Humid and dry air injection represents a relatively low-cost technology for increasing gas turbine power output and reducing heat rate over a wide range of ambient temperature and part-load operating conditions.

Several companies are evaluating the technology and cost effectiveness of injecting externally compressed, heated and humidified air (can also be dry air) to increase gas turbine output during hot day operation.

Air augmentation is a relatively low-cost technology applicable to simple cycle and combined cycle plants on a new installation or retrofit basis.

Enhanced performance is most dramatic at higher temperatures and altitudes but is also attractive at lower temperatures:

- **Increased power.** Humidified air injection can increase gas turbine output by up to 20% at 95°F ambient temperature.
- **Lower heat rates.** Can reduce gas turbine heat rate by 8% to 15% over entire operating range from full to part-load output.
- **NOx emissions.** Can reduce NOx emissions by 15% (lbs per kWh) compared with simple cycle gas turbine output.
- **Installed costs.** Turnkey cost of humidified air augmentation system estimated at roughly $180 to $220 per kW.

Engineering and mechanical aspects of injecting air into a gas turbine for power augmentation are similar to those for steam injection.

The same restrictions apply to make sure that the incremental increase in power does not exceed operational limitations.

Incremental increases in power must be kept within the bounds of maximum allowable torque, compressor surge, combustion parameters, flame stability, and electric generator capacity.

Air augmentation works by introducing an external supply of pressurized air into a gas turbine upstream of the combustors to increase mass flow. The incremental power added is proportional to the mass of the injected flow.

The air can be either humidified or dry. Humidification has the added benefit that it reduces the amount of supplementary air needed to increase the gas turbine total flow and saves on compressor work otherwise needed to pressurize a higher flow.

The simplified explanation for gas turbine hot day loss is that inlet air loses density, thereby reducing mass flow and hence power output. Compressor section power consumption also increases because it must work harder as air density falls off, further reducing net plant output.

In effect, with air augmentation, gas turbines operate as though at much lower ambient temperatures. Dr. Michael Nakhamkin, president of Energy Storage and Power Consultants, developed and owns the patents on the use of air injection technology for gas turbine power augmentation.

Last year, Calpine obtained a non-exclusive license from ESPC to apply humid air technology to its service fleet of simple cycle gas turbine and combined cycle power plants.

The company has since validated performance improvement guarantees and is getting ready to run more extensive tests at higher power ratings.

Calpine conducted its validation of humid air augmentation...
tests on a PG7241FA gas turbine peaking installation, unit #3, at the Broad River energy center in South Carolina.

This particular gas turbine is equipped with a once-through steam generator and ports for injecting high-pressure steam that is generated into combustors for power augmentation.

Those same steam ports are easily adapted for air injection so that project test engineers are able to evaluate gas turbine performance with and without humid air injection, dry air injection, steam injection, and, for a reference base, no injection at all.

Special measures were taken to make sure air injection would not damage the gas turbine during the test runs, including instrumentation to monitor and record compressor flow disturbances, mechanical and thermal stresses, vibration levels, and combustion dynamics.

As a precaution, for this initial series of tests, the pressurized and humidified air injection for power augmentation was limited to the same 3.5% moisture limit that General Electric specifies for Fr7FA steam injection power augmentation.

Calpine's external air pressurization and humidification system consists of two motor-driven air compressors with intercoolers, an air pre-heater, and a mixer supplied with steam to humidify the pressurized air for injection (does the same job as the air saturator).

Test results confirmed an 18.3-MW increase in power output at 95°F inlet air temperature with the 3.5% humidity limitation.

Upcoming tests are expected to run at humidity levels of 5% and then go progressively higher to establish comfortable operational limits for optimum performance.

It is reasonable to believe that some of the tests will also be directed towards determining whether turbine rotor inlet temperature control with air augmentation should be referenced to "wet" or "dry" curve operation.

Normal control routine when using steam injection for power augmentation is to operate on the "dry" curve which reduces turbine rotor inlet tem-
perature by 30°F to 50°F to guard against over-temperaturing the turbine blades.

Steam has a much higher heat transfer factor than air. As a result, says Nakhamkin, any steam coming into contact with surrounding surfaces of combustors, transition pieces and turbine blades can create localized thermal spikes that overheat and, in time, cause damage.

Pockets of steam can also cause significant pressure oscillations in the combustors. Humidified air does not pose any of those same problems. Its heat transfer characteristics are lower and therefore more benign than with steam. There is not the same risk of localized overheating as there is with steam.

Technically, at least, a good argument can be made that humidified air should be able to have higher moisture levels than deemed acceptable for steam injection.

