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Efficient Power Augmentation with Dry Air Injection

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Abstract

An inherent characteristic of all gas turbines (GT) is their inability to maintain constant power output as ambient temperature increases or at high elevation. Consequently, electrical generation and horsepower output are in greatest demand at high ambient temperatures. On a 35°C (95°F) day, a GT's air mass flow-rate is reduced by up to 10% and power reduced by 15% compared to its ISO performance. Dry air injection (DAI) provides constant replacement of air mass flow-rate, injected into the gas turbine's compressor plenum over a wide range of ambient temperatures and altitudes allowing the GT to maintain ISO-like or better conditions irrespective of temperature or elevation. The ability to generate additional, cost-effective, fast & reliable power solutions in challenging conditions, enable industrial gas turbine (IGT) owners to realize a distinct competitive advantage, generate a return on their investments and drive stakeholder value. Dry air injection stands out as the world's first and only commercially viable solution across all ambient conditions for gas turbine performance enhancement. With a six-month lead time, installation achievable in less than a week and the ability to add 20% additional power to gas turbines in under 60 seconds, while improving fuel efficiency - operators, owners and investors will find the offering equally attractive from technical, commercial and financial aspects.

Broad Industrial Overview

Faced with difficult capital decisions and increasing demand for cost effective peak power, both the electrical generation industry and petrochemical industry seek new solutions to meet customers' demands and satisfy shareholder interests through increased profits. Current baseload capacity in the electrical generation market is comprised primarily of coal, nuclear and natural gas plants. Intermediate load and peak power is provided mainly by gas turbines. Petrochemical compression processes and electrical power generation are achieved with gas turbines or reciprocating engines. Asset owners and investors are motivated by reliable power and attractive ROI, leaving gas fired generation as the optimal commercial choice to support the bulk of new capacity, energy and horsepower demand for the foreseeable future. DAI is a proven solution and adds fast, efficient and cost-effective power output to all IGTs.

Performance Calculations

A simplified power plant analysis can be made by accounting the energy input and extracted from the system, using fuel (Q_{in}) as input and electricity (P_{out}) as the output. For the cases discussed in this document, gas turbine performance has been calculated with Thermoflow® software that performs the energy balance across the power plant. For this analysis inlet temperature, site elevation, ambient relative humidity and external gas temperature and pressure are the system inputs, while gross power output at the generators and fuel consumption are the outputs of interest.

Plant net power (P_{net}) is calculated as the difference between generator output and auxiliary electrical loads, such as condensate and fuel pumps and cooling fans:

$$P_{net} = P_{out} - P_{aux} \quad (1)$$

The heat rate of the system compares the rate of energy supplied by the fuel to the amount of power produced by the system, and thus is a measure of the system efficiency.

$$HR = \frac{Q_{in}}{P_{net}} \quad (2)$$

In order to compare the relative effectiveness of the DAI system, and other alternatives for power increase, two metrics will be used: incremental power and heat rate, with incremental power given by the following expression:

$$P_{inc} = P_{net,inj} - P_{net,base} \quad (3)$$

Auxiliary electrical loads for the power augmentation (water and fuel pumps, cooling tower fans, refrigerant compressors, etc.) are included in the P_{net} calculation. Finally, the incremental heat rate for the gas turbine is calculated as:

$$HR_{inc} = \frac{(Q_{in,inj} - Q_{in,base})_{GT} + Q_{in,DAI}}{P_{inc}} \quad (4)$$

The heat rate formula used above takes into account the additional fuel burned by the gas turbine due to increased air mass flow rate through combustion and the fuel burned by the DAI reciprocating engine.

The Brayton Cycle defines the theory by which all gas turbines are engineered and operated. Thermodynamics dictate that the higher the firing temperature, the higher the power per unit mass of air. Today it is common to fire gas turbines above 1315°C (2400°F), with a GT air mass flow rate greater than 450kg/s. As ambient temperature or elevation increases, air density decreases, reducing mass flow through the turbine and power output. DAI restores the airflow through the gas turbine rapidly and efficiently. The system takes advantage of the fundamental characteristic that in virtually all plants the gas turbine, generator, transformer and electrical grid connection are designed to limits based on cold day conditions where the plant can produce its maximum output. Using air injection into the compressor discharge plenum (seen in figure 1), the GT's mechanical limits can be approached when previously unachievable.

