Land-Based Gas Turbines for Power Production

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I. Introduction

The new challenge facing the power industry today is to generate and provide clean, efficient energy that creates a minimal carbon footprint to match the growing demands for electricity. Recent developments in renewable energy provide a promising outlook for ‘clean’ energy, but because of its unreliability, green energy must be coupled with a dependable, manageable power source. Land-based gas turbines (LBGT) are the perfect candidate to fill this void in the power generation market.

Today, LBGTs account for nearly 30 GW per year of energy produced (Fletcher). LBGTs can be manufactured and installed within a few months, whereas coal-fired power plants for example take years to construct. LBGTs address the customer’s needs regarding fuel diversification, as they are able to harness the energy from a wide range of fuels. Cheap, abundant natural gas is primarily chosen as the working fluid in LBGTs. This fuel is dense in hydrogen, which translates into less CO_2 emissions when compared to other conventional fuels. LBGTs are available in a vast variety of peak power outputs, with maximums on the order of 300-500 MW (Fletcher).

LBGTs can be broken into two main functional groups. Power-producing gas turbines that mirror the basic core of jet propulsion engines are known as *aeroderivative* gas turbines. These turbines are able to be placed online during peak hours to meet the electrical demands and turned off when needs diminish. A second type of LBGT is known as a *heavyweight* engine. These industrial gas turbines can supplement both baseload and peak-energy demands.

Weight to power ratio is not an issue for LBGTs as it is for their flying counterparts. Because of this, LBGTs allow for a heavier frame, thicker casings, and solid rotors. Low cost, thermal efficiencies, and heat to power ratios are the primary areas of interest to constantly improve upon for LBGT manufacturers. As the worlds power demands continue to rise, LBGTs will play a crucial role in power generation for years to come.

II. History

Truly understanding the history of the gas turbine requires one to delve into the literature and bias development perspectives of the aviation and land-based sectors, as both sides credit one breakthrough more so than the other. One thing is for certain though, advancements in gas turbine processing, design optimization, and metallurgical technologies in the aerospace industry, for example, influenced success in the power generation division.

The LBGT maintained a fairly low profile throughout the end of the 1800's, with improvements in compressor pressure ratios and steam piston engines highlighting much of this time period. The major hurdle shared amongst all initial designers of gas turbines built for power production was proving the viability of a gas turbine system that could extract more energy from the turbine than what was required to operate the compressor. This was finally accomplished in 1906, when the first ever stand-alone gas turbine was manufactured that generated net work (Eckardt). This first engine incorporated a 25-stage radial compressor, a single-stage turbine, and a 'steam-injection' system (Eckardt). But because of its poor efficiencies (around 2-3%) and trivial power output of only 6-10 kW, its use as an industrial gas turbine was deemed impractical (Eckardt). Admissible turbine blade temperatures were low for this time period due to a lack in metallurgical expertise and technology, which placed a ceiling on the turbine inlet temperatures, therefore limiting thermal efficiencies and specific work. This can be seen in Fig. 1, which compares the thermodynamics of an engine built in the early 1900's to a present-day engine.

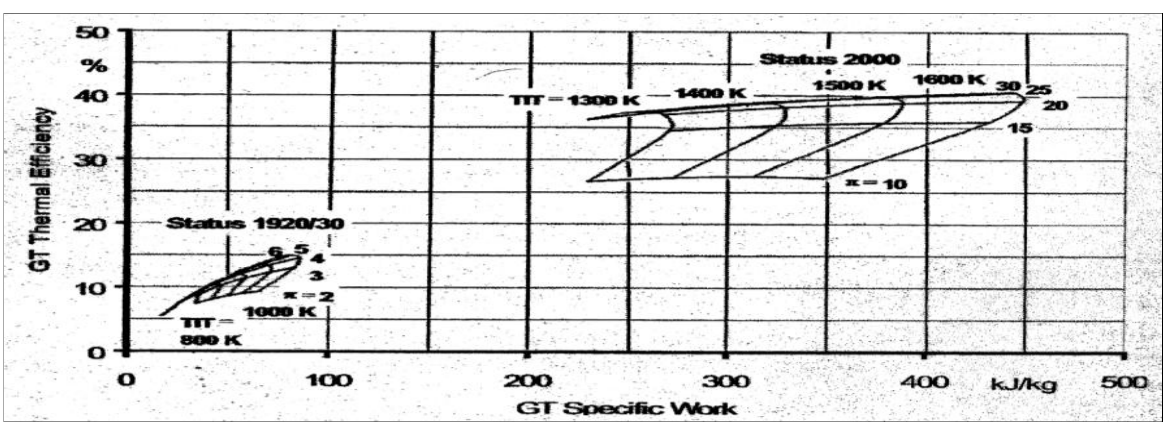

Fig. 1 Comparative plot of thermodynamics for two engines of different time periods

An axial flow compressor capable of ingesting large volumes of air was still in the initial design stages during the early 1900's. Intent on manufacturing a gas turbine that produced a substantial amount of net work, the industry first focused its attention on constant-volume, internal combustion machines. Constructed in the mid-1920s, these coal-burning turbines generated enough power to offset the poor inefficiencies of the compressor, allowing for power outputs in the 5 MW range (Eckardt). The explosive atmosphere inside the turbine required components to have a high-level of structural integrity, leading to higher costs per unit. Also, with the manufacturing of these engines came considerable complications. Therefore, the workforce of explosion turbines remained limited.

