Turbophase Dry Air Injection for Aeroderivative Combustion Turbines

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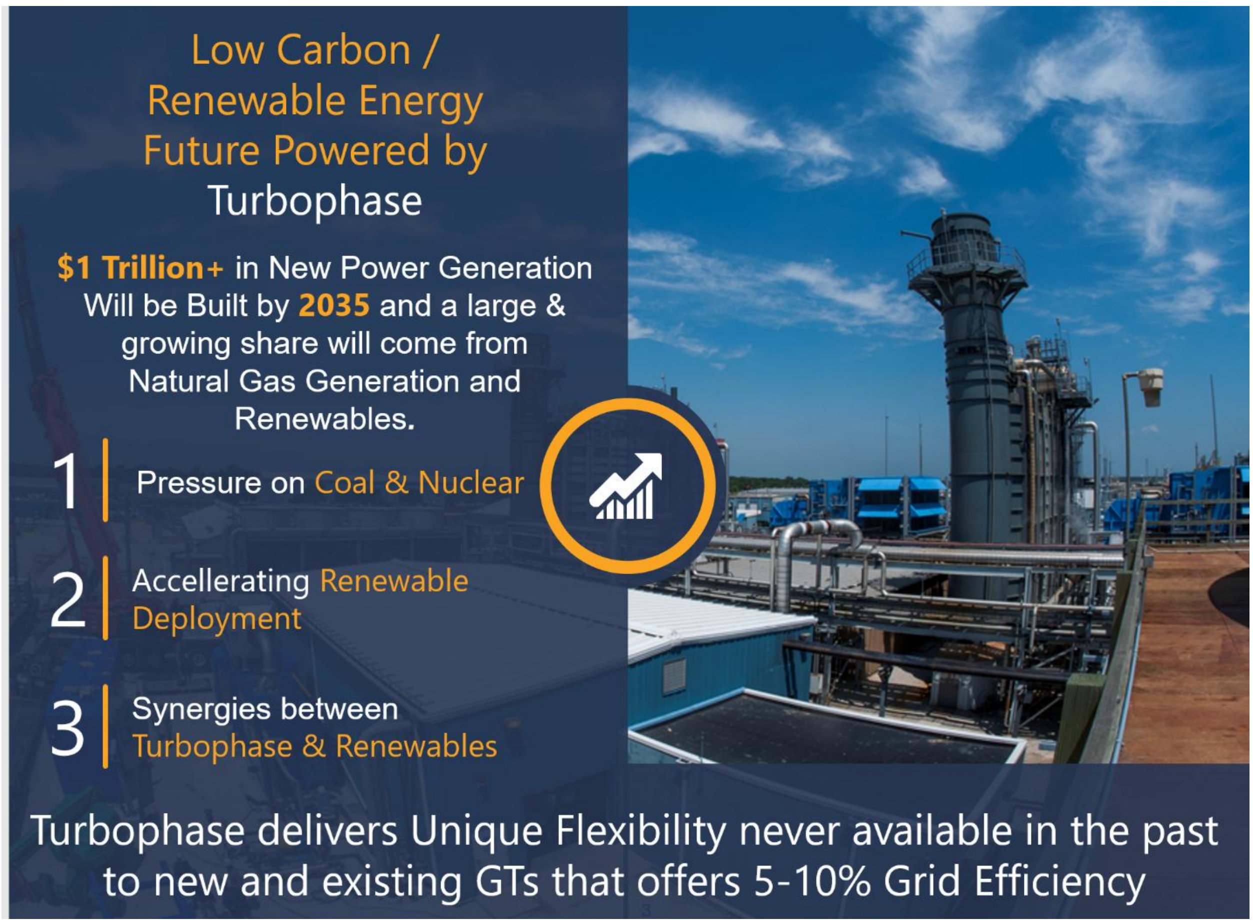
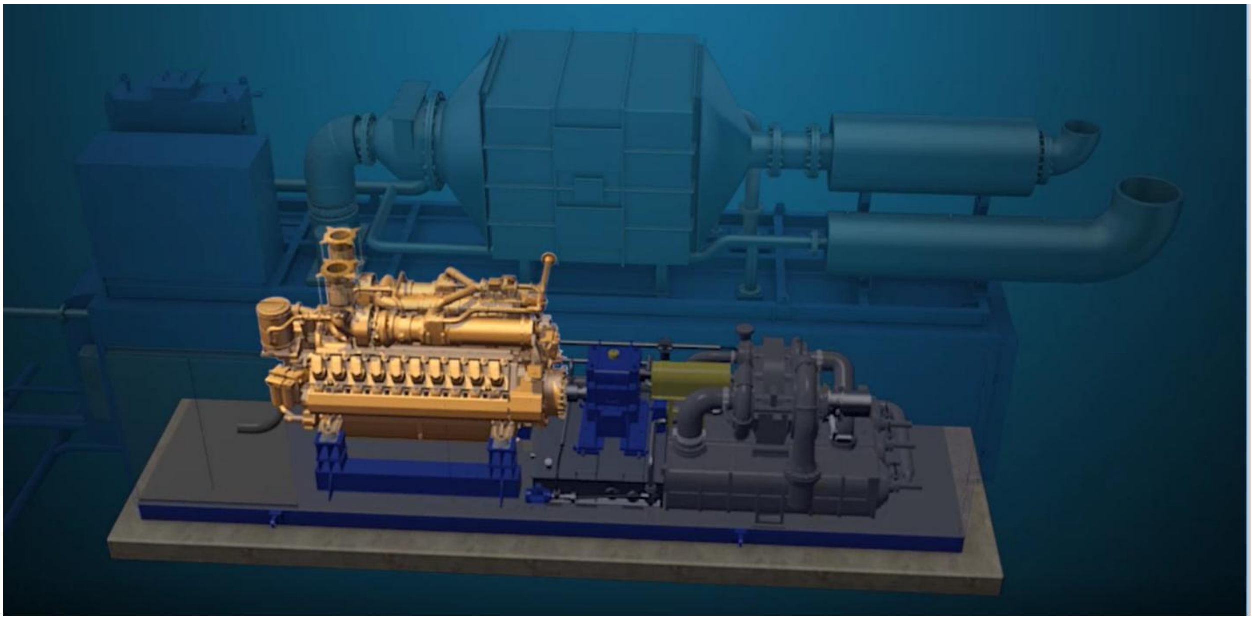
Why Turbophase and Aeroderivatives? Most visions of power generation in the future include the following: more renewables, more decentralization and more combustion turbinesincreasingly powered by natural gas. It is projected that 1+ Trillion USD of new electric power generation will be built by 2035 and a large and growing share will come from natural gas power combustion turbines and renewables. Three key trends are driving the greener energy future: 1. Pressure on coal & nuclear driven by consumer demand and government regulation; 2. Accelerating renewable energy deployment driven by rapidly falling costs, particularly of solar panels and 3. The synergies between renewables and combustion turbines, specifically the intermittent nature of renewables coupled with the dispatchable, flexible nature of combustion turbines. Of all combustion turbines, aeroderivatives are typically the most flexible and decentralized, making them uniquely suited this new paradigm.



