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The Turbophase dry air injection system
Credit: Powerphase

Improving gas turbine performance with dry air injection

In the Middle East, gas turbine efficiency at high ambient temperatures is crucial. A demonstration project in Saudi Arabia installed a dry air injection system upgrade with the aim of improving fuel efficiency, writes Tildy Bayar

Demand for fuel oil for power generation during a Saudi Arabian summer reaches between 420,000 and 430,000 barrels per day.

With 58 per cent of global use, the nation is the world's largest user of crude oil for generating power. Iraq, Kuwait and the UAE were ranked third, fourth and fifth respectively; together with Saudi Arabia, these countries account for almost 80 per cent of the crude oil that is burned for power generation worldwide.

One company says it can potentially offer gas turbine-based power generators savings of over 18 million barrels of oil equivalent (or a 5 per cent fuel efficiency improvement) per year through its dry air injection system.

Powerphase, with offices in Florida and Dubai, has one such system, called Turbophase, installed at a cogeneration plant in the US. The Morris Cogen plant, which came online in 1997, is a 177 MW combined-cycle facility featuring three GE Frame 6B gas turbines with HRSGs, and a 60 MW steam turbine. It supplies power and process steam for a large ethylene manufacturing plant near Chicago, Illinois. Two Turbophase modules have been operational at Morris Cogen since September 2014 and have accumulated over 2000 hours of operation.

In late summer 2015, Powerphase installed its first Turbophase upgrade in the Middle East on an operational GE 7FA gas turbine. The company says it installed the upgrade in four months in order to meet the customer's summer peak load requirements.

Technology configuration

In simple or combined cycle applications the skid-mounted Turbophase system consists of an air compressor driven by a reciprocating engine and a heat recovery system which captures the engine's exhaust heat and adds it to the compressor discharge, enabling the system to match the turbine's compressor discharge temperature.

On combined cycle and cogeneration systems, the module can be configured with a steam turbine drive for the air compressor which enables zero incremental air emissions and, Powerphase says, helps improve output from plants which are facing limits on the air cooled condensers for the steam turbine.

The Turbophase system "takes advantage of the fact that all gas turbines loser power as ambient temperatures or elevations rise", explains Bob Kraft, Powerphase president and chief executive. The system "adds the air that is naturally missing back into the turbine". The air is injected into one or more of the existing ports, "typically about 5 per cent air, which results in 10 per cent more turbine power".

"We are the first commercial air injection system available on market," he adds, "and for the next 18 to 20 years we expect to be the only one because of our patent portfolio."

In the Middle East, he notes, chillers are competitive with the Turbophase system. Chillers effectively cool the gas turbine inlet to allow it to generate additional mass flow, "whereas we just generate it with an auxiliary gas-driven module and drive the air into the turbine. We do something similar but in a much different way, and the big difference is that we generate that air between 30 and 40 per cent more efficiently than the turbine can generate its own air."

Chillers store cold water for 16 or 18 hours a day, using the turbines to run an electricity-driven chilling process. During six peak daytime hours, the chillers cycle cold water from a cold tank to a hot tank through the turbine's inlet to produce additional power. In

Number of TPMs		1	2	3	4	5	6	7
Incremental power	MW	4.50	9.00	13.50	18.00	22.50	27.00	31.50
GT HR improvement	%	0.70	1.40	2.10	2.80	3.50	4.20	4.90

Figure 1. Predicted incremental output with additional TPMs on the gas turbine (5% air flow) at 2420°F firing

contrast, Kraft says a Turbophase unit can run 24/7. "The chiller is running harder at night to do the storage process and only gets auxiliary power during the day. The customer generates about six times the revenue stream with our system compared to a chiller system."

New aeroderivative gas turbines are also competitive. These units suffer similar output reductions due to high ambient temperatures. Turbophase mitigates, and in some cases eliminates, the need to install new peaking gas turbines by providing an alternative at much better fuel efficiency, Kraft says.

And, he adds, the Turbophase system has other advantages. "Especially in the Middle East, maintenance is expensive so they try to drag out their outage intervals. With our system you get the extra power at the same internal temperatures to the turbine, so you don't affect what's going on there. If you don't need the extra power, if you're operating at base or part load, you can still use our air in the system to get the efficiency improvement – but you'll also get a secondary benefit: parts life extensions.

"For big companies in the US, this can push their outage interval from basically a 24,000-hour interval, which is the normal interval OEMs offer today, to adding an additional year or so, from 8000 hours to 32,000 hours. Take a $5 million outage: instead of every three years you can do it every four years, and you've avoided lost revenue from the downtime."

