Direct Injection SCR

Matthew R. Zedler, PE, MBA (LP Amina)

ABSTRACT

LP Amina (LPA) has demonstrated its direct liquid ammonia injection selective catalytic reduction (SCR) technology on a 1x1 combined-cycle plant built by Mitsubishi in Beijing, China. The plant, which was built without space for the SCR in the heat recovery steam generator, was retrofitted in 2013 using LPA's patented direct injection technology with Haldor Topsoe corrugated catalyst. Emissions were reduced 82% (from 34 ppmvd at 15% O2 to 5.9 ppmvd) with amazingly low ammonia slip (1 ppmvd) and extremely low pressure drop (< 1.0 iwcd). The direct injection technology sprays 25% aqueous ammonia directly into the combustion turbine exhaust duct, using the extreme velocities and high temperatures to mix and vaporize the liquids. The advantages of this technology include cheaper capital cost, much safer and easier tuning and commissioning, better distribution of ammonia to NOx, and higher reliability. The system is able to use pumps instead of hot gas fans, and there is no need for an external vaporizer. LPA has been actively marketing this technology in the United States to customers including GE and Siemens, and we are planning on doing our first US demonstration in 2017. For combined cycle power plants in India, this technology represents a superior option in terms of cost and reliability when compared with traditional hot flue gas recirculation SCRs, and it is also easy to retrofit on existing units where space was not left for the traditional ammonia injection grid / mixing zone / SCR catalyst.

BACKGROUND

Nitrogen oxides (abbreviated as NO_x and consisting of NO and NO_2 are one of the major air pollutants from thermal power plants. NO_x is formed during combustion by the oxidation of the nitrogen component in the air (thermal NO_x formation). NO_x can be significantly reduced by modifying the combustion process. Such techniques, including wet low NO_x and dry low NO_x technologies, involve lowering the combustion temperature to reduce NO_x formation. These combustion modifications were the first techniques used by the utility industry to reduce NO_x emissions. To achieve the higher level of NO_x reductions that required today, utilities have relied on back end processes to reduce NO_x in the flue gas. The technique that can achieve the highest level of NO_x reduction is selective catalytic reduction (SCR). In the SCR process, ammonia (NH_3) is injected into the NO_x-containing flue gas ahead of a catalyst. As the NH_3-NO_x mixture flows over the catalyst, the catalyst allows the ammonia to selectively react with NO_x in the presence of oxygen forming primarily water (H_2O) and nitrogen (N_2).

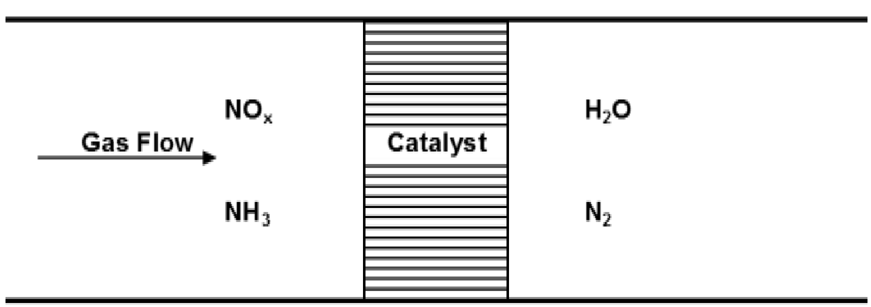


Figure 1. Schematic of SCR Process

Distributed with permission of author(s) by GETS 2016
Published at GETS 2016 http://www.NTPCGETS.com

The overall reactions that occur on the catalyst are as follows:

$$NO + NH_3 + \frac{1}{4}O_2 \rightarrow N_2 + \frac{3}{2}H_2O$$
$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 6H_2O$$
$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

The vast majority of the NO_x from coal firing is in the form of NO (very little, if any, NO_2 is present), so the first reaction dominates; this requires one molecule of NH_3 to react with one molecule of NO. Thus, if a NO_x reduction of 60% is required, NH_3 will be injected such that the proportion of NH_3 to NOx is about 0.6 (i.e., 0.6 molecule of NH_3 per molecule of NO_x). For gas turbines, about 20% of the NO_x generated is in the form of NO_2, so the second and third reactions are also important to consider. The amount of NH_3 required will therefore be slightly higher for a gas turbine than for the same reduction on a coal-fired plant because of the higher presence of NO2. In addition to forming N_2 and H_2O, some NH_3 may exit the process (referred to as ammonia slip). This slip occurs because of imperfect mixing of the NH_3 with the NO_x in the flue gas, or because the catalyst ages and loses its reactivity [1].