Graphic 1: Synergies between Turbophase and Renewables

What is Turbophase?

Turbophase is a combustion turbine optimization system which utilizes a high-speed reciprocating engine to drive a multi-stage intercooled centrifugal compressor and then uses the engine exhaust energy to heat up the compressed air, resulting in dry, hot compressed air that is then injected into the combustion turbine (CT).



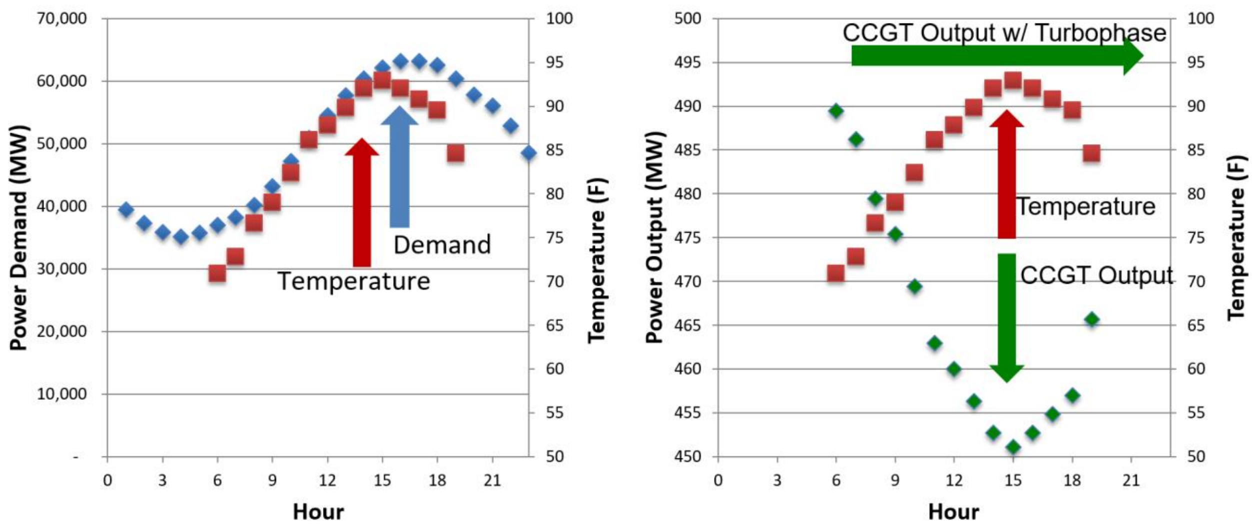
Graphic 2: 3D Rendering of a Turbophase system with Sound Enclosure Faded

Turbophase Benefits on an Aeroderivative CT

The result of adding Turbophase to the CT is the CT is able to generate optimal performance in both output and fuel efficiency in all ambient conditions regardless of ambient temperature, relative humidity and altitude. By applying Turbophase to asimple cycle Aeroderivative CT, the CT gets an additional 20% output when needed, delivered immediately when called and the CT operates at 5% better fuel efficiency. In a world of high renewable penetration with a premium on green energy, this fast response, improved efficiency Aeroderivative CT is very desirable.

