Analysis and Optimization of Spray Tower in WFGD

F. Li*, K. J. Brown, W. Kalata, and R. J. Schick
Spraying Systems Company
P.O. Box 7900
Wheaton, IL 60187 USA

Abstract

Sulfur dioxide is the major environmental contaminant that contributes to smog and soot. The reduction of air pollutants is a worldwide goal that has become a focus for sustainable environmental development strategies. As emission standards increase, the waste gas cleaning system will be required to adapt or be upgraded. Wet FGD is characterized as one of the most reliable and effective SO_2 removal techniques, with the added benefit of low operating cost. However, implementation and maintenance is considered high.

Spray towers are essential elements in the emission cleaning system. Control of the droplets throughout the tower geometry is critical to ensuring maximum reduction and minimal scaling. In order to improve the scrubber, nozzle characteristics and placement must be optimized to reduce the cost of the system implementation and mitigate risks of inadequate pollution removal. A series of large flow rate, hydraulic full and hollow cone injectors were investigated for this study.

Computational Fluid Dynamics (CFD) simulations were used to examine a standard industrial-size wet scrubber design for injection system optimization. ANSYS Fluent solvers were used with Lagrangian particle tracking method for heat and mass transfer between gas and liquid. The alkaline sorbent material and SO_2 reaction was modeled to determine uniformity and efficacy of the system. Surface chemical mechanisms were used to simulate the reaction rate. Drop size, liquid rheology, and injector array layout were examined to achieve SO_2 removal above 90%. Wall impingement and flow pattern results were evaluated, due to their impact in minimizing equipment corrosion and plugging.

*Corresponding author: Fang.Li@spray.com

Introduction

Sulfur dioxide (SO_2) is a chemical substance form of pollutant emitted into atmosphere from volcanic activity or various industrial processes of fossil fuel as their energy source. Since sulfur is a common compound of coal and petroleum, the combustion often produces sulfur dioxide, except for specific sulfur removal procedure done before burnt. Sulfur dioxide is a reactive and acrid gas, which in large quantities versus small portion of atmosphere would cause serious environmental impacts, such as smog and soot. As the strategy of environmental sustainable development got attentions and commission globally, control of SO_2 emission becomes a subject and focus for industry with fossil-fuel power. As the restrictions for pollutant release are highly regulated, all above mentioned industries, especially power plants, need to adapt or upgrade pollutant control systems to meet the emission requirements [1][2].

Flue gas desulfurization (FGD) is one of the major applications in SO_2 emission control, which can achieve expected sulfur dioxide removal from exhaust flue gases or other emitting processes, economically. Among FGD technologies, wet-scrubbing, using slurry of alkaline sorbent, is characterized as one of the most reliable and effective SO_2 removal techniques with low operating cost. However, implementation and maintenance costs are an investigation consideration to reduce the cost of wet FGD as a pollution control option. Hence, an optimal system or procedure is required to improve the situation without any influence to production.

Process improvement and optimization is a constantly ongoing effort. The wet FGD method is widely used and employs limestone/ lime or seawater slurry as absorbent material to reduce SO_2 prior to exhausting process gases to the atmosphere. Hereby spray towers and spray chambers are essential elements in the pollutant emitting-cleaning systems. Control of droplets introduced into the systems is critical to ensure maximum reduction with minimal scaling. The liquid slurry is known to have density, viscosity and surface tension values that deviate from water spray characteristics. Uncontrolled injection performance could result in buildup of slurry on walls and may cause corrosion in areas of wall attachment. To make systems relatively inexpensive for implementation and to mitigate risks of inadequate SO_2 removal, nozzle characteristics and placement must be optimized by evaluation and control of the injected slurry, sulfur dioxide removal effectiveness, and wall impingement.

In situ analysis would provide the best assessment of the spray's characteristics in the tower, however, this is often cost prohibitive or not physically possible. On-site engineers rely heavily on experience and case studies from past scrubber performance. Contemporary practices include the application of computational fluid dynamics (CFD), which has become very useful by making predictive analysis to validate the expected system performance and minimize the risk. Engineers will be able to determine system resiliency and operating limits, as well as assess the spray quality referred from results of simulation.

Spraying Systems Co. has a unique combination of laboratory equipment and computational resources required to optimize spray applications. The expertise allows for a rigorous validation of spray modeling techniques often used to simulate un-testable situations like wet FGD. This body of work was performed to prove the ability to simulate and compare the data of a standard industrial-size wet spray scrubber and to analyze various Spraying Systems Co. injectors for evaluation of efficacy in SO_2 reduction.

