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DESIGN CONSIDERATIONS FOR AIR DILUTION COOLING OF GAS TURBINE EXHAUST – A CASE STUDY

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Abstract

Industrial gas turbine exhaust temperatures regularly exceed 538 C (1000 F) during part and base load operation. In combined cycle applications with heat recovery steam generators or simple cycle applications with NOx reduction equipment, the maximum gas temperature must be controlled to maintain equipment integrity and/or maximize emission reduction efficiency.

Various methods can be used to control the gas turbine exhaust temperature. One method of cooling gas turbine exhaust is air injection. This involves the controlled introduction of ambient air into the exhaust duct to uniformly reduce temperatures at the heat recovery steam generator (HRSG) boiler tubes or selective catalytic reduction (SCR) catalyst blocks. However, certain gas turbine (GT) exhaust phenomena, such as turbine swirl and back pressure limitations, must be considered in order to optimize temperature control and steady-state GT performance.

A case study involving a GE Frame 6FA turbine will be used as an example to describe in the steps required to ensure a uniform temperature profile after air injection. This will encompass computational fluid dynamics (CFD) modelling, ducting design and equipment selection.

1 Introduction

Once Through Steam Generators (OTSGs) are boilers designed to capture waste heat from the exhaust of a combustion turbine to generate steam for process or power augmentation. An OTSG differs from a conventional HRSG type boiler in that the pressure tubes run horizontally rather than vertically, nor does it incorporate separate economizer, evaporator and superheater sections. An example of an OTSG pressure part layout is displayed in Figure 1.

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Figure 1: Simplified OTSG Layout

Materials commonly used in the OTSG permit dry running in most applications. Extended dry running beyond 1050 Degrees F is attainable but requires the use of more costly materials.

Simple cycle Ammonia Injection Grid / Selective Catalyst Reduction (AIG/SCR) NOx control units channel combustion turbine exhaust over catalyst blocks where reactions take place to reduce NOx. It is a challenge of owners of mature gas turbines to maintain NOx reduction of the AIG/SCR system as a result of higher gas turbine exhaust temperatures.

Both operating scenarios require certain temperatures at the boiler/catalyst interface with the GT exhaust in order to keep materials within ASME limits or at an optimum operating point for operation of a NOx catalyst.

1.1 Methods of Cooling Gas Turbine Exhaust

There are many pre-existing methods of reducing gas turbine exhaust temperature. Several of these methods are presented in

Table 1:	Methods o	f Coolina	GT	Exhaust
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Method	Advantages	Disadvantages	
Water Injection into Exhaust Plenum	Straightforward Rapid response rate	May cause dew point deposition on feedwater tubes or stack corrosion if the boiler is in operation	
		Treated water is required due to Ca, K, Na salts poisoning the catalyst [1]	
		Water makeup rate of polisher	
		Water availability may be a problem	
STIG	Power augmentation effect	Degradation of combustion	
(Steam Injected Gas	Lower NOx emissions	Need for treated water	
		May cause dew point deposition on feedwater tubes or stack corrosion if the boiler is in operation	
Air Dilution	Dilution media is inexpensive	Large capital investment	
	Air dilution equipment could potentially be used for fresh air firing for steam production if GT is inoperative	Large equipment footprint	
	Low operating cost		
Heat Exchanger	Process is understood by boiler	Added plant complexity	
	manufacturers	Expensive	
		Need for a condenser or large heat sink to reject waste heat	

1.2 Case Study – Guaracachi, Bolivia

Overview of plant

- GE Frame 6FA combustion turbines
- 2 OTSGs total combined steam production
- 1 steam turbine
- · Base loaded plant

This electrical generating plant contributes a substantial amount to the generating capacity of Bolivia (total gas fired power generation in 2004 = 870 MW [3], while the combined cycle output of Guaracachi Plant is 2×70 MW GT + 85 MW Steam Cycle).