SCR of NO_x by nitrogen compounds, such as ammonia, urea, or anhydrous ammonia, has been well proven in industrial stationary applications. The technology was first applied in thermal power plants in Japan in the late 1970s. In the USA, SCR systems were introduced for gas turbines in the 1990s, with a growing number of installations for NOx control from coal-fired power plants. In addition to coal-fired plants and gas turbines, SCR applications also include plant and refinery heaters and boilers in the chemical processing industry, furnaces, coke ovens, as well as municipal waste plants and incinerators. The list of fuels used in these applications includes industrial gases, natural gas, crude oil, light or heavy oil, and pulverized coal.

In many countries, aqueous ammonia and aqueous urea are the reagents of choice because of the inherent safety risks associated with anhydrous ammonia. When injecting either of the aqueous reagents, industry practice has been to vaporize the reagent external to the boiler in an ammonia flow control unit (AFCU). The AFCU can use ambient air heated by resistance heaters or by natural gas firing, flue gas extracted from the heat recovery steam generator (HRSG), or some combination of the two methods. Advantages and disadvantages of the two different conventional methods are outlined below:

Table 1. Comparison of Traditional SCR AFCU Systems

SYSTEM	ADVANTAGES	DISADVANTAGES
Ambient Air Fans + Electric Heaters	• Cheaper, more reliable fans • No need for large-bore takeoff piping from the HRSG	• Large parasitic power consumption from requirement to be constantly running heaters (1,000+ kW continuous)
Hot Flue Gas Recirculation	• Nominal parasitic power consumption (motors size ranges from 50 – 150 HP)	• Fans are expensive and have reliability issues • Requires large-bore takeoff piping

Both systems require a vaporization vessel which typically uses either a mechanical or air-driven atomization nozzle. Additionally, traditional SCR systems require an ammonia injection grid (AIG) installed in the HRSG to allow the ammoniated flue gas to properly mix back into the bulk flue gas before reaching the catalyst. The AIG is an engineered injection system that is critical for the performance of the SCR. One of the key SCR operating parameters is the NH_3/NO_x distribution entering the catalyst, which is typically measured using a mathematical average called the root mean square (RMS). Root mean square is a mathematical term that can be found by

Distributed with permission of author(s) by GETS 2016
Published at GETS 2016 http://www.NTPOGETS.com

dividing the standard deviation of a population by the average. The smaller the RMS, the lower the variation of the distribution.

Typically, one of two AIG designs is utilized for HRSGs, as shown in Figure 2. The left sketch shows a series of lances that traverse the full width of the reactor with penetrations on one side. This arrangement allows the ammoniated flue gas to be biased up-down but not side-side. The other commonly used design in the right sketch. In this case, the lances only extend halfway across the reactor, creating two horizontal "zones" across the reactor width. This design affords both up-down and some side-side adjustability.

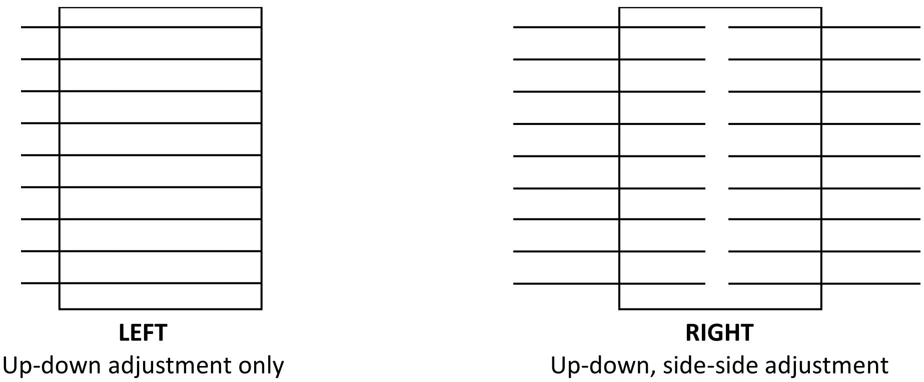


Figure 2: One- & Two-Zone AIG Arrangement Sketches

The designs shown in Figure 2 allow some adjustability; however, in cases with NO_x reduction levels at or above 90%, it is necessary to be able to bias the ammonia to the center of the reactor to achieve the lowered required RMS. This center biasing cannot be achieved with either design shown in Figure 2. LPA has overcome this shortcoming with an AIG incorporating three zones across the width of the reactor, as shown in Figure 3. Each zone is adjustable using the tuning/damper valve installed near the distribution header. The distribution headers can be installed either vertically or horizontally, with LPA's standard design involving a single vertical manifold on the side of the HRSG closest to the AFCU skid [2].

