The planning and design of effective wet duct/stack systems For coal fired utility power plants

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As environmental regulations with respect to SO_2 emissions become tighter many coal fired utility power plants are adding new flue gas desulfurization systems or upgrading existing ones. The majority of these systems utilize wet flue gas desulfurization (WFGD) technologies. A number of plants with existing WFGD systems still use gas reheat to reduce the relative humidity the saturated gases to prevent condensation before exiting the absorber before it is discharged to the stack. However, because of the increasingly high cost of the energy and/or the need to decrease total plant SO_2 emissions, flue gas reheating is typically no longer used on new plants and is being eliminated from existing ones. Without reheat, saturated flue gases exiting the absorber enter the stack directly and in combination with droplet carryover and condensation the walls of the absorber outlet ducting and stack liner are covered with a liquid film which must be collected and drained from the system. This is called wet stack operation. If the ductwork and stack liner are not properly designed, the stack may experience unacceptable levels of Stack liquid Discharge (SLD).

Trouble-free operation of a FGD unit with wet ducts and stacks requires investigation of several potential problem areas related to the handling and discharge of wet flue gas during the design of the stack and duct system. This paper will outline the important design aspects which must be addressed to minimize liquid discharge from both new and retrofit wet stack installations.

While WFGD systems have been around from many years, the majority of these units utilized reheat and operated with dry stacks. In the late 1970's some utilities considered the possibility of using wet ducts and stacks as a means of reducing their operating costs. As more plants began to operate this in this manner, many experienced unacceptable high levels of SLD. Because of this, it became clear that a better understanding of the physical processes involved in WFGD systems and wet stack operation was needed and in the 1980's EPRI sponsored a number of programs to determine the key variables contributing to liquid re-entrainment. The results of one of these studies were summarized in EPRI Report No. CS-2520, "Entrainment in Wet Stacks".

By the late 1990, there were many plants operating with wet duct/stack systems and a sufficient body of experience had been developed for EPRI to sponsored a another program aimed at the development of practical guidelines for wet stack design and operation. The results of this study were summarized in EPRI Report No. TR-107099, "Wet Stacks Design Guide".

Based on the approach detailed in these reports, one of the key steps in the development of an effective wet stack installation is the proper fluid dynamic design of the wet duct/stack system. The design process, usually performed by a flow modeling laboratory with experience in this area, typically consists of five distinct phases:

- Phase 1 - Initial Review of Proposed System Designs
- Phase 2 - Condensation Calculations
- Phase 3 - Liquid Collection System Design and Development
- Phase 4 - Plume Downwash Study
- Phase 5 - Field Installation and Operational Inspections

Using the results of the first four phases the unit design can be finalized and the specifications for the bids for construction can be written. The fifth phase supports the installation of the recommended liquid collection system.

Phase 1: Initial Review of Proposed System Designs

Past experience has shown the value of an early review of the plant's initial or proposed absorber outlet duct and stack breach/inlet geometry with respect to making the geometry more suitable for wet operation. This review should be performed by an organization with experience in wet stack system design and operation so that the industry's experience with such systems can be utilized. Key system design variables such as gas velocities, breach height, breach width, and liner diameter will be evaluated with respect to values which have been proven to be favorable for wet operation at other installations. Simple changes in the system geometry, such as adjusting the breach aspect ratio or relocation of a liner expansion joint, can often result in significant improvements in the efficacy of the liquid collection system by improving the flow patterns in the lower liner, minimizing the potential for liquid re-entrainment, reducing the total number of liquid collectors required, and/or reducing the complexity of the required liquid collection system.