Project specifications

The installation in Saudi Arabia was designed to demonstrate the Turbophase system's performance at high ambient temperatures. The project was operational between mid-July and early October 2015.

Powerphase requested "any F-class units" for the installation of its system, and a GE-MS7001FA-(7FA.03) gas turbine was selected. "Depending on the vintage of the turbine," Kraft says, "a B-class GT, whether a GE, Siemens, Mitsubishi, those were developed and delivered in the 1960s and '70s. In the '70s and '80s there was the E-class; the next generation of GTs out there in significant quantity are the D and E classes. In the '90s the F class came out, and now in the 2010 frame and above, the H and J class. Those GTs basically have an increased firing temperature, which is the temperature that the GT inlet sees.

"The efficiency of the GT and the CCGT are directly proportional to the firing temperature. So basically, for every unit of air that the GT pumps through it with the compressor, it makes more power in the turbine and steam turbine with the elevated firing temperature.

"The reason we like the F-class units is because they are today considered mature-frame GTs, so there are a lot of competitors out there supplying parts and services and customers are used to operating and maintaining those GTs. So we can sell a third-party product to them and they feel comfortable putting it on.

"Our box works on every GT on the planet, but on those B-class machines it might make 3 MW per box whereas on a J machine it will make 6 MW per box with the same fuel consumption and air output.

"On more advanced frames you will see some of the OEMs offering our equipment. This business works nicely with OEM offerings. It could be viewed as a competitive product because OEMs like to upgrade their GTs, however it's such a unique product and we see OEMs moving towards putting it on their engines, either in new or existing offerings, on both mature and advanced fleet GTs."

Due to schedule constraints, it was decided to not install a complete system consisting of five or seven Turbophase modules (TPMs) on a single F-class turbine. Instead, two TPMs were installed to demonstrate performance and the resulting values were extrapolated to model a complete system.

In May, before the installation of the TPMs, a boroscope inspection of the compressor, combustor, turbine and exhaust was carried out. The compressor, combustor and exhaust were found in the expected condition for the turbine's operating hours. The turbine portion, however, was heavily eroded, with significant gaps between stationary and rotating parts.

"The customer's engine was about ready to go into outage so they basically took a GT that they were going to do a major overhaul on anyway and let us install there," says Kraft, adding that "we made our incremental power and efficiency even on a GT that was basically worn out. It was a little risky – if the GT broke, we would get blamed. Because of our extensive background on this type of gas turbine, we were confident that even though the GT was heavily deteriorated, there wasn't going to be any failure."

The go-ahead for the project was given in early March, and in mid-July the first injection was made. Due to the short time period available, Powerphase needed to adapt some of the auxiliary systems. The TPMs' power supply was planned to be provided from the turbines' motor control centre (MCC). Due to logistics issues with material deliveries and cable installation from the MCC to the TPM location, which was some distance from the plant, it was decided to use diesel generators to supply the required power.

This choice "worked out well for us, from two perspectives", Kraft says. "One, it was very easy for the customer to look at the diesel genset's power output and be able to calculate that the Turbophase module's electricity consumption was on the order of 35 kW, which is about 0.5 per cent of the power that we make. So our box makes 4.5 MW; 99.5 per cent of that goes to the grid and 0.5 per cent goes to internal loads if it's hooked up to a power plant electrical system. In this case it was all to the grid, but the customer could easily see what the power draw was – and we also had a cooling system that took some power. But most of our installations are going to be of a nature where the plant is providing cooling water, so the auxiliary load is just the module.

"A second benefit: the customer is able to get comfortable with what happens if our system trips offline. Our diesel genset ran low on oil or had some issue and quit running in the middle of the night while we were injecting air, so we had an unplanned trip test. The customer wanted to make sure we were not going to harm their GT if something goes afoul on our end, and we were able to prove that by shutting off the fuel to our system."

The expected performance for the two TPMs was calculated based on the turbine model type and a constant firing temperature of 2420°F.

- **Expected Output:** 4.5 MW incremental power for one TPM, 9 MW in total for both;
- **Minimum Output:** 4.05 MW incremental power for one TPM, 8.10 MW for both;
- **Heat Rate:** Consistent with 5 per cent plant heat rate improvement.

Based on the 5 per cent plant heat rate improvement from a full TPS installation, the predicted heat rate improvement per TPM was around 0.7 per cent at 4.5 MW incremental output and 2420°F firing temperature.

Firing temperature impacts the turbine's output, which is defined as MW/(lb/s). The higher the firing temperature, the more output per lb/s of air flow and the more additional output per lb/s of air and steam injection.