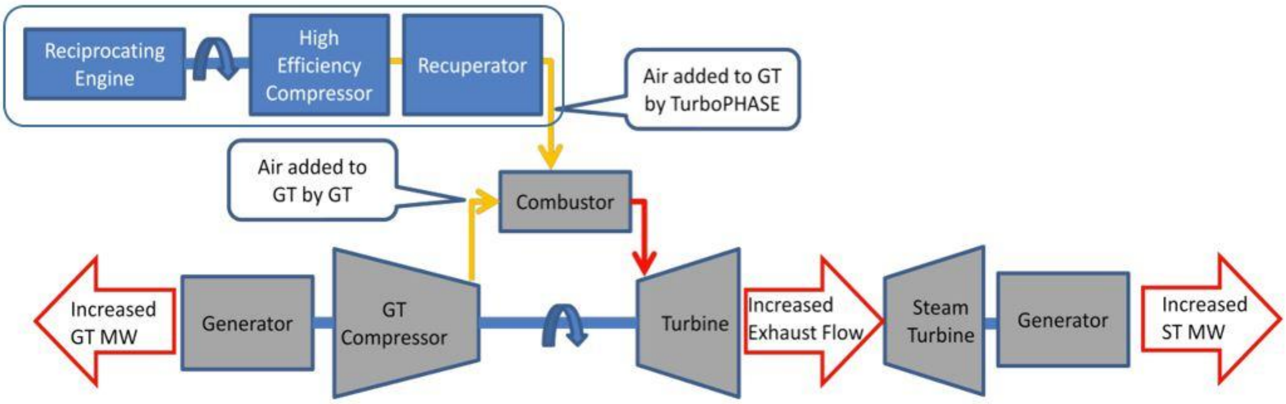

Figure 1: Block Diagram illustrating Air Injection into Combined Cycle Power Plant

A DAI system, commercially known as "Turbophase" combines a highly efficient reciprocating gas or dual-fuel engine driving an intercooled four-stage centrifugal compressor that routes its air flow output through a recuperator where it is heated by recovered engine exhaust and flows directly into the combustion section of the gas turbine. This system is modular, allowing it to put online as demanded. With each module producing 230°C – 340°C (450°F - 650°F) air at 4.1 – 6.4kg/second (9-14 lbs/second) between 1.2 - 4.1MPa (170-600psi).

The System is designed to operate and produce consistent power output across all ambients, 8760 hours/yr. Maximum efficacy is realized as ambient temperatures peak during summer months when electricity and horsepower production is in highest demand or shortest supply, respectively. On combined cycle plants, the incremental power boost gained from DAI is produced at significantly improved heat rates compared to any simple cycle peaking plants. When the DAI system is running on simple cycle plants, the overall heat rate of the plant is improved.

The Turbophase Module ("TPM", "the Module", "the System") is a fully mobile, skid-mounted engine-driven compressor built with off-the-shelf OEM components. The TPM is designed as a modular package and the only DAI technology capable of increasing gas turbine output by 20%. The System improves gas turbine heat rate by as much as 10%. It measures approximately 9.8x2.4x3.5m (32x8x10ft) making it one of the most power-dense solutions available and a perfectly mobile system with minimal auxiliary equipment. Figure 2 provides a visual on the minimal footprint and auxiliary equipment that this technology requires

Figure 2: TPM installed at the Morris Cogeneration 3x1 Combined Cycle Plant

The major OEM components of the system include a 2MW reciprocating engine, four-stage intercooled centrifugal compressor, gear box and recuperator / economizer. Figure 3 shows a Computer generated image of the major components used in this DAI technology.