Spray analysis and characterization was performed in the laboratory to get real droplet distribution and spray details for the nozzles. This data was combined with various models embedded in CFD to provide accurate input to start simulation. Comparison of nozzle selections and locations, operation parameters were presented as direct results through evaluation of fluidization behavior. The results demonstrated the expected liquid-gas interaction relative to the system efficiency. Drop size, liquid rheology, and injector array layout were examined to achieve SO_2 removal above 90% or 10% higher than original setting by appropriate spray level setup. Wall impingement and flow pattern results were evaluated due to their impact in minimizing equipment corrosion and plugging as required for continuous scrubber.

Equipment and Methods

Test Setup and Data Acquisition

For drop sizing, the nozzle was mounted on a fixed platform in a vertical downward orientation. The data was acquired at 600mm 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 Technologies PDI-200MD [3,4] system was used to acquire drop size and velocity measurements. The solid state laser systems (green 532 nm and red 660 nm) used in the PDI-200MD are Class 3B lasers and provide 50-60mWatts of power per beam. The lasers were operated at an adequate power setting to overcome interference due to spray density.

The transmitter and receiver were mounted on a rail assembly with rotary plates; a 40° forward scatter collection angle was used. For this particular test, the choice of lenses was 1000mm for the transmitter and 1000mm for the receiver unit. This resulted in an ideal size range of about 4.0μm – 1638μm diameter drops. 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 10,000 samples were acquired. The experimental setup can be seen in Figures 1and 2.

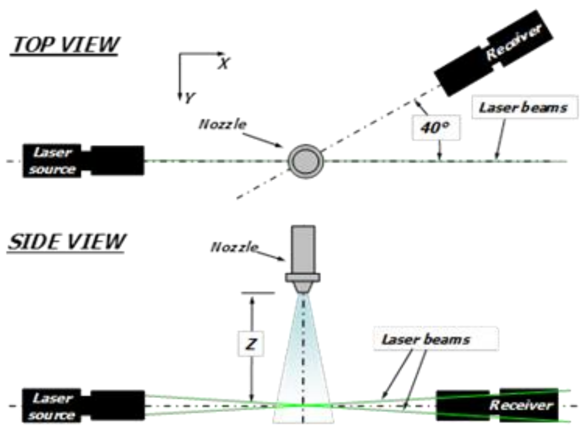

Figure 1. Illustration of PDI layout for drop size and velocity data acquisition.

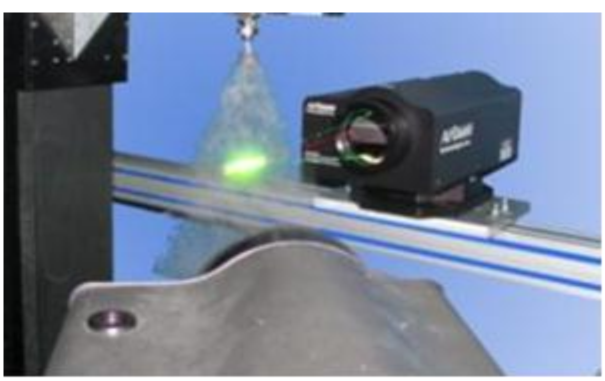

Figure 2. Illustration of PDI during experiment.

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 solution to simulate the fluid properties of limestone slurry. 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

The nozzle options used in FGD are extensive and include precise performance, trouble-free operation and long service. Considering the rheological properties of the slurry spray material, injectors were selected. The Spraying Systems Co. WhirlJet® style were particularly suitable for this application. Nozzles were picked by pattern, flow rate, quantity and spray angle with corresponding system designs. A total of four types of injectors were evaluated in nine configurations to determine the effectiveness for the application. All injectors considered provide hollow cone patterns. Target flow rate of feed slurry is 204,225lb/hr in the form of solid suspension. Multiple capacity sizes and configurations were used to achieve this design requirement.

Numerical Simulations

CFD Background

Computational Fluid Dynamics (CFD) is a numerical method used to numerically solve fluid flow problems. Today's CFD performs use extremely large number of calculations to simulate the behavior of fluids in complex environments and geometries. Within the computational region, CFD solves the Navier-Stokes equations to obtain velocity, pressure, temperature and necessary chemical reactions for removal of SO_2. Recently, CFD has become a popular design and optimization tool with the help of commercially available software and advancing computer technology. The commercially available CFD package ANSYS FLUENT (version 14.5) was used for the simulation

