1.3.2

Advanced Brayton Cycles

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1.3.2-1 Introduction

Gas turbines could play a key role in the future power generation market addressing issues of producing clean, efficient, affordable, and fuel-flexible electric power. Numerous projections estimate that gas turbines will comprise a significant portion of the required generation capacity in the 21st century. Novel advanced gas turbine cycle modifications intended to improve the basic Brayton cycle performance and reduce pollutant emissions are currently under development or being investigated by gas turbine manufacturers and Research and Development (R&D) organizations. Preliminary conceptual analyses of advanced cycles indicate that it may be possible to achieve an improved combination of efficiency, emissions, and specific power output which in turn should reduce the power generation equipment cost on a $/kW basis.

Developing turbine technology to operate on coal-derived synthesis gas and hydrogen is critical to the development of advanced power generation technologies and the deployment of FutureGen plants. The FutureGen plant concept may also be deployed in natural gas-based plants with respect to generating power with near-zero emissions while utilizing these advanced Brayton cycle machines and securing fuel diversity.

1.3.2-2 Gas Turbine Technology

A conventional gas turbine cycle consists of pressurizing a working fluid (air) by compression, followed by combustion of the fuel; the energy thus released from the fuel is absorbed into the working fluid as heat (see figure 1). The working fluid with the absorbed energy is then expanded in a turbine to produce mechanical energy, which may in turn be used to drive a generator to produce electrical power. Unconverted energy is exhausted in the form of heat which may be recovered for producing additional power. The efficiency of the engine is at a maximum when the temperature of the working fluid entering the expansion step is also at a maximum. This occurs when the fuel is burned in the presence of the pressurized air under stoichiometric conditions.

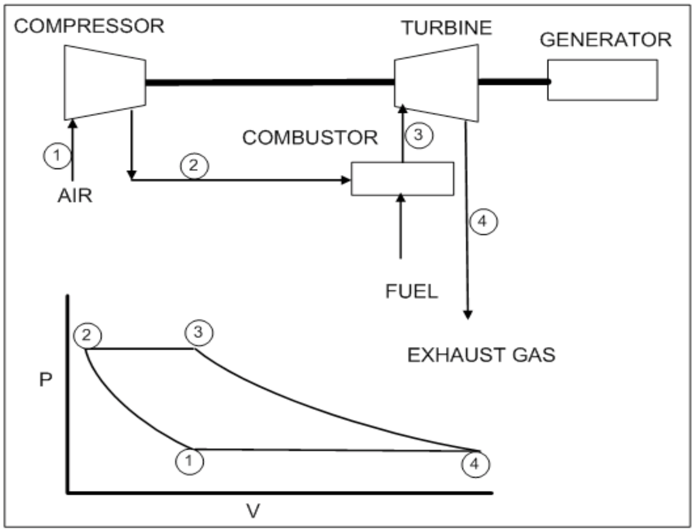

Fig. 1. Gas Turbine and the Ideal Brayton Cycle P-V Diagram

When natural gas is burned with air under stoichiometric conditions, however, the resulting temperature is greater than 1940ºC (3500ºF) depending on the temperature of the combustion air. It is therefore necessary to utilize a large excess of air in the combustion step, which acts as a thermal diluent and reduces the temperature of the combustion products, this temperature being dependent on the gas turbine firing temperature which in turn is set by the materials used in the turbine parts exposed to the hot gas and the cooling medium (its temperature and physical properties) as well as the heat transfer method employed for cooling the hot parts. A fraction of the air from the compressor is bled off as cooling air when air is utilized for cooling, the air being extracted from the compressor at appropriate pressures depending upon where it is utilized in the turbine. From a cycle efficiency and engine specific power output (kW per kg/s of suction air flow) standpoint, it is important to minimize the amount of cooling air as well as the excess combustion air.