Finally, in the summer of 1939, after a considerable amount of work had transpired, geared towards designing an efficient axial compressor, the first practical, industrial gas turbine was placed online in Switzerland. This simple, constant-pressure engine was capable of generating 4 MW with a turbine inlet temperature of 820 K, pressure ratio of 4.4:1, mass flow rate of 62 kg/s, and a total thermal efficiency of 17% (Eckardt). Capitalizing on this success, extensive research went into optimizing this design to improve the overall efficiency and increase the permissible inlet temperature into the turbine, hence raising the bar on the net work these machines were capable of generating. Investments in gas turbine design and manufacturing over the next decades slowly fueled their way to the top, making gas turbines one of the key players in the power industry today.

III. LBGT Calculations and Configurations

a. LBGT Efficiency and Power-Generated Calculations

Power turbine efficiency and amount of available net energy are two key specifications to consider when sizing a gas turbine engine. The following is the equation for the efficiency (η_{PT}) of a simple-cycle gas turbine:

$$\eta_{PT} = \frac{1-\frac{T_o}{T_i}}{1-(\frac{P_{AMB}}{P_i})^{\frac{k-1}{k}}}$$ Eqn. 1 (Giampaolo 51);

where T_o is the exit temperature [K] of the power turbine, T_i is the turbine inlet temperature [K], P_i is denoted as the turbine inlet pressure [Pa], κ is the ratio of specific heats [c_v/c_p], and P_{AMB} corresponds to the atmospheric pressure [Pa]. When calculating efficiencies for combined cycle configurations, P_{AMB} is replaced by P_{out}, which is the total discharge pressure.

The second equation of interest calculates the power generated [W] by a free-power turbine and is displayed below:

$$P = 1.40 * J\dot{m}C_pT_i\eta_{PT}(1-(\frac{P_{AMB}}{P_i})^{\frac{k-1}{k}})$$ Eqn. 2 (Giampaolo 51);

where J is the ratio of unit work by the system [N*m/kg] to unit heat transferred to or from the system [J/kg], m is the mass flow rate [kg/s] at the turbine inlet, and C_p is the specific heat at constant pressure [J/kg*K]. The constant 1.40 represents the conversion factor from horsepower to Watts. As can be seen in Eqn. 2, the turbine inlet temperature and efficiency carry considerable weight in the power calculation.

b. Simple-Cycle Single-Spool Shaft-Power Engine

Simple-cycle refers to an inefficient system where heat exchangers or steam turbines are not integrated into the design to capture the excess heat generated and convert it into additional energy. Aside from the intake and exhaust, a simple-cycle single-spool shaft-power engine reflects many of the inner workings of a turbojet, with one major difference. The entry pressure into the turbine is allowed to expand through the turbine blades, allowing them to spin. The rotating turbine blades drive a generator which converts the spinning energy into electricity. A schematic of a simple-cycle single-spool shaft-power engine is shown in Fig.2.

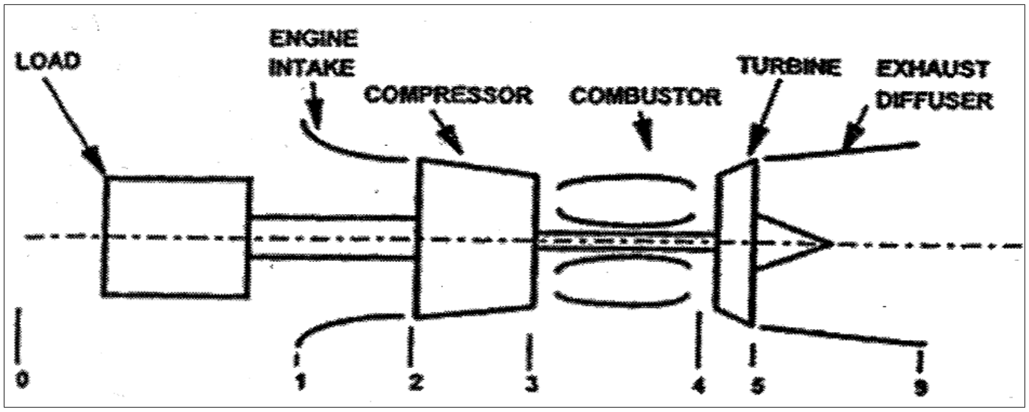

Fig. 2 Simple-Cycle Single-Spool Shaft-Power Engine Schematic

c. Simple-Cycle Free-Power Turbine Engine

The simple-cycle free-power turbine's diagram clearly models the basics of a single-spool shaft-power engine (Fig. 3). The difference lies in the fact that a free-power turbine (gas generator and power section are separate and allowed to rotate at their own speeds, whether it be 50 Hz or 60 Hz depending on location) is employed to drive the load, separate from that which drives the compressor.

