TECHNICAL PUBLICATION

Evaluation of Design Alternatives for an SCR System Downstream of a Simple Cycle Combustion Gas Turbine

by:

Jilin Zhang
Engineer
jzhang@babcockpower.com

Vlad Zarnescu, Ph.D
Principal Engineer
vzarnescu@babcockpower.com

Enrique Vega
Sr. Program Engineer
evega@babcockpower.com

Riley Power Inc.
5 Neponset Street
Worcester, Massachusetts 01606
www.babcockpower.com

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ABSTRACT

A recent CFD study was conducted to evaluate various design options for the placement of a Selective Catalytic Reduction (SCR) system downstream of a nominal 200 MW Simple Cycle combustion gas turbine. The average temperature of the flue gas leaving the turbine is in excess of 1125 °F. In this application, tempering air is mixed with the flue gas stream to reduce the temperature of the gas prior to the SCR catalyst beds. CO catalyst is optionally installed downstream of the flue gas mixing location to reduce carbon monoxide emissions in the flue gas. An ammonia injection grid is installed before the NO_x *catalyst to reduce nitrogen oxide (*NO_x*) emissions in the flue gas. The efficiency of the* NO_x *removal process is dependent on the uniformity of flue gas velocity, gas temperature,* NH_3 *to* NO_x *concentration ratio at the catalyst inlet. A detailed CFD design analysis was conducted to evaluate various options for the injection of tempering air into the flue gas stream and to optimize flow distribution upstream of the CO and* NO_x *catalyst beds.*

This paper describes Riley Power Incorporated (Riley Power), a Babcock Power Inc. company, evaluation of various design options to achieve the optimal flow conditions for best operation of the current simple cycle SCR system. A number of flow control devices, including Delta Wing® mixers were evaluated in combination with different injection methods for the tempering air. Inlet conditions were based on the flow, gas composition and temperature profiles at the combustion turbine outlet provided by the turbine manufacturer. Velocity and temperature profiles at particular sections of interest were monitored for each studied configuration. Various locations and designs for the mixing devices were evaluated and compared for mixing optimization and local areas of peak velocities. The different configurations, modeling results and their impact on flue gas velocity and temperature distribution are discussed in detail.

INTRODUCTION

In contrast to a combined cycle system that has a steam generator/turbine in addition to the combustion gas turbine, a simple cycle system has no provision for heat recovery. Therefore, in the case of a simple cycle, the exhaust gas maintains a high temperature as well as high non-uniformity of the flow, which increases the challenge of maintaining uniform distributions of flow and temperature at the entrance to the SCR catalyst beds. Due to the high temperature and non-uniform velocity and temperature distributions of the exhaust gas discharged from the gas turbine, serious challenges exist in effectively utilizing the catalyst surface area. The simple cycle SCR system evaluated in this paper is conceptually designed to reduce NO_x and CO emissions from a simple cycle combustion gas turbine. In the current simple cycle SCR system, tempering air is used to mix the cool ambient with the hot exhaust gas stream in order to reduce the temperature. A CO catalyst bed and an ammonia injection grid (AIG)/NO_x catalyst are installed downstream of the stream mixing location in order to reduce the CO and NO_x emissions.

The current study presents several representative design options evaluated by Riley Power for the placement of an SCR system downstream of a nominal 200 MW simple cycle gas turbine. Design variables included different tempering air injection systems, number and placement of various flow control devices, such as Delta Wings® and turning vanes and different types of perforated plates/distribution grids. Three (3) representative CFD cases are presented in this paper: 1) Base Case — Simple cycle SCR system with no control devices; 2) Case I — Simple cycle SCR system with two pairs of Delta Wing® mixers; 3) Case II — Simple cycle SCR system with a combination of two pairs of Delta Wing® mixers and a perforated plate/distribution grid.

Velocity and temperature planar uniformity was monitored in a plane (called "Criteria Plane") located approximately 2 feet upstream of the first catalyst bed. The design criteria used herein for evaluating velocity uniformity was the Relative Standard Deviation (RSD).[1] This parameter is known as the "percent (%) rms", expressed as the ratio of the Standard Deviation (SD) to the average mass flow velocity. A higher RSD value corresponds to a less uniform flow whereas a lower RSD value is interpreted as an indication of a greater flow uniformity. No deviation means perfectly mixed. The corresponding design criteria used for evaluating temperature uniformity were as follows: the percentage of the surface area within ±25°F of the average temperature to the total surface area and the maximum temperature. Typically, the specification for SCR catalysts allows a flow mal-distribution at the catalyst face not to exceed ±15 % rms and a temperature variation of ±25 °F entering the catalyst face.[2]