Simulation Description

The geometry for CFD came from a standard industrial size limestone spray scrubber, which was published by the B&W Company. State-of-the-art systems required improved cleaning performance, therefore the idea of system design, which would blow air into slurry to force oxidation, came out as a preference named the Limestone Forced Oxidation (LSFO) system [5]. The absorber had a height of 32 meter with an inner diameter of 12.3 meter, as shown in Figure 3. The gas flow comes through the inlet was 5,521,000 lb/hr, including 240,000 lb/hr water vapor and 34,900 lb/hr sulfur dioxide with 5% forced oxygen [6]. Gas passed through the open area in the scrubber and came out through the narrow turning area toward the outlet. Feed slurry enters from the injectors and moves out of the system either by release from the bottom of the absorber or collection at the top portion before flowing out the narrow region with gas. The importance of the pollutant removal process is determined through the observation of the gas liquid interactions at the tray, which can be improved by optimization of the spray system. In this paper, some additional parts (mist eliminator, flow straightener right below spray level, etc.) on the purpose of system performance improvement were ignored for simplification as to reduce the mesh size and also the simulation time.

All the gaseous species entering the scrubber were set as primary phase flow (Eulerian approach). The primary phase used coupled models (momentum, turbulence, energy, species mixing and reaction) which required boundary conditions (BC's). This simulation consisted of inlet BC and outlet BC, set as "mass flow rate inlet" and "constant pressure outlet" respectively. The limestone slurry, also known as calcium carbonate (major component), injection was set as secondary phase (Lagrangian approach) where its inlet BC's are based on nozzle features and parameters as determined empirically. The Lagrangian particles were set under "wet combustion" model when reacted with fuel gas controlled by surface reaction chemical model. These particles were tracked using Discrete Phase Model (DPM). During computation, heat and mass transfer was coupled between primary and secondary phases. CFD Multiple Surface Reaction Model set-up reaction kinetic parameters and factors were extracted through experimental results and methodology from Qiu [7] and Zevenhoven [8].

To generate the computation domain (mesh) for the scrubber shown in Figure 3, ANSYS workbench mesher (version 14.5) was utilized. The mesh consisted of 2.5 million polyhedral cells and 13 million faces; minimum cell size is 1e-3m. Due to its size and modeling complexity, the simulation required significant computational power and processing time. The walls had a common (standard) setup, with no slip, adiabatic (insulated) and wall-jet BC for the particles. Based on different spray configuration, injectors in this mesh were set as "on/off" status.

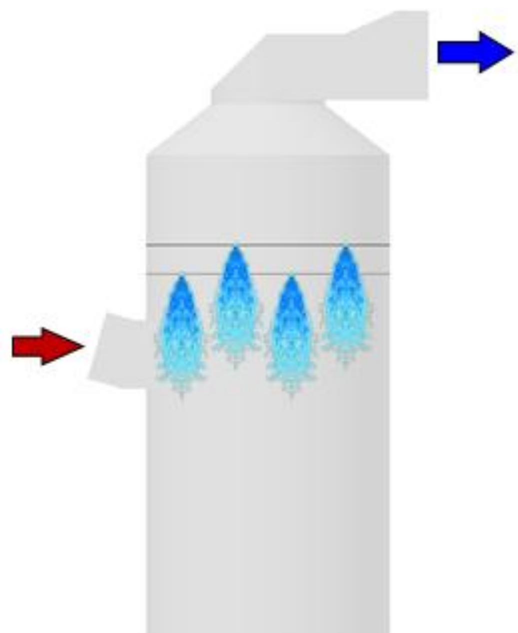

Figure 3. Scrubber Geometry for CFD

Wet Combustion Particle Surface Reaction

In this work, the main mechanism of CFD simulation is using ANSYS Fluent wet combustion particle surface reaction models, which involved those models described above. The alkaline sorbent material and SO_2 reaction was simulated to determine uniformity and efficacy of the tested system, in which this surface chemical mechanism were used to simulate the reaction to first prove match of existing data and CFD and second parametric test the system with various spray configurations.

ANSYS Fluent models the mixing and transport of chemical species by solving conservation equation describing convection, diffusion, and reaction sources by its multiple surface reaction models [9]. Reaction occurred in the bulk phase is dealt with volumetric reaction, and particle surface reaction. For gas-phase reactions, the reaction rate is defined on a volumetric basis and the rate of creation and destruction of chemical species. Particle surface reaction is used to model surface combustion on a discrete-phase particle. In the discrete phase model, modeling multiple particle surface reactions makes the surface species as a "particle surface species".

A particle undergoing an exothermic reaction in the gas phase is shown schematically in Figure 4. Based on the analysis above, ANSYS FLUENT uses the following equation to describe the rate of reaction of a particle surface species with the gas phase species.