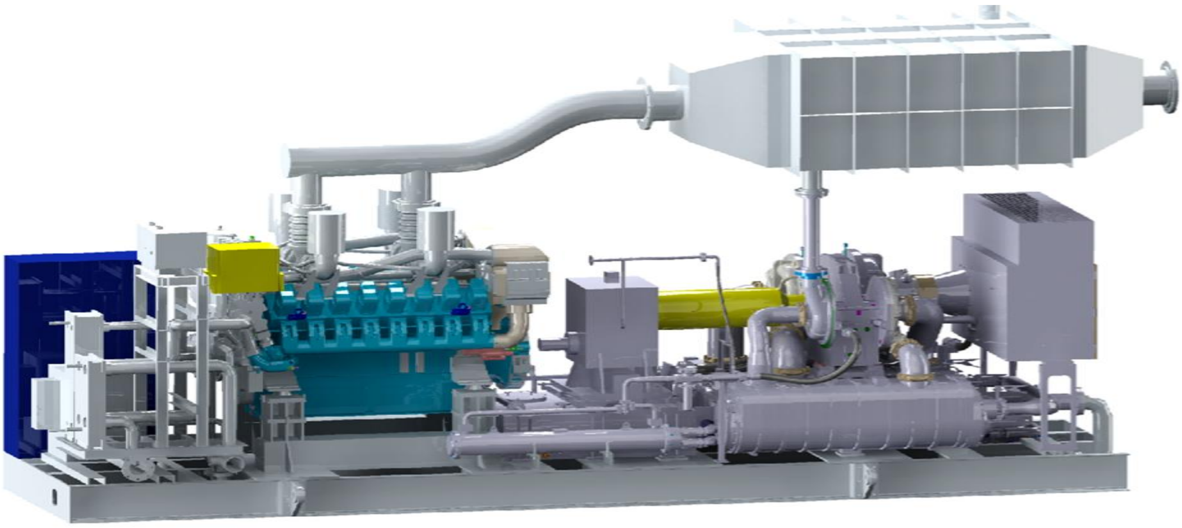

Figure 3: CAD model of internal TPM Components

Engine Selection

The reciprocating engine driving the intercooled compressor produces 2MW (2800HP) and 482°C (900°F) exhaust. A key feature of the on-board reciprocating engine, includes the fully integrated turbochargers which allow the engine to achieve constant output up to 1520m

(5000’) elevation and 55°C (130°F) ambient temperatures. Exhaust backpressure for the reciprocating engine has a negligible effect on efficiency compared to that of a Gas Turbine. The reciprocating engine tolerates backpressure up to 70cm (28”) of water, or 0.69MPa (1psi) before any significant power deterioration is noted. In contrast, typical gas turbine performance is measurably impacted with only a fraction of this backpressure. A simple cycle “F” class would experience power and efficiency degradation close to 5% when increasing backpressure from 10cm to 70cm (4” to 28”). It is the reciprocating engine's high relative tolerance for backpressure that enables an efficient and low cost recuperator to heat the TPM's compressed injection air.

System Efficiency

Heat rate of the gas turbine improves markedly with the introduction of hot, compressed air. The TPM compresses and injects air much more efficiently than the gas turbine’s own axial compressor. This is possible thanks to the intercooled compression process and by recovering waste heat from the reciprocating engine, to match GT compressor discharge temperature.

The heart of this system is a 43% fuel efficient reciprocating engine as prime mover, driving an intercooled compressor. By comparison, the most advanced aero derivative gas turbines yield fuel efficiencies between 39% and 41% in simple cycle, while the fuel efficiency of the workhorse combined cycle F class engine is approximately 36%. Additional economies are realized via the TPM's intercooled compression process whereby work and therefore fuel required to produce additional flow are less than that of the gas turbine. The waste exhaust heat from the reciprocating engine is routed through a counterflow heat exchanger or recuperator to heat 5.4-6.8kg/sec (12-15lbs/sec) of compressed air from the compressor. The thermal efficiency of the system is improved to 63% through this relatively simple heat recovery process.

Non-Parasitic

An important aspect of the system is the absence of any “netting” effect to the power boost provided by each Module —meaning that no energy is drawn from the gas turbine or steam cycle to drive the system. Each Module uses approximately 50kW to maintain its auxiliary systems which include controls, fan motors, oil pumps and lighting. Comparable after-market technologies can consume up to 2MW of electrical load, producing a netting effect which yields less than half the gross power output. In many of these cases the net power output to the grid is comparably lower, while also penalizing efficiency. Because the Dry Air Injection system uses a gas-fueled prime mover rather than plant electrical power or steam to generate up to 20% additional gas turbine power, it is very cost effective on a net-$/kW-basis.

