SNCR Efficiency Study of Optimization of Spray Systems in CFB

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Abstract

High-level Nitrogen oxides (NO_x) released to the atmosphere cause health and environmental hazards. Conventional power plants are required to have NO_x emission control systems to abide by local environmental regulations. Common post-combustion techniques include selective non-catalytic reduction (SNCR) or selective catalytic reduction (SCR) techniques. SNCR is a proven technology that can be implemented virtually without affecting existing industrial operations with low capital cost. SNCR is a method involving either aqueous ammonia or urea as the reagent injected into flue gas in the boiler/furnace within specific temperature range. This method commonly reduces the emission of NO_x by 30-50%. However, high reductions can be achieved by system optimization. Placement within the proper temperature window, distribution within the cross section and residence time of reagent significantly influence performance of an SNCR system. Therefore, spray lance and nozzle design is crucial for assurance of operating efficiency and ammonia utilization.

In this paper, an SNCR system in a circulating fluidized bed (CFB) boiler was studied with using Computational Fluid Dynamics (CFD) simulations, as it relates to spray technology. The simulation solves Navier-Stokes equations with heat and mass transfer using ANSYS Fluent SNCR model with Lagrangian multiphase models and species transport model. CFD was used to diagnose the gas phase behavior and thermal distribution, to determine optimal spray placement and maximum penetration. The focus of this work was the parameters of the injection, which were determined based on test data acquired through in-house laboratory equipment. Temperature profile, pollutant reduction, ammonia slippage and wall impingement were used from the CFD results to assist determining the best spray design to achieve the greatest efficiency.

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Introduction

NO_X is the term of nitrogen oxides, in atmospheric chemistry referring to total concentration of nitric oxide (NO) and nitrogen dioxide (NO_2), which is produced mainly from the endothermic reaction of nitrogen and oxygen in the high temperature combustion process. With industrial development and heavy traffic, air pollution of nitrogen oxides emitted into atmosphere can be significant. In 2013, vehicles produce more than 30% of carbon monoxide and nitrogen oxides in our environment with over 25% of global warming pollution [1]. Meanwhile, power generation is the largest source of air pollutants and global warming emissions in U.S.[2]. High-level NO_X causes health and environmental hazards by deteriorating water quality, forming smog and acid rains even tropospheric ozone. On March 2014, the U.S. Environmental Protection Agency (EPA) announced new, tighter fuel standards as part of ongoing initiatives to lower greenhouse gas emissions. Waste, cement, glass, power and steel plants along with OEMs around the world are required to have $DeNO_X$ solutions in their process.

Although coal contributes nearly 80% of all power plant carbon emissions, it produces about half our electricity. Conventional power plants, which burn coal, waste and biomass, are required to have nitrogen oxide emission control systems met local environmental regulations. With the need of production and more stringent NOx emission requirement, primary NO_X abatement (low NO_X combustion technology) was no longer sufficient. Therefore, secondary abatement techniques are getting increasing consideration, normally known as selective non-catalytic reduction (SNCR) or selective catalytic reduction (SCR). In China, SCR is preferred in the new, renovated or expanded units and anthracite burning units; while SNCR is often selected in units burning bituminous coal and lignite[3]. In Japan, SNCR technologies came into commercial use on oil- or gas-fired power plants in the middle of the 1970s. In Europe, new biomass fired plants and co-combustion plants prefer SNCR. On the other hand, waste fired plants choose SCR[4]. In the USA, SNCR systems have been used commercially on coal-fired power plants since the early 1990s.

The attractions of SNCR systems are their lower capital equipment cost and extremely versatile nature for medium levels of NO_X control. Also SNCR is quite compatible with other upstream and downstream NO_X removal technologies, which might have been permanently placed in the process. Nowadays, SNCR is applied in many industries including: power, steel, pulp and paper, petrochemical, waste to energy, glass and others.

In this paper, a SNCR system in Circulating Fluidized Bed (CFB) boiler was studied and diagnosed by using Computational Fluid Dynamics (CFD). It solves Navier-Stokes equations with heat and mass transfer using ANSYS FLUENT SNCR model, Lagrangian-Eulerian multiphase model and species transport model to examine the measured data from industrial units. CFD was used to diagnose the gas behavior, bypasses, spray coverage, temperature field, pollutant reduction, ammonia slippage, and wall impingement to assist determining the best spray design for achieving the greatest efficiency. All parameters for the injections were from nozzle characterization tests at Spraying Systems Co.

Technical Approach

SNCR

SNCR is a proven technology that can be implemented virtually without affecting existing industrial operations and considerable low capital cost. It is often selected for cement industry, as it is suitable for both new and existing dry kiln systems in operation or to be on market. This is a method involving either aqueous ammonia or urea as the reagent injected into flue gas in the boiler/furnace within temperature window range of 1400-2000°F. Urea is a safe material and is easy to handle and store; while use of aqueous ammonia reagent is a popular way of dealing with exhaust for avoiding harmful of side products and ammonia slip. SNCR method commonly reduces the emission of NO_x by 30-50%, where NO_x react with reagent to form nitrogen and water. No consideration is needed for the cost and placement of catalyst, with the high stoichiometric ratios. SNCR process requires three or four times as much reagent as SCR to achieve similar reduction. Therefore, efficiency improvement can be achieved by system optimization, especially spray control. The proper temperature window, distribution within the cross section and residence time of reagent significantly influence performance of a SNCR system. Therefore, spray lance and nozzle design for getting uniform spray distribution into the process gas is crucial for assurance of operating efficiency and ammonia utilization.