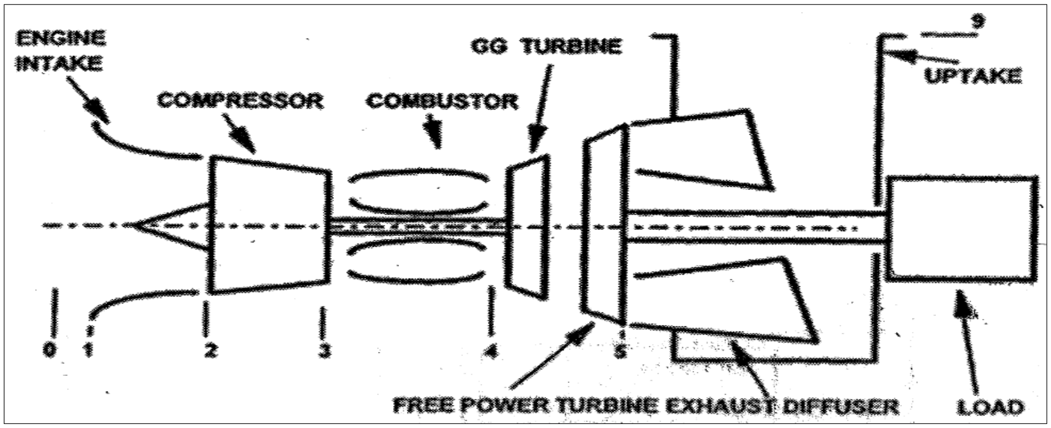

Fig. 3 Simple-Cycle Free-Power Turbine Schematic

d. Recuperated/ Regenerated Free-Power Engine

Free-power turbine engines transfer the would-be-lost hot exhaust gases back to the engine by using either a recuperator or regenerator heat exchanger. There are two basic configurations of a recuperator heat exchanger. The first is a honeycomb matrix of metal sheets stacked on top of one another that allows for the passage of hot gases to flow through one layer and cooler air to flow through neighboring sheets. The exchange of heat occurs at the interface of the metal sheets. This is known as a primary surface recuperator (Fig. 4). The second type is referred to as a secondary surface recuperator, which is far more robust than a primary surface recuperator (Fig. 5). In order for heat exchange to occur within a surface recuperator, the majority of the heat must pass through the wavy secondary sheet before it reaches the cool side (Fletcher). In both cases, the hot gases and cool air flow in opposing directions.

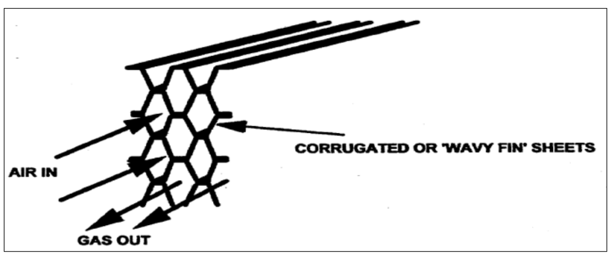

Fig. 4 Primary surface recuperator

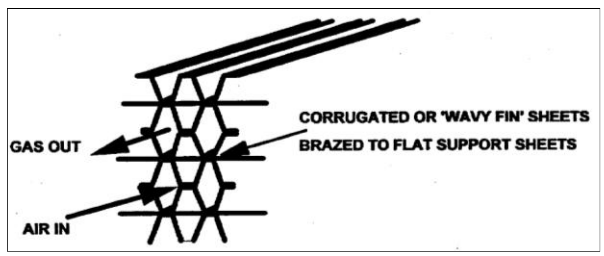

Fig. 5 Secondary surface recuperator

The regenerator heat exchanger (Fig. 6) on the other hand is comprised of a ceramic disk which rotates at roughly 30 rpm powered by an electric motor (Fletcher). Heat transfer occurs when the ceramic disk rotates between the cool air and hot gases, consequently causing the air ducts to be alternately cooled and heated (Fletcher). This method of heat exchange is radically different than recuperation and can reach thermal efficiencies of up to 90% (Fletcher).

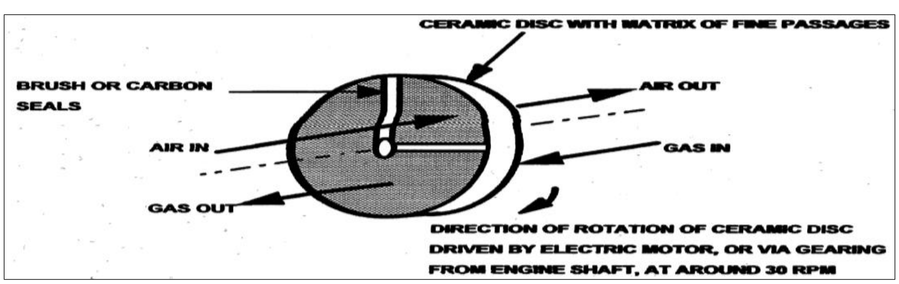

Fig. 6 Regenerator heat exchanger

As can be seen in the schematic of a recuperated free-power turbine (Fig. 7) , pressurized air exits the compressor and passes through the heat exchanger, where it is eventually heated by hot exhaust gas. Next, the hot air travels to the combustor for additional heating. Less input energy into the combustor is required to attain the same turbine inlet temperature as before. This is a result of initial heating inside the heat exchanger, drastically improving overall efficiencies.