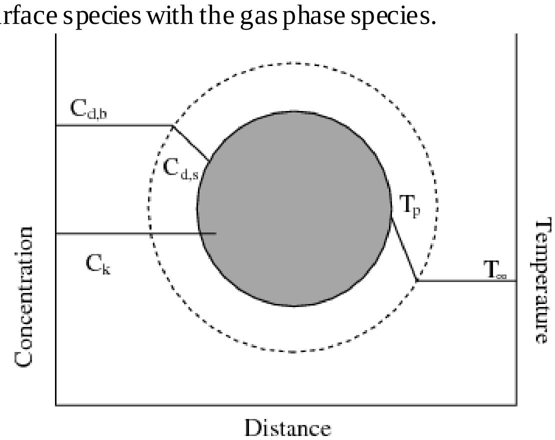

Figure 4. A Reacting Particle in the Multiple Surface Reactions Model

The initial relationship for calculating particle burning rates were presented and discussed by Smith [10]. The particle reaction rate, $\mathcal{R}$ (kg/m2·s), can be expressed as

$$\mathcal{R} = D_0 (C_g - C_s) = R_c (C_s)^N \quad (1)$$

In above equation, the concentration at the particle surface, C_s, is unknown and eliminated as follows:

$$\mathcal{R} = R_c [C_g - \mathcal{R}/D_0]^N \quad (2)$$

This equation has to be solved by an iterative procedure in Fluent, with the exception of the cases when N=1 or N=0, which can be written as

$$\mathcal{R} = \frac{C_g R_c D_0}{D_0 + R_c} \quad (3)$$

In the case of N=0, if there is a finite concentration of reactant at the particle surface, the solid depletion rate is equal to the chemical reaction rate. If there is no reactant at the surface, the solid depletion rate changes abruptly to the diffusion-controlled rate. ANSYS Fluent will always use the chemical reaction rate for stability reasons.

Based on the above explanation, ANSYS Fluent uses the following equation to describe the rate of reaction r of a particle surface species j with the gas phase species n. The rate is given as

$$\overline{\mathcal{R}}_{j,r} = A_p \eta_r Y_j \mathcal{R}_{j,r} \quad (4)$$

$$\mathcal{R}_{j,r} = \mathcal{R}_{kin,r} \left(p_n - \frac{\mathcal{R}_{j,r}}{D_{0,r}} \right)^N \quad (5)$$

The effectiveness factor is related to the surface area, which can be used in each reaction in the case of multiple reactions. $D_{0,r}$ is given as

$$D_{0,r} = C_{1,r} \frac{\left[\left(T_p + T_\infty \right) / 2 \right]^{0.75}}{d_p} \quad (6)$$

The kinetic rate of reaction r is defined as

$$\mathcal{R}_{kin,r} = A_r T_p^{\beta_r} e^{-\left(E_r / R T_p \right)} \quad (7)$$

The rate of the particle surface species depletion for reaction order $N_r = 1$ is given by

$$\overline{\mathcal{R}}_{j,r} = A_p \eta_r Y_j p_n \frac{\mathcal{R}_{kin,r} D_{0,r}}{D_{0,r} + \mathcal{R}_{kin,r}} \quad (8)$$

For reaction order $N_r = 0$,

$$\overline{\mathcal{R}}_{j,r} = A_p \eta_r Y_j \mathcal{R}_{kin,r} \quad (9)$$

The surface reaction consumes the oxidant species in the gas phase, also consumes or produces energy, in an amount determined by the heat of reaction. The particle heat balance during surface reaction is

$$m_p c_p \frac{dT_p}{dt} = h A_p \left(T_\infty - T_p \right) - f_h \frac{dm_p}{dt} H_{reac} + A_p \varepsilon_p \sigma \left(\theta_R^4 - T_p^4 \right) \quad (10)$$

It includes the diffusion and convection control of the vaporization model. An investigation of reacting limestone particle attrition rate was found similar to this mechanism[11].

Results (Experimental and Numerical)

Experimental Results

The results of the PDI measurements provide a representative characterization of the atomizer effectiveness at 600mm downstream. As outlined and described in the above sections, the results from testing are provided in Table 1. The Volumetric Mean Diameter ($D_{V0.5}$) as well as other representative diameter statistics based on the volume flow is presented. These results allow the evaluation, qualitatively, of the dependence of drop size on the liquid flow rate and pressure.

There are notable trends that persist throughout the data. With an increase in liquid feed pressure, there is a decrease in median drop size and an increase in mean drop velocity.