The selective non catalytic reduction of NO_x is a technique to reduce the emission of nitrogen oxides from combustion by injection of a reductant like ammonia (NH_3) or urea ($CO(NH_2)_2$), which was first described by Lyon[5]. The process involves injecting the reductant into the boiler at a specific temperature window location, where it reacts according to Equation (1) and (2):

$$NH_2CONH_2 + H_2O \rightarrow 2NH_3 + CO_2 \qquad (1)$$

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \qquad (2)$$

The mechanism involves NH_2 radicals attach to NO and decompose. Ammonia can react with other combustion species to form side products, it also decomposes at high temperature to create NO instead of removed. Therefore, non-reacted ammonia is called ammonia slip, which is undesirable.

In this work, ammonia was selected as the reagent for SNCR process. Ammonia utilization factors (AUF) is one important index to evaluate efficiency of SNCR process. AUF reflects directly the material utilization and NO_x removal rate. In many cases, difficulty has been reported to attain AUF above 40-45% (for each 100 moles of ammonia injected, 40-45 moles of NOx were removed). Generally 60-75% obtained by SNCR systems. Distribution of injected ammonia or urea is a pre-requirement for determining ammonia vapor uniformity. Spraying Systems Co. has multiple types of technology to acquire full spray characteristics and nozzle features combined with computational ability to better achieve SNCR target by built-in the optimal spray systems. The in-house empirical data of the nozzles were applied to better represent the true nature of sprays. In order to more accurately assess the system, simulations were used to investigate gas phase with monitoring injection distribution, removal rate and system potential damages, etc.

Equipment and Methods

Test Setup and Data Acquisition

For drop sizing, the nozzle was mounted on a fixed platform in a vertical downward orientation. Testing was performed in a single plume of the spray. The data was acquired at 300mm downstream of the nozzle exit orifice. Drop size and velocity information was collected at various operating conditions. Multiple points throughout the spray plume were measured with a mass and area weighted average reported for comparison purposes.

A two-dimensional Artium PDI-HD system with the integrated AIMS software was used to acquire drop size and velocity measurements. This technique measures angle of trajectory and time of arrival of each particle passing through an optical measurement volume formed by pairs of intersecting laser beams. The ability to measure accurately requires the reliable characterization of the size, velocity, and transit time of each droplet. The PDI system is a validated method for droplet size and velocity measurement; in addition, spray concentration measurements are possible, described by Bade et al. [5].

The Artium PDI system utilizes a unique digital signal burst detection method which reliably detects droplets, even in complex environments. This is an advance over the earlier Fourier transform burst detection method invented by Ibrahim and Bachalo (U.S. Patent 5,289,391). This detection system is also critical to the in situ approach for measuring the effective diameter of the sample volume as a function of drop size. The Fourier transform based signal processor uses quadrature down-mixing to position the signals in an optimum range for processing. The real and imaginary (shifted by 90 degrees) components of the signals are sampled and a full complex Fourier transform is used to obtain the signal frequency and phase. Each of the three signals for the phase measurements is sampled in this manner and the phase differences computed at the same frequency for each signal. Three phase differences are computed, AB, AC, and BC for detectors A, B, and C from the Channel1 velocity component. These three phase differences are compared for consistency as one of the validations for each droplet signal detected. The approach has proven to be very effective in detecting and eliminating sizing errors due to the well-known trajectory problem.

The Artium AIMS software incorporates an auto-setup feature that serves to optimize the frequency and phase shift processing. The auto-setup feature acquires a small number of signals produced by droplets passing through the measurement volume and is discussed in detail in Bachalo, et al. [patent pending]. User-to-user setup differences that have been known to produce varying results and accuracy in PDI data results, often relying upon the operator's individual experience and understanding of the PDI principals, have been significantly minimized with this approach. The laser transmitting lens focal length was 500mm for all tests; the receiving unit focal length was 500mm for all tests and was oriented at the 40° off-axis forward scatter position. Masking was employed as necessary to provide an effective measureable drop size range of 10.6 to 584μm (6.7 to 1349μm mask 2). The optical setup was used to ensure acquisition of the full range of drop sizes, while maintaining good measurement resolution. The particular range used for these tests was determined by a preliminary test-run where the $D_{V0.5}$ and the overall droplet distribution were examined. For each test point, a total of 15,000 samples were acquired. The experimental setup can be seen in Figures 1 and 2.

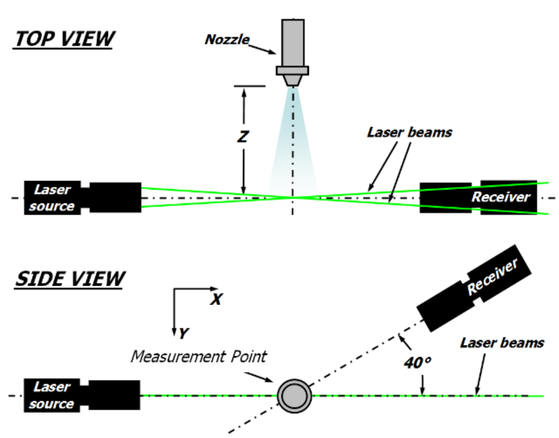

Figure 1. Illustration of PDI layout for drop size and velocity data acquisition.