The necessity to use a large excess of pressurized air in the combustor as well as for turbine cooling when air cooling is employed creates a large parasitic load on the cycle, since compression of the air requires mechanical energy and this reduces the net power produced from the system, as well as reducing the overall efficiency of the system.

Some of the technological advances being made or being investigated to improve the Brayton cycle include the following, in addition to the changes in the basic cycle configuration such as the inclusion of reheat combustion, intercooling (which is justified for very high pressure ratio cycles), recuperation and humidification:

- Rotor inlet temperature of 1700ºC (3100ºF) or higher which would require the development and use of advanced materials including advanced thermal barrier coatings and turbine cooling techniques including closed loop steam cooling
- Advanced combustor liner (combustion air and combustion products being hotter) required due to increases in rotor inlet temperatures
- High blade metal temperature in the neighborhood of ~1040ºC (1900ºF) while limiting coolant amount would again require the development and use of the advanced materials including advanced thermal barrier coatings
- Pressure gain combustor
- Cavity or trapped vortex combustor
- High pressure ratio compressor (greater than 30 to take full advantage of higher firing temperature)
- Integration capability with high temperature ion transport membrane air separation in IGCC applications.

Addition of novel bottoming cycles is yet another approach to improving the overall plant (combined cycle) performance. Overall cycle efficiencies utilizing advanced technology gas turbines approaching 65% on natural gas on an LHV basis may be expected (see figure 2). Some of these developments are described in the following.