RILEY POWER DELTA WING® — SCR MIXING TECHNOLOGY OVERVIEW

Riley Power is the leading designer of new SCR systems in North America. The Delta Wing® mixing system is a widely used and proven solution for the mixing of turbulent flows and pulverized solids (e.g. ash flow). The Delta Wing® mixing system is provided to Riley Power under exclusive license from Balke-Dürr GmbH. Figure 1 shows the installed Delta Wing® system in a conventional SCR duct physical flow model[3]. Noticeable features of the Delta Wing® technology[3-4] include:

* *Creates a homogeneous NH_3/NO_x mixture, consistent temperature and uniform flow distribution at the catalyst face*
* *Represents the highest standard for gas mixing at the lowest pressure drop*
* *Independently of the load case, the Delta Wing® mixer design provides the best mixing performance even in very short ducts*
* *Reduces commissioning time to as little as 2 weeks*
* *Flexibility of installation and control*

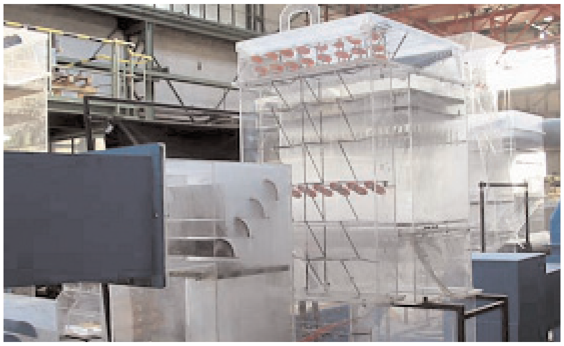


Figure 1. Installed Delta Wing® in a typical SCR Physical Flow Model

The working principle of the Delta Wing® static mixer[4] is characterized by the creation of steady state vortices at the leading edges of delta-shaped plates as shown in Figure 2. The intense rotational motion of these vortices is enhances the macro-mixing activity in their immediate proximity. The key benefits of this mixing technology are the formation of these vortices and the fact that their formation is independent of the gas flow rate.

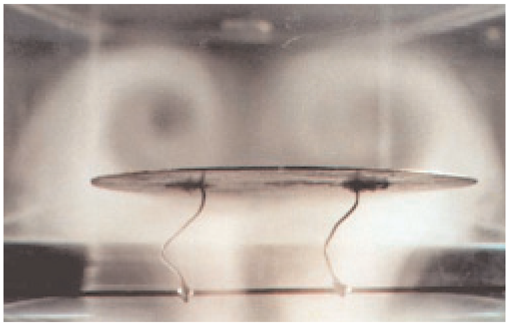


Figure 2. Illustration of the formation of Delta Wing® vortices

STUDY CASE: SCR SYSTEM DOWNSTREAM OF A SIMPLE CYCLE COMBUSTION GAS TURBINE

The SCR system is a widely used and effective technology for nitrogen oxide pollutant control. Three examples of the use of SCR technology for different applications are shown in Figure 3. The conventional SCR system arrangement[6] is illustrated in Figure 3a. The SCR reactor in this case is located downstream of the economizer in utility boiler systems. Figure 3b presents a typical heat recovery steam generator (HRSG) system configuration.[7] HRSG systems are located downstream of a combustion gas turbine and are used to recover heat from the exhaust gases. In this case, the SCR reactor is located within the HRSG, at a location where the exhaust gas is cool enough for efficient catalyst operation. Figure 3c shows the simple cycle SCR arrangement. This type of SCR system has a similar geometry with the HRSG system but without the heat recovery modules. As discussed in this paper, the simple cycle SCR system is conceptually designed to be employed downstream of a combustion gas turbine in order to reduce NO_x and CO emissions from the hot exhaust gas. Although the SCR reactor is installed at different locations in these configuration systems (due to the different gas flow conditions), the SCR principle for removal of pollutants from the exhaust gas is the same.[2][8][9] Uniform gas flow, temperature distributions and adequate gas temperature ranges are required by all NO_x and CO catalyst systems within the SCR reactor in order to achieve their performance targets.