Distributed with permission of author(s) by GETS 2016
Published at GETS 2016 http://www.NTPOGETS.com

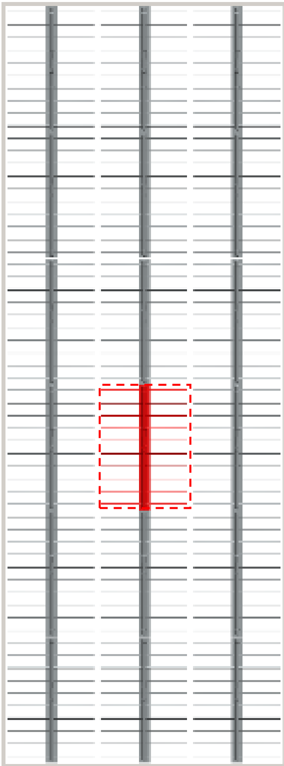
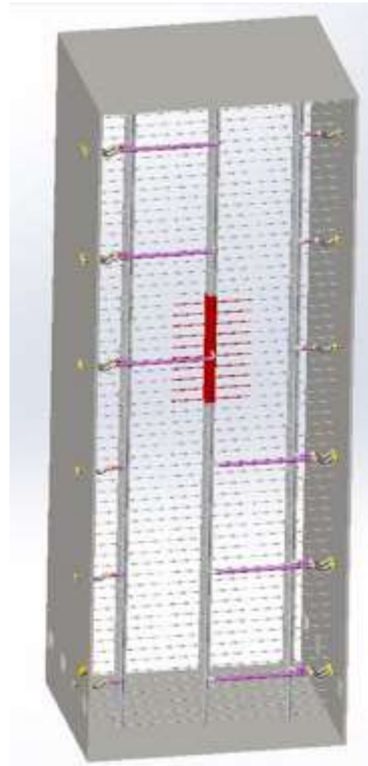


Figure 3: Three-Zone AIG Arrangement Elevation (Left) and Conceptual 3D Model (Right) (Horizontal HRSG)

In the elevation view on the left, one of eighteen AIG "zones" is shown in the red box. Note how LPA's design has three zones across, including a center zone, which allows better tuning and control of NH_3 distribution. The 3D model cut on the right shows a version of the piping. LPA will connect each module to the wall penetration using a flexible connection. Manifolds can be arranged vertically or horizontally on one or both sides of the HRSG.



Typically, the OEM will leave 8 to 10 feet from the AIG to the face of the catalyst to allow for proper mixing. The end result is a costly grid of piping and large empty cavity in the HRSG. One US OEM has estimated that removing the AIG and SCR cavity would allow them to remove a column line and reduce casing around the "emissions cavity" by roughly 50% [3], leading to significant capital cost savings during the construction of a new combined-cycle power plant.

For coal-fired power plants, one alternative has been the direct injection of liquid reagent. Alstom (now GE) and other companies have experimented with such systems, utilizing air or mechanical atomized nozzles in the boiler to distribute and vaporize the reagent. Another common option for coal-fired units is the hybrid SNCR-SCR technology where excess ammonia is injected in the front pass of the boiler to participate in high temperature, non-catalytic reactions before slipping to the back pass where it reacts in the traditional SCR process. Up until 2011, no company had tried to directly inject aqueous reagent into a HRSG downstream in combined-cycle operation.

JINGFENG POWER PLANT

LPA had established itself as a US provider of emission control solutions for coal- and gas-fired power plants in China in 2007, and in 2010 LPA was awarded the contract for the SCR system on a vertical-flow HRSG being built in the south of Beijing City, China. LPA designed, engineered, procured, constructed, and commissioned a traditional SCR utilizing aqueous ammonia and a single hot flue gas recirculation fan to reduce the NO_x emissions 82% to 12.2 mg/Nm^3 (15% O_2 dry basis) with slip less than 5 mg/Nm^3. This plant, Caoqiao, was owned by Beijing Energy Group (BEG), and they came to LPA in 2011 with a unique challenge.