While there are many economic drivers for minimization of the stack liner diameter, it must clearly be understood that the primary controlling parameter for effective wet stack operation is the liner gas velocity. Different liner materials and construction techniques have different velocities for favorable wet operation. Figure 1 presents the velocities originally recommended in the EPRI Wet Stack Design Guide. These original values were developed based on laboratory testing of different liner material surfaces in a vertical wind tunnel. Since this testing was performed, a large amount of valuable field experience has been obtained and based on this experience, the recommended velocities have been slightly reduced to accommodate "practical variabilities" in the quality of the field installation such as weld bead heights on alloy liners and joints in FRP liners. These reduced values also provide some margin to the plant to account for increases in the flue gas flow rate due to changes in fuel source, increases in plant efficiency and/or future increases in the plant output. Based on this experience we are now recommending that C276 and FRP liners should be operated at a velocity of 55ft/s while brick liners which inherently have a less smooth surface should operate at gas velocities no higher than 45 ft/s. If properly installed, modern materials, such as borosilicate block liners can operate effectively at velocities up to 65 ft/s.

Liner Material	EPRI Design Guide	Current Recommendations
Alloy	60-70	55
FRP	50-60	55
Brick	45-55	45
Borosilicate	50-60	60
Coatings	60-70	55

Figure 1: Stack Liner Velocities

These velocity ranges are safe for the different liner materials in fully developed turbulent and axial symmetric flow in the liners. This condition exist in stack liners only 3 to 4 liners diameters above the breeching duct. These velocity limits have to be reduced sometimes when the horizontal weld beads or FRP joints create a surface discontinuity on the liner. Special care must be taken to design the stack entrance area where the gas flow is 3-dimensional and highly non uniform, with velocities two or more times higher than the area average value.

Phase 2: Analytical Calculation of Liner Condensation

One of the major sources of liquid that must be collected and drained from a wet stack is from condensation on the duct and stack liner walls. This condensation is from two main sources: 1) thermal condensation on the wall as a result of heat transfer from the flue gas to the outside air through the liner, insulation, annulus air, and concrete shell, and 2) adiabatic condensation in the bulk of the gas flow due to the expansion of the saturated gases as a function of the pressure change along the height of the stack.

The quantity of thermal condensation on the duct and liner surfaces is a function of the stack construction and thermal conductivity, the internal flow conditions, the atmospheric temperatures, wind velocity, and in some instances, wind direction.

Thermal insulation is a key parameter in controlling the quantity of thermal condensation experienced within a stack liner. Previous condensation studies have shown that the addition of two inches of liner insulation can reduce the quantity of thermal condensation by a factor of approximately four.

The second source of condensation experienced within a stack liner is caused by adiabatic expansion along the height of the stack. The relatively small pressure drop due to the change in elevation from the breeching duct to the top of the stack may produce an appreciable rate of liquid by adiabatic condensation. A small fraction of this liquid will deposit on the liner surface due to turbulent diffusion and the rest will be discharged from the liner as part of the bulk gas stream in the form of very small droplets. These droplets do not represent a problem because the size of these droplets is very small and they will evaporate before reaching the ground.

The total quantity of liquid collected on the stack liner walls due to thermal and adiabatic condensation are calculated using specially developed heat transfer computer programs. The rate of liquid condensation is a function of ambient air temperature, wind velocity and liner design variables are necessary for the development of an effective liquid collection system as it will affect the number, sizing and location of the various liquid collection gutters and drains. In addition to the liquid generated due to thermal and adiabatic condensation, the contribution from mist eliminator carryover is also calculated and added to the total liquid load on the liner surface.