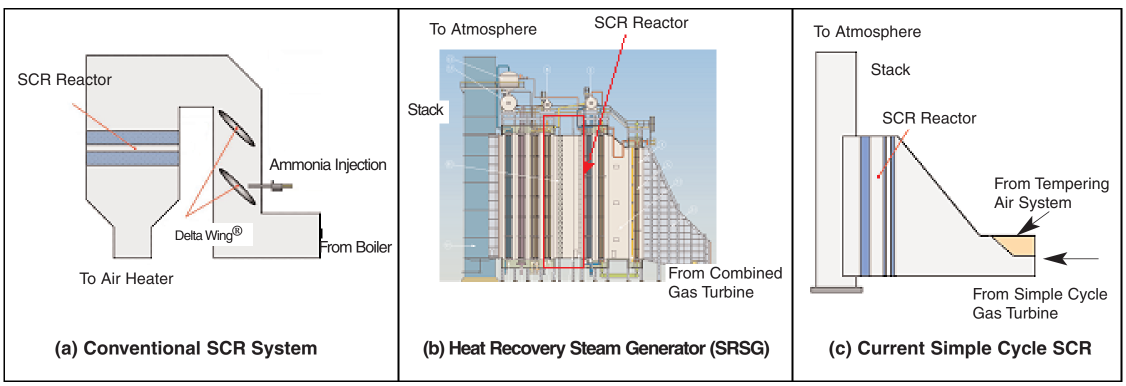


Figure 3. Schematic Illustration of Different Selective Catalytic Reduction (SCR) Systems

The simple cycle SCR system as shown in Figure 3c includes a tempering air system (to introduce ambient air into the SCR system), the CO catalyst bed, an ammonia injection grid (AIG), the NO_x catalyst bed and a discharge stack. The tempering air system is required to lower the flue gas temperature to be within the optimum temperature window for efficient SCR operation and emissions reduction.

DESIGN ANALYSIS OVERVIEW

The simple cycle SCR system design analysis was conducted in three stages. First, the simple cycle SCR with no mixing devices shown in Figure 3c was modeled as the "Base Case". The flow characteristics from this base case were used as a starting point for the optimization analysis conducted for this project. In the second stage, various flow distribution devices including Delta Wing® mixers, turning vanes and perforated plates were added into the system. Their effect on the flow distribution was combined with parameters such as the length of the inlet duct in order to allow more distance for the mixing of the ambient air with the exhaust gas. In the third stage of this study, several options for the injection of the tempering air into the system were investigated. It was noted that mixing between the tempering air and the exhaust gas improved with the new injection methods.

This study discussed three (3) representative configurations for the simple cycle SCR system design. A schematic of these different configurations is shown in Figure 4. The first configuration, illustrated in Figure 4a is the base case which was described previously and which has no mixing devices. In this case, ambient air is introduced through two inlets positioned above the inlet duct, passes through an ambient air screen and mixes with the hot exhaust gas turbine flow. Case I, which represents the simple cycle SCR system with two pairs of Delta Wing® mixers, is presented in Figure 4b. In this configuration, two inclined pairs of Delta Wing® mixers and a bottom kicker are added into the system. Case II, which represents the simple cycle SCR system with a combination of two pairs of Delta Wing® mixers and a perforated plate/distribution grid, is shown in Figure 4c.

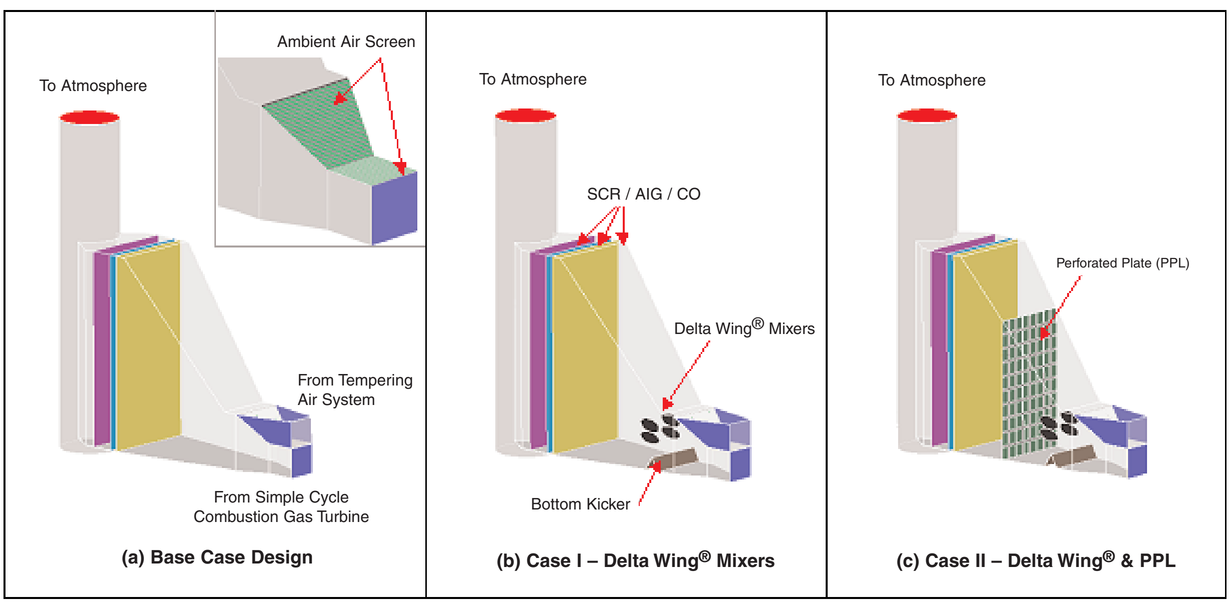


Figure 4. Schematic of the Three (3) Representative Simple Cycle SCR Configurations