Figure 2. Illustration of PDI during experiment.

The $D_{V0.1}$, $D_{V0.5}$, D_{32}, and $D_{V0.9}$ diameters were used to evaluate the drop size data. This drop size terminology is as follows:

$D_{V0.1}$: is a value where 10% of the total volume (or mass) of liquid sprayed is made up of drops with diameters smaller or equal to this value.

D_{32}: Sauter Mean Diameter (also known as SMD) is a means of expressing the fineness of a spray in terms of the surface area produced by the spray. SMD is the diameter of a drop having the same volume to surface area ratio as the total volume of all the drops to the total surface area of all the drops.

$D_{V0.5}$: Volume Median Diameter (also known as VMD or MVD). A means of expressing drop size in terms of the volume of liquid sprayed. The VMD is a value where 50% of the total volume (or mass) of liquid sprayed is made up of drops with diameters equal to or smaller than the median value. This diameter is used to compare the change in average drop size between test conditions.

$D_{V0.9}$: is a value where 90% of the total volume (or mass) of liquid sprayed is made up of drops with diameters smaller or equal to this value.

By analyzing drop size based on these standardized drop statistics it is possible to objectively characterize the quality and effectiveness of this atomizing nozzle for the prescribed application.

Test Fluids and Monitoring Equipment

All testing was conducted using water and compressed air. Flow to the system was supplied using a high volume pump. The liquid flow rate to the injector was monitored with a MicroMotion flow meter and controlled with a bleed-off valve. The MicroMotion flow meter is a Coriolis Mass flow meter which measures the density of the fluid to determine the volume flow. The meter is accurate to 0.4% of reading. Liquid pressures were monitored upstream of the injector with a 0-1.03MPa, class 3A pressure gauge.

Injectors

Performance of spray nozzles is critical for effectively removal of NO_x. Precision injection of the reagent requires expertise in drop size, distribution, velocity, spray angle and spray direction. Nozzles suitable for this application are particularly required to tight control of drop size and spray coverage. Spraying Systems Co. provides a large selection of nozzles for SNCR and SCR, where typical products are two-fluid and hydraulic spray nozzles. Both types of nozzles are available in a wide range of capacities, materials and connections. Normally, injectors are selected based on capacity requirement and allowable drop size for fast and complete evaporation and dwell time analysis for less risk of wetting. In this paper, two-fluid atomizing nozzles are selected. Spraying Systems Co. FloMax® nozzles (Figure 3) are able to control large and frequent variations in gas temperature, as well as produce predictable small drops using minimal compressed air and energy.

A total of 12 FloMax® FMX-Series nozzle were used at an equal distance mounted on one selected plane. Flow rate was determined by the NOx removal requirement for the SNCR system in this study. These nozzles use patented multi-stage atomization processes to produce very small drops with exceptional efficiency. A multi-stage cross-hole nozzle design provides superior atomization by shearing the liquid prior to mixing with the high velocity air stream. The nozzle offers significantly higher turndown ratios, up to 10:1, than standard air atomizing nozzles for maximum operating flexibility. This capability allows the air pressure to be constant while the liquid varies based on process requirements. The nozzle also features a large free passage design to minimize clogging and provides a fairly uniform spray pattern with various spray angles. A patented anti-bearding air cap design to prevent material build-up near the nozzle orifice and prevent performance problems is also available.

Figure 3. Spraying Systems Co. FloMax® FMX Air Atomizing Nozzles

Numerical Simulations Setup and Methods

CFD Background

Computational Fluid Dynamics (CFD) is a numerical method used to predictably solve fluid flow problems, like heat and mass transfer, chemical reactions and related fluidization phenomena. Today's CFD simulations perform an extremely large number of calculations to simulate the behavior of fluids in complex environments and geometries, such as SNCR or wet FGD. Within the computational region, CFD solves the Navier-Stokes equations and the set of governing mathematical equations to obtain flow pattern, velocity, pressure, temperature and various parameters. In this work, computation was performed with commercial software ANSYS Fluent version 15.0. CFD model was reproduced according to circulating fluidized bed boiler geometry with some simplifications to reduce mesh size and computational time. Meshing was done within ANSYS Workbench using custom automated meshing tools.