The Practical Limits of Boost & Operating Characteristics on Gas Turbines

Figure 4 shows typical Gas Turbine performance variation vs. temperature. By convention, the nameplate performance (100% in the figure) is taken at sea level, 15°C (59°F) and 60% relative humidity - ISO conditions. As temperature is reduced below 15°C (59°F), the mass flow increases and so does power output. This trend continues until the mechanical limit of the shaft is reached and IGVs begin to close, and/or firing temperature decreases. In a similar manner, lower inlet temperatures translate to less compression work and heat rate improvements. For high temperatures the opposite occurs.

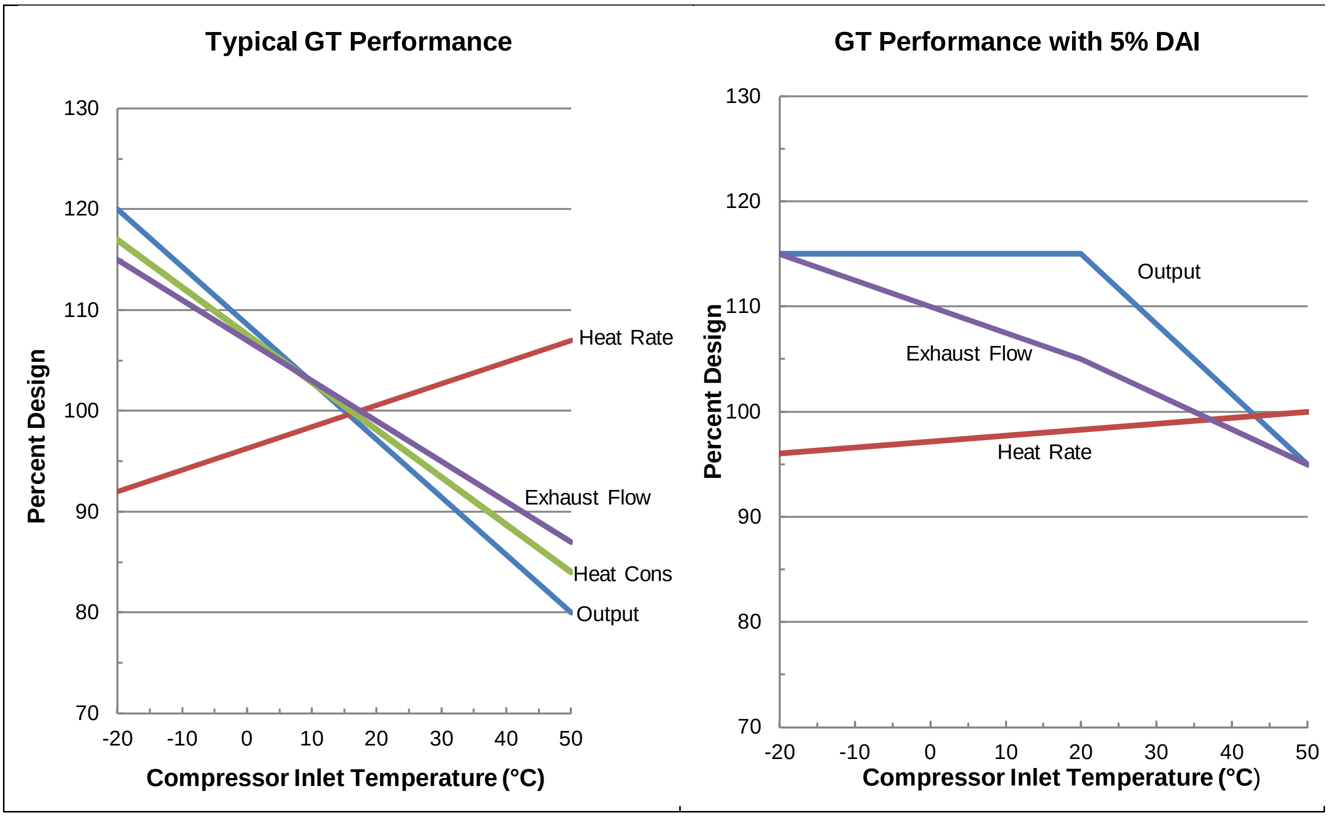

Figure 4 : Side by Side Comparison of GT Performance Curves with and without 5% DAI