Figure 5 illustrates typical gas turbine velocity and temperature profiles used as model inputs in the cases that were studied. The core velocity of the swirling hot gas reaches up to 600 ft/s, while variations of the bulk velocity are as much as ±130 %. The highest temperature is above 1100 °F. Table 1 lists typical SCR operating conditions used in the CFD modeling. It is assumed that the tempering air is uniformly introduced into the SCR system.

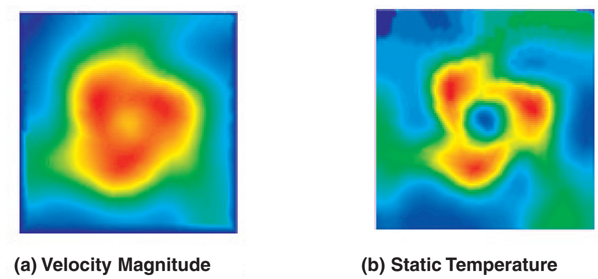


Figure 5. Typical Gas Turbine Velocity and Temperature Profiles Applied at the CFD Model Inlet

Table 1

Typical SCR Operating Conditions used in the CFD Modeling

Parameters	Unit	Exhaust Gas	Tempering Air
Mass Flow Rate	Lb/Hr	6,463,971	2,468,459
Density	Lb/Ft3	0.0322	0.0765
Temperature	°F	Profile Input	59
Velocity	Ft/Sec	Profile Input	—

RESULTS AND DISCUSSION

1) Modeling Results — Base Case: simple cycle SCR with no mixing devices

As detailed previously, velocity and temperature profiles from the gas turbine are applied at the inlet of the model. Tempering air is added and mixed into the SCR system in order to cool and dissipate the hot gas turbine exhaust. Figure 6a shows the velocity distributions in several vertical planes along the length of the SCR system. Figure 6b details the velocity distribution in the Criteria Plane, which has been described previously as the vertical plane located approximately two feet upstream the CO catalyst layer. It can be seen that the flow is primarily concentrated at the bottom of the duct, from the inlet to the system and all the way to the catalyst face due to the very high velocity core at the inlet. In the Criteria Plane, the velocity is high at the bottom while the rest of the plane experiences backflow.

Figure 7 shows the velocity uniformity variation in six vertical planes as expressed by the velocity uniformity criteria (% rms). The blue and magenta bars represent the relative uniformity of the positive and negative velocities in these planes, respectively. It can be seen that the positive velocity (blue bars) increased from about +50% rms at the inlet to +125% rms in plane 4 and then decreased to +106% rms at the Criteria Plane. The negative velocity (magenta bars) is -41% rms at the Criteria Plane.