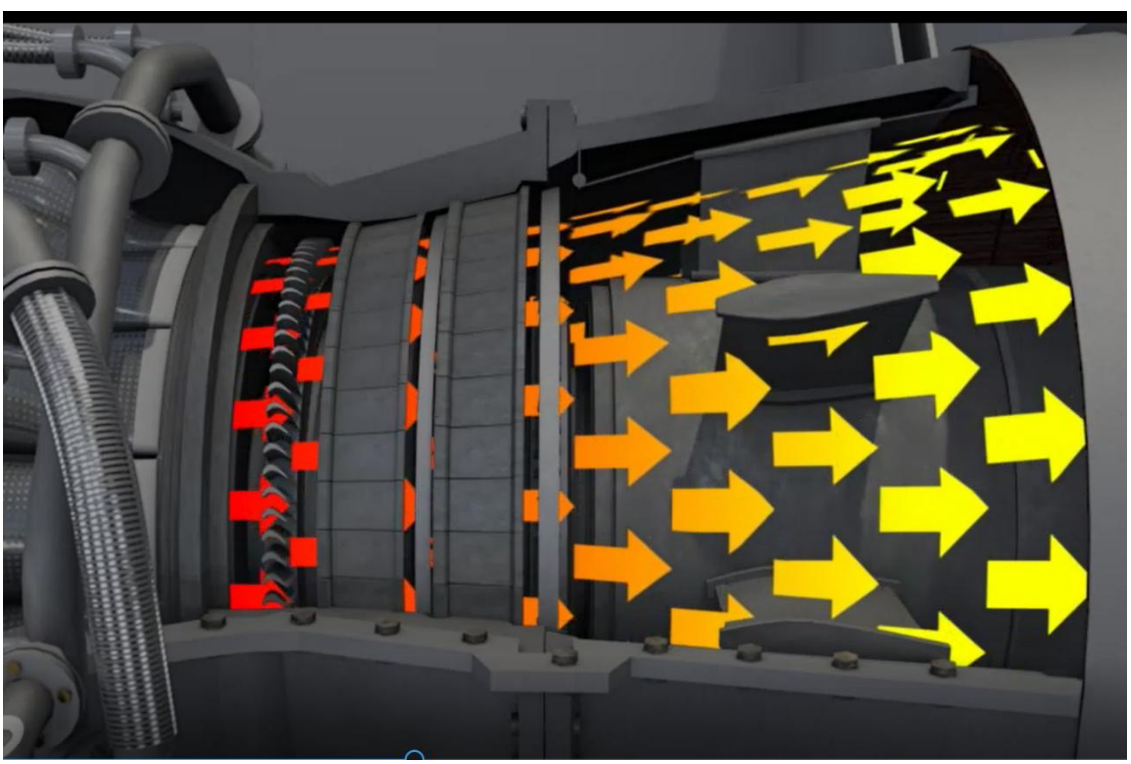
How it Works

It's a commonly known fact that all CTs lose power as ambient temperatures rise, which is typically when power is needed the most. The reason CTs lose power is that as ambient temperature or elevation rises, the density of the air decreases naturally reducing the mass flow into the combustion turbine. The reduced mass flow results in decreased fuel flow to hold turbine inlet temperatures constant with the ultimate result being lower output. Turbophase restores the mass flow that is naturally missing by injecting air into the compressor discharge. The combustion turbine control system reacts automatically and increases fuel to account for the increased air mass flow resulting in constant turbine inlet temperature. The increased mass flow through the turbine section increases the mechanical torque to the compressor and generator.