Phase 3: Development of Wet Stack Liquid Collection Devices

The problem of stack liquid discharge from a power plant duct and stack system operating in an "all scrubbed" mode is caused by a two-phase flow interaction of gas and liquid. The liquid enters the ducts and stack as droplets and water vapor carried over from the mist eliminators of the absorbers. These liquid carryover rates can increase significantly over their "as designed" rates during normal wash cycles or should the mist eliminators become fouled with time. This liquid accumulates on the walls and internal structures within the ducts and stack by inertial deposition of droplets and by condensation of water vapor from the saturated gas. The amount of deposition is governed by the gas velocity, duct and stack geometry, the liquid loading level, and droplet size distribution. The deposited liquid and condensate will form a liquid film on the exposed surfaces which will be moved under the influence of gravity and gas shear forces. This liquid film will either move to locations where it will accumulate or be re-entrained from liner walls, internal struts, dampers or vanes, and stack top by the high velocity gases. The re-entrainment process is dependent on gas velocity, the amount of liquid on the wall, surface roughness and discontinuities such as duct/liner weld seams or FRP liner joints. Liner expansion joints can be major source of liquid re-entrainment if not properly located and arranged. Most of the liquid re-entrained within the stack does not redeposit on the liner wall and will exit the stack in the form of droplets that are sufficiently large to reach the ground before fully evaporating.

The behavior of droplets entrained in the gas flow from the absorber mist eliminators and the motion of the resulting liquid

