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Project Summary

Effective Mixing Processes for SO_x, Sorbent, and Coal Combustion Products

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This report describes an evaluation of the mixing of jets of calcium based sorbents injected into large wall-fired coal burning utility boiler furnaces for sulfur dioxide (SO_2) emission control.

Isothermal flow experiments evaluated the mixing characteristics of single and multiple jets into idealized cross-flow streams and into flow fields simulating the upper regions of boiler furnaces, where gas temperatures are most conducive to sulfur capture. Pilot scale combustion experiments at 1.41 and 24 MW thermal input tested the dependence of overall sulfur removal efficiency on injection parameters and sorbent type. Several computational and empirical models of jet behavior were adapted for use in sorbent injection system design.

An effective injection system design methodology is based on a hierarchy of design and interpretation procedures. The methodology includes: (1) the use of simple empirical jet relationships to provide preliminary estimates for injection system parameters (number, size, and velocity of jets); (2) isothermal physical flow modeling of the boiler to evaluate and optimize injection system mixing parameters; and (3) coupling of jet mixing results with experimental sorbent sulfation data, or sulfation calculations, to predict the impact of mixing on overall SO_2 capture.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Control of SO_2 emissions from large utility boilers burning high sulfur fuels has gained considerable attention because SO_2 is believed to be a major precursor to acid rain. Many efforts are focused on the use of dry desulfurization processes which have shown promise of economical SO_2 emission control, especially as a retrofit technology.

One dry desulfurization process involves injecting calcium based sorbents, such as $CaCO_3$ or $Ca(OH)_2$, directly into the combustion chamber. When heated, sorbent particles decompose into CaO particles which react with SO_2 in the furnace gas stream to form $CaSO_4$. This process is limited to a narrow temperature range (window) where sulfation reactions proceed rapidly. The upper temperature limit of this window is about 1200°C and is dictated by the thermodynamic stability of the product $CaSO_4$ and the loss of sorbent reactivity at high temperatures. The lower temperature is about 800°C, below which the sulfation reaction rates are too slow for the available residence times. This temperature zone in utility boilers lies in the upper furnace, beginning around the radiant furnace exit extending into the convective passes. Because the flue gas loses heat rapidly in the convective passes of the boilers, the residence times in this temperature window are usually in the order of 1 sec. Studies on sulfation of calcium based sorbents indicate that residence times of the order of 1 sec are required in the sulfation temperature zone for the sulfation reactions to proceed effectively. Therefore, it is important that sorbents are dispersed and mixed with the boiler flue gas in the smallest space and shortest time to effectively utilize the available residence time in the sulfation window. The mixing time cannot be extended by injecting the sorbent at higher temperatures, because sorbent reactivity is reduced by deactivation processes (sintering, dead burning) at high temperatures.

Results and Discussion

Studies were conducted on the mixing of the sorbent stream with the flue gas stream of wall-fired utility boilers. The key objective of the studies was to devise a sorbent injection system design methodology for wall-fired boilers.

Isothermal Modeling Studies of Jet Injection

Flow modeling studies of jet injection into boiler geometries were conducted in several isothermal flow models. Figure 1 is an example of a single jet injected into a wall-fired boiler upper furnace at the nose elevation. In the flow field of such enclosure, the jet penetrates a certain depth into the furnace cross-flow after which it is carried by the furnace flow toward the convective sections of the boiler. Key results were:

- The two key jet parameters determining the jet trajectory in boiler-like flow fields are the jet-to-cross-flow momentum flux ratio and the jet diameter.
- The trajectories of the jets injected from the front wall were affected by such enclosure characteristics as nose confinement factor and the injection location in relation to the nose point. The side spacing of a row of jets appeared to have negligible impact on jet trajectories for the typical boiler injection configurations.
- In the flow field of the boiler around the nose, the initial bending of the jets injected from the front wall can be well predicted by the average jet trajectory equation. However, as the furnace flow turns to the horizontal passes, the jet trajectory naturally deviates from the predictions.

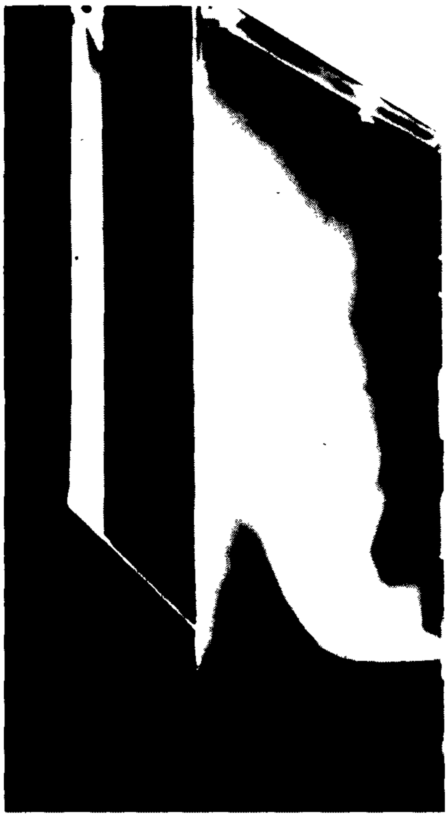

Figure 1. *A single 2.54 cm (1.0 in.) diameter jet injected into a boiler geometry at a momentum flux ratio of 100.*