However, figure 4 also shows improved gas turbine operation over the entire ambient range, increased exhaust flow and improved (reduced) heat rate or fuel consumption over the entire operating range when 5% more mass flow is injected into the GT.

Figure 5, is a typical correction chart for GT performance vs altitude, similar to the one provided by OEMS. For example, a typical “F” class gas turbine makes about 20% less power at 1520m (5000’) compared to its sea-level operating conditions for the same temperature. The TPM compensates for this loss because the reciprocating engine uses variable speed turbochargers to keep the engine at a constant speed and load. It can be seen that an altitude correction factor is unnecessary when 5% DAI is used when below 1520m.

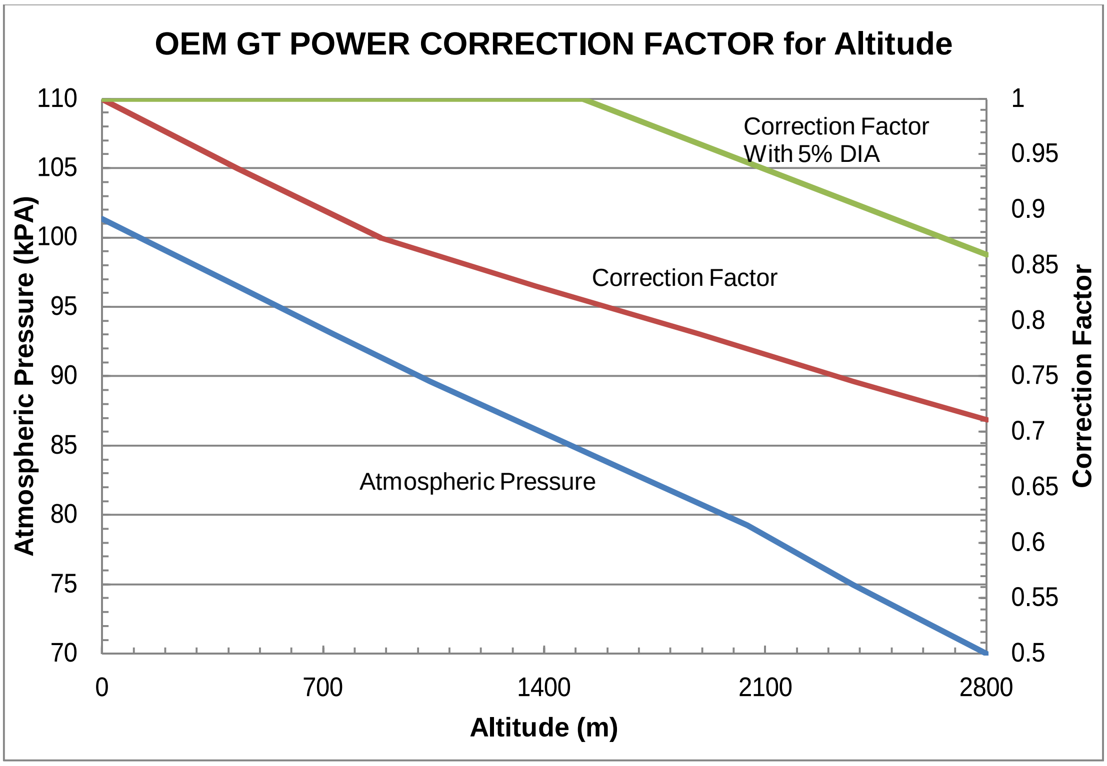

Figure 5: Difference in correction factor when using 5% DAI

Since typical air injection results in large power increase (5% airflow injection increases power above 10%, as described earlier), the aerodynamic and mechanical aspects of the gas turbine, not flow characteristics, will likely limit how much injection can be implemented. This must be checked for each gas turbine, as different models may have other limiting conditions, such as turbine area, compressor surge margin, or the electric generator power limit. Figure 6, below shows 5% injection (5% of ISO GT compressor inlet flow) and the resulting 12% power increase from the gas turbine. Depicted are the mechanical limits, primarily shaft torque and how much flow can be added. In this example, at 19°C (67°F), the flow limits have significant margin while the mechanical limits are being reached.