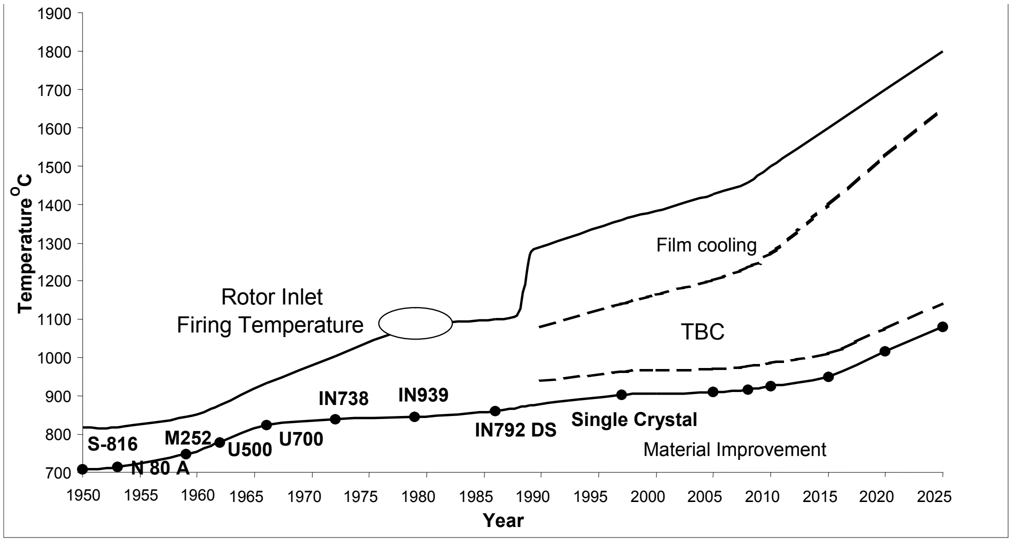

Fig. 2. Impact of Firing / Metal Temperature on Efficiency

Gas Turbine Firing Temperature

Current-state-of-the-art gas turbines have firing temperatures (rotor inlet temperatures) that are limited to about 2600ºF. This increase in firing temperature has been made possible by being able to operate the turbine components (that come into contact with the hot gasses) at higher temperatures while at the same time utilizing closed circuit steam cooling. In a state-of-the-art air-cooled gas turbine with firing temperature close to 1320ºC (2400ºF), as much as 25% of the compressor air may be used for turbine cooling, which results in a large parasitic load of air compression. In air-cooled gas turbines, as the firing temperature is increased, the demand for cooling air is further increased. Closed circuit steam cooling of the gas turbine provides an efficient way of increasing the firing temperature without having to use a large amount of cooling air. Furthermore, steam with its very large heat capacity is an excellent coolant. Closed circuit cooling also minimizes momentum and dilution losses in the turbine while the turbine operates as a partial reheater for the steam cycle. Another major advantage with closed circuit cooling is that the combustor exit temperature and thus the NOx emissions are reduced for a given firing temperature; the temperature drop between the combustor exit gas and the turbine rotor inlet gas is reduced since the coolant used in the first stage nozzles of the turbine does not mix with the gasses flowing over the stationary vanes. Note that control of NOx emissions at such high firing temperatures becomes a major challenge. The General Electric (GE) H series gas turbines as well as the Siemens and Mitsubishi G series gas turbines incorporate steam cooling although the GE turbine includes closed circuit steam cooling for the rotors of the high pressure stages.

Taking the firing temperature beyond 1430ºC (2600ºF) poses challenges for the materials in the turbine hot gas path. Single crystal blading has been utilized successfully in advanced turbines but in addition to this, development of advanced thermal barrier coatings would be required. Extensive use of ceramics may be predicated. Reheat or sequential combustion is an alternate approach to decreasing the amount of excess combustion air without increasing the firing temperature.

Gas Turbine Pressure Ratio

The optimum pressure ratio for a given cycle configuration increases with the firing temperature of the gas turbine. Thus to take full advantage of the higher firing temperature of the gas turbine with firing temperature in the neighborhood of 1700ºC (3100ºF) the required pressure ratio may be in excess of 30. Another constraint to consider is the temperature of the last stage buckets in the turbine. This temperature may have to be limited to about 650ºC (1200ºF) from a strength of materials standpoint since the last stage buckets in large scale gas turbines tend to be very long and a certain minimum pressure ratio would be required to limit this temperature.

Combustor Developments

Pressure Gain Combustor

A pressure gain combustor produces an end-state stagnation pressure that is greater than the initial state stagnation pressure. An example of such a system is the constant volume combustion in an ideal spark ignited engine. Such systems produce a greater available energy in the end state than constant pressure systems. It has been shown that the heat rate of a simple cycle gas turbine with a pressure ratio of 10 and a turbine inlet temperature of ~1200ºC (2200ºF) can be decreased by more than 10% utilizing such a constant volume combustion system[1]. Pulse combustion which relies on the inherent unsteadiness of resonant chambers can be utilized as a pressure gain combustor. Research continues at the U.S. DOE and at NASA for the development of pressure gain combustors.

Trapped Vortex Combustor

The Trapped Vortex Combustor (TVC) has the potential for numerous operational advantages over current gas turbine engine combustors. These include lower weight, lower pollutant emissions, effective flame stabilization, high combustion efficiency, and operation in the lean burn modes of combustion. The TVC concept grew out of fundamental studies of flame stabilization and is a radical departure in combustor design using swirl cups to stabilize the flame. Swirl-stabilized combustors have somewhat limited combustion stability and can blow out under certain operating conditions. On the other hand, the TVC maintains a high degree of flame stability because the vortex trapped in a cavity provides a stable recirculation zone that is protected from the main flow in the combustor. The second part of a TVC is a bluff body dome which distributes and mixes the hot products from the cavity with the main air flow. Fuel and air are injected into the cavity in a way that it reinforces the vortex that is naturally formed within it.

The TVC may be considered a staged combustor with two pilot zones and a single main zone, the pilot zones being formed by cavities incorporated into the liners of the combustor[2]. The cavities operate at low power as rich pilot flame zones achieving low CO and unburned hydrocarbon emissions, as well as providing good ignition and the lean blowout margins. At higher power conditions (above 30% power) the additional required fuel is staged from the cavities into the main stream while the cavities are operated at below stoichiometric conditions. Experiments have demonstrated an operating range that is 40% wider than conventional combustors with combustion efficiencies of 99%+. Use of the TVC combustor holds special promise as an alternate option for suppressing the NOx emissions in syngas applications where pre-mixed burners may not be employed. More details on this type of combustor may be found in Section 3.2.1.4.1.