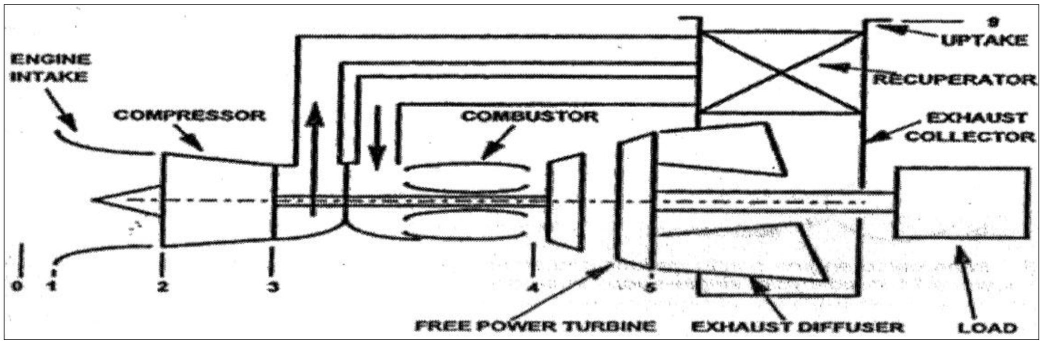

Fig. 7 Schematic of a recuperated free-power turbine configuration

e. Intercooled Free-Power Turbine Engine

Engine power outputs and efficiencies typically diminish as heat is rejected to the surroundings, but this is not the case for an intercooled free-power turbine. This particular design employs an intercooler between the first and second compressor (Fig. 8), rejecting heat to an external heat sink, such as water. This reduction in heat increases performance and power generation because of the decrease in power absorption that occurs in the second turbine as a result of lower inlet temperatures. These lower inlet temperatures correspond to a decrease in work necessary for a given pressure ratio.

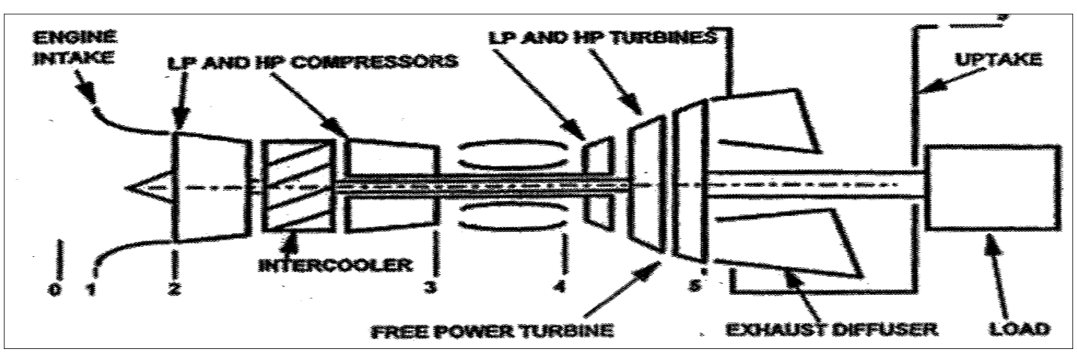

Fig. 8 Schematic of an Intercooled free-power turbine configuration

IV. LBGT Applications

a. Standby power generators

Simple-cycle single spool gas turbine engines are typically chosen over free-power turbines for this class because with fewer parts, their overall cost per unit is considerably less. Simple-cycle engines are withdrawn from major power producing systems because of the heat or potential energy they expel that goes unharnessed. These types of turbines are never connected to a grid and are utilized for local power generation only. They are primarily used in emergency applications, such as in hospitals, where in case the main power supply is lost, they can be brought online in a short amount of time to meet the power demands. Standby gas turbines incorporate a centrifugal compressor with a pressure ratio range of 5:1 to 10:1, which brings down the overall cost (Soares). Axial flow compressors are not chosen for this design because they are inefficient at such low volume flow rates. A turbine blade cooling system is unnecessary for this particular type of turbine because the stator outlet temperature never exceeds 1250 K (Soares). Power outputs per engine range from 0.25 MW – 1.5 MW (Soares).