Figure 2: Typical Single Absorber Wet Stack Flow Model

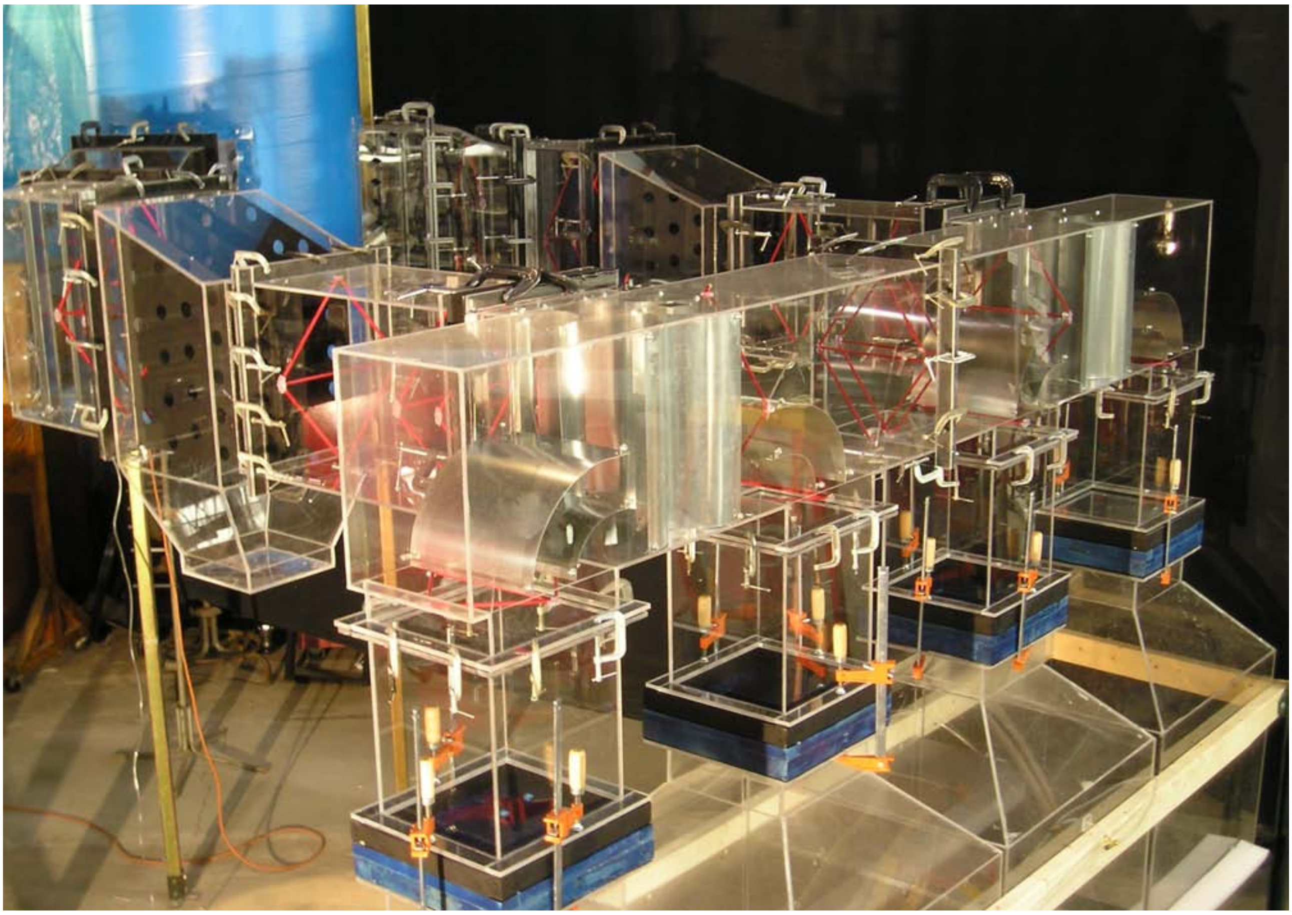

Figure 3: Typical Multiple Absorber Wet Stack Flow Model

films on the duct and stack liner surfaces must be evaluated in physical flow model of the subject unit. Using this model, effective internal liquid collection devices can be designed and developed to optimum to improve primary droplet deposition and liquid collection as well as minimize the potential for re-entrainment of droplets from liquid pools and films. Computational fluid dynamic (CFD) models cannot be used for liquid collection system development because the computer codes, while effective at predicting droplet trajectories and droplet collection patterns, are currently not capable of accurately simulating the development of liquid films on the duct and liner walls due to droplet deposition and condensation or the subsequent motion of these liquid films under the influence of gravity and gas shear forces.

Physical flow models of wet duct and stack installations are normally built to a scale of between 1:12 and 1:16 and typically encompass the system from the outlet of the absorber mist eliminator to a point in the stack liner approximately 3 to 4 liner diameters above the roof of the breaching duct. Typical single and multiple absorber wet stack flow models are shown in Figures 2 and 3 respectively. To the extent possible, models are primarily fabricated from clear plexiglass to allow detailed visualization of the internal gas and liquid flows. To ensure that the liquid film motion in the primary collection zone of the lower liner are accurately simulated, care must be taken however to ensure that the surface of the material used in this area has wetting properties similar to that in the field.

Using the physical flow model, droplet trajectories and the motion of the resulting collected liquid films are observed. Based on these flow patterns turning vanes, liquid collection gutters, ring collectors, dams, baffles and drains are developed and optimized until a system has been developed which works effectively across all expected boiler loads and operating scenarios. To the extent possible, liquid collectors and gutters are fabricated from commercially available structural shapes made of non-corrosive materials such as C276 or FRP.

Phase 4: Stack Downwash Modeling

A cross-wind at the top of the stack will deflect the plume from its vertical path. As the ratio of vertical plume momentum to horizontal wind momentum decreases, the plume may become partially entrained in the wake that is formed on the downwind side of the liner and stack shell. At lower momentum ratios the reduced static pressure in the wake can draw the flue gas into a downwash pattern along the downwind side of stack shell, Figure 4. The saturated flue gas that is drawn into the wake comes into contact with the roof and sides of the