Catalytic Combustor

Lean stable combustion can be obtained by catalytically reacting the fuel-air mixture with a potential for simultaneous low NOx, CO and unburned hydrocarbons. It also has the potential for improving lean combustion stability and reducing combustion-induced pressure oscillations. The catalytic combustor can play a special role in IGCC applications to reduce NOx emissions. More details on this type of combustor may be found in Sections 3.2.2 and 3.2.2.1.

IGCC Applications

The H_2O vapor content of the working fluid flowing through the turbine when firing syngas while utilizing water vapor as the diluent, is significantly higher than that in the case when natural gas is the fuel (i.e., compared to the case when natural gas is fired in dry low NOx combustors). The following implications exist for the gas turbine in such applications:

1. Derating of the turbine firing temperature due the different aero-heat transfer characteristics and
2. Life of the thermal barrier coatings, and any ceramics that may be utilized in advanced gas turbines in the future.

Additionally, a gas turbine designed for a certain firing temperature on natural gas would see derating of the firing temperature not only due to the increased concentration of H_2O vapor in the working fluid but also due to the increase in the pressure ratio since the temperature of the cooling air increases as the pressure ratio is increased. In the case of a steam-cooled gas turbine, however, derating of the firing temperature may be less significant (since the cooling steam temperature may be maintained independently of the gas turbine pressure ratio), unless the low pressure air-cooled stages of the gas turbine become the bottleneck.

Furthermore, if dual fuel capability, i.e., operating capability on natural gas and on syngas is required, a large surge margin would be necessary for the compressor with a pressure ratio in excess of 30 and may require a twin-spool aero-compressor for high pressure ratios. Air extraction from the engine to supply the air separation unit may alleviate some of these challenges.

Integration capability with high temperature membrane air separation in IGCC applications may be a requirement in the future when these advanced gas turbines are deployed. Capabilities for extraction of ~ 50% of the compressor discharge air for the membrane unit while introducing hot (~800ºC or 1500ºF) depleted air from it into the gas turbine combustor would be required. Within the combustor, its liner design and materials would be impacted.

Novel Cycles

Humid Air Turbine (HAT) Cycle

The mechanical energy required for air compression in the Brayton cycle can be reduced by utilizing interstage cooling. However, from an overall cycle efficiency standpoint, interstage cooling can be utilized advantageously if the heat removed from the compressed air in the intercooler can be efficiently recovered for conversion to power. If the entire heat is simply rejected to the atmosphere, the overall cycle efficiency may actually decrease depending upon the cycle pressure ratio, since it results in the consumption of more fuel to compensate for the energy lost through the intercooler. Only at very high pressure ratios can intercooling be justified in most cycles.