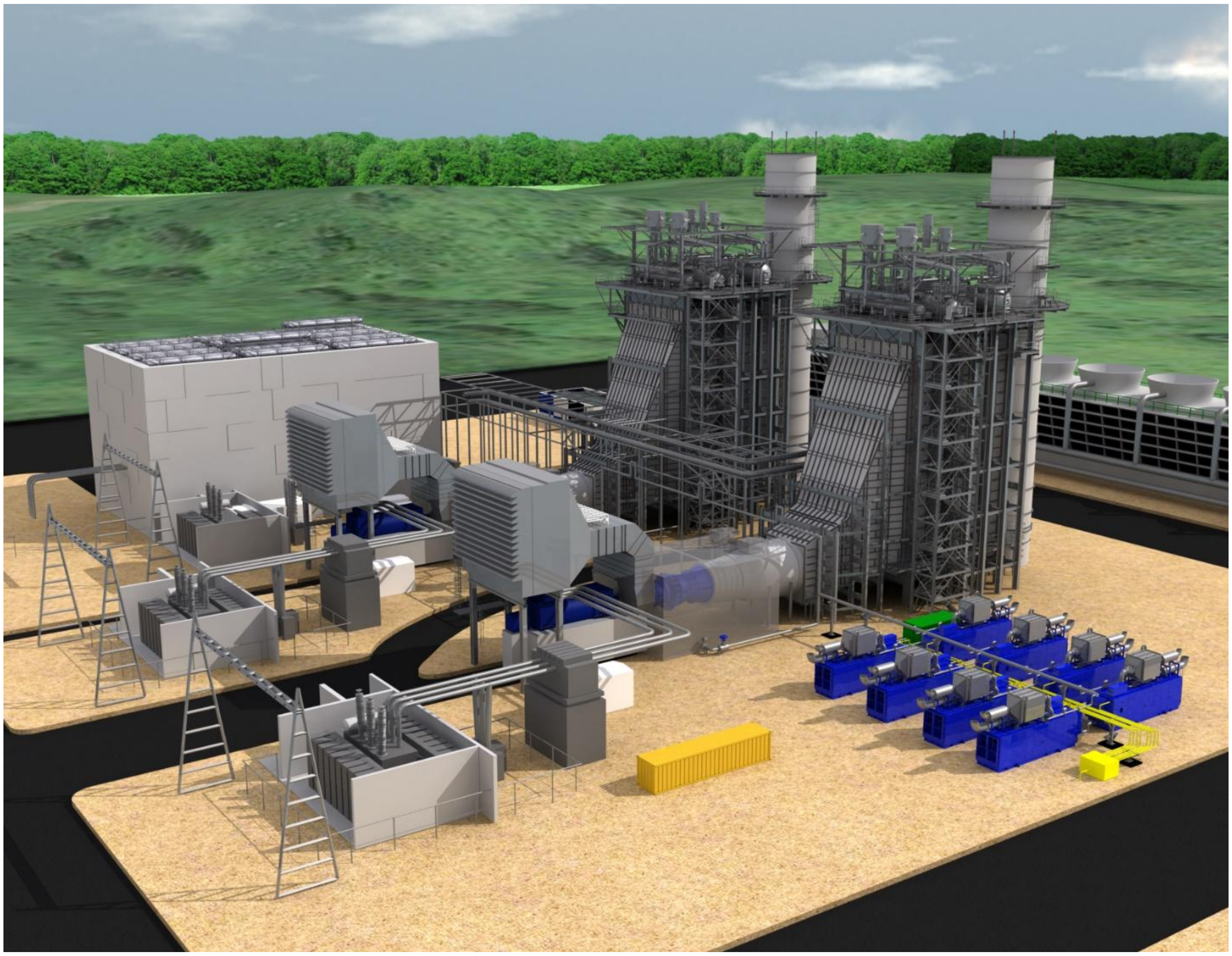


Turbophase Restores missing Power naturally with air that is generated 30-50% more efficiently than the GT

Graphic 3: CCGT Output Disconnect from Power Demand



Graphic 4: Mass Flow through the Turbine Stages

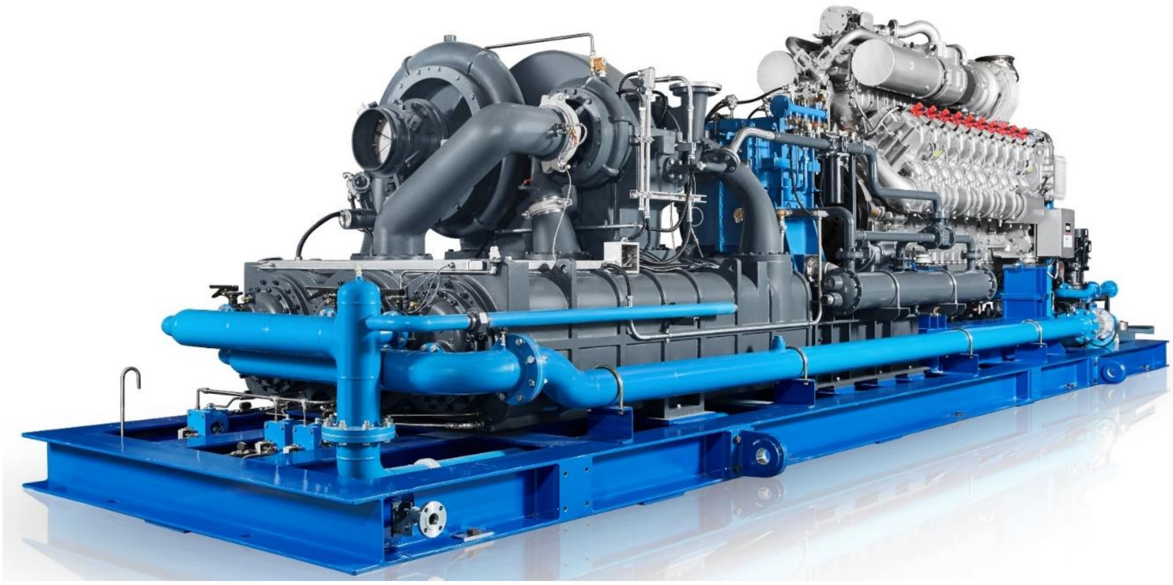


Graphic 4: 3D Rendering of CCGT Plant with 8 Turbophase Module Installation

Aeroderivative CT Technical Details

PowerPHASE LLC has recently signed a partnership agreement with PWPS to offer its Turbophase products to PWPS combustion turbine owners, specifically the Aeroderivative FT8® which will give FT8® owners the flexibility to increase combustion turbine power, efficiency and/or durability based on site and market requirements.