Combustion turbine output was as high as 1150 Degrees F during high ambient conditions. The turbines had been in service for 10 years and were suffering from elevated exhaust temperatures associated with turbine degradation.

SA213 T22 tubing was extensively used in the boiler pressure tubing. However, T22 will undergo a rapid increase in oxidation if temperatures exceed 950 deg F for extended periods of time. As such, it was necessary to limit temperature excursions in order to mitigate potential oxidation damage to the boiler pressure tubing.

Exhaust gas attemperation through air dilution cooling was selected to protect the boiler components during start-up or to maintain boiler integrity during dry running in the event that the steam circuit was inoperative. There were several criteria which guided this choice:

- The plant currently relies on well water resources. High mineral content of the well water requires more extensive water treatment.
- Water polishing was accomplished through the use of a Powdex-type polisher. Shipping and availability of the Powdex resin is costly considering the geography of the plant.
- The addition of the boiler and steam circuit to the existing simple cycle plant was already a significant undertaking. The air attemperation system was to cause as little strain on existing plant infrastructure as possible.
- In the event of an outage on the steam circuit, the air dilution system would be expected to operate continuously. The loss of the air dilution system would not enable the simple cycle plant to operate without risking damage to the boiler. If an extended outage on the steam turbine was realized, the air dilution system would be required to operate continuously.

2 Implementation of the Air Dilution System

2.1 Challenges

There were several challenges in implementing the air dilution system. These were:

Space Limitations

A plan view of the plant is show in Figure 2. The OTSG site was bordered by an access road to the North of the plant as well as chillers for the GT lubrication oil to the South. The area at the rear of the OTSG was kept clear for boiler maintenance purposes. In addition, an access road between the 2 OTSGs, to permit extraction of the turbine rotors needed to be kept clear.



Figure 2: Plan View of Guaracachi Combined Cycle Plant Layout

The air dilution ducting needed to be unobtrusive enough such that it did not encroach on any of the spaces mentioned above as well as be of a geometry that would allow adequate distribution of dilution air within the GT exhaust ducting.

Any ducting connecting to the boiler would have to be supported with expansion joints in order to allow for expansion and contraction of the casing.

Uniformity of Temperature Within the Boiler Tube Bundle

ASME Boiler and Pressure Vessel calculations indicated that the SA213 T22 alloy selected to construct the boiler heat transfer tubes could only withstand a maximum temperature of 950° F. As such the air dilution system needed to prevent temperature excursions which would expose the tubing to temperatures that would cause it to fail from an ASME allowable stress standpoint during dry operation.

In addition, the flow control devices and air dilution equipment needed to ensure that the temperature profile was as uniform as possible upstream of the boiler pressure tubes during supplementary firing when the air dilution system was not operating. A contour plot displaying the temperature profile prior to the addition of flow control devices at a plane through the midsection of the boiler may be viewed in Figure 3 below:



Figure 3: Uncorrected Temperature Profile Through Midplane of Boiler

Need for the Air Dilution to Operate During Startup

The startup curve for the GE Frame 6FA engine illustrating time vs. temperature can be viewed in Figure 4 below.



Figure 4: GT Startup Temperature Profile - 1998 Vintage Frame 6FA

Exhaust temperatures generated during start up to base load are in excess of 950° F. As such, the air dilution system was required to operate during start up of the GT as well as when the steam circuit was inoperative. Considering the contribution of the generating plant's output to the Bolivian national electrical grid, loss of both the GT and steam circuit was not acceptable.

Load Required to Operate the Air Dilution System

When the air dilution system was expected to operate, the steam circuit was either inoperative or the GT was in the process of starting up. As such, the air dilution system was required while the plant was not contributing to the electrical grid. As such, the load required to operate the air dilution system was to be kept to a minimum as to not draw more power from the grid than was necessary.

Structure

The unabated exhaust temperature is a maximum of 1150° F. As such, any air dilution equipment exposed to the GT exhaust temperatures should be able to support itself at temperature when cooling air is not supplied.