CFD Results

Referred to in the previous work [12] of sulfur dioxide spray scrubber in pilot scale, the industrial size scrubber was investigated to demonstrate the capability of CFD simulations of various spray applications in complex environments, like spray towers. In the previous discussion, water evaporation and diffusion had a non-negligible effect on fluidization, reaction and removal capability. One of the reasons was that the system temperature of pilot scale operated just above boiling temperature of water to increase reaction rate in the tests. However, this was outside of operation parameters in industry ,due to the energy effort required to heat and consequently reduce humidity in the large scale system. Therefore, the operating temperature in standard industrial size spray scrubbers was fairly low to avoid limestone build-up on the wall and make whole tower passage open by keeping slurry always in a liquid form. Hence, the importance of spray system behavior and its removal capability is very obvious for optimization.

Considering the volume flow rate of the fuel gas and the size of absorber, a total quantity from ten to twenty nozzles was designed for this system optimization. Six rows at two spray levels, for the purpose of even distribution into absorber, were utilized to determine optimal operation and spray parameters. All simulations were performed with a consistent total feed volume flow rate of 330 gpm. The applicability of the injector is evaluated based on accordance with the target removal requirement, minimal waste and wall contact, and reasonable maintenance of the system. The results were indicated by the SO_2 mass fraction in each case and sulfur dioxide final removal detection coordinated with limestone usage for each case. Other determining factors were velocity magnitude and vertical velocity profile, slurry droplet concentration and particle tracking. These parameters are commonly used to better understand the flow behavior for the baseline and gas phase situation following injections. Case comparison is shown in Table 2.

In the comparison of the number of injectors used, the injections were adjusted to not reach the maximum pollutant removal. This allows for better contrast of sulfur dioxide reacting capability and wall wetting degree, making the optimal design configuration easily evident. Most cases achieved good SO_2 reduction (85% is desired in this condition) as designed. CRC series at location 2 in ten-nozzle scrubber had the best SO_2 removal capability (Figure 5 and 6), location 3 and location 5 was best in twelve-nozzle(Figure 7) and sixteen-nozzle (Figure 8) configuration, respectively, based on

Nozzle ID	Units	1-1/4CRC-2045	1-1/4CRC-2045	1-1/4CX-12	1-1/2CX-16	1-1/2CX-25
Quantity	/	12	10	20	16	10
Pressure (dP)	psi	13.24	19.06	13.24	11.63	12.2
$D_{V0.5}$	micron	1218	1155	1122	1150	1188
Spray Angle	/	47°	47°	70°	75°	74
Injected Flow	gpm	27.5	33	16.5	20.625	33
No. of Spray Levels	/	2	2	2	2	2

Table 1. Drop Size and Velocity Results of Empirical Investigation

Nozzle ID	Quantity	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6	Location 7
CRC45	10	X	X					
CX25	10	X	X					
CRC45	12			X	X			
CX16	16					X	X	
CX12	20							X

Table 2. Case Comparison for Nozzle Configuration

slurry consumption and wall wetting amount.

With respect to nozzle maintanence, CRC series had bigger passages and exits with relative narrow spray angle and higher supply pressure than CX series which could provide better spray distribution considering the liquid and gas contact area and droplet characteristics. However, the limitation was CRC series designed to be suitable for enormous flow rate and fewer nozzles operated, which results in reduced turndown ratio.

Initial determination of injection locations was done based on attaining distribution uniformity of the spray system. Preliminary settings for each nozzle was selected for nearly equal diameter coverage, without overlapping. With fewer nozzles adopted in the system, better SO_2 absorption capability and less wall contact was discovered closer to the center. In the contrast, more nozzles introduced resulted better absorption closer to the edge.