b. Small-Scale Combined Heat and Power (CHP) Producing Systems

In comparison to standby power generators, CHP systems either use the waste heat directly for drying processes such as in the ceramic, brickwork, and animal feed industries, or utilize a heat recovery steam generator (HRSG) to convert the waste heat into steam for a variety of uses. The temperature of the waste heat is a function of both the turbine pressure ratio and its respective firing temperature. The hotter the waste heat expelled, the greater the amount of thermal energy available to produce additional electricty. As can be seen in Fig. 9, the exhaust gases from the turbine are on the hot side of the heat exchanger, while highly pressurized water is pumped into the cold side, thus creating steam. The beginning stage of the HRSG is known as the *economizer*. The water is initially heated to its saturation temperature while a constant pressure is maintained. The water becomes vaporized at this point. The vaporized steam is heated even further in the next stage of the HRSG, known as the *superheater*. Finally, the vaporized steam is allowed to expand across a steam turbine. This CHP process accounts for up to an additional 45% power generated on top of what was already produced by the gas turbine engine (Fletcher). Any remaining steam after the steam turbine stage is condensed and pumped back to the inlet of the *economizer* to be reused again.

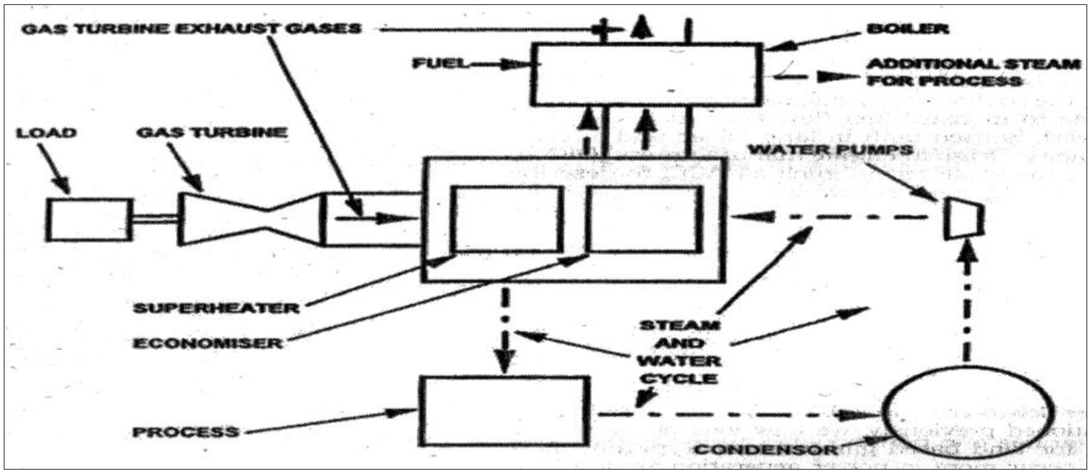

Fig. 9 Schematic of a combined heat and power (CHP) configuration

Small-scale CHP systems produce power mainly for local consumption but have the added benefit of being tied to an electrical grid. These gas turbines are usually custom designed to allow the customer flexibility when choosing how the vaporized steam is allocated, whether it be used for space heating in a building or sent to a steam turbine for additional power, as described in the section above. This way the unit may be designed, for example, to fit the customer's heating requirements, and any electricity not consumed can be sent to the grid for profit. Heat is a lesser valued commodity than electricity, so smaller heat to power ratios are desired for a CHP system.

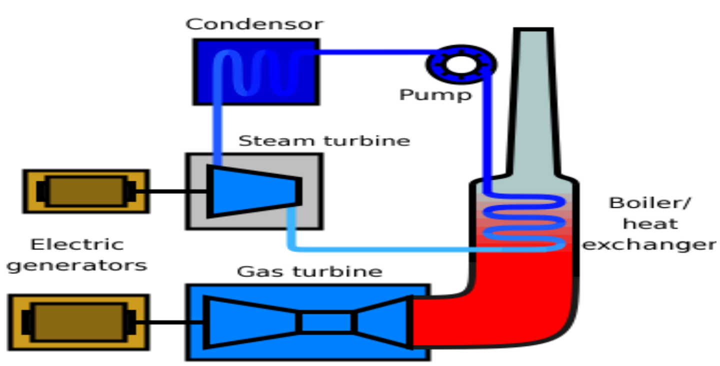

Fig. 10 Diagram of combined heat and power (CHP) configuration

A majority of small-scale CHP systems are single-spool with power outputs per unit ranging anywhere from 0.5 to 10 MW (Soares). Centrifugal compressors are exclusively employed in gas turbine units producing below 3 MW, with pressure ratios from 8:1 to 15:1. At the lower end of the power spectrum, stator outer temperatures can see highs around 1350 K, necessitating the need for cooling techniques in the nozzle guide vanes at the first stage of the turbine (Soares). Small-scale CHP systems rated above the 3 MW capacity require additional cooling of the first stage rotor blades since stator outer temperatures may reach up to 1450 K.

c. Large-Scale Combined Heat and Power (CHP) Producing Systems

For large-scale CHP systems, all of the waste heat is converted into steam through the HRSG. The vaporized steam is generally used for large-scale applications such as space and water heating (district heating). Similar to small-scale CHPs, these systems produce power for local use, and off-load excess electricity to the power grid. Also, the desired specifications for small CHP systems such as high thermal efficiencies and low heat to power ratios are applicable to larger scale CHPs. One major difference though is large scale CHP systems are subjected to harsher emission standards because they emit higher levels of harmful pollutants, resulting in the need for advanced emission-reduction systems.