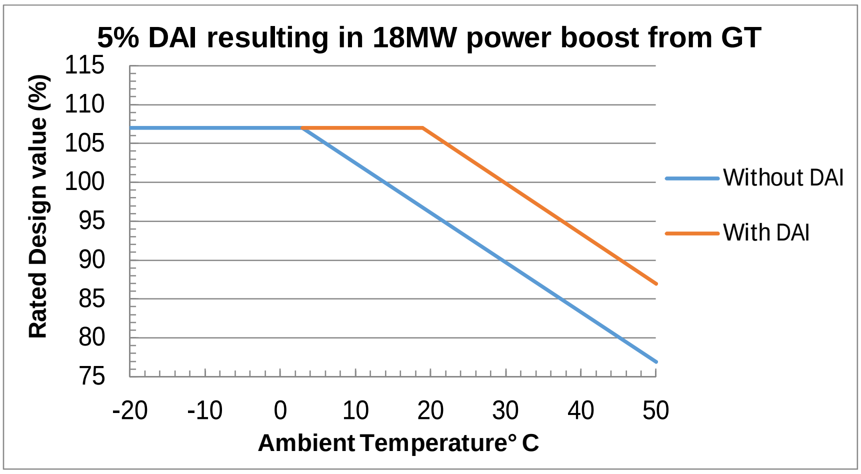

Figure 6 : Illustrating 5% air injection with mechanical limits to 3°C and increasing power output by 12% from 19°C to 49°C

Analysis of Frame & Aeroderivative Machines in both Simple & Combined Cycle

As the firing temperature and pressure ratio of gas turbines increase, the specific output, or the power derived from each pound per second of compressor inlet airflow also increases. Since DAI works on a variety of gas turbines, the same TPM package can be applied to an E-class, F-class or aeroderivative unit. However, this same TPM package will produce more power with the same air and thus will cost significantly less on a $/kW basis for the F-class or greater engine. This rationale holds true whether applied to a peaking or combined cycle plant. Because the DAI system does not net out any significant energy from the simple cycle or combined cycle configured plants, but makes additional power in the steam turbine, the cost of incremental power on a $/kW basis is lower for the combined cycle plant. The major benefits to simple cycle configuration include, vastly improved heat rate and the greater incremental power output.

The table on the following page displays the output and heat rates of various engines in simple cycle and combined cycle configuration with 5% dry air injection rates. For 10% injection rates, the power output will be approximately double the values shown in the table. Engines with higher firing temperatures receive greater benefit from this injection method.

Table 1: Simple and combined cycle gas turbines with DAI (5% injection on a 35°C day)

Frame	TPM Incremental Output (MW)	TPM Incremental Heat Rate (kJ/kWh)	Number of TPMs per GT
GE Fr5	3.5	9173	1
RB-211	4	7698	1
GE 6B	4.4	7698	1
GE 7E/A	13.5	7275	3
GE 7FA	27.5	6853	6
SGT5-3000E (V94.2A)	20.0	7275	4
SGT5-4000F (V94.3A)	33.0	6853	6
LM6000	5.0	7380	1

Variable Operation and Maintenance & Fuel Burn

The reciprocating gas engine has a 63,000 hour time between overhaul (TBO) intervals with minor periodic maintenance duties between. The diesel engine TPM has a 21,000 TBO. The engine coupling and gearbox are made by industry-accepted OEMs for extensive and demanding use in oil, gas and mining operations around the world. The compressor employs conventional bearing and centrifugal compression technology, and is designed for on-condition operation of impellers and bearings with intercoolers and oil pump overhaul at 48,000 hours.