Simulation Description

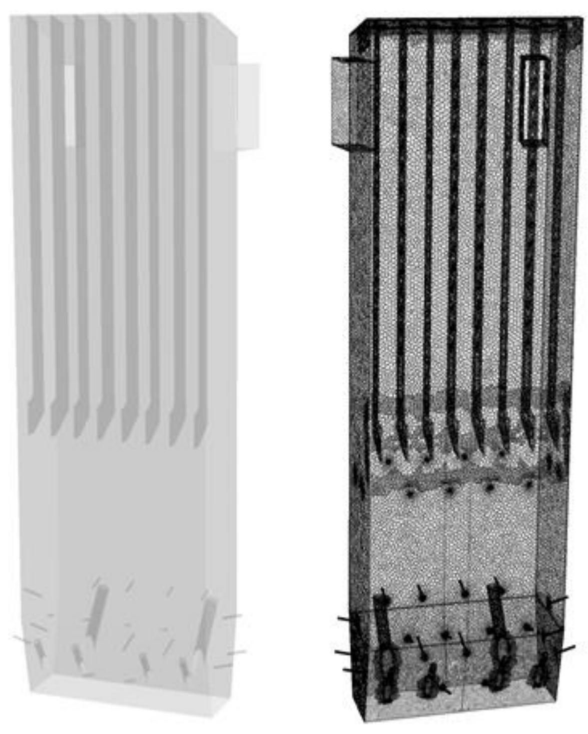

Figure 4. 3D Circulating Fluidized Bed Boiler Geometry for CFD

The 3D mesh consisted of 1.7million hexahedral and polyhedral mixed cells with max skewness of 0.85. The geometry of CFB boiler was shown in Figure 4. Boiler was about 31 meters high and 4.5 × 9.6 meters wide, respectively. Air was blown into the system through one wide inlet at the bottom and eighteen reblown inlets on the side walls. There were four coal pipes and two reburnt ash pipes fed toward the combustion zone. As the SNCR happened in boiler section for this CFB, cyclone was not included in the CFD study. Two connection paths to the cyclone were set up as the outlet of the boiler. Boiler was covered with cooling walls and eight pieces of superheater amounted near the outlet at the top of the duct.

Considering computational cost and the symmetric structure of this boiler, half of the geometry was applied in simulation. CFD model was used to reproduce the mixture behavior of solid and gas in CFB, with spray and size distribution presented as discrete phases. The coal fired process was simulated initially using a combustion model and the result was proven by 1-D heat balance with industrial data to establish reasonable results. Hence, in this work the combustion process in the boiler was simplified by applying equivalent energy source substitute to rebuild the heat transfer balance and gas species components after combustion.

CFD model was set up with uniform mass flow inlet boundary conditions while varying the relative spray injection parameters by operating conditions in the duct, which showed in Table 1. The outlet was defined as a constant pressure boundary condition and allowed particulates to flow out the system, which were supposed to direct mixture to the cyclone and circulation in the CFB. Boiler and thin super-heaters walls were defined as rigid, no-slip with relative thermal conditions considering their cooling effects in reality. The following models were included in the whole simulation: Eulerian Multiphase Model, Dense Discrete Phase Model (DDPM), k-ε Realizable Turbulence Model, Species Transport model, DPM for Lagrangian tracking of aqueous ammonia droplets, and NO_x pollutant model for representing SNCR. Those models were performed in both transient and steady state by better matching the fluidization features.

Parameters for injections such as the drop size distributions, exit velocity, and spray plume angle were obtained with PDI measurements in a vertical orientation at ambient conditions and were used to define the CFD model spray injection parameters.

Embedded SNCR model

A two-step scheme describing a single initiation step followed by two parallel reaction pathways, proposed by Ostberg and Dam-Johansen, was used in ANSYS Fluent SNCR model to simulate NOx formation and reduction[9].

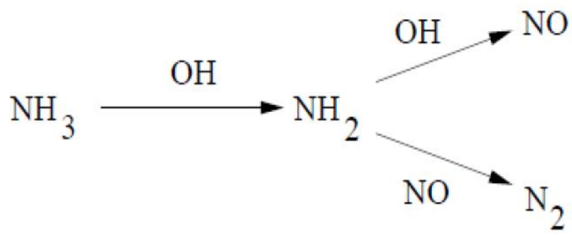

Figure 5. Simplified Reaction Mechanism for the SNCR process

Chemical equations (3) and (4) for above mechanism are listed as below:

$$NO + NH_3 + \frac{1}{4}O_2 \rightarrow N_2 + \frac{3}{2}H_2O \quad (3)$$

$$NH_3 + \frac{5}{4}O_2 \rightarrow NO + \frac{3}{2}H_2O \quad (4)$$

The reaction orders of NO and NH3 and the empirical rate constant for those equations from Brouwer et al.'s work was embedded in Fluent solver[6]. The following reaction rates in Equation (5) and (6) for NO and NH_3 was calculated.

$$\mathcal{R}_{NO} = -k_r[\mathrm{NO}][\mathrm{NH}_3]+k_{ox}[\mathrm{NH}_3][\mathrm{O}_2] \quad (5)$$

$$\mathcal{R}_{NH_3} = -k_r[\mathrm{NO}][\mathrm{NH}_3]-k_{ox}[\mathrm{NH}_3][\mathrm{O}_2] \quad (6)$$

The rate constants were defined as below, with units of m3/mol•s:

$$k_r = 4.24\times10^2 T^{5.30} e^{-E_r/RT} \quad (7)$$

$$k_{ox} = 3.50\times10^{-1} T^{7.65} e^{-E_{ox}/RT} \quad (8)$$

, where Er = 349937.06 J/mol and Eox = 524487.005 J/mol.

This model has proven to give reasonable prediction of SNCR process in fluidized bed combustion applications. It captures the influence of the critical factors in SNCR, such as temperature of flue gas at the injection position, resident time, NH_3 to NO molar ratio, and other parameters expected to be known.

Results (Experimental and Numerical)

Experimental Results

The process of combining the initial velocity characteristics and downstream drop size characteristics was necessary in order to account for the lack of droplet collision and coalescence in the steady state model. The ANSYS Fluent input for droplet population and size distribution in a spray was specified using the Rosin-Rammler distribution function, see Equation 9.

$$F(D) = 1 - \exp\left(-\frac{D}{X}\right)^q \quad (9)$$

F(D) is the fraction of total volume of drops with diameter less than D. X and q are constants inherent to the Rosin-Rammler function associated with the distribution center and width, respectively [8]. This function is used to convert raw measure drop data into drop size distribution function for CFD. The minimum diameter input for CFD was specified based on volume flux and area weighted average of $D_{V0.01}$. The maximum diameter for the CFD model was specified based on volume flux and area weighted average of $D_{V0.99}$. This data is contained in Table 1.