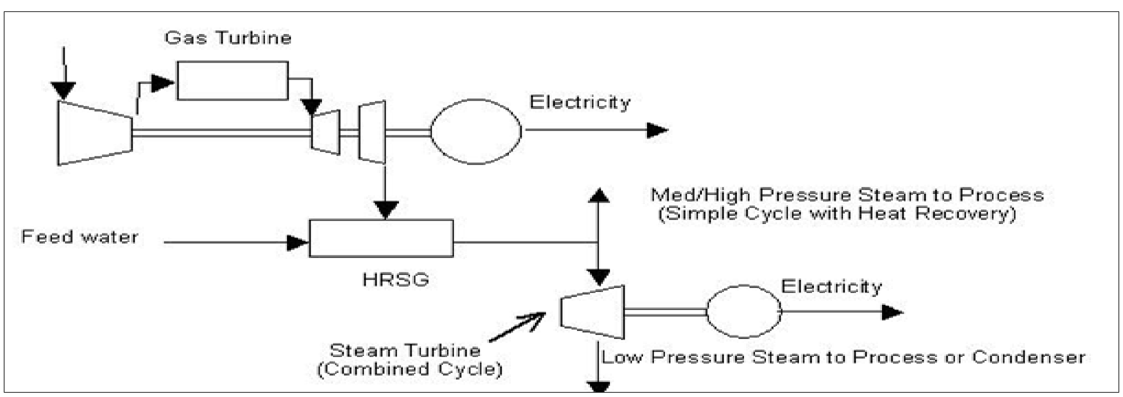

Fig. 11 Combined Heat and Power (CHP) configuration

The two types predominately used in this category are *aeroderivative* and *heavyweight* gas turbines. Stationary models of aeroderivate engines mirror the basic structure of large civilian turbofans as gas generators with a free-power turbine to produce shaft power. Large aeroderivative gas turbine capacities exist up to 50 MW (Fletcher). The turbofan core results in an overall pressure ratio of 15:1 to 25:1, requiring the use of an axial flow compressor (Soares). Aeroderavitive engines have the capacity to be employed in mobile applications, such as on marine crafts. Heavyweight gas turbines, on the other hand, are used exclusively for stationary power generation. They are more rugged, heavier, and are generally less expensive than aeroderivative engines. These engines are best suited for continuous base-load operations and require less maintenance than aeroderivatives over the same amount of time. Power outputs for heavyweight gas turbines range from 30 to 350 MW capacities (Soares). Overall pressure ratios are more modest than aeroderivate engines and exist up to 16:1. Advanced cooling systems must be integrated into the turbine nozzle guide vanes and blades for both types of gas turbines because stator outer temperatures can reach up to 1550 K (Soares). A CHP plant can achieve efficiency ratings of up to 98% (GE Energy).

d. Solely Power-to-Grid Systems

For this class of LBGT, higher efficiencies are crucial to allow the system to extract the greatest amount of potential energy from the fuel as possible. Natural gas, and on occasion, diesel, is used as the burning fuel. Gas turbines which export their power directly to the electrical grid fall underneath three categories: *peak lopping, base-load, and mid-merit* engines.

Peak lopping engines are implemented on a needs basis to satisfy peak electrical demands. Therefore, quick start and acceleration times are crucial. These simple-cycle gas turbines are only utilized for less than 10% of the time. Aeroderivative and heavyweight gas turbines can be used for this application, as either in a single-spool or free-power turbine orientation. Pressure ratios for these units are between 15:1 to 25:1 with corresponding stator outer temperatures reaching 1500 K (Fletcher). Peak lopping gas turbine engines available are 20 to 60 MW in capacity (Soares).

The next grid-tied gas turbine is the mid-merit engine. Advanced heating, cooling, and combustion technologies found within the mid-merit engine boost overall efficiencies, setting this gas turbine apart from peak lopping engines. Mid-merit engines are typically utilized in temperate climates where power demands are even steeper, primarily due to domestic heating and cooling. As was the case for peak lopping engines, the time it takes to bring the mid-merit engine online should be kept to a minimum. These simple-cycle engines are employed 30-50% of the time with aeroderivatives making up the majority of this power class (Soares). Power outputs for this type of gas turbine range from 30 to 60 MW capacities. As stator outer temperatures can reach 1600 K, cooling systems must be integrated within the turbine. Pressure ratios are slightly higher than peak lopping engines, with maximums reaching up to 35:1.