The Turbophase compressor is designed to supportthe higher-pressure ratio Aeroderivative CTs with either a 4-stage compressor up to 270psi CT compressor discharge pressure or a 5-stage compressor > 270psi.



Graphic 5: Photo of Turbophase Module, showing Multi-Stage Compressor and Reciprocating Engine (no sound enclosure)

Turbophase on an FT8® ®

The FT8® combustion turbine is derived from a Pratt & Whitney® JT8D™ engine. The high-pressure (HP) shaft connects the 7-stage high pressure compressor and a single-stage high pressure turbine, and the low-pressure (LP) shaft connects the 8-stage low pressure compressor, 2-stage LP turbine. A 3-stage free power turbine drives the electric generator (or mechanical drive). The combustor chamber has 9 cans arranged around the turbine circumference, terminating in an annular transition section leading to the HP turbine. The 2 spool HP and LP turbine sections are also known as “gas generator”.

Figure 1 shows CT power as function of temperature. Results have been obtained through cycle calculations carried out in GTPro/GTMaster® and SOAPP® software based on a “generic” FT8® -3 combustion turbine in simple cycle. Air density is higher at lower temperatures, and as consequence the mass flow through the turbine is higher, resulting in more power.CT performance was simulated with 5% air injection of the base case. Average incremental output is ~2.7 MW across the temperature range.Non-injection cases are shown as triangular blue markers in the figure.Injection cases are shown as circular red markers in the figure.

Normally FT8® combustion turbines used in power generation are provided in a **SWIFTPAC**® configuration where 2 combustion turbines are connected to a single generator. Therefore, the actual power output for a **SWIFTPAC**® is >60 MW at ISO conditions. In such application the nominal Turbophase air injection flow for one module is equal to providing 5% air injection to each CT resulting in more than 5.4 MW of incremental power per TPM per **SWIFTPAC**®.

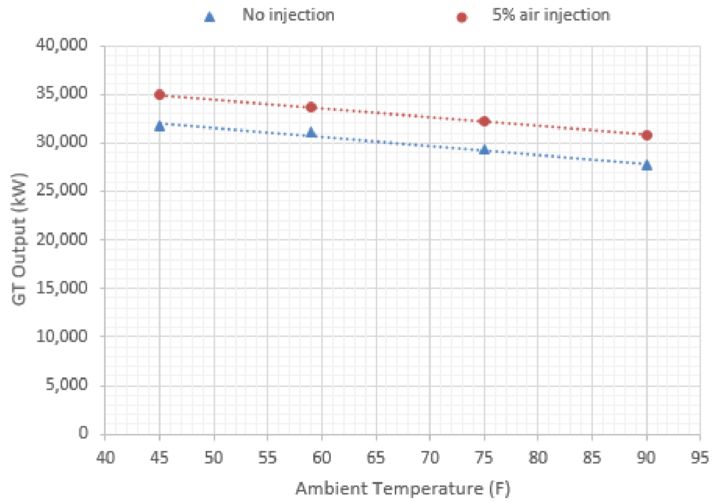


Figure 1.FT8® -3 output vs ambient temperature (with, and without 5% air injection)

The air injection manifold is connected to the 13th stage bleed port at the discharge of the HP compressor (see Figure 2). Injection air is mixed with compressor discharge air, and thenflows to the combustion cans, and then is expanded through the HP, LP and power turbines.

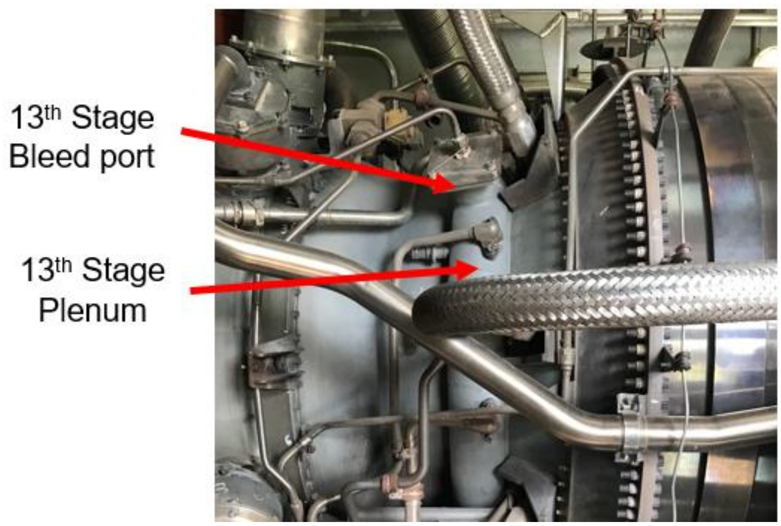


Figure 2. FT8® -3 13th stage bleed port (air injection location)

Turbophase on an LM6000

The LM6000 is a two-shaftcombustion turbine derived from the CF6 engine. It has a nominal output of 42.5 MW and a heat rate of 8,350 BTU/kWh (LH).The high-pressure (HP) shaft connects the 14-stage high pressure compressor and 2-stage high pressure turbine, and the low-pressure (LP) shaft connects the 5-stage low pressure compressor, 5-stage LP turbine and electric generator. Engines use either a Single Annular Combustor (SAC) or a Dry Low Emissions (DLE) combustor.