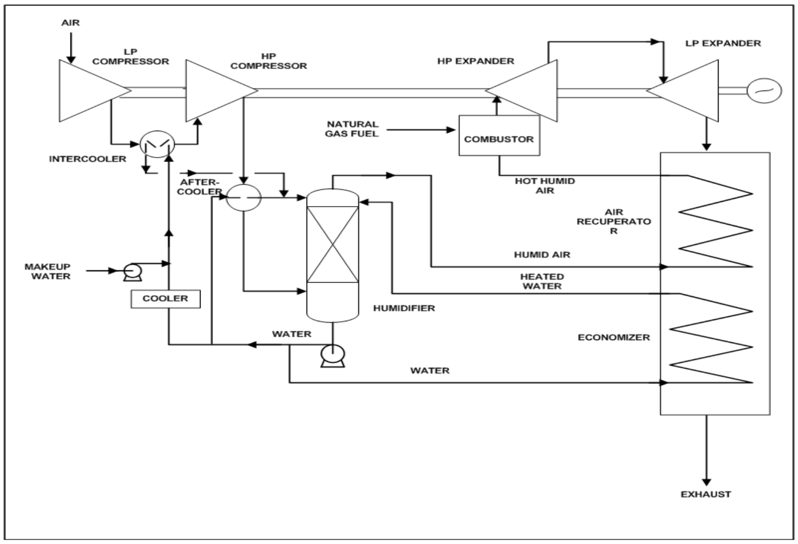

Fig. 3. HAT Cycle

In the HAT cycle a significant portion of the excess air that is required as thermal diluent in a gas turbine, is replaced with water vapor (see figure 3)[3]. The water vapor is introduced into the system in an efficient manner, by pumping of a liquid followed by low temperature evaporation. Pumping a liquid requires less mechanical energy compared to gas (air) compression. Evaporation of the water into the compressed air stream is accomplished using low temperature heat, in a counter-current multistage humidification column, rather than generating steam in a boiler. This method of humidification permits the use of low temperature heat for accomplishing the evaporation of water. For example, water which boils at 100^{o}C or 212^{o}F at atmospheric pressure may be made to evaporate at room temperatures when exposed to a stream of relatively dry air.

The process also reduces the parasitic load of compressing the combustion air by intercooling the compressor, while recovering most of the heat removed in the intercooler for the humidification operation. Thus, a more thermally efficient power cycle is achieved. Humidification of the compressed air also leads to a reduction of NO_x emissions. The humid air is preheated by heat exchange with the turbine exhaust in a recuperator to recycle the exhaust energy to the combustor, thereby eliminating the expensive steam bottoming cycle required in a combined cycle.

The advantages of the HAT cycle are:

- Less than 5 ppmV NO_x without post-combustion treatment
- High efficiency without a steam bottoming cycle
- Applicable to micro- and mini-turbines for distributed generation
- Excellent part-load performance, efficiency essentially constant down to 60% of full load
- Performance quite insensitive to ambient temperature
- Water usage less than that for a combined cycle employing wet cooling tower and if desired, water may be recovered from HAT exhaust
- High specific power
- Integrates synergistically with reliable low-cost "Total Quench" gasifier
- In coal based Zero Emission plants, the "Total Quench Gasifier" option is of choice
- In natural gas Zero Emission based plants where CO_2 is recovered from exhaust, CO_2 concentration is higher (dry basis).

The disadvantages of the HAT cycle are:

- Requires intercooled-regenerative gas turbine for optimum performance
- Compressor / turbine flow mismatch deviates from normal gas path design
- Development cost could be high although possible for compressor / turbine "mix and match"
- Does not take advantage of steam-cooled blade technology (water cooled technology could prove better in advanced machines)
- Use of ceramics in hot gas path may be a challenge due to high moisture content of the working fluid.

Inlet Air Fogging

Another approach to reducing the parasitic load of air compression in a gas turbine is to introduce liquid water into the suction air[4]. The water droplets will have to be extremely small in size and be in the form of a fog to avoid impingement on the blades of the compressor causing erosion. As the water evaporates within the compressor from the heat of compression, the air being compressed is cooled which in turn causes a reduction in the compressor work. Note that the compression work is directly proportional to the absolute temperature of the fluid being compressed.

A benefit in addition to increasing the specific power output of the engine is the reduction in the NOx due to the presence of the additional water vapor in the combustion air. A number of gas turbines have been equipped with such a fogging system. Care should be taken, however, in specifying the water treatment equipment since high quality demineralized water is required as well as in the design of the fogging system to avoid impingement of the compressor blades with water droplets.