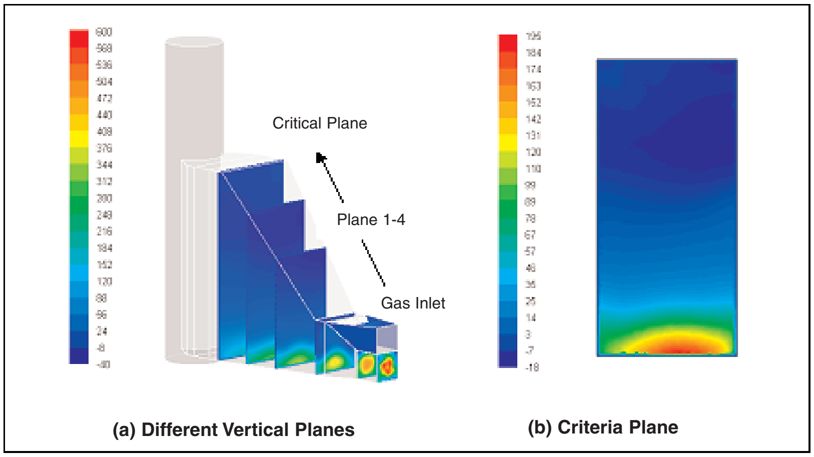


Figure 6. Calculated Axial Velocity Distributions (ft/s) for the Base Case

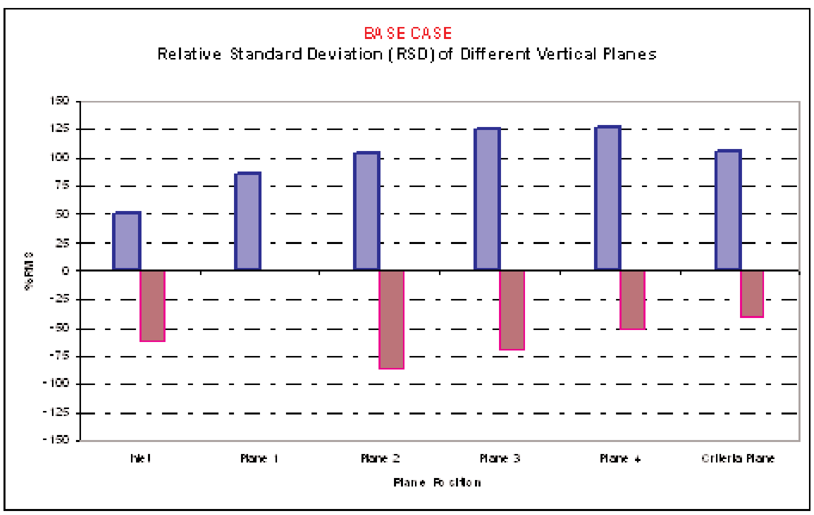
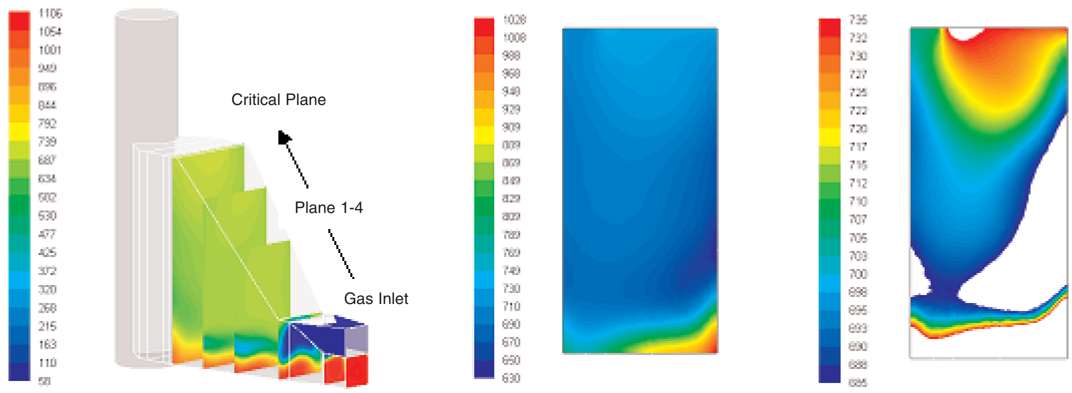


Figure 7. Calculated RSD (% rms) through Vertical Planes for the Base Case

Figure 8a shows the corresponding temperature distributions in the same vertical planes presented for the velocity distributions. Very little mixing is observed between the tempering air and the exhaust gas due to the inability of the tempering air to penetrate the bulk flow. Consequently, the temperature remains high at the bottom of the duct, all the way to the face of the CO catalyst. Figures 8b and 8c show the temperature distribution in the Criteria Plane in the full contour range and clipped to ±25 °F of the average plane temperature, respectively. As calculated, the temperature span is about 400 °F in the Criteria Plane and approximately 70% of the plane area temperature is within ±25 °F of the average value. These results were used as a starting point for the optimization analysis conducted for this project.

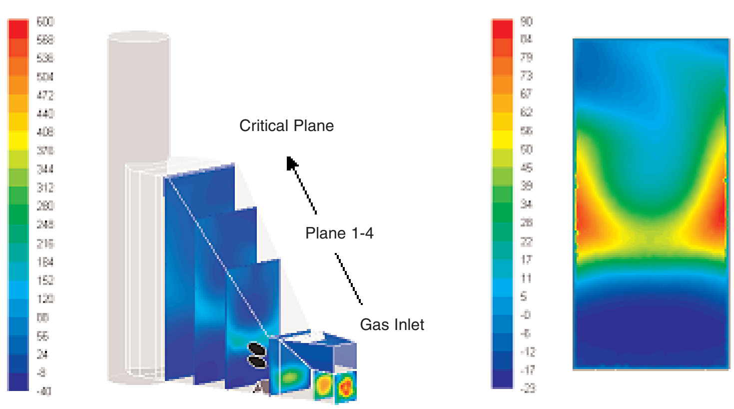


(a) Different Vertical Planes **(b) Criteria Plane** **(c) Clipped to ±25°F of Average Value @ Criteria Plane**

Figure 8. Calculated Temperature Distributions (°F) for the Base Case

2) Modeling Results — Case I: simple cycle SCR with two pairs of Delta Wing® mixers