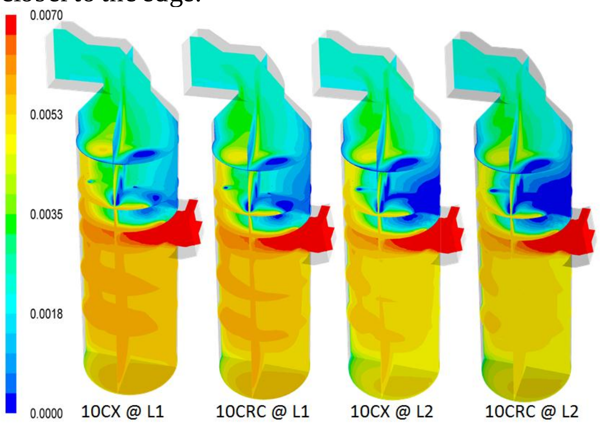

Figure 5. Mass Fraction of SO_2 for 10-Nozzle Case

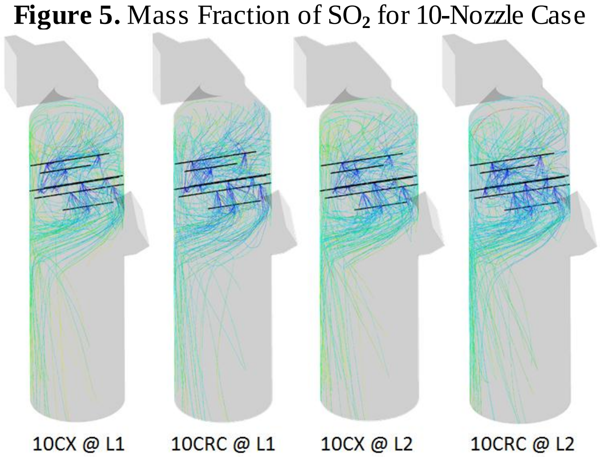

Figure 6. Particle Tracking for 10-Nozzle Case

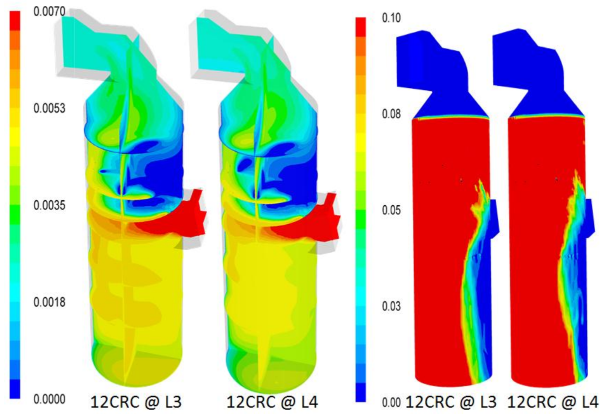

Figure 7. Mass Fraction of SO_2 and Wall Wetting for 12-Nozzle Case

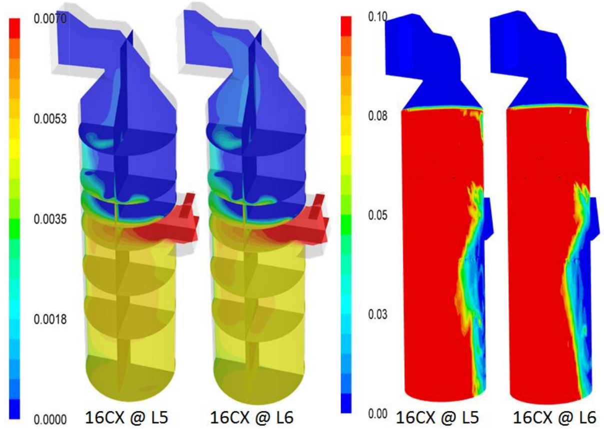

Figure 8. Mass Fraction of SO_2 and Wall Wetting for 16-Nozzle Case

Figures 9-11 represent 16-nozzle and 20-nozzle combination designs. These demonstrated superior wet scrubber performance, which was quite obvious in Figure 11. This trend can also be observed in the distribution layout of slurry injection from Figure 9. Quantitatively, the ten-nozzle case attained 90% SO_2 removal with 6.55 kg/s limestone usage in the slurry, twelve-nozzle case attained 89% removal and 6.58kg/s used. The sixteen- and twenty- nozzle applications achieved 94.5% and 95% objective removal, 6.86 kg/s and 6.89 kg/s material consumption, respectively.

The results indicated a similar trend as previous work, that greater efficacy of SO2 removal can be achieved through relatively small droplet sizes. Due to the relationship of drop size volume to surface area, with equivalent volume introduced into the system, it is possible to significantly increase surface area and associated surface reaction rate in the tower. Moreover, increasing spray zone flow distribution will lead to higher efficiency. Due to the increased scale, the velocity behavior exhibits less oscillation and recirculation than the pilot scale study. Reduced wall wetting can be achieved with proper balance of spray angle combined with nozzle selection and location design. Results also proved the overall absorber structure was critical for the efficiency improvement and optimization, since the L/D issue was clearly addressed in this industrial size absorber. Wall impingement may cause equipment erosion when injection fluid has corrosive property. Figure 10 illustrates an especially high concentration area of wall impingement on the opposite wall of inlet. The ratio of wall contact mass compared to the whole injection could be evaluated at regular time intervals to make further modifications to the system.