Distributed with permission of author(s) by GETS 2016
Published at GETS 2016 http://www.NTPOGETS.com

Jingfeng Energy Center, another plant in Beijing City, had been built by Mitsubishi-Hitachi (MHI). This combined-cycle plant was one of the first to be built in China, so no space was left for the traditional AIG-SCR cavity. Since the policymakers had recently lowered emissions standards for Beijing City, BEG was now forced to install a SCR on this plant.

Jingfeng Power Plant was built in 2006 to replace two smaller, aging coal plants. The plant consists of a 1x1x1 combined-cycle unit, with all the major components being provided by MHI or licensees of MHI. The HRSG is a horizontal flow, three pressure unit with the capability to flow the steam to a steam turbine or to the capital's central heating system. The HRS was built by Dongfang Boiler using a license from MHI. The capacity of the power plant is 410 MWe, and it was designed to operate 5,200 hrs per year (65% availability). The plant is typically cycled during the spring, summer, and fall and baseloaded in the winter to make the winter heating demand. The gas turbine had dry low NOx capabilities when installed, with estimated full-load emissions of 80 mg/Nm^3 (15% O2, dry). However, Dongfang had minimized cost by removing the emissions casing section of the HRSG, leaving no easy option for installing a traditional SCR system (Figure 4). BEG needed to drop emissions below 20 mg/Nm^3 to be in compliance. LPA proposed using its unique direct injection solution as a way to cost-effectively retrofit the Jingfeng power plant.