The air injection manifold is connected to the CDP customer bleed ports at the compressor rear frame (CRF). In SAC combustion turbines, injection air is distributed via struts 2-4 to the internal-diameter of combustor section, downstream of the compressor discharge plenum (see Figure 3). In combustion turbines equipped with dry low emissions (DLE) combustor, injection air is distributed via struts 2-3. Injection air is evenly distributed with compressor discharge air, and then flows to the combustion chamber (either SAC, or DLE), and then is expanded through the high-pressure, and low-pressure turbines.

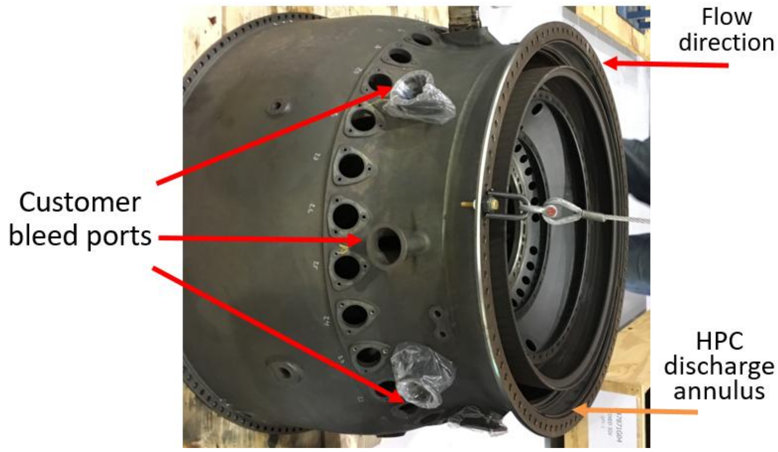


Figure 3. LM6000PC HPC customer bleed ports (air injection location)

Figure 4 shows simulation results for CT power as function of temperature for the LM6000 engine without SPRINT. Incremental output for the same amount of air injection varies between 4 and 5.6 MW across the temperature range. Note that nominal air injection temperature is ~580F which is below the discharge temperature of the CT compressor discharge. At higher ambient temperatures the mixing effect of the injection air and the compressor discharge air allows for the reduction of T3. Consequently, the HP-shaft speed can be increased and there is an added benefit of the increased air flow due to the higher shaft speed. This explains why the incremental power with air injection is higher at higher ambient temperatures. Similarly, air injection can result in heat rate improvements above 7% at high ambient temperatures.

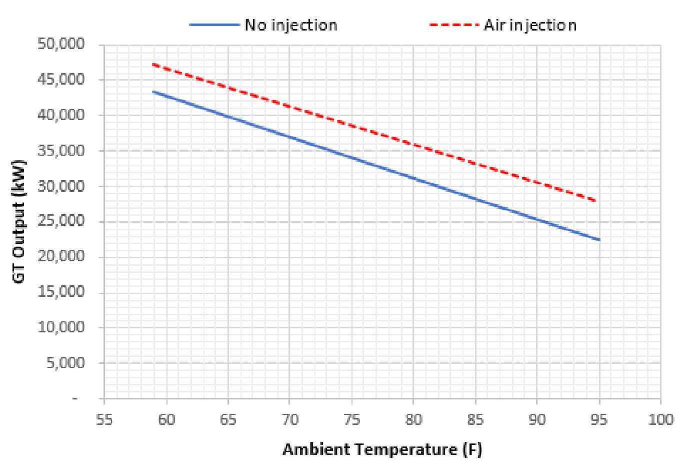


Figure 4. LM6000 output vs ambient temperature SRPINT-off (with, and without air injection)

Turbophase on an LM6000 in tandem with Sprint

Under nominal conditions, LM6000 engines are controlled by the temperature at the inlet of the low-pressure turbine (LPT), or T48. As ambient temperature increases, so does the compressor discharge temperature (T3). When T3 reaches approximately 1,008F, this becomes the control parameter. Operation above this can result in increased life reduction of turbine components.

As a measure to overcome T3 limitations, and increase the CT power output LM6000 turbines use a "Spray intercooling" (SPRINT) system. A fine mist of water is injected at the compressor reducing the temperature and acting as an intercooler. There are two SPRINT systems: a LP SPRINT at the front of the LPC, and a HP SPRINT that injects water mist at the discharge of the LPC.

Turbophase air injection can be used in conjunction with the SPRINT system. Figure 5 shows simulation results for CT power as function of temperature for the LM6000 engine with SPRINT. Compared to air injection with "SPRINT-off", the amount of incremental output for the same amount of air injection is lower when the SPRINT is activated. At 59F this occurs because the CT reaches its maximum allowable compressor discharge pressure (P3). At 95F the CT is limited by T48.