Numerical Results

Preliminary Gas Monitoring

The key of optimization the SNCR process is reagent injection into the flue gas within a specific temperature window. Since the reductant in SNCR can be oxidized as well to form NOx, the desired reaction selectivity decreases with increased temperature. This limits the SNCR process to a narrow temperature window, where residence time is an important parameter to evaluate the efficiency. Based on multiple data sources, the temperature window for efficient SNCR operation typically occurs between 850°C and 1100°C depending on the reagent and condition of SNCR operation[9]. When the reaction temperature increases over 1000°C, NOx removal rate decreases due to thermal decomposition of ammonia. Meanwhile, the NOx reduction rate decreases below 1000°C and ammonia slip may increase. The optimum temperature window generally occurs somewhere in the steam generator and convective heat transfer areas. In this work, temperature and gas streamlines

Parameters	Unit	Case 1	Case 2	Case 3	Case 4
Nozzle	ID	FMX15-20			
Air Flow Rate	scfm	6.7	6.43	6.1	5.5
Liquid Pressure	psi	39.7	40.7	43.4	46.8
Liquid Flow rate	gpm	0.14	0.16	0.20	0.25
Dv0.5	micron	48	49	52	55

Table 1. Injector Parameters Setup for Cases

in the circulating fluidized bed boiler region was predicted and examined to ensure the temperature window for the optimal location for the injectors.

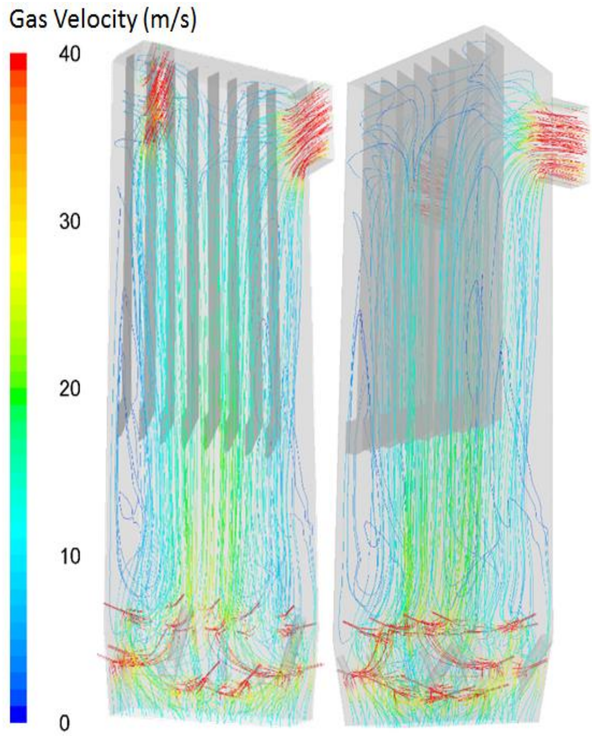

Figure 6. Gas Phase Pathlines Colored by Gas Velocity in CFB Boiler

Figure 6 showed the streamlines in the boiler. As described before, whole air and solid mixing happened at the bottom portion of the boiler. Under given conditions, it showed the mixing was heavier by the turbulence under the height of 5 meters. There was a vacancy of gas at the top (center line) of the boiler, due to lower location of the outlet than the top of boiler. This would cause some vortex at this location and make gas acts detrimental on mixing than lower planes in the duct. This behavior may also interfere with the intended path of the droplets and result in wall wetting, if droplet was involved in this zone. Coal and ash particulates interaction can be seen in Figure 7. Except for the mixing zone and the top of the boiler, where trapped the smaller ash particulates in the turbulence, all the particulates were uniformly distributed through the duct. The circulated mixing of solid particulate and gas species was beneficial to the heat transfer between phases. However, the installation of SNCR had to avoid this zone due to the long residence time of ammonia and disturbed uniformity.

Temperature profile was checked in this stage to give reference to injection point selections. As shown in Figure 8, gas temperature ranged from 1073K (800°C) to 1273 K (1000°C), with respect to high temperature