The schematic representation of Case I configuration was presented in Figure 4b. The method of introducing the exhaust gas and tempering air into the system is identical to the base case. However, in this case, a kicker is positioned at the bottom of the duct and two inclined pairs of Delta Wing® mixers are added downstream of the bottom kicker. Based on the flexibility in operation of the Delta Wing® mixers, many different settings were modeled in the current study. The Case I configuration presented here is one of the settings that showed good results by improving both the velocity and temperature uniformity in the planes of interest. Figure 9a presents the axial velocity distributions for Case I in the same vertical planes as for the base case. It can be seen that for this configuration, the bulk flow is pushed upward by the kicker and then is broken into separate zones by the Delta Wing® mixers. The resulting axial velocity distribution in the Criteria Plane is illustrated in Figure 9b. As compared with base case, it is noted that the maximum velocity decreased from ~195 ft/s to ~90 ft/s. This shows that the flow uniformity is improved by smoothing out the peak velocities. This in turn would translate into a more effective utilization of the catalyst.



(a) Different Vertical Planes **(b) Criteria Plane**

Figure 9. Calculated Axial Velocity Distributions (ft/s) for Case I

Figure 10 shows the velocity uniformity variation in the same vertical planes as for the base case expressed by the velocity uniformity criteria (% rms). As before, the blue and magenta bars represent the relative uniformity of the positive and negative velocities in these planes, respectively. It can be seen that unlike the trend of the RSD value for the base case, the positive velocities (blue bars) decrease starting with Plane 3. This agrees with the fact that the flow uniformity for Case I configuration is improving once it passes the flow devices (kicker and Delta Wing® mixers) placed before that location. The positive velocity value is about +68% rms in the Criteria Plane for Case I. The negative velocity value (in magenta) is about -47% rms in the Criteria Plane respectively for this configuration. Figure 11 shows the corresponding temperature distributions in the same vertical planes of interest, as well as the full contour range and clipped to ±25°F of the average plane temperature profile. As compared to the base case, the maximum temperature decreased by 125 °F (903°F vs. 1028°F) and the variance of minimum to maximum temperature is decreased by approximately 200 °F in the Criteria Plane. Less than half of the Criteria Plane temperature is within ±25°F of the plane average value.

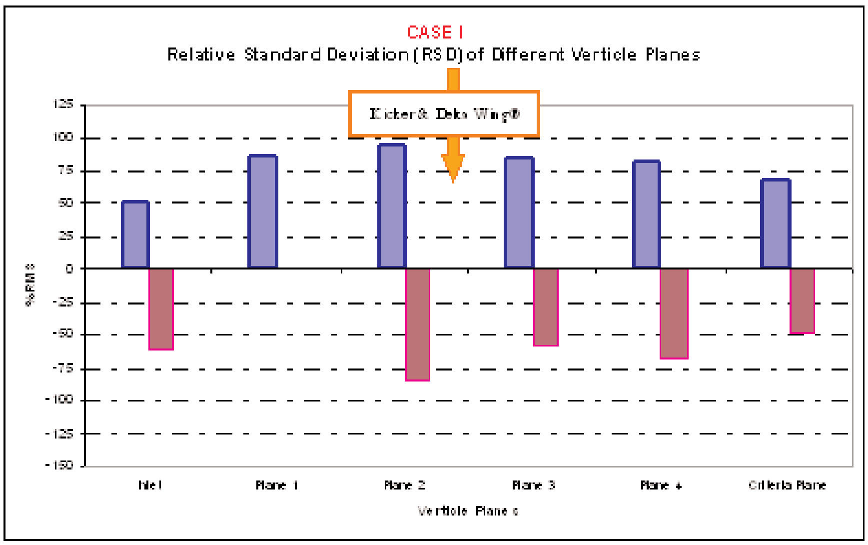
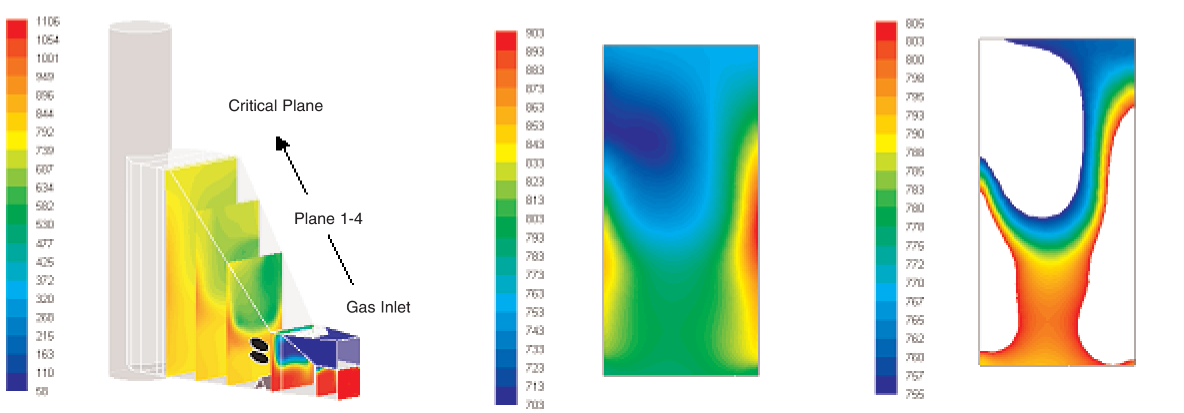