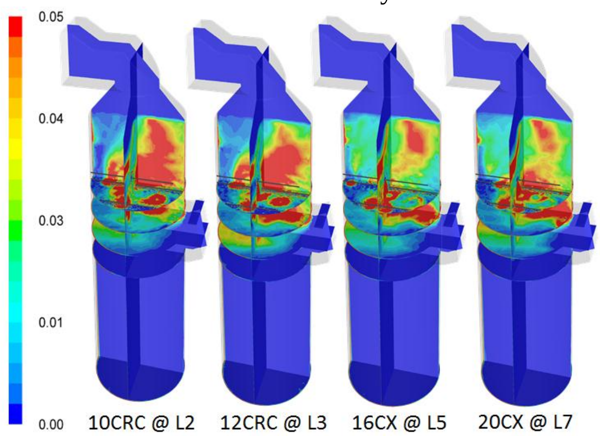

Figure 9. Slurry Injection Concentration in the Scrubber for Final Comparison

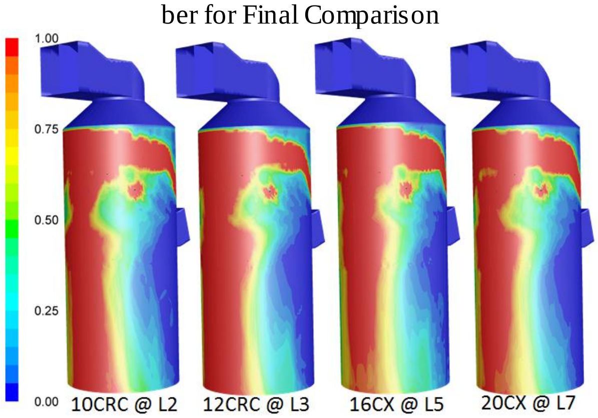

Figure 10. Wall Impingement in the Scrubber for Final Comparison

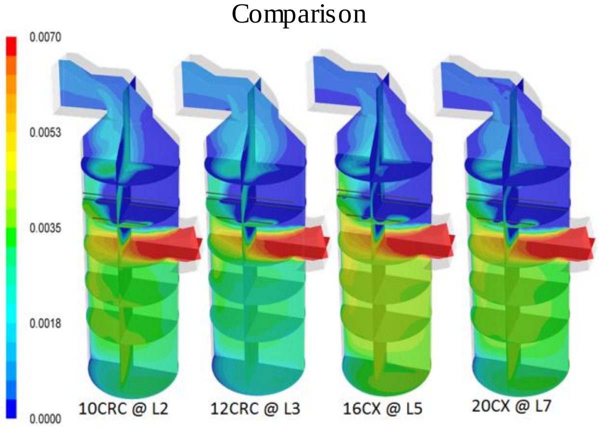

Figure 11. Mass Fraction of SO_2 in the Scrubber for Final Comparison

In addition, the limestone/slurry usage was confirmed effective in the system, which matched with industrial mark. As the temperature in the absorber was quite low, CFD results verified there was merely evaporation occurring and limestone consumption was about 80-85% to complete predominant SO_2 removal in the absorber. Efficient use of materials was always a consideration in optimization process.

Furthermore, from comparison of all 10-, 12-, 16- and 20- nozzle location configurations in the final iterations, results showed the 16-nozzle case was the optimal setup. Although this case had wide injection location close to absorber edge, it had the least wall wetting compared to other three cases. It is noteworthy that in both the previous study and this work, the addition of nozzle locations always had some advantageous removal performance compared to fewer nozzles. The key to optimization is the balance of effective pollutant removal and minimal slurry deposition (wall impingement). This is achieved through control and reduction of droplet size distribution, as well as spray coverage uniformity. Spray coverage is a significant factor for process optimization, since overlapping will cause less contact between pollutant gas and absorbent and also heavier wall wetting near the vessel wall. Although the 20-nozzle application had better pollutant removal, it also exhibited heavier wall impingement. This could result in more frequent maintenance issues, resulting in increased cost for this type of large absorber.

Considering the 16-nozzle application satisfied the pollutant removal range with less wall sludge building, this could be adopted for optimization to this particular system. This specific result is distinct to the absorber geometry (tower/chamber) should be adapted and carefully examined based on its own setting. This work was specifically tested for the geometry layout attached. Nevertheless, CFD and expert spray characteristic technology will be helpful in solving same type or similar validations.