Engine and compressor cooling is accomplished with plant supplied cooling water. Alternately an auxiliary system (wet cooling tower) can be installed, if the plant capacity is not available for the additional cooling demand. Air-cooler cooling systems are also available for places with limited cooling water. The addition of the auxiliary cooling system adds less than $10/kW to the system cost. The recuperator section is designed to run on condition with at least 63,000 hours between inspections. In the unlikely event of damage, high-pressure air will leak into the exhaust gas, which is a benign event detected by loss of pressure on the compressed air side. Two valves control the interface with the gas turbine – the first located at the gas turbine end of the air delivery pipe and the second located at the TPM unit. The valves are controlled by a system that interfaces with the reciprocating engine controls and the compressor standard instrumentation and protection equipment. The control logic and operation is very similar to steam injection and the capacity to implement the required changes to the gas turbine's control system already exists. Overall, this DAI system is built on proven and rugged components, designed to last the life of the power plant with an incremental maintenance cost ranging between $0.0027 and $0.0049/kWh of operation.

Emissions

The prime mover natural gas reciprocating engine used by this DAI system meets all current United States federal regulation limits in accordance with the *Standards of Performance of New Stationary Sources* outlined by 40 CFR part 60, subpart JJJJ, table 1. Part 60 maximum emissions allowed are 1.36g/kWh NOx, 2.72g/kWh CO and 0.95g/kWh VOC. The 2MW Series gas engine using a conventional 93% CO catalytic exhaust system has emissions of 0.68g/kWh NOx, 0.16g/kWh CO and 0.53g/kWh VOC, well below federal requirements. Power plants incorporating a power augmentation system will evaluate its emissions with particular interests in mass flow related emissions levels, a common requirement in operating permits. Each plant has its own permits and thus evaluated individually. An optional SCR can be built into the system, reducing NOx from 0.68g/kWh to 0.068g/kWh.

TABLE 2: Emissions before and after treatment (PPM at 15%O_2)

	Untreated NG Engine Exhaust			After Supplied Treatment System		
	g/kWh	PPM	kg/h	g/kWh	PPM	kg/h
CO	2.27	224.2	4.12	0.16	15.7	0.29
NOx	0.68	44.4	1.34	0.068	4.4	0.14

When the compressed air is injected into the gas turbine, there are two sources of incremental emissions, the gas turbine and the DAI module. The gas turbine PPM level for all emission elements is relatively unchanged, however, because the power increase is two times the level of the air and fuel increase, the incremental emissions are half the rate on a kg/h basis for the incremental power as compared to the base plant without air injection. The actual kg/h numbers will vary with gas turbine power and PPM level, therefore, they must be calculated on a case by case basis as previously stated. The TPM's emissions are independent of the gas turbine and can be calculated directly from the TPM in g/kW-h numbers listed above. Each module emits 1.34kg/h (2.96 lb/h) NOX, 0.29kg/h (0.64 lb/h) CO and 1.07kg/h (2.36 lb/h) VOC from the

2MW engine with an exhaust flow of 2.7 kg/sec. There is also 1.06 tons per hour of CO_2 emitted in the TPM exhaust.

If the gas turbine has an SCR reducing NOx to 2PPM for example, the TPM's exhaust can be mixed with the GT's exhaust, resulting in an increase from 2.0PPM to 2.1PPM which can be tuned back to 2.0 with an ammonia adjustment to the SCR. In a similar way, for a gas turbines without an SCR operating at 9ppm, the reciprocating engines can be outfitted with an SCR, reducing NOx emissions of the unit by a factor of 95%, equivalent to half the emissions of the gas turbine.

In locations requiring the diesel engine driven DAI, the engine produces 7 g/kWh NOx, 0.91g/kWh CO, 0.072 g/kWh PM and 0.15g/kWh THC. If required, the unit can be fitted with an optional PM filter and SCR, which is capable of reducing nitric oxides in more than 95%, complying with the most strict tier 4 regulations for compression ignited engines.

As an example, baseloaded 7FA plants running TPMs for 8000 hours annually, will increase their NOx emissions by 12tons/yr per DAI Module (5MW of boost) with an untreated system. If an on-board SCR system is supplied with the module, NOx is reduced up to 95% to 0.6tons/yr.