And finally, base-load power turbines perform on a continuous basis to fulfill the energy demands. Historically, coal burning plants have dominated this power-producing sector. Only until recently, with advancements in combined turbine cycles resulting in higher thermal efficiencies and greater power outputs have gas turbine engines been able to control a portion of the market share. Another reason for their growing numbers in this field is the abundance of low-cost, natural gas. Using natural gas is cost-effective and also lowers emissions of harmful pollutants such as NO_x and CO_2, when compared to coal-burning. Base-load gas turbines can reach power levels from 50 to 500 MW, depending on their applications (Soares). Aeroderivative engines barely make headway in this market because they are constrained by the size of the largest available aerospace engine, which is limited to about 50 MW (Soares). Therefore, single-spool heavyweight gas turbine engines secure most of the work. Since stator outer temperatures can reach 1750 K, cooling the turbine nozzle guide vanes and blades is imperative. With pressure ratios hovering around 22:1, thermal efficiencies for these rugged engines tend to exceed 60% (Soares).

e. Closed-Cycle Power Producing Systems

As the name implies, air is inept as the working fluid for closed-cycle gas turbines. Combustion, therefore, is unsuited for closed-cycles. Helium is often chosen as the working medium because of its high specific heat. Power generation in the form of solar and nuclear energy is applicable to close-cycles. But, with the exorbitant manufacturing costs and mediocre thermal efficiencies due to a limit on exhaust gas temperatures, few closed-cycle power generating systems are in operation today. A schematic of a closed-cycle, high temperature reactor, helium turbine system is shown in Fig. 12.

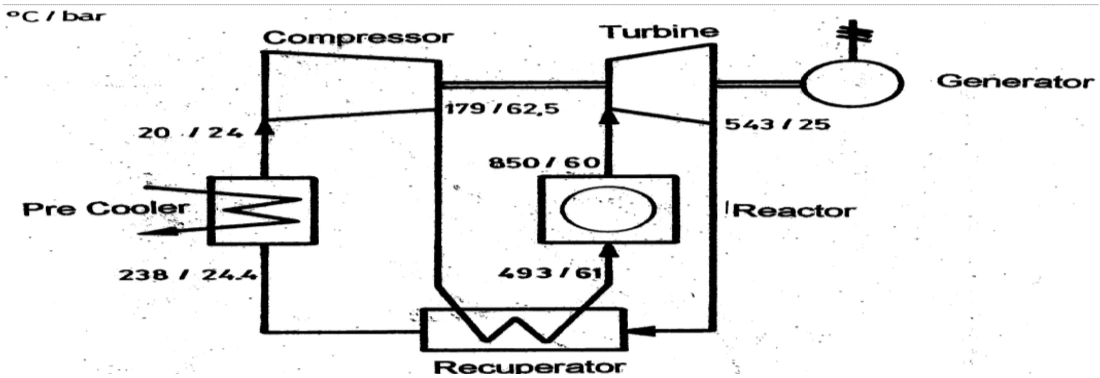

Fig. 12 Closed-cycle power system that uses helium as working fluid

V. Comparative Analysis of Ansaldo Energia V94.38 and General Electric 'F-Class' Gas Turbines for Power Production

The Italian-based company, Ansaldo Energia, started in 1853 and, on the basis of its operating experiences, has become one of the world leaders in the manufacturing of gas turbines for power production. They strive to "satisfy the most complex power generation demands" with their gas turbines to meet the personal needs of the customer (Ansaldo). The company aims at maintaining the highest levels of efficiency and reliability per unit while keeping the environmental impacts of their machines to a minimum (Ansaldo). This commitment is clearly reflected in their V94.3A gas turbine. With 31 units currently online in Western Europe, this 50 Hz machine can produce on average 285 MW, burning a variety of fuels such as natural gas, heavy oil, and naphtha (liquid hydrogen mixture) (Ansaldo). The turbine entry temperature can reach up to 1500 K, necessitating the need for film-cooled, single-crystal blades, coated with a thermal barrier. A pressure-ratio of 17.7, an exhaust gas mass flow rate and temperature of 690 kg/s and 850 K respectively, makes the V94.3A the largest gas turbine Ansaldo manufactures (Ansaldo). Incorporated into a combined cycle, the V94.3A can produce up to 413 MW with an efficiency rating of almost 58% (Ansaldo). Due to the stringent environmental constraints and regulations placed on gas turbine producers in Western Europe, Ansaldo Energia has invested much of its resources to ensure their energy-generating gas turbines comply with these standards. The V94.3A is equipped with a advanced combustion system that emits less than 30 mg/Nm^3 NO_x and less than 30 mg/Nm^3 CO (Ansaldo).

Fig. 13 Ansaldo Energia V94.3A heavy-duty turbine

General Electric acknowledges the urgent challenges of climate change and energy security and consistently produce noteworthy solutions to these problems with their energy-producing products. This is clearly evident in their heavy-duty gas turbine engines. With more than 6,000 LBGTs installed worldwide, GE leads the way as the number one gas turbine supplier (GE Energy). Their ‘F-series’ class of heavy duty turbines is one example of how their pledge to manufacture efficient and environmentally-conscious turbines translates through to their products.