- Injection from the rear wall at the nose location can be an effective way to introduce the sorbent into the bulk of the flow near the nose. However, this region of the boiler is generally inaccessible.
- Injection from the roof of the boiler or steeply down-angled from the front wall require very high injection velocities to penetrate the opposing flow. Although roof injection may be a viable way to control the injection temperature, high velocities make it impractical. There also appears to be marginal or no gain in residence time due to the increased path of the jet because of the high injection velocities.
- Effects of sorbent particles can be incorporated in the bulk jet properties; i.e., jet density and momentum. Photographic evidence and particle dispersion measurements support this view. If limestone particles are small (less than 20 μm) and the particle loadings are not high (less than 10^7 particles/cc), the dispersion characteristics of particle laden jets and the equivalent air jets are similar.
- Simulation of cold dense jets into a hot combustion environment in an isothermal study requires modifying the jet diameter with the square root of the free stream to jet density ratio if near field dilution rates are to be properly simulated. However, in the far field (greater than 10-15 jet diameters from the jet nozzle), different scaling approaches give similar results. For example, geometric scaling of jet diameters can be employed.
- Comparison of measured isothermal and combustion dispersion patterns suggest approximate similarity of the dispersion patterns with similar distributions of the tracer concentrations.

Computational Modeling of Jet Injection

A computational model of a gas jet injected into a cross flow was developed to evaluate temperature/time and concentration/time profiles in sorbent jets. This model, based on integral mass, momentum, and energy balances, was used to describe the temperature and concentration histories early in the injection jets. The profiles of temperature/time and concentration/time were input into a sulfation model to predict the sulfur capture. The final value of the sulfur capture compared favorably with the range of the experimentally measured values. The jet modeling was included as part of the sorbent injection design methodology to evaluate the dynamic behavior in the sorbent jets.

Pilot Scale Experiments in a Tower Furnace

Sulfur capture tests were conducted in a 1.2 MW_{th} (4.2 x 10^6 Btu/hr) pilot scale furnace to evaluate the impact of sorbent injection parameters on sulfur capture. The furnace modeled the upper furnace section of a wall-fired boiler with sorbent injection through nozzles located near the nose section. The following results were obtained from these experiments

- The sorbent injection velocity (or jet momentum) had virtually no effect on sulfur capture. In these tests, a commercial atmospheric hydrate (Linwood) was injected through six injectors on the front wall at three different velocities, corresponding to three momentum flux ratios. It was shown that the dependence on the jet velocity is in fact small, if the jet penetration is not greatly impaired.

- Sorbent dispersion, as influenced by a number of sorbent jets, had an impact on sulfur capture levels. Decreasing the number of jets from six to one reduced the sulfur capture by about 55%. However, the dispersion effect became important when the sorbent was highly maldistributed in the furnace flow.

- An empirical scheme, based on isothermal dispersion experiments and small scale sorbent injection tests, was developed to explain the dispersion effects.

Large Pilot Scale Experiments

A series of sorbent injection tests were conducted in the Large Watertube Simulator (LWS) furnace, in a geometry resembling that of a small wall-fired utility boiler. Sorbents were injected through 4.4 and 9.8 cm diameter jets in the upper furnace. The results from these tests showed:

- Upper furnace injection showed a dependence of sulfur capture on the jet velocity and momentum.

- The effect of dispersion altered by the number of injection jets was found to be small for these injection configurations.

Although both results appear to contradict the smaller pilot scale tests, the results were due to the nature of the flow field in the LWS model and its interaction with sorbent jets. Isothermal flow modeling studies in a 1/15 scale model of the furnace and the observations in the LWS furnace itself revealed that the flow patterns in the furnace caused the sorbent jets to be entrained to the lower furnace where high temperatures prevailed. A simple modeling of the observed phenomena explained the sulfur capture test results. These tests and the subsequent data analysis provided useful information in the development of the sorbent injection system design methodology.

Injection System Design Methodology

The ultimate goal of this program was to develop a design methodology that can be applied to utility boilers with relative ease. The elements, described earlier, were used to formulate such a methodology. The methodology, a hierarchy of design and interpretation procedures to be used in the actual design and performance prediction phases, consists of three levels of sophistication:

(I) Simple empirical relationships which were developed and tested during this study. These refined formulas can be used to determine the injection system parameters (number, size, and velocity of injection jets) based on the operational characteristics of the boiler and such other constraints as the availability of injector sites.

(II) Isothermal modeling which can be used, together with Level I results, to study the effects of varying the injection system parameters roughly determined in Level I and optimize mixing in an isothermal model. This requires constructing an isothermal model of the boiler furnace (or at least the upper furnace) and studying the dispersion of the sorbent jets in the furnace flow. This scheme also provides an empirical capability which can be utilized to predict the sulfur capture potential for particular injection systems.

(III) Computational models of jet injection and calcination/sulfation processes which can be used to investigate and predict the time-dependent nature of the sorbent injection process.

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The complete report, entitled "Effective Mixing Processes for SO_x, Sorbent, and Coal Combustion Products," (Order No. PB 87-188 892/AS; Cost: $36.95) will be available only from:
National Technical Information Service
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