It also suggests that humid air injected gas turbines should be able to operate on the normal “wet” control curve without having to reduce turbine rotor inlet temperature.

Calpine’s Fr7FA test results, for example, measured an 18.3 MW increase in power while operating on the “dry” curve (reduced firing temperature).

On “wet” control, the increase in power output at 95°F would have been closer to 22.3 MW — even with only 3.5% humidification.

Dr. Michael Nakhamkin, president of ESPC, says that increasing the humidity level to only 5.0% would have increased net power output by more than 28 MW even even with “dry” curve control.

Operating on the “wet” curve, Calpine should expect to see a more than 32 MW increase.

Dry air is not as effective as humid air injection. But dry air also can increase power output at any ambient temperature — again subject to torque, compressor surge, combustion, torque and electric generator limitations.

At 95°F ambient, for example, the PG7241FA operates at 150.4 MW output with a heat rate of 9760 Btu/kWh without an evaporative cooler, inlet chilling, or inlet fogging.

Dry air injection, studies indicate, can increase output to an estimated 166.4 MW with a slight improvement in heat rate to 9720 Btu/kWh.

Dr. Nakhamkin sees steam injection as a major but less effective competing technology for gas turbine power augmentation.

Humid air provides at least 35% more power augmentation than steam injection, he claims, and slightly better heat rates.

Steam injection also has some major drawbacks when it comes to service life, operating costs, and operational flexibility, he says.

Reportedly steam augmentation can cut the life of “hot gas path parts” in half, even for operation at lower turbine inlet temperatures.

There should be no impact all on service life with dry air injection, he maintains, and significantly less impact with humid air injection.

Further, humid air injection does not require demineralized water so that there is a significant savings in terms of treatment, personnel, and operating and maintenance costs otherwise associated with the use of demineralized water.

Lastly, air injection can introduce incremental power instantly as opposed to the 30 to 40-minute delay typical for steam injection, says Nakhamkin.

Instant start-up may not be an advantage for base load operation but is important for short-duration daily peaking cycle installations.

Humid air injection is also said to be superior to inlet fogging and wet compression for improving hot day output and heat rate.

Water is introduced after the air has been compressed, he explains, whereas fogging and wet compression adds water to the compression cycle.

With fogging or wet compression, the
Humid air injection NOx emissions
Logarithm plot of test combustor results shows dramatic decrease from close to 100 ppm NOx without any humid air injection to less than 10 ppm at 10% moisture level and less than 5 ppm at 15% moisture level. Combustion became unstable at around 30% humidity. Tests sponsored by EPRI were conducted by Textron and Aero Industrial Technology.

Estimated Fr7FA Humid Air Plant Costs
Turnkey cost for supply and installation of Fr7FA-sized humid air plant based on non-competitive quotes for engineering, construction and equipment. Total cost is estimated for budgeting purposes at around $4.75 million.

<table>
<thead>
<tr>
<th>Mechanical equipment</th>
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<tbody>
<tr>
<td>2.35 MW compressor train</td>
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<td>heat recovery unit</td>
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<td>air saturation column</td>
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<tr>
<td>Total cost</td>
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Vaporized water must be pressurized along with the air, significantly increasing compressor power requirements. In addition, only demineralized water must be used to avoid blade erosion attacks and compressor fouling.

Both dry air and humid air augmentation technology can be retrofitted to existing installations. Humid air injection is particularly effective for gas turbines not equipped with dry low NOx combustors.

Non-DLN combustors allow operation at higher moisture levels leading to higher relative power augmentation and lower heat rates.

In general, older gas turbines have more forgiving surge margins that can tolerate higher volumes of air injection for greater output without interfering with compressor operation.

TVA engineering studies indicate that gas turbines like Fr7Es that have decent heat rates, stand to benefit the most because they can be readily upgraded to be more competitive with advanced FA, G and H technology simple cycle peakers and combined cycle plants.

Air augmentation may also make sense for gas turbine powered pipeline compressor stations where unit sizes are relatively small and water is not available. It offers a relatively inexpensive way of expanding station capacity without having to permit and install additional gas turbine sets.

For stations with multiple gas turbine installations, dry air injection system components could be optimized to serve overall power augmentation needs — with significant cost savings and increased system reliability, availability and flexibility.

An initial budget for a Fr7FA-sized package, based on bids submitted by competitive suppliers for major items such as the compressor train and saturator, came in at $4.75 million total.

That is still probably on the high side, says Nakhamkin, as evidenced by the fact that Calpine was able to shave $400,000 off the estimated cost of the compressors they installed. On that basis, he considers $5 million as a good conservative number for budgeting purposes.