The OEM's design data for the GE-MS7001FA-(7FA.03) specifies performance at a firing temperature of 2420°F. However, due to its degradation, Powerphase estimated that the turbine was actually operating at a firing temperature of 2370°F. This was confirmed in site operations and validated with a ThermoFlow model matching the site operating conditions. This deviation had an impact on both the turbine's and the TPM's performance. Powerphase noted that, if the turbine had been firing at 2420°F as designed, the incremental output per TPM would have increased by 0.2 MW.

Hitting targets

The initial performance test was conducted on 28 July. The Turbophase system achieved its output and heat rate targets of 4.5 MW per TPM and 5 per cent heat rate improvement for a full installation. These values are based on the measured performance corrected for firing temperature and extrapolated to a full installation. "Every day the system was turned on and off and you could see the incremental power and efficiency," says Kraft.

At the customer's request, a second performance test was conducted in early September and confirmed the results of the first test. In both cases, the upgrade demonstrated that a full installation of seven TPMs per turbine would produce a 5 per cent fuel efficiency improvement and 31.5 MW power increase on the 7FA gas turbine. Additionally, the system demonstrated as high as 99.3 per cent availability in ambient conditions up to 55C. The fuel efficiency improvement was demonstrated at both baseload and part-load operating conditions.

The turbine was set to baseload select for the duration of the performance test. During the testing the fuel gas compressors were operational, which ensured a ~50 psi delta pressure across the turbine's stop ratio valve (SRV) at all times. The generator readings were recorded as found. However, the recorded values for single TPM injections included the other TPM in cool-down/standby mode, which added another ~40 kW. The cooling water system was also running double to support both TPMs even when only one was operational. For these reasons, the generator loading recorded values were divided by two to provide more accurate results, as if only one TPM was operating.

During commissioning of the TPM, injection tests were performed at various inlet conditions. A change in inlet temperature resulted in a change in gas turbine base output. Much care was taken to go through the data and match up inlet temperatures as closely as possible to show the incremental output at the same temperature. OEM inlet air temperature correction factors were not used, as they would scale the incremental output up or down.

It was also observed that there were swings in the turbine's fuel flow for constant turbine output, which would indicate that either the flow meter had some drift or fuel content was swinging during the testing.

After the first injection into the turbine the hot commissioning phase was conducted, followed by the performance test. The first two weeks after the performance test were used to address commissioning issues on the system. In the weeks of operation, about 3.2 GWh were produced by the TPMs and provided to the grid. The TPM's availability was above 97 per cent.

At the as-found condition of the turbine, each TPM added 4.25 MW at 8650 BTU/kWh to the GT, for a total of 8.5 MW at 8100 heat rate. (The fuel flow readings from the gas turbine OEM flow meter are not accurate or stable enough to confirm the heat rate output. Performance calculations showed the heat rate closer to 8000 BTU/kWh.)

By extrapolating the TPM's output from the current firing temperature of 2370°F to the design point of 2420 F, the output increases to 4.5 MW at 7600 BTU/kWh heat rate.

An installation of five modules would result in an output increase of 22.5 MW. At an ambient temperature of 50°C, this results in a 19 per cent output increase and 3.5 per cent heat rate improvement.

An installation of seven modules would result in an output increase of 31.5 MW. At 50°C ambient temperature, this results in a 26 per cent output increase and a 5 per cent heat rate improvement.

A new business model

"A turbine has to be down for six weeks or more if you're installing a new hot gas path or putting on an inlet cooling system – you're basically building a power plant," Kraft says. "Our system can load follow – at the end of the day it's really just a reciprocating engine driving the process, so we can move it around quickly – we have one air pipe that hooks to the GT and, in both installations so far, outage has been less than one day. So when the plant is down for something else, we tie in and we're done. There can be a month or two of relatively minor site work, the primary piece being the air pipe and fuel line. So it's a really simple installation and leads to unique opportunities in that we can do something like the aircraft business does: power by the hour.

"Most engines on airplanes are leased rather than owned," he explains. "You run it for a certain number of hours and turn it in, get a new one, and keep going – like leasing a car. Our system is extremely quick to install or uninstall; the installation part is typically between 5 and 10 per cent of the overall cost to the customer, and we offer a leasing model.

"If you're putting an inlet chilling system on a GT you're buying it, and it's only good for that GT. Our system works on all of the GTs at the plant that it's piped to; we can pipe it to all of them, and you can lease it for a short period of time while building a new plant or just for the summer. This business model hasn't been around the large frame GT business ever. There have been businesses like this for the aeros – several of the OEMs offer mobile or relatively mobile aeroderivative engines – but nothing on large frame GTs."