Fuel Cell Hybrids

A fuel cell, as an electrochemical device is similar to a battery that converts chemically bound energy directly into electricity but unlike conventional batteries, the chemical energy to the cell is supplied on a continuous basis in the form of a fuel such as natural gas or synthesis gas while the oxidant (air) is also supplied continuously. Higher conversion efficiencies are achievable with a fuel cell when compared to heat engines; the chemical energy is directly converted into electricity, the intermediate step of conversion into heat as in a heat engine is eliminated and thus without being constrained by temperature limitations of the materials as is the case with heat engines.

A fuel cell-based hybrid cycle consists of combining a fuel cell with a heat engine to maximize the overall system efficiency. Overall system efficiencies greater than 60% on natural gas on an LHV basis may be achieved. High temperature fuel cells such as solid oxide and molten carbonate fuel cells are most suitable for such applications. In the case of a high pressure fuel cell based hybrid (see figure 4), the combustor of the gas turbine is replaced by the fuel cell system while in the case of a low pressure fuel cell based hybrid, the heat rejected by the fuel cell may be transferred to the working fluid of the gas turbine through a heat exchanger (indirect cycle)[5].

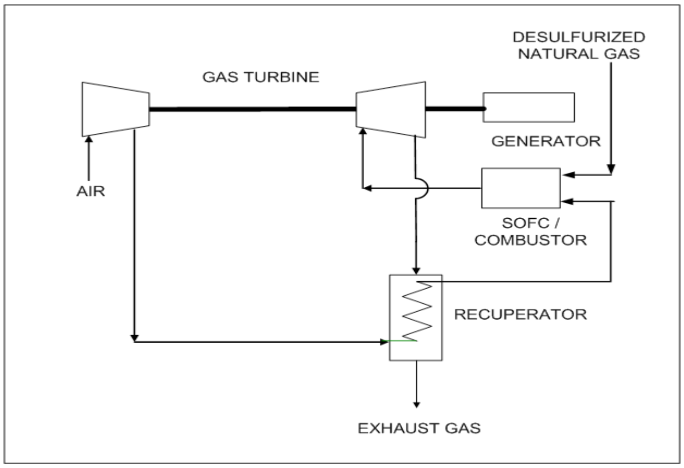

Fig. 4. A Pressurized SOFC Hybrid

The characteristics for gas turbines needed in these hybrid applications are:

- Recuperation (currently only small gas turbines, i.e., less than 15 MW are offered as recuperated engines for generator drives)
- Low firing temperature of less than 1000ºC (1800ºF) and pressure ratio in the range of 4 to 12
- Combustors accepting hot and depleted fuel and air when gas turbine combustors are utilized for oxidation of the fuel cell anode exhaust gas
- Oil free bearings to avoid carbon deposition in the anode section of the fuel cell.

1.3.2-3 Conclusions

Gas turbines could play a key role in the future power generation market including coal based FutureGen plants. Potential exists to take the overall cycle efficiencies to 65% on natural gas on an LHV basis, 60% being the state-of-the-art combined cycle efficiency with the technological advances being made or being investigated which include higher rotor inlet temperature of 1700ºC (3100ºF) or higher and higher blade metal temperature ~1040ºC (1900ºF) made possible with the use of advanced materials including advanced thermal barrier coatings and turbine cooling techniques including closed loop steam cooling, advanced combustor liners to handle the higher temperatures within the combustor, pressure gain and cavity combustors, high pressure ratio compressors (greater than 30 to take full advantage of higher firing temperature) and integration capability with high temperature ion transport membrane air separation in IGCC applications. In tandem, changes to the basic cycle configuration such as the inclusion of reheat combustion and intercooling which is advantageous in very high pressure ratio cycles would be complementary in achieving the goals of higher thermal efficiency and higher engine specific power output. These desirable attributes could also be further enhanced by the use of advanced combustor concepts such as the pressure gain combustor while the TVC holds the promise of an alternate option for suppressing the NOx emissions, especially in syngas applications.

1.3.2-4 Notes

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1.2.2 Implications of CO_2 Sequestration for Gas Turbines
1.3.2 Advanced Brayton Cycles

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