Turbine Back Pressure

The OTSG and associated ducting provides an increase in ducting back pressure at the exhaust flange of the gas turbine when compared to the simple cycle exhaust ducting. Additional equipment such as air flow distribution screens and air dilution equipment should be as contribute to backpressure as little as possible or the boiler may have to be reduced in size and corresponding steam production in order to decrease backpressure to acceptable levels. Turbine back pressure also contributes to turbine inefficiency.

Uniform GT Exhaust Velocity Upstream of the Duct Burner

The air dilution airfoils were located approximately 3 feet upstream of the duct burner that was used for supplementary firing. When the air dilution system was not in operation, the air dilution equipment could not cause sufficient turbulence in the ducting to interfere with the operation of the duct burner.

3 Analysis and Design

For the purposes of organization, this paper will divide the boiler into the following zones for analysis and subsequent design (See Figure 5):

- Inlet plenum and flow distribution screens
- Air dilution airfoils
- Air dilution ducting
- Ducting Isolation & Forced Draft Fan



Figure 5: Cross Section Through OTSG

3.1 Inlet plenum and flow distribution screens

All gas turbines will have exhaust characteristics such as:

- Velocity profile
- · Swirl angle at load
- Temperature profile

All of these factors contribute to the non-uniformity of GT exhaust downstream of the gas turbine. ISTs experience with GTs has indicated that GT swirl characteristics are unique to each turbine design.

Due to space limitations, a steep inlet plenum angle was used. This caused significant recirculation in the upper part of the inlet plenum (See Figure 6). This flow needed to be more uniform prior to injecting the dilution air into the duct. This was accomplished through the use of a variable porosity perforated screen.



Figure 6: Straightening of GT Exhaust Flow through Inlet Ducting Flow Control Devices. Prior to the Addition of Flow Control Devices (Top) After the Addition of Flow Control Devices (Bottom)

To make the airflow more uniform, two flow screens were used – one upstream of air dilution system and one downstream of air dilution system. The function of the first screen is to make the airflow more uniform prior to air injection. The function of the second flow distribution screen is to make the airflow uniform enough as to not impede operation of the burner. However, the operation of both sets of flow distribution screens were considered in providing a flow distribution at the surface of the boiler uniform enough as to not compromise the pressure tube assembly due to variations in temperature.

The CFD package Fluent was used in order to determine the configuration for the air distribution screens to give a velocity distribution of +/- 7% RMS downstream of the second screen with a minimal pressure drop. This was essential for correct operation of the duct burners while firing.

The exhaust profile and swirl of the Frame 6FA GT supplied by GE at full load conditions were used to optimize the flow control devices. Part load conditions were considered to be transient and not included in the flow control device optimization provided that temperature at the boiler tube bundle was kept below 950° F. On cycling plants that have multiple operating points, this is examined over the entire operating band of the GT.

Once the flow distribution screen configuration was determined, based on the pressure drop experienced across the screen, mechanical loads to the underlying screen support structure could be determined. The screen support structure was optimized such that the stresses generated within the screen were minimized (see Figure 7).



Front View

Side Viev



3.2 Air Dilution Airfoils

3.2.1 Air Distribution

It was found that air injection ducts in an airfoil shape presented the best compromise between minimum disruption of the airflow within the duct as well as sufficient flow area to allow enough dilution air to reach the ports on the surface of the air injection lance. By preventing flow separation along the trailing edge of the wing, the formation of vortices downstream of the airfoils was mitigated. The airfoil shape has a secondary benefit of creating a lower pressure area local to the air injection slots. This reduces the pressure required by the forced draft fan in supplying air to the GT exhaust duct.

A literature search revealed that there were several methods for determining the distribution of air through slots from a common manifold [4],[5]. Several methods were examined, most with origins in HVAC design. Sizing of the slots that would admit air into the exhaust plenum was initially done to allow the pressure drop along the axis of the duct is less than 10% of the loss through the air injection slots [4]. However, initial designs were verified using CFD analysis in order to determine the optimum size, shape and location of the air injection ports.