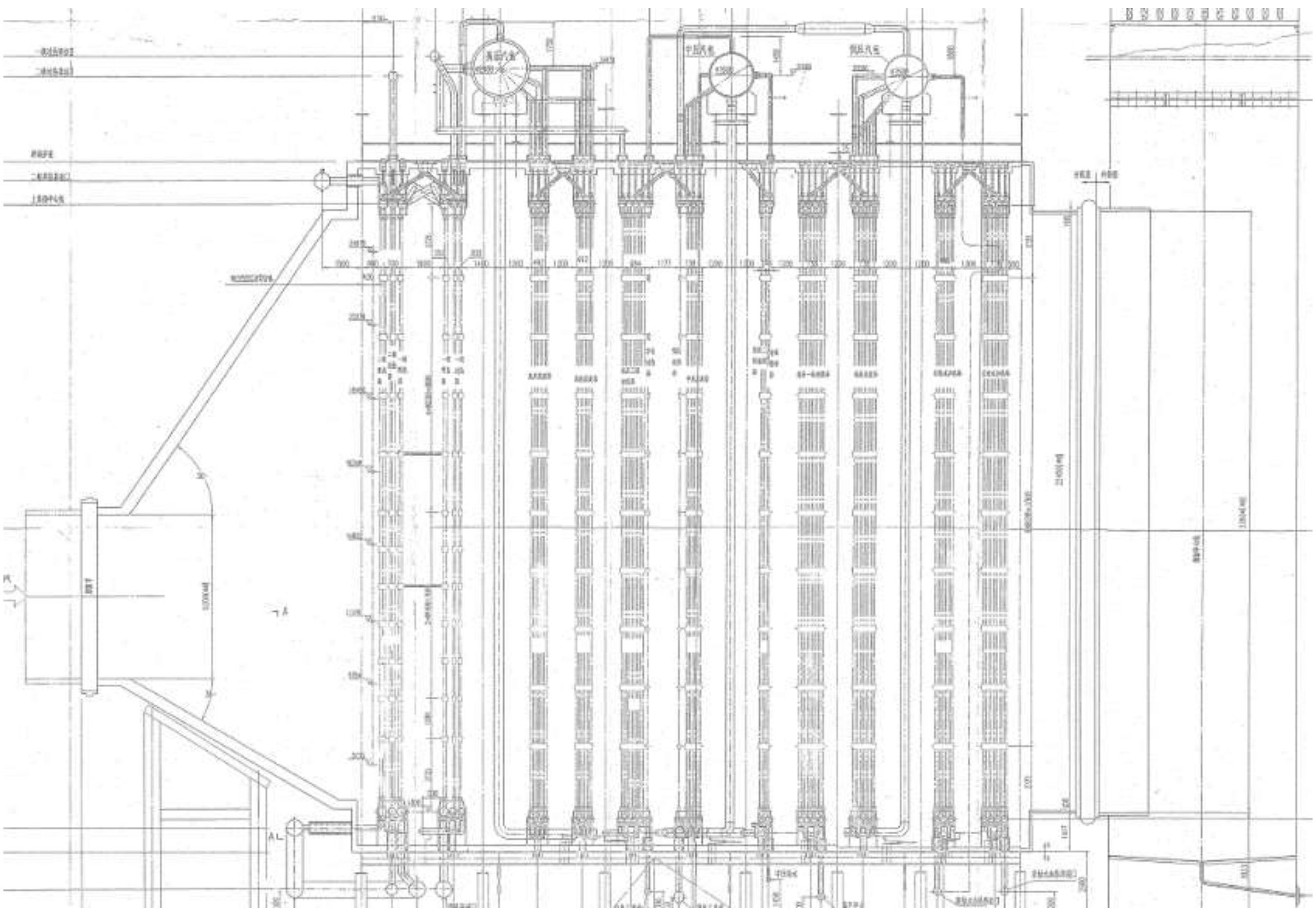


Figure 4. Elevation Drawing of HRSG Showing Lack of Emissions Casing Section [courtesy of Jingfeng Power Plant]

LPA'S DIRECT INJECTION SCR SOLUTION

LPA had developed the direct injection SCR with support from its US partner Fossil Energy Research Corporation by reviewing emissions control experience in the coal-fired boiler sector and by conducting both computational and cold flow modeling analyses. The technology, which was patented in February 2016 as US patent 9,255,507 B2, injects liquid reagent in the exhaust duct of the gas turbine or the inlet section of the HRSG through a number of injection lances utilizing a dual-fluid air-atomized nozzle arrangement. The injection lances are encased in an insulated, aerodynamic sheaths that are specially designed for the high velocities present at the gas turbine exhaust (over 100 m/s). Aqueous ammonia is fed from a storage tank through a metering pump to a distribution manifold. From the distribution manifold, each line is locally metered and valved to allow balancing of the ammonia injection.

JINGFENG DIRECT INJECTION SCR SOLUTION

A single layer of Haldor Topsoe corrugated catalyst (GT-201) was installed in the 914 mm of space between high pressure evaporator sections where the temperature would allow the SCR reaction to occur. The catalyst and frame had a total depth of 560 mm, leaving just enough space for a person to enter the cavity and inspect the catalyst. A pressure drop guarantee of 350 Pa or less was demanded by the customer. The catalyst vendor mandated a NH_3/NO_x maldistribution of 10% RMS or less and a velocity maldistribution of 15% RMS or less to meet the performance guarantees.

LPA determined that a series of eight injectors equally spaced around a ninth center injector would result in a NH_3/NO_x maldistribution of 7.8% RMS and a velocity maldistribution of 5.6% RMS (the pressure drops through the upstream superheater and evaporator sections helped to significantly flatten the velocity profile) using a 1/16 scale cold flow modeling with propane as a tracer gas (Figure 5). Additional CFD was done on each injector to ensure that the liquid reagent would not overheat and vaporize in the lance. A small portion of cooling air was added to the inside of each injector sheath based on the CFD results.

Figure 5. 1/16 Cold Flow Model (courtesy of FERCo)

Distributed with permission of author(s) by GETS 2016
Published at GETS 2016 http://www.NTPOGETS.com

One additional challenge was created by BEG insistence that industrial-grade 20% aqueous ammonia be used as the design reagent. Typically, reagent grade ammonia is specified to ensure that the nozzles do not plug due to the presence of dissolved solids in the water. BEG wanted LPA to make sure each injection lance could be removed from the outer sheath during operation to check and potentially replace the air-atomized nozzle. To allow for safe removal of the lances while the unit was running, LPA had to install knife gate valves and Swagelock fittings on each lance, significantly complicating the design and fabrication of the sheath and lance. Figure 6 shows a preliminary sketch of the design that was eventually implemented.