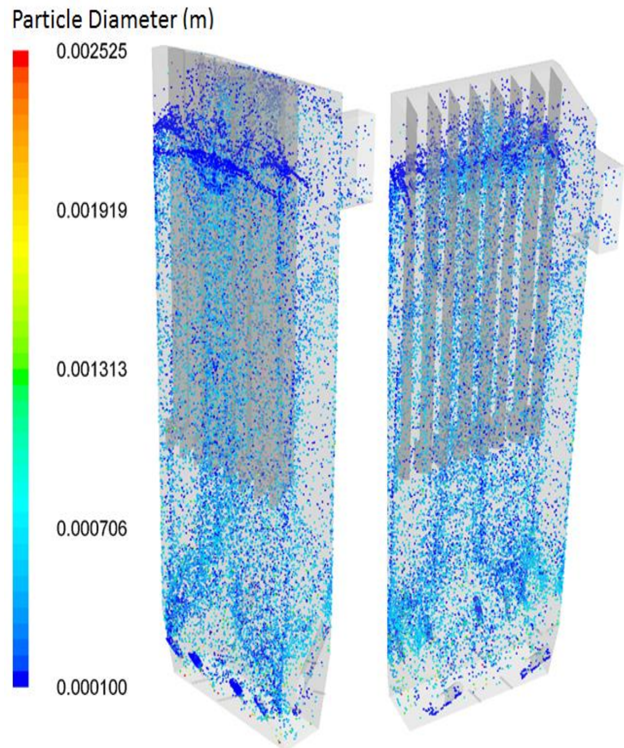

Figure 7. Solid Phase Particulate Distribution Colored by Diameter in CFB Boiler

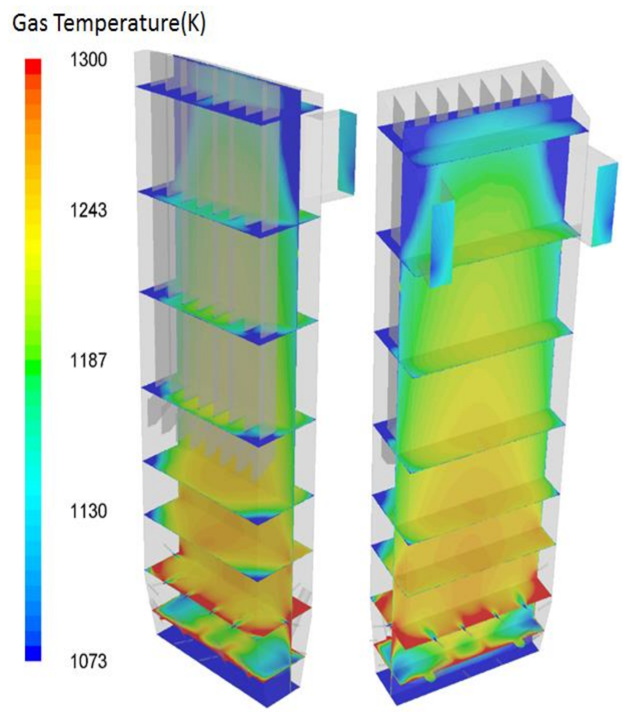

Figure 8. Temperature Profile at Various Heights of Gas Phase in the CFB Boiler

around the wall section at the combustion zone where particulates were turbulently mixed and the uppermost section ,where gas were trapped and whirled. With the heat loss of cooling walls and super-heaters, temperature decreased with increased height, after leaving the combustion zone. Temperature increased in the combustion region until the trend of particulate and gas recirculation disappears. The temperature monitored at outlet was 849°C, which nicely matched with the industrial data (849.5°C) for this boiler. In the well-mixed regime, gas temperature was from 850°C to 980°C.

Spray monitoring

The SNCR reaction requires ammonia as the primary reducing agent. In this study, 5% aqueous ammonia was used as reagent. Proper chemical interaction depends not only on temperature windows but also contact area. From a spray point of view, liquid atomization and controllable drop sizes will be used to ensure rapid evaporation and even distribution in the cross section. The reagent is piped to distribution and mixing modules for metering to each of the injectors. Spray patterns and dispersion is critical to ensure achieving proper reduction levels. The injectors installed in the system are preferred to get as much coverage and uniformity as possible.

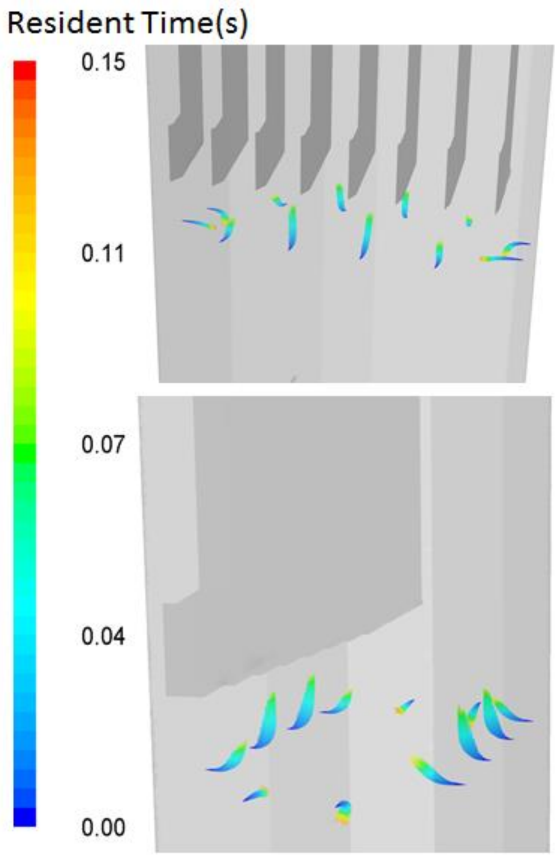

Figure 9. Tracked Reagent Droplet Residence Time in Seconds at Injection Points

The available injection points are from 6m to 25m, according to temperature windows. In industry, some restrictions on injector locations are normally set based on physical constraints and accessibility. After evaluating the temperature profile for gas phase and estimating the residence time of aqueous ammonia, the injectors were mounted at the plane of 11 meters for this study, which had a temperature of 941°C. As the gas and solid fluidization behavior was quite uniform in this regime, injectors can be equal distance along the periphery. An injection system that has too few injection control points or injects a uniform amount of ammonia across the entire section of the boiler will almost certainly lead to a poor distribution ratio and high ammonia slip. Distribution of the reagent can be especially difficult in larger coal-fired boilers because of the long injection distance required to cover the relatively large cross-section of the boiler. In this stage, droplet trajectories were tracked for each design and vaporized reagent. Multiple liquid flows were evaluated as shown in table 1. The results shown are for case 2, with nozzle liquid capacity of 0.16gpm.. Tracking of residence time of aqueous ammonia can be seen in Figure 9 and mass fraction of ammonia in gas species in Figure 10.