Figure 4: Plume Downwash

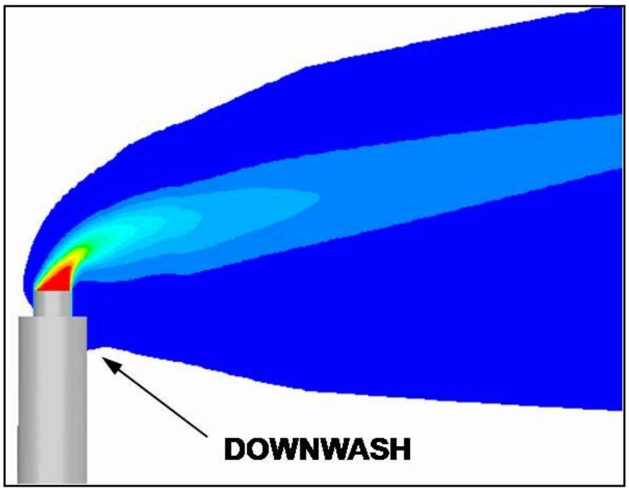

Figure 5: Typical Plume Downwash Study CFD Model Results

stack liners and shell leading to problems of metal corrosion, concrete deterioration and ice build-up during winter months. This is a particularly important problem for stacks with multiple liners and interacting discharge plumes. Severe downwash situations can also allow contact with lower surrounding plant structures and, in extreme cases, even produce plume touch down at ground level near the stack.

The interactions between the prevailing wind and the individual plumes will also play a significant role in the propensity and extent of downwash for stacks with multiple flues. The wind direction relative to the plumes can result in differing degrees of downwash. For a given momentum ratio, plume downwash will be greater in a dual liner stack if the prevailing wind direction is perpendicular to the axis of the two liners as compared to conditions where the wind direction is parallel to that axis. Evaluating the downwash potential for two (or more) wind directions allows the maximum downwash potential to be defined and the appropriate liner extensions or stack top geometry developed to mitigate the problem.

Ultimately, all stacks can get into a downwash mode at low unit load and at high wind velocities. The only question is under what conditions and how frequently during a year of operation will downwash occur, given the expected boiler load schedule and wind frequency profile, and what degree of downwash is considered acceptable.

Computational fluid dynamic modeling is ideally suited for this type of evaluation which is typically limited to gas-gas interactions. Figure 5 presents a typical output from such a study showing good stack operation without downwash. Various liner velocity/atmospheric conditions can be evaluated to determine the liner extension height or exit choke size reduction required to eliminate downwash or the extent to which the top of the stack shell should be covered with an acid resistant coating. The evaluation of stack top icing potential can also be evaluated by including heat transfer in the model and predicting cooling of the plume after it exits the stack.

Phase 5: Field Installation and Operational Inspections

The first four phases described the steps necessary for the development of an effective wet duct/stack system. The final phase provides support to the field installation. The field construction and installation drawings of the liquid collection system should be reviewed by the group that developed the system design to ensure their recommendations have been interpreted correctly and to evaluate any changes made by installation company to accommodate fabrication, assembly, installation or structural support.

During the field installation process deviations from the specified design are often required due to unanticipated interferences or installation issues. To ensure that the liquid collectors have been installed properly, an on site inspection of the installation by the liquid collection system designer is highly recommended for a day when the installation is 80% to 90% complete. This way, errors can be identified, on-the-spot modifications can be defined if necessary, and corrections can be made while the construction crew is on site before the unit start-up.

Inspecting the liquid collection system after several months of operation is also highly recommended. If any stack emission incidents occurs during normal operation, the need for inspection is obvious. However, if stack liquid discharge is not experienced, it is still important to inspect the liquid collectors to ensure satisfactory long-term operation. Different problems such as solid depositions and liquid drainage problems can be detected and corrective measures developed which can be addressed during future scheduled or unscheduled outages.

Summary

A utility considering a wet stack installation should remember that a number of design variables must be accounted for during the design and development of an effective wet stack system and a basic understanding these variables applied early in the absorber/wet stack system design process will help guide early design decisions which should result in system which is favorable for wet operation.

The five phase wet stack system design process detailed in this paper has been proven effective on over 60 wet stack system design studies. These studies utilize physical, computational and analytical modeling techniques to determine the quantity of liquid expected to be removed from the system, to design and optimize the liquid collectors and drains, and to evaluate the potential for stack plume downwash. This approach, combined with a basic absorber outlet/stack arrangement favorable for wet operation provides the best overall approach for the development of an effective wet stack system.