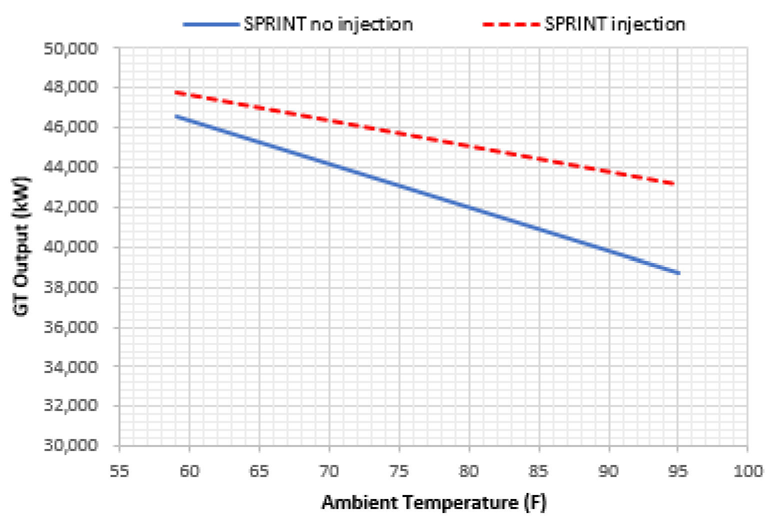


Figure 5. LM6000 output vs ambient temperature SPRINT-on (with, and without air injection)

Turbophase on an RB211

The RB211 combustion turbine is a multi-shaft axial flow turbine derived from the Rolls Royce RB211 engine.

The high-pressure (HP) shaft connects the 6-stage high pressure compressor and a single-stage high pressure turbine, and the intermediate-pressure (IP) shaft connects the 7-stage intermediate pressure compressor and single-stage IP turbine. A 2-stage (RT62 power turbine) or 3-stage (RT61) free power turbine drives the electric generator (or mechanical drive). The combustor chamber has an annular combustion system equipped with multiple fuel injectors.

The Turbophase air injection manifold is connected to the high-pressure air-offtake port at the discharge of the HP compressor (see Figure 6). Injection air is mixed with compressor discharge air, and then goes to the combustion cans, and then expanded through the HP, IP and power turbines.

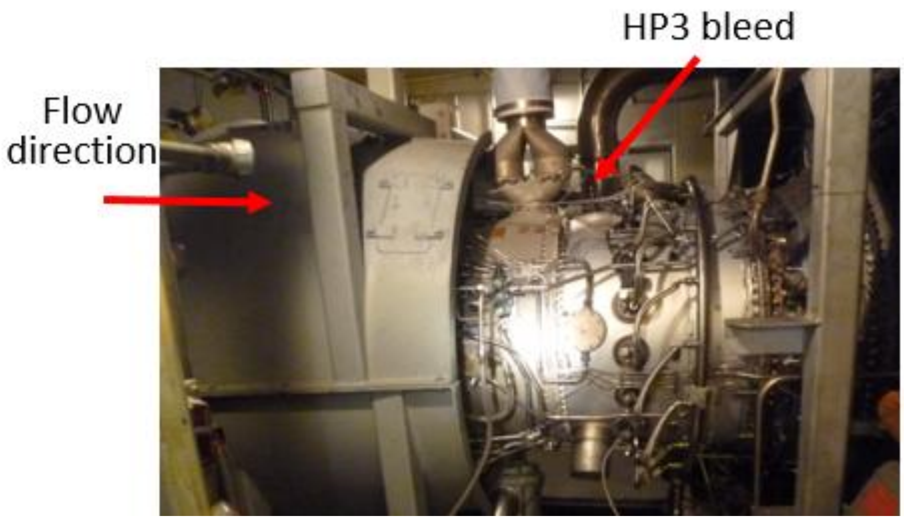


Figure 6. RB211 HP3 bleed port (air injection location)

Nominal injection rates for the RB211 are roughly 10 lb./s, which is approximately to 5% of the CT mass flow. Although injection can be made at any ambient temperature, incremental output benefits are seen at temperatures above 59F. Below 59F the engine is close to the IP shaft power limit, and any air injection results in a modest power increase (<1.6% at 0F), and a reduction of the fuel flow. As ambient temperatures increase, the benefit of the air injection is more evident (as seen in Figure 7). Average incremental output above 59F is ~4.1 MW

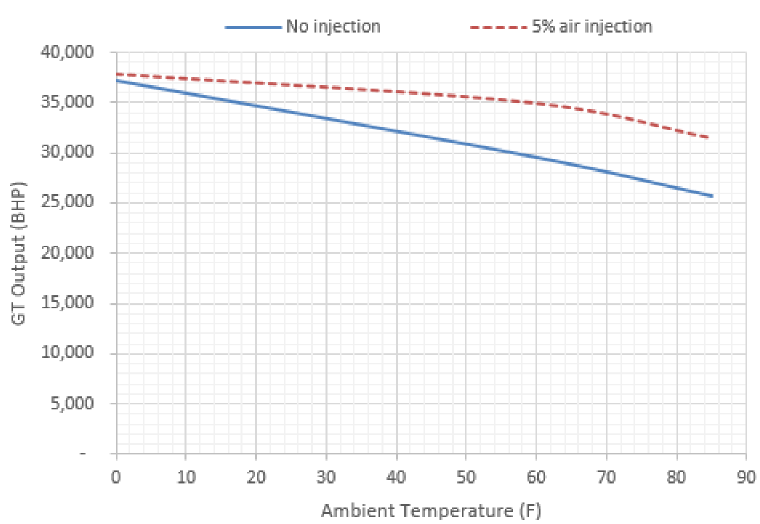


Figure 7. RB211 output vs ambient temperature (with, and without 5% air injection)