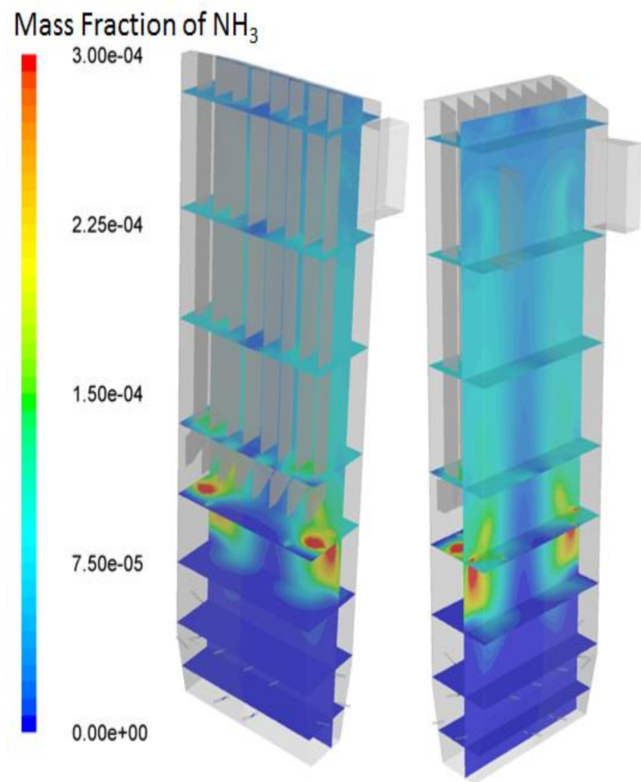

Figure 10. Mass Fraction of Vapor Ammonia Evaporated into Gas Phase Species

Wall impingement problems could result from large droplets produced by the nozzles and incomplete evaporation within allowable dwell time in the duct.

Wetting will cause damage to downstream equipment and damage the system. Results showed all of the liquid was fully evaporated within 0.14 seconds, and no wall contact was detected. Vapor ammonia was fairly uniformly distributed through the NOx reduction zone toward the outlet. The contour of liquid penetration and distribution within the cross section was displayed in Figure 11.

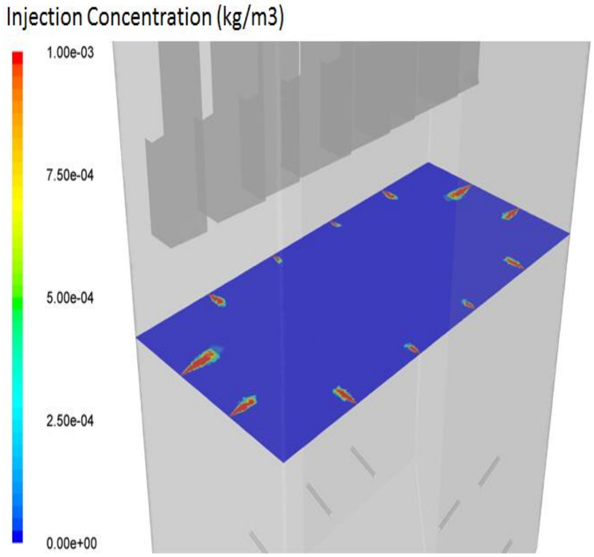

Figure 11. Contour of Aqueous Ammonia Concentration on the Injection Plane

SNCR monitoring

The longer the reagent is in the optimum temperature window, the better the NOx reduction. Residence times in excess of 1 second yield optimum NOx reductions. However, a minimum residence time of 0.3 second is desirable to achieve moderate SNCR effectiveness. In this study, as mentioned above, the evaporation of liquid occurred in a fairly short time. Hence the vaporized ammonia has enough residence time for SNCR process.

High ammonia slip rates could cause side reaction between ammonia and SO2. Ammonia slip from SNCR systems occurs either from injection at temperatures too low for effective reaction with NOx or from over-injection of reagent leading to uneven distribution. The reagent injection system must be able to place the reagent where it is most effective within the boiler because NOx distribution varies within the cross section. Controlling ammonia slip in SNCR systems is difficult since there is no opportunity for effective feedback. However, CFD could help to provide a close prediction as the practical guideline. Fraction of vapor ammonia and NO after SNCR was shown in Figure 12 and 13, respectively. Case 3 of nozzle capacity 0.2gpm was used here as example.