Figure 10. Calculated RSD (% rms) through Vertical Planes for the Case I



(a) Different Vertical Planes **(b) Criteria Plane** **(c) Clipped to ±25°F of Average Value @ Criteria Plane**

Figure 11. Calculated Temperature Distributions (°F) for Case I

Although not enough to reach the target values set for this application, these results suggest better mixing of the tempering air with the bulk flow for Case I configuration and confirm the effectiveness of using a combination of flow devices for further optimization.

3) Modeling Results — Case II: simple cycle SCR with Delta Wing® mixers & perforated plate

Based on the Case I results, it was concluded that an additional mixing stage was needed to further dissipate any remaining peak velocities and thus to improve the flow uniformity at the catalyst face. Consequently, a perforated plate/distribution grid was added downstream of the Delta Wing® mixers to serve as an additional mixing stage. Although various open area percentages were studied, only the 70% open area will be presented here, as it was one of the cases that produced the best results. The schematic representation of Case II configuration was presented in Figure 4c. Figure 12 presents the axial velocity distributions for Case II in the same vertical planes as before (Fig. 12a) and the Criteria Plane (Fig. 12b), respectively. Figure 13 shows the corresponding velocity uniformity variation in the same planes expressed by the velocity uniformity criteria (% rms). The location of the mixing devices is indicated relative to the axial position of the planes.