Choose Power or Parts Life Improvement

Unlike industrial combustion turbines where base load operation is controlled with a relatively simple relation between the exhaust temperature and compressor discharge pressure, aero-derivative engines have several limiting factors used to protect the engine. During nominal operation the parameter in control is the HP turbine discharge temperature (T48) for LM6000 engines. For engines like the RB211, or the FT8® this control parameter is the power turbine inlet temperature. As operating conditions change, other control parameters can be the limiting factors. For example, at cold ambient temperatures, the HP shaft speed is increased due to the higher mass flow to the HP turbine. If the HP speed reaches its limit, this becomes the operating limit, and the CT controller reduces the fuel input to reduce the HP-shaft speed, limiting output.

As previously discussed, for the LM6000 SPRINT application when ambient temperatures increase so does the compressor discharge temperature (T3). When T3 reaches approximately 1,008F, this becomes the control parameter. Operation above this parameter can result in increased life reduction of turbine components. Similarly, when Turbophase air is injected at the CT the HP-shaft speed is increased due to the higher mass flow to the turbine resulting in higher compressor discharge pressure and higher compressor discharge temperature.

The previous discussion of Turbophase dry air injection in aeroderivative combustion turbines has shown that under certain conditions Turbophase air injection results in a reduction of the fuel flow (and thus the firing temperature) while maintaining output. When this occurs, the thermal stresses on the turbine components are reduced, and the life intervals can be increased. In the contrary, operation above the temperature limits increases the thermal stresses on the turbine reducing service intervals. The following section covers an assessment of the turbine components life with 5% air injection adjusting the CT control to regulate the fuel flow and turbine inlet temperature in such a way that life intervals of the turbine components can be affected. The obtained results are based on FT8® -3 turbine data, but can be applied to all aero-derivative machines.

Figure 8 summarizes the effects on the output, efficiency, and turbine components life of an aeroderivative engine when 5% Turbophase air is injected. All simulations were made for an FT8® -3 engine at ISO conditions

Life mode

The first mode of operation iscalled “life mode”. At this condition, air injection results in a slight increase in T3 temperature however the CT controller then reduces the fuel flow to the combustor resulting in a minor decrease of the turbine inlet temperature. At this condition the efficiency and combustion turbine output arenominally the same, while the turbine component life is significantly increased.

Power mode operation

The “Power Mode” provides the operator with the most incremental power and the best heat rate improvement. In this mode, the CT controller maintains the turbine inlet temperature constant resulting in no effect on the durability or life of the turbine components

Intermediate mode operation

“Intermediate Mode” Falls between the life mode and power mode. Application of Turbophase results inincreased output and heat rate improvement, however less than the power mode. In addition to the power and fuel savings, the resultant lower turbine inlet temperatures result in a life improvement.

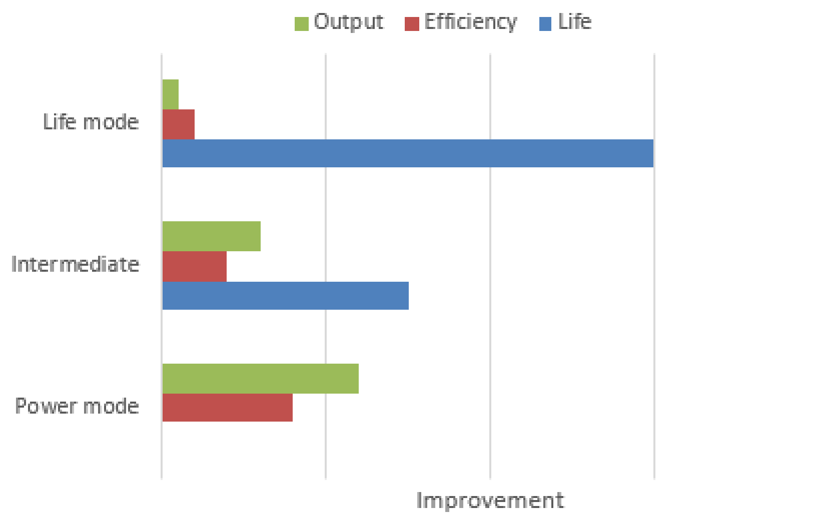


Figure 8. Effects of air injection (5%) on Aeroderivative engine at different operation modes

The operators of Aeroderivative combustion turbines will have the ability to seamlessly transition the value proposition of Turbophase between the three modes of operations. This flexibility allows the operators to maximize the value of a Turbophase equipped system.

Conclusion

In a world of increasing renewables with a premium on flexibility and fuel efficiency, Turbophase combined with Aeroderivative combustion turbines delivers a desirable combination of benefits. Increasingly the Turbophase system will be accepted as standard equipment both as an aftermarket retrofit and on new installs as a reliable and cost-effective method to improve output, efficiency and durability of Aeroderivative combustion turbines.