Chennaoui, L. (2013) *General Method for the Development of Gas Turbine Based Plant Simulators: An IGCC Application*. ASME Turbo Expo, GT2013-94040, Berlin, Germany.

Doom, T.R. (2013) Aero Derivative Gas Turbines, Case Studies on Government's Role in Energy Technology Innovations, American Energy Innovations Council.

Emmanuel-Douglass, I. (2008) Performance Evaluation of Combined Cycles for Cruise Ship Applications, IMECE2008-67393, Boston, MA.

Haglind, F. (2008a) A review of the use of gas and steam turbine combined cycle as prime movers for large ships, Part I: background and design. *Energy Conversion and Management*, **49**, 3458–3467.

Haglind, F. (2008b) A review of the use of gas and steam turbine combined cycle as prime movers for large ships, Part II: previous work and implications. *Energy Conversion and Management*, **49**, 3468–3475.

Haglind, F. (2008c) A review of the use of gas and steam turbine combined cycle as prime movers for large ships, Part III Fuels and emissions. *Energy Conversion and Management*, **49**, 3476–3482.

Hunt, R.J. (2011) The history of the industrial gas turbine – (part 1 the first 50 years 1940–1990). Independent Technical Forum for Power Generation (idgtE) Publication 582.

McMullen, J.J. (1955) Gas Turbine Installation in Liberty Ship John Sergeant. SNAME, The International Community for Maritime and Ocean Professionals. http://www.sname.org/communities1/resources/viewtechnicalpaper/?DocumentKey=2a0ee04d-da56-4319-9728-3dfe42f7e9a4 (accessed 5 Jan 2016).

Millsaps, K.T. and Rodman, B. (2004) *Thermodynamic Analysis of Inter-Turbine and Intra-Turbine Reheat for Marine Gas Turbines*. Proceedings of ASME Turbo Expo, GT2004-54174, Vienna, Austria.

Rolls Royce (2014) *The MT30 Marine Gas Turbine*, Bristol, Rolls Royce. Rolls Royce. Web. 24 Nov. 2015

Royal Academy of Engineering (RAE) (2013) Future Ship Powering Options – Exploring Alternative Options for Ship Propulsion, July 2013.

Saravanamuttoo, H.I.H., Rogers, G.F.C., Cohen, H., and Straznicky, P.V. (2009) *Gas Turbine Theory*, 6th edn, Pearson.

Schulte, R., Holst, K., Critelli, N., and Huff, G. (2012) Lessons from Iowa, Development of a 270 MW compressed air energy storage Project in Midwest Independent system operator. Sandia National Laboratory Report SAND2012-0388.

Encyclopedia of Maritime and Offshore Engineering, online © 2017 John Wiley & Sons, Ltd.

DOI: 10.1002/9781118476406.emoe227
Also published in the *Encyclopedia of Maritime and Offshore Engineering* (print edition) ISBN: 978-1-118-47635-2