Considering the results of CFD analysis, the following foil configuration was selected (See Figure 8).





Figure 8: Air Dilution Airfoil Configuration

3.2.1 Structure

After the geometry of the airfoils had been determined through CFD, the airfoil structure was required to support the air dilution lances within the GT exhaust duct.

The structure of the air dilution lances is comprised of two elements:

- A semi-stressed skin that is the boundary between the GT exhaust and the dilution air
- A trellis frame structure attached to a mounting plate at the open end of the structure (See Figure 9)



Section-A

Figure 9: Trellis Frame Structure within Airfoil

The majority of the weight of the airfoil is borne by the trellis frame and the support pipe at the trailing end of the airfoil. The connection between the trellis frame and the skin is a sliding connection: The skin is attached to the frame with clips that allow the skin to expand when hot and allow the frame underneath to contract when admitting cold dilution air into the ductwork.

The trellis frame is supported on the closed end of the airfoil with a series of pockets that the pipes can expand into.

The mounting plate of the open end of the frame serves three purposes:

• It ties the trellis frame into the ducting structure while accommodating thermal growth of the frame

- It provides a boundary between the GT exhaust within the duct and the dilution air
- It supports a flow distribution device to allow even distribution of air between airfoils

The installation of the airfoils within the burner duct may be viewed in Figure 10:



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3.3 Dilution Air Supply Ducting

There were two main competing factors which determined the size and shape of the dilution air ducting: The duct should allow the flow from the forced draft fan to become as developed as possible while occupying a minimum of space. As such, it was decided to arrange the ducting in a horseshoe fashion that extended over the top of the GT exhaust duct (See Figure 11).



Figure 11: Burner Duct Cross Section (View along GT Axis)

The airfoil mounting plates also supported variable porosity perforated screens to aid in the distribution of dilution air from the top foil to the bottom foil (See Figure 10). The exact size of the holes in the variable porosity perforations were determined through parameter optimization within the CFD program fluent. A sample CFD run showing a cross section through the burner duct and the air dilution airfoils may be viewed in Figure 12.



Figure 12: Vector Plot of Velocity within Burner Duct and Air Dilution Airfoils

Air dilution supply ducting was supported by the GT exhaust ducting. This was done to take advantage of existing sliding supports which supported the GT exhaust ducting. Structural analysis was conducted to ensure that the structural members were sufficient to support the load.

The cold to hot transition occurred on the top of the ducting with a double louver damper. This style of damper was chosen as it can be actuated remotely and rapidly in the event that the steam circuit failed and dilution air needed to be brought on line quickly.

The forced draft fan is a large piece of equipment weighing over 16 tons. It's mass as well as the need to have the fan bearing supports and motor aligned and the vibration generated when in operation precluded the option of having the fan foundation translate (i.e. slide) along the ground in order to stay aligned with the air dilution ducting mounted on the GT exhaust ducting.

The movement of the dilution air ducting was isolated from the forced draft fan by means of an expansion joint which allowed movement in three directions. This expansion joint was able to accommodate thermal expansion of the ducting as well as isolate the ducting from vibrations generated by the FD fan.

4 Conclusion

Certain operating scenarios (dry-running and/or startup) require the use of air attemperation methods to maintain boiler pressure parts and structure within safe operational limits.

Based on the operating conditions and location of the Guaracachi combined cycle power plant, it was decided to attemperate the gas turbine exhaust using air dilution with ambient air versus other methods of cooling the exhaust. The footprint of the equipment is not large enough to impede existing plant ancillary equipment or operations.

Air dilution was selected in this case in order to protect the integrity of OTSG components. However, the same approach could be used to allow a simple cycle plant with an AIG/SCR pollution control module in order to optimize catalyst efficiency or prevent damage to the catalyst from overheating.

Air attemperation on future power plants will need to be considered on a case-bycase basis to determine the method which will encompass the best combination of cost effectiveness, complexity and available resources.

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