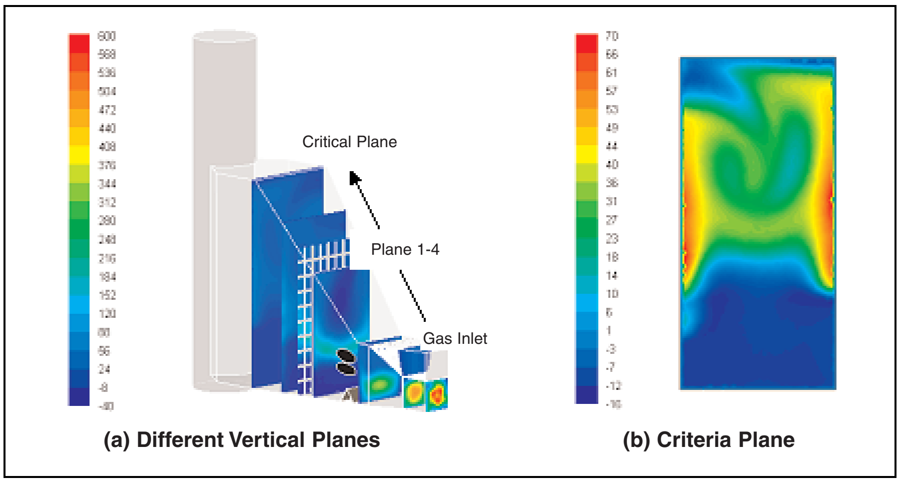


Figure 12. Calculated Axial Velocity Distributions (ft/s) for the Case II

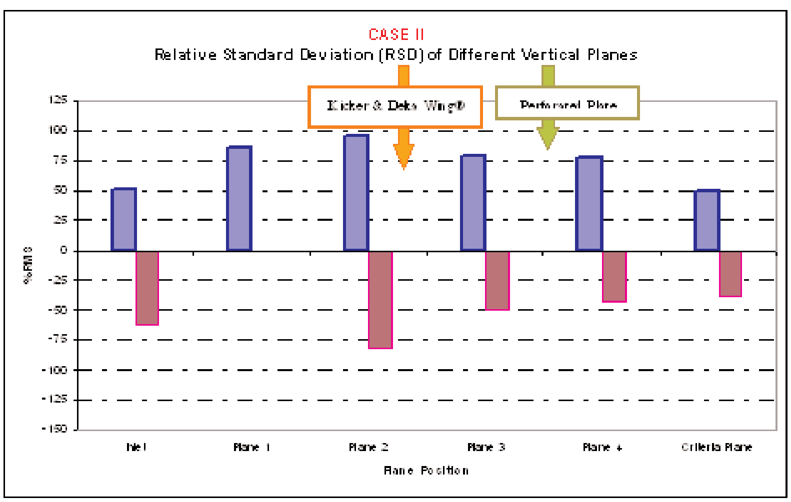


Figure 13. Calculated RSD (% rms) through Vertical Planes for Case II

It can be seen that the effect of the perforated plate is to further re-distribute the mixture flow. As compared to Case I, the high velocity area in the Criteria Plane has been eliminated in the central area and is now limited to the sides. The maximum axial velocity at the Criteria Plane has decreased from ~90 ft/s to ~70 ft/s and the RSD value decreased as well from +68% rms to +49% rms for the positive velocities (blue bars) and decreased from -47% rms to -37% rms for the negative velocities (magenta bars). Figure 14 shows the corresponding temperature distributions in the same vertical planes of interest, as well as the full contour range and the clipped to ±25°F of the average plane temperature profile. As calculated, the maximum temperature is approximately 925 °F and the variance of minimum to maximum temperature is approximately 315 °F in the Criteria Plane. As compared to Case I, the velocity uniformity is improved, while less area of the Criteria Plane is within ±25°F of the plane average value.

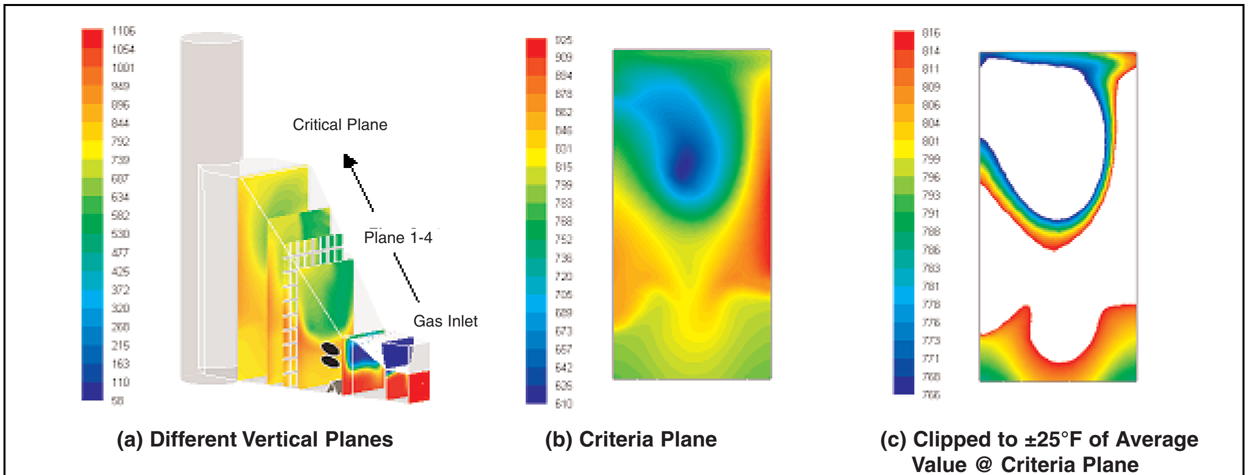


Figure 14. Calculated Temperature Distributions (°F) for the Case II

4) Summary

Table 2 summarizes the results of the three (3) representative cases evaluated during this project. Compared to the base case, the velocity uniformity was improved by 36 % in Case I configuration and by 54% in Case II configuration. Peak temperatures are decreased and temperature uniformity improved for both cases as compared to the base case, however the temperature uniformity is slightly better for Case I than for Case II. Work is continuing on further optimizing the Case II design concept to improve flow and temperature uniformity at the catalyst layer.

Table 2

Calculated Velocity & Temperature Uniformities in "Criteria Plane" for all cases

CFD Results	Relative Standard Deviation (%RMS)	% of Area within ±25°F of Average Temp	Maximum Temperature (°F)
base case	+106.2 / -41.4	70.3	1028
Case I	+68.4 / -47.6	42.8	903
Case II	+49.2 / -37.7	30.9	925
Specifications	±15	100	~900

CONCLUSIONS

The current study presents several representative design options evaluated by Riley Power Inc. for the placement of an SCR system downstream of a nominal 200 MW simple cycle gas turbine. Design variables included different tempering air injection systems, number and placement of various flow control devices, such as Delta Wings® and turning vanes and different types of perforated plates/distribution grids. The three (3) representative CFD cases presented in this paper included a base case, where no mixing devices were included and two design concepts in which different flow straightening devices and mixers were combined. Results for both Case I and Case II showed improved flow and temperature uniformity over the base case. Specifically, the velocity uniformity was improved by 36% in Case I configuration and by 54% in Case II configuration. Also, the peak temperatures were decreased and temperature uniformity improved for both cases as compared to the base case, however the temperature uniformity was slightly better for Case I than for Case II. Currently, work is continuing to further optimize the Case II design concept, in order to improve the flow and temperature uniformity of the gas flow entering the catalyst layer.

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