Humid Air Injection Turns to Off-the-Shelf Equipment to Enhance Viability for Combustion Turbine Power Augmentation

Various power augmentation methods have emerged in recent years to enable gas turbine owners to recover some of the power that is lost as ambient air temperatures rise. Extensive analyses conducted by end users, consultants and equipment manufacturers comparing humid air injection (HAI) power augmentation technology with competing alternatives has demonstrated that HAI technology delivers the highest amount of power augmentation over a wide range of ambient temperatures with the best economics. Further, recent design and engineering advances have led to newer HAI configurations that simplify construction and maintenance and reduce capital costs by incorporating off-the-shelf technology from the oil industry.

Design Basics
Combustion turbine air injection technologies can be applied either wet (humid air injection/HAI) or dry (dry air injection/DAI). Several HAI/DAI power augmentation concepts as applied to simple-cycle combustion turbine (CT) and combined-cycle (CC) plants are available for commercial implementation. Table 1 summarizes the performance characteristics of HAI and DAI as applied to CT and CC plants based on a PG7241FA combustion turbine. HAI and DAI provide power boosts of about 15-25 percent for simple-cycle operation and about 13-18 percent for combined-cycle operation. Ongoing enhancements have resulted in improved economic performance and operational optimization as well.

Figure 1 is a simplified heat and mass balance of a CT-HAI plant based on the PG7241 (FA) combustion turbine. It utilizes a standard industrial compressor and conventional heat and mass exchange equipment installed external to the CT. Mechanically, combustion turbine humid air injection is similar to steam injection and can utilize existing ports for steam injection; further simplification is possible by injecting the humid air into the compressor discharge plenum or at any point upstream of the combustors. The CT-HAI concept requires only filtered and softened make-up water to produce humidified air of steam quality. The augmented power is produced almost instantaneously and NOx emissions are significantly reduced due to the combined effects of heat rate reduction and humid air injection.

Various design concepts are possible in addition to the one shown in Figure 1. In a CC-HAI configuration, for example, mixing steam extracted from the steam turbine with the supplementary airflow from the auxiliary compressor can create the humid air. This concept capitalizes on the fact that the bottoming cycle already has steam available for the supplementary air humidification and available demineralized water resources.

Figure 2 presents a CC-HAI configuration where the supplementary air from the additional compressor and the steam generated in the HRSG/OTSG (once-through steam generator) are mixed and then injected into a CT. This concept has only two additional components (compared with three in Figure 1), and both components –

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CT-HAI (5.5% total moisture)</th>
<th>CT-HAI (7.5% total moisture)</th>
<th>CT-DAI</th>
<th>CT</th>
<th>CC-HAI</th>
<th>CC-DAI</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net power (MW)</td>
<td>177.0</td>
<td>182.6</td>
<td>166.4</td>
<td>150.4</td>
<td>250.3</td>
<td>240.3</td>
<td>221</td>
</tr>
<tr>
<td>Incremental power (MW)</td>
<td>27.4</td>
<td>32.2</td>
<td>16.8</td>
<td>N/A</td>
<td>29.3</td>
<td>19.3</td>
<td>N/A</td>
</tr>
<tr>
<td>Net heat rate (Btu/kWh)*</td>
<td>9380</td>
<td>9160</td>
<td>9770</td>
<td>9740</td>
<td>6690</td>
<td>6750</td>
<td>6500</td>
</tr>
<tr>
<td>Incremental heat rate (Btu/kWh)</td>
<td>7020</td>
<td>6550</td>
<td>9345</td>
<td>N/A</td>
<td>7530</td>
<td>8630</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Fuel lower heating value = 21,520 Btu/lb
POWER AUGMENTATION

an HRSG and an auxiliary compressor – are commonly used by end-users. This configuration could be preferred in cases where an HRSG is already installed, although there are some drawbacks typical with steam injection, such as delays in the additional power due to HRSG thermal inertia and the need for demineralized water.

HAI IN THE FIELD
The theory and technical validity of the HAI concept have been evaluated and accepted by several end users. After exhaustive comparative evaluations of the HAI technology and other competitive power augmentation options, TVA contracted Parsons Infrastructure and Technology Group to perform engineering and cost estimates of HAI technology for application to CT and CC plants based on the GE 7121(EA) gas turbine. The study concluded that, at summer peak ambient temperatures of 90 F, the conversion of the 7EA turbine into CT-HAI would increase power output from 75.9 MW to 103 MW and reduce the heat rate from 10630 Btu/kWh to 9610 Btu/kWh. Parsons estimated the installed specific costs at $180/incremental kW. For a 7EA-based combined-cycle plant, a CC-HAI conversion would increase power output from 123.4 MW to 154.8 MW with a heat rate of 6390 Btu/kWh, which is slightly lower than the 6700 Btu/kWh pre-conversion heat rate. Installed specific costs at 90 F were estimated at $160/incremental kW.