Conclusion

In a successful spray scrubbing system, nozzle selections and their spray characteristics are the determining factors. Understanding the spray behavior, especially the interaction with gas and surrounding environment, is extremely important in scrubbing tower system design. This design influences not only the efficacy of the scrubbing process in the system, but also the length of the absorber's life time. Hence optimization is getting increased attention. The optimization process requires a balance of mitigating the wall impingement while achieving outstanding pollutant removal. Nozzles play an important role in achieving this goal. From decision of the quantity of nozzles in the system, to location / or layout selection; each step could lead to costly system failure with carelessness, imprecise calculation or misunderstanding of the complex interaction of system parameters. Therefore, full knowledge of nozzles combined with CFD in untestable situation is valuable in the prediction of such pollutant cleaning systems like spray tower or spray chamber. It is necessary to take into consideration the evaluated factors of spray coverage, droplet control, flow profile, gas-liquid-wall interaction to achieve a successful, repeatable wet FGD design.

In the actual system install, flow straightener and mist eliminator may be employed to better control the spray carry over and gas distribution in the absorber. However with additional complexity, there is also potential for increased maintenance issues and additional analysis is required for proper inclusion into the system.

Nomenclature

u_θ	velocity in the direction of (m/s)
A	radius of (m)
B	position of
C	further nomenclature continues down the page inside the text box
D_0	bulk diffusion coefficient (m/s)
C_g	mean reacting gas species concentration in the bulk (kg/m^3)
C_s	mean reacting gas species concentration at the particle surface (kg/m^3)
R_c	chemical reaction rate coefficient (units vary)
A_p	particle surface area (m^2)
Y_j	mass fraction of surface species *j* in the particle
η_r	effectiveness factor (dimensionless)
$\mathcal{R}_{j,r}$	rate of particle surface species reaction per unit area (kg/m2·s)
$\overline{\mathcal{R}}_{j,r}$	rate of particle surface species depletion (kg/s)
p_n	bulk partial pressure of the gas phase species (Pa)
$D_{0,r}$	diffusion rate coefficient for reaction *r*
$\mathcal{R}_{kin,r}$	kinetic rate of reaction r (units vary)
N_r	apparent order of reaction r

Greek symbols

γ	stoichiometric coefficient
δ	boundary layer thicknesses (m)

Subscripts

r	radial coordinate

References

1. Rubin, E.S., Yeh, S., and Hounsell, D.A., etc., “Experience curves for power plant emission control technologies”, Int. J. Energy Technology and Policy, Vol. 2, Nos. 1/2, 2004
2. Beychok, M.R., “Comparative economics of advanced regenerable flue gas desulfurization processes”, Electric Power Research Institute, EPRI CS-1381, 1980
3. Bachalo, W.D., "Experimental Methods in Multiphase Flows", International Journal on Multiphase Flow, Vol.20, Suppl. pp.261-295, 1994
4. Bachalo, W.D., "A Method for Measuring the Size and Velocity of Spheres", by Dual Beam Light Scatter Interferometry, Applied Optics, Vol. 19, No. 3, February 1, 1980.
5. Nolan, P.S., “Flue Gas Desulfurization Technologies for Coal-Fired Power Plants”. The Babcock & Wilcox Company, 2000.
6. Kitto, J.B., Stultz, S.C., “Steam/its generation and use”, 41st Edition. The Babcock & Wilcox company, 2005.
7. Qiu, K., Lindqvist, O., “Direct Sulfation of Limestone at Elevated Pressure”, Chemical Engineering Science, Vol 55, pp 3091-3100, 2000.
8. Zevenhoven, R., Yrjas, P., and Hupa, M., “Sulfur Dioxide Capture under PFBC Conditions: the Influence of Sorbent Particle Structure”, Elsevier, PII: S0016-2361, 1997.
9. The Multiple Surface Reactions Model in Discrete Phase. ANSYS FLUENT Theory Guide for Version 14.0, 427-428, 2011.
10. Smith, I.W., "The Combustion Rates of Coal Chars: A Review". In 19th Symp. (Int’l.) on Combustion. The Combustion Institute, 1045–1065, 1982.
11. Shimizu, T., Peglow, and M., Sakuno, S., etc., “Effect of Attrition on SO_2 Capture by Limestone under Pressured Fluidized Bed Combustion Conditions-Comparison between a Mathematical model of SO_2 Capture by Single Limestone Particle under Attrition Condition and SO_2 Capture in a Large-Scale PFBC”, Chemical Engineering Science, Vol. 56, pp. 6719-6728, 2001.
12. Brown, K., Kalata, W., Schick, R.I., “Optimization of SO_2 Scrubber using CFD Modeling”. Atomization and Sprays – Int’l J. of the Institute of Liquid Atomization and Spray Systems. 2013