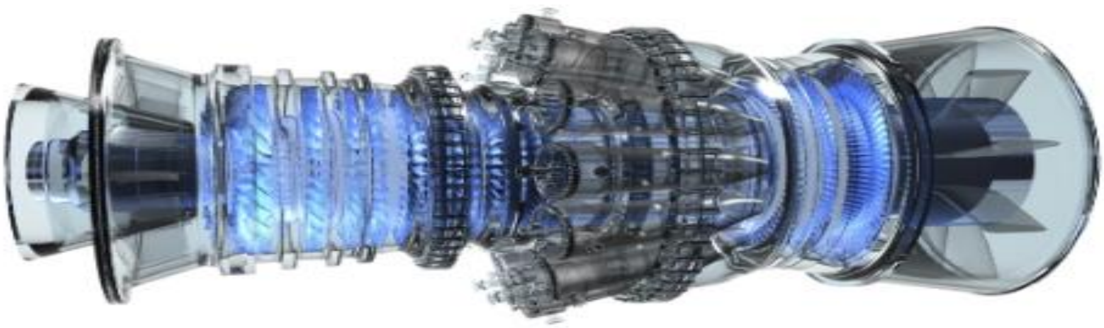

Fig. 14 General Electric ‘F-Series’ heavy-duty turbine

One gas turbine in particular is the simple-cycle MS9001FA engine. This highly successful 50 Hz gas turbine is suited for a wide range of fuels allowing for customer flexibility. Its specifications include a mass flow rate of 641 kg/s, a pressure ratio of 17, and an exhaust temperature of 875 K, all corresponding to a power output of 255.6 MW (GE Energy). Emitting less than 25 ppm NO_x, the combustor within the MS9001FA is one of the most efficient in the industry for pollution prevention (GE Energy). A net plant output of 390.8 MW and a 56.7 % efficiency rating is achieved when the engine is incorporated into a combined cycle for increased performance (GE energy).

VI. Conclusion

According to the International Energy Agency (IEA), the world's electricity demands will more than double by the year 2030 due to an ever increasing population. Today, nearly 40% of electricity generated to meet the world's power-consumption needs is derived from coal. Greenhouse gas emissions from coal-burning power plants contribute heavily to climate change, impacting ecosystems at an alarming rate. Advancements in the technology of today have made naturally replenished resources such as wind, solar, and geothermal heat a viable source of 'clean', renewable energy. But because of their intermittent delivery of power, renewable energy sources fall short of providing energy security. Land-based gas turbines for power production possess the necessary qualities to meet the world's baseload demands now and into the future and curb the energy sector's emissions of harmful pollutants. Coal-fired power plants take years before they are operational, whereas LBGTs required merely a few weeks from time of manufacturing to installation before they are online producing electricity. Power-producing turbines are available in a wide variety of capacities and configurations to meet the needs of the customer. LBGT systems are capable of being implemented to satisfy peak electrical demands, requiring quick start-up and acceleration times, or used on a continuous basis to fulfill baseloads. They can be operated individually or integrated into a combined-cycle to increase performance and efficiency. Fuel diversification in LBGTs allow for flexibility when choosing a working fluid. Natural gas is primarily selected as the medium in LBGTs because of its abundant reserves and low CO_2 emissions when compared to coal-burning. LBGT manufactures such as Ansaldo Energia and General Electric strive to ensure their reliable, energy-generating machines meet the growing electrical demands. Both companies have also made commitments to aggressively target areas in their LBGTs that directly impact improvements in energy efficiency and reduce greenhouse gas emissions. With the economic incentives and the ability to help mankind with providing electricity in a more efficient manor with less pollution, these power-producing gas turbine manufacturers will be critical in solving the energy needs of a burgeoning global population.

Works Cited

Ansaldo Energia. “Gas Turbines.” Web. 5 Dec. 2009. <http://www.ansaldoenergia.com/PDF/Gas_Turbines.pdf>

Eckardt, D. and P. Rufli. “Advanced Gas Turbine Technology: ABB/BCC Historical Firsts.” *Journal of Engineering for Gas Turbines and Power* 124.3 (2002): 542-549.

Fletcher, Paul, and Philip Walsh. *Gas Turbine Performance*. New Jersey: Blackwell Science Ltd and ASME, 1998.

Frutschi, Hans. *Closed-Cycle Gas Turbines: Operating Experience and Future Potential*. New York: ASME Press, 2005.

Giampaolo, Tony. *Gas Turbine Handbook: Principles and Practices*. 3rd ed. Liburn, GA: The Fairmont Press, Inc., 2006.

GE Energy. “Heavy Duty Gas Turbines & Combined Cycle.”. Web. 5 Dec. 2009. <http://www.gepower.com/prod_serv/products/gas_turbines_cc/en/index.htm>.

Sawyer, John. *Gas Turbine Engineering Handbook.* 1st ed. Stamford, CT: Gas Turbine Publications, Inc., 1966.

Soares, Claire. *Gas Turbines: A Handbook of Air, Land, and Sea Applications*. Burlington, MA: Butterworth-Heinemann, 2008.