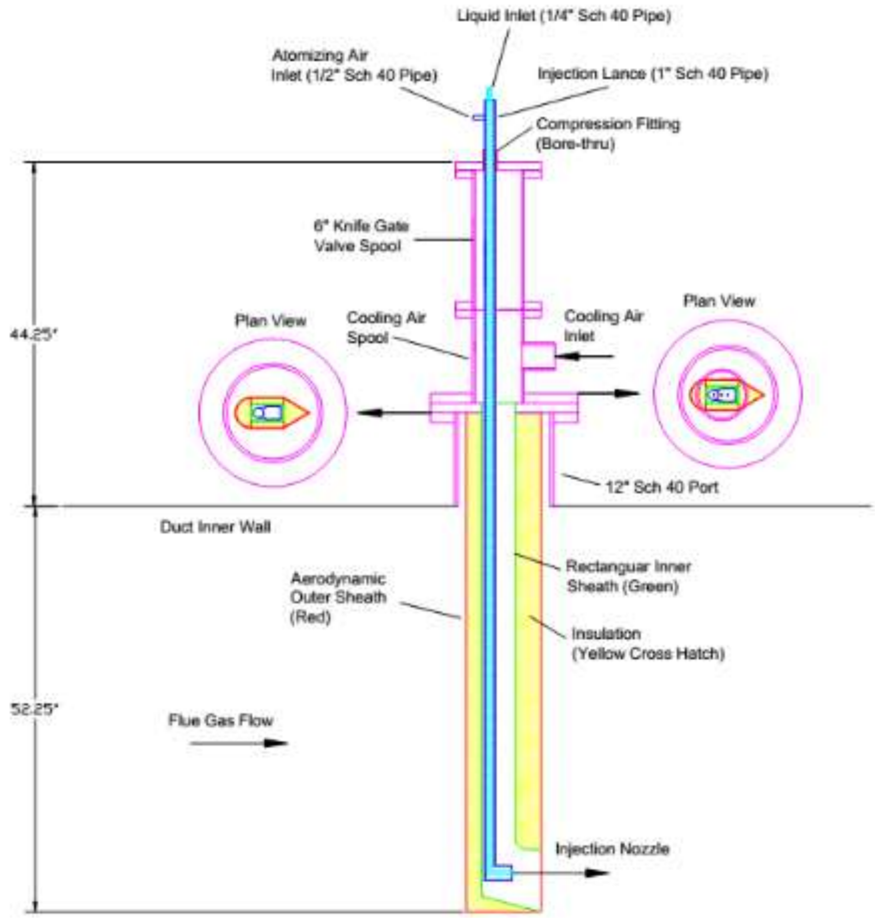


Figure 6. Schematic Showing Implemented Lance & Sheath Design for Jingfeng

LPA's scope included the full engineering, procurement, and construction of the system, as well as commissioning and tuning. Construction was completed during a 45-day period in the fall of 2013, with some significant challenges overcome including the welding of the sheaths to the gas turbine exhaust duct (SS304 sheath and SS410 series casing). The total scope of LP Amina's service exceeded 2.4 million USD. Tuning was completed in under three days as there were only nine injectors to adjust (rather than the 40+ injection points typical on a gas turbine AIG).

The SCR system was commissioned in Q4 of 2013 and has been in operation continuously since. 82% NOx reduction was achieved with an outlet NOx of 12.2 mg/Nm^3 and an ammonia slip of 1.8 mg/Nm^3. The pressure drop through the entire system was under 250 Pa, and the NH3/NOx maldistribution was calculated to be 5% RMS. The plant engineers, BEG, and LPA were all quite satisfied with the results. Haldor Topsoe also took out a catalyst test sample for analysis in January 2015 and found no noticeable performance degradation.

Distributed with permission of author(s) by GETS 2016
Published at GETS 2016 http://www.NTPCGETS.com

CONCLUSION

LPA's experience retrofitting the Jingfeng Power Plant with direct injection has proven the commercial viability of this technology for combined-cycle gas turbine applications. The technology removes the parasitic power consumption and high capital cost of the traditional SCR system without compromising performance. In fact, the low NH_3/NO_x maldistribution leads to lower than normal ammonia slip and the potential for greater than 95% NOx removal. Both of these advantages suggest that direct injection SCR could soon replace the traditional SCR as the "best available control technology."

REFERENCES

[1] FERCo, *SCR Primer,* Laguna Hills: FERCo, 2010.

[2] LP Amina, LLC, *SCR Proposal Template (July 18, 2016 update),* Charlotte: LP Amina, 2016.

[3] CMI Energy, LLC, *Technology Presentation for GE Power & Water,* Schnectady, NY: LP Amina, 2015.

Distributed with permission of author(s) by GETS 2016

Published at GETS 2016 http://www.NTPOGETS.com