Following these developments, TVA decided to demonstrate the CT-HAI concept on one of their operating PG7661 gas turbines at the Colbert Power Plant. Engineering analysis predicted a 30 percent power augmentation and a 15 percent heat rate reduction at 95 F. TVA estimated specific incremental capital costs of the CT-HAI or CC-HAI conversion for this combustion turbine at about $200/incremental kW. The project was in a well-advanced stage (RFP

FIGURE 1
CT-HAI CYCLE CONFIGURATION

FIGURE 2
CC-HAI CYCLE CONFIGURATION

had been issued, turnkey proposals submitted and evaluated), but ultimately was indefinitely postponed for budgetary reasons.

Calpine Corp., a licensee of the HAI/DAI technologies for application to Calpine-owned CT and CC plants, conducted validation tests on the PG7241(FA) at the Broad River Energy Center in Cherokee County, South Carolina. The tests compared humid air injection, dry air injection, steam injection and no injection. Test results indicated power augmentation of 18.3 MW when operating dry, with humidity levels of only 3 percent of the total airflow. This level of power augmentation extrapolates to 22.3 MW when operating wet. No known operating limits of the CT were exceeded. Extrapolation of the test results also indicates that an increase in humidity to 5 percent will result in power augmentation of approximately 28 MW for dry operation and more than 32 MW for wet operation.

ENGINEERING EVOLUTION
Concerns about capital costs, materials of construction, and air supply and quality has provided the impetus behind further HAI design enhancements. For example, any steam or humid air stream injected into a CT must be of sufficient purity so that the CT blades will not be damaged. Nonvolatile or condensable matter, such as entrained solid particles that could melt in the combustor and deposit on the turbine blades, must be minimized. The specific limit for solids content depends on the turbine design, the purity of the intake air, and the purity of the fuel, among other
variables. One rather strict solids concentration limit for CT-HAI is 0.5 ppm solids by mass in the injection stream, which will be suitable for nearly all applications.

For CT-HAI configurations using a saturator, the generation of injection-quality humid air requires only softened, potable make-up water. Alternative CT-HAI concepts with a once-through steam generator (OTSG) and a steam-air mixer require higher quality demineralized make-up water with associated additional capital and operating costs. A third concept, incorporating a once-through boiler with partial steam generation, combines the best features of the other concepts: it is relatively simple (two additional components vs. three) and does not require demineralized water.

**Once-through Steam Generation.** In the OTSG concept, demineralized water is fed to an OTSG (actually a combination of an economizer, boiler, and superheater) where it is evaporated and superheated. All solids in the boiler feedwater (BFW) are either entrained in the steam or deposited on the heat transfer surfaces of the once-through boiler. Steam purity is strictly controlled by controlling boiler feedwater purity. As steam is formed, the very low concentration of solids in the BFW becomes progressively higher until, as the last of the water is evaporated, the solution becomes concentrated and potentially corrosive. If the water is not deaerated, there is also the potential for oxidation. To mitigate these problems, once-through boilers generally are made of high-alloy tubes such as Alloy 800. The economic drawbacks of the OTSG concept are obvious: the variable and fixed operating costs are high due to the need for demineralized water.

Comparative cost analyses show that the OTSG concept is more economic than the OTSG concept. However, although the concept eliminates the need for demineralized water, it still requires expensive alloys and adds an extra component (the saturator) to the system.

**Once-Through Boiler with Partial Steam Generation (OTBPS).** A newer configuration eliminating the drawbacks of the previous concepts is shown in Figure 3. Once-through partial steam generators are a well-proven technology, having been used extensively in enhanced oil recovery applications to generate high-pressure steam from softened high-TDS feedwater. In a CT-HAI application, potable water is deaerated, and therefore may be heated in carbon steel or chrome-moly tubes, which are not susceptible to chloride SCC. Instead of completely evaporating the BFW as in a traditional OTSG, the BFW is only partially evaporated (to about 80 percent steam quality), with the remaining unevaporated BFW separated, and all or a portion of it discarded as blowdown. The blowdown rate is controlled to limit the TDS concentration in the water.

A steam/water separator vessel with mist eliminator is used to provide steam with about 0.05 percent entrained droplets, essentially the same entrained
Relative to the OTSG with air-steam mixer concept, the OTBPS concept has the following advantages:

- The demineralized water system is eliminated, replaced by a simple water softener, which provides substantial savings in both capital cost and operating cost by eliminating full-time personnel supervising a demineralized water system.
- The tube material for the once-through boiler with partial steam generation can be chrome-moly, which is much less expensive than the alloys required for the tubes of a demineralized water once-through boiler/superheater. This tube material cost savings more than offsets the cost of the deaerator that is used with the partial steam generator, reducing capital costs for the heat recovery system.

Although the OTBPS configuration described has not yet been tested at full scale for the power augmentation application, it uses off-the-shelf technology from the oil recovery industry and should not pose any design or operational problems. In fact, several licensees now offer turnkey firm price retrofit projects based on the concept. In addition to Calpine Corp., the HAI/DAI technology has been licensed to Hill Energy Systems and HRT-Power, which are actively marketing various HAI/DAI technology configurations. Analysis shows that for many projects, the OTBPS concept is the most attractive at this stage.

References

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