Ancillary Benefits of Dry Air Injection

Duct Burner Capacity - Additional changes occur when air is injected into the gas turbine, affording the operator beneficial opportunities as a result of TPM operation. Most significantly, GT exhaust temperature drops while at the same time the exhaust flow increases. This is a result of pushing more flow through the turbine, causing an increased pressure ratio and therefore an increased temperature ratio. On a typical “F” class GT at 35°C, 5% injection results in an exhaust temperature drop of 10°C. Since the firing temperature is unchanged, the larger temperature ratio across the turbine results in a lower exhaust temperature. These temperature and flow effects partially counterbalance each other. Although exhaust temperature drops 10°C, because the flow increased by 5%, the net output of the steam turbine only increases by 5 MW on a 2x1 combined cycle plant, or 3%. Depending on HRSG flow capacity, HRSG metal temperature limits, duct burner capacity, and steam turbine flow capacity the increased exhaust flow at a 10°C lower temperature creates an opportunity to add 13.5 MJ/s (~6%) more duct burner capability to each gas turbine, likely at very little cost. In another example if the air injection rate can be increased to 10%, creating potential for 12% additional duct burner capacity.

Improved GT Response Time – This DAI system uses control valves to modulate the flow of air injected into the gas turbine. Up and down modulation occurs in seconds, allowing the gas turbine to accurately follow fast AGC demand signals, improving mileage in ancillary services markets. The ability to ramp in under 60 seconds, provides operators and plant owners to bid into a spinning reserve market, yet leaving the gas turbine at baseload, its most fuel efficient operating condition. The reserve margin requirement may be maintained by the module instead of turning down the plant to part load conditions and wasting fuel resources.

Inlet Anti-Icing – A function of many gas turbines in cold climates is an “inlet bleed heat” (IBH) system. The TPM has the ability to not only provide hot, pressurized air for inlet bleed heat, but it can also be manifolded to create a filter house inlet anti-icing system. Plants sometimes suffer from the detrimental effects of prevailing winds blowing cooling tower vapor and mist across the GT filter house inlet. The ice formed on the filter house causes a differential pressure across the intake and has the potential to prevent the machine from running.

Black Start – The use of a 2MW engine allows for a 2MW generator to be installed normal to the gearbox where the engine and compressor are coupled. Multiple TPMs can be coupled in series to provide black start or emergency gen-set capability in 2MW increments. The generator operates independently from the compressor and could also be used to satisfy house load requirements when the plant is shut down, and heat can be recovered in the winter to provide heating to indoor spaces at enclosed power plants.

Closing Thoughts

Utilities, IPPs, grid operators and industrial users call for additional peak power on warm to hot days, or at elevation to satisfy demand and produce acceptable financial returns to their stakeholders. In order for asset owners to maintain a competitive edge in today’s market, they are forced to make either exorbitant capital expenditures or the addition of inefficient augmentation, parasitic to the gas turbine and netting a fraction of the power provided by DAI. DAI replaces unused capacity in the gas turbine at simple or combined cycle plants at moderate to high ambient temperatures and/or elevations, allowing the gas turbine to operate at ISO-or-better conditions at all times. The incremental power it produces is significant and the incremental efficiency of the Module(s) is an improvement when compared with the gas turbine heat rate. When applied to any industrial gas turbine larger than 15MW, DAI is a highly economical source of additional power. The system is modular, compact, pre-assembled and tested prior to being shipped to the plant. Thus, installation is simple, predictable, quick and the smartest solution to being competitive in today’s market.

Nomenclature

DAI Dry Air Injection

HR Heat Rate

IGT Industrial Gas Turbine

P Power

Q Fuel

Recuperator Counter-flow heat exchanger

ROI Return On Investment

Thermoflow Software used to calculate GT power

TBO Time Between Overhaul

TPM Turbophase Module

Subscripts

inc – Incremental

inj – Injection

aux – Axillary Electrical Load

base – GT Base Load

References

[1] *GER3567: Effect of Ambient Temperature on Gas Turbine Performance - GER3567 "GE Gas Turbine Performance Characteristics"*