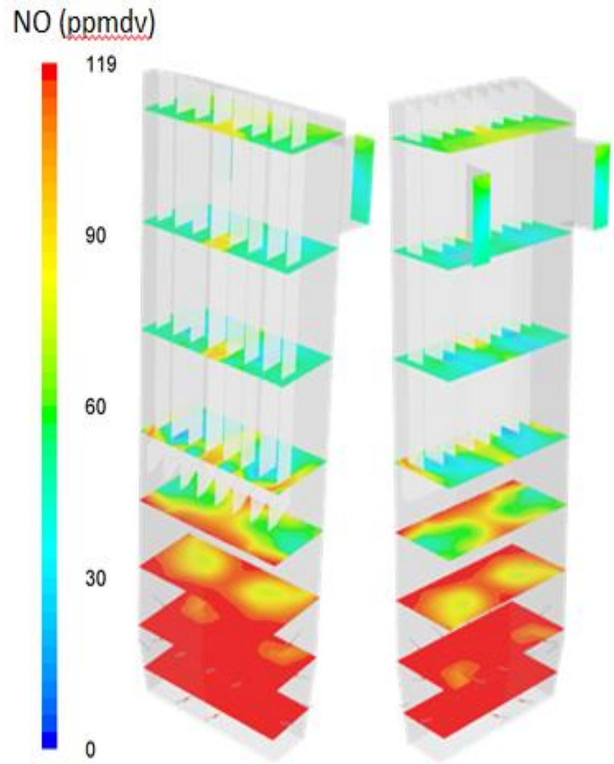

Figure 12. Contour of Nitrogen Dioxide Distribution after SNCR

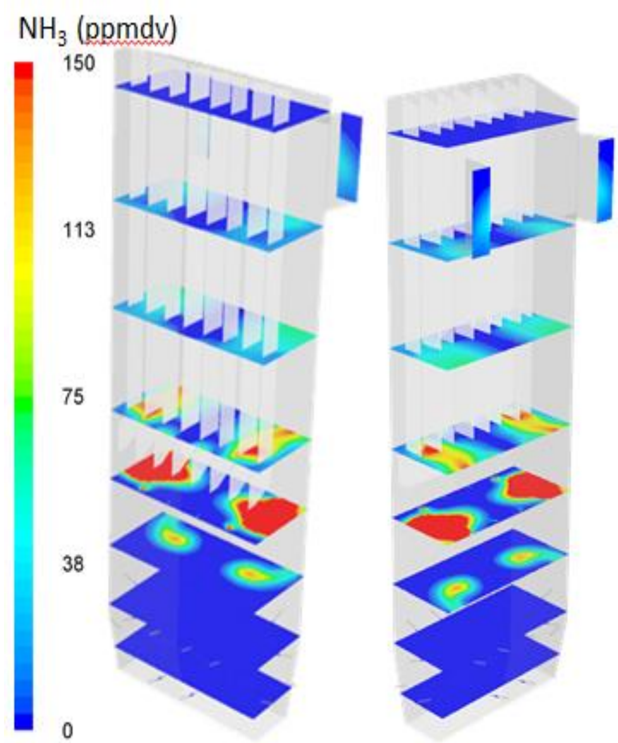

Figure 13. Contour of Ammonia Distribution after SNCR

The resulting NOx values indicate a favorable result in NOx reduction. The outlet surface is used to determine the approximate NOx levels that could be expected to be exhausted with ammonia injections. The optimal setting for spray systems was 0.2gpm capacity, considering good NOx reduction rate and fairly small ammonia slip. The average NOx level across the outlet is 46.6ppmdv with ammonia injections, compared to the inlet level of 119.5ppmdv. This would indicate an approximate 61% reduction in NOx levels. This would indicate an efficient reduction based on the input level of the ammonia. The carryover of ammonia was also examined at the outlet, which was calculated to be about 10ppmdv. AUF factor was about 42% for this case.

Conclusions

NOx removal process requires a highly controlled, predictable and repeatable spray to function effectively for SNCR. Due to the expense and effort required to add a spray system, a computational fluid dynamics (CFD) study of gas conditioning was examined to determine feasibility prior to purchase or installation. In this case, fluidized bed mixing behavior was also investigated to improve accuracy. CFD indicated an average gas exit temperature of 945 ºC, which matched with industrial site measured data. Additionally the behavior of the circulating fluidized bed boiler was reasonably represented by CFD and verified with the industrial conditions.

Guided by the CFD result from the temperature windows of the boiler, areas of recirculation and high swirl were avoided as potential injection locations. CFD revealed, at the selected injection location, 100% evaporation of the reagent (aqueous ammonia). There were no indications of potential issues with wall wetting or wall buildup/damage for this design. This result was deemed to be within an acceptable range for the spray system design.

In this paper, the critical use of CFD was to optimize injection parameters and operating conditions. Through this case study, various factors which impact the NOx reduction were quickly investigated and prioritized. The aim of this study was to demonstrate effectiveness of applying CFD tools in such applications to reduce risk and evaluate environmental impact of designs.

More work may be desired in order to further improve the spray systems design for this SNCR application. Some minor adjustments to nozzle flow rate and drop size may allow for additional effectiveness. As discussed earlier, injectors could be further inserted from the side into the system to ensure more uniform distribution of ammonia and avoid a recirculating zone. Multiple layers of reagent injection, as well as individual injection zones in cross-section of each injection level, are commonly used to follow the temperature changes caused by boiler load changes. It is difficult to make fine adjustments due to the complexity of these injection levels and zones, but this can be achieved through the use of CFD.

Nomenclature

x direction of horizontal plane parallel to laser
y direction of horizontal plant perpendicular to laser
z vertical distance from orifice to test point
D droplet diameter
$\mathcal{R}$ reaction rate
k rate constant
E activation energy

Subscripts
x amount of oxygen

Reference

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