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COAL-FIRED EQUIPMENT**

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CONDENSING ECONOMIZERS FOR SMALL COAL-FIRED EQUIPMENT

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OBJECTIVE

Condensing economizers can be used to increase the thermal efficiency of boilers and furnaces. This study focuses on evaluating indirect contact economizers as applied to heating equipment burning coal-water mixtures although the results can be extended to other fuels. In addition to dry gas sensible heat, latent heat is recovered from flue gas water vapor, improving system efficiency markedly. In addition to improving thermal efficiency, condensing economizers can also capture particulates. In tests to date up to 98% total removal has been measured. The primary objectives of this project are to evaluate the most important mechanisms involved in particle capture and to enhance capture in practical systems.

The intent of the work is to contribute to the ongoing program at the Department of Energy/Pittsburgh Energy Technology Center in the development of coal-fired combustion equipment. These results are expected to be most applicable to smaller scale equipment where the low temperature heat from the economizer can be used. However, interest in the use of condensing economizers for industrial and utility applications is increasing and this work certainly is relevant in these sections also. The approach involves determining thermal efficiency improvement and particulate removal efficiency (experimental), and developing models capable of predicting system performance under varied operating conditions (theoretical). Gas temperature and condensation profiles through the economizers have been predicted and overall predicted performance are consistent with test results. Mechanisms for particle removal are discussed in this paper and predicted removal efficiencies as a function of particle diameter are presented.

ACCOMPLISHMENTS AND RESULTS

Introduction

Condensing economizers improve efficiency by recovering both sensible and latent heat from flue gas. The economizers are commonly indirect contact, tubular heat exchangers with flue gas passing around the outside of the tubes and cooling medium, such as water or air, passing through the tubes. Condensing economizers have thus far been applied primarily to gas-fired equipment and to some extent oil- and wood-fired boilers. For small heating equipment condensing boilers are packaged with the condensing heat exchanger as an integral unit. For commercial and industrial scale equipment a condensing economizer may be added onto an existing boiler. Condensing systems with gas-fired units can cool flue gas to about 90 F. Boiler or thermal efficiencies of 95% are possible.^[1] On the utility scale, heat exchangers of this type are used in Europe for flue gas reheat in FGD applications.^[2] One U.S. utility is currently running a demonstration of a condensing economizer on an oil-fired power plant.^[3] At this site the economizer is being used to preheat makeup water and energy savings of about 800 Btu/kWh have been reported.

In addition to improving thermal efficiency, condensing economizers remove particulates from the flue gas. In one field test of a boiler plant fired with No. 6 fuel oil the particulate removal efficiency across the economizer was found to be 70%.^[4] Additional saturation of the flue gas by spraying water into the combustion products might enhance particle removal by impacting with the particles or simply increasing the amount of water condensed in the heat exchanger. In some configurations water sprays may be used either upstream of the condensing heat exchanger in a presaturator section or in the heat exchanger itself.

This project was originally planned to provide an evaluation of the feasibility of the use of condensing economizer as the sole particulate collection device on small scale, coal-water slurry fired heating equipment. All of this planned work has been completed and a project report prepared.^[5] This work included theoretical and experimental evaluation of heat transfer and particle capture. Effects of temperature conditions, presaturation, direct water sprays and economizer pressure drop were evaluated.

Experimental

A schematic of the experimental arrangement used is shown in Figure 1. The main components of this setup consist of the heating system, water and slurry spray systems, the condensing economizer, and multiple sampling points used for flue gas analysis. Two types of condensing economizers, an air-cooled and a water-cooled unit, were evaluated for thermal and particulate removal performance.

Figure 1. Experimental Arrangement

As part of this study, the measurements and testing were conducted in two ways: (1) firing No. 2 oil with fly ash spray-dried into the flue gas stream to simulate coal-firing conditions with respect to the concentration of fly ash; and (2) with actual coal water slurry firing. Most of the tests were conducted with the oil-fired case. The purpose for these two different experimental setups was to initially demonstrate economizer performance without the added complications of coal-slurry firing, and then to compare and/or validate those results with a few tests consisting of actual coal-slurry firing. In the oil-fired tests, fly ash was introduced into the combustion chamber with a spray assembly that injects an ash/water mixture. The ash was obtained from a precipitator hopper of a coal-fired utility and it was assumed that this provided a representative size distribution for fly ash in the flue gas. The mixture consisted of 10-15% solids (ash) in water. This mixture could then be sprayed with a siphon-type air atomizing nozzle into the combustion chamber through the back end of the boiler, opposite from the burner assembly. Flue gas moisture content was adjusted by spraying water with a siphon nozzle into the flue gas stream at locations upstream of the economizer or directly into the combustion chamber. The air atomized, siphon nozzle provided a low flow rate and a very fine spray which helped to assure that all of the water was vaporized. The moisture content of the flue gas was measured with an EPA-5 train. Samples were taken simultaneously with multiple sampling trains at locations upstream and downstream of the economizer and, in some tests, at the outlet of the induced draft fan.

The locations of the spray points used were selected based on numerous tests in which the water injection rate and the flue gas moisture content were measured. A mass balance on the amount of water input, assuming total evaporation, and the amount measured indicated that in some configurations the spray system was more effective than in other configurations. When the flue gas water content was found to be less than predicted, and therefore not all of the water was evaporated, it was instead collecting on duct walls or on tops of the heat exchanger surfaces. In the configurations used for the particulate tests, a good mass balance for the spray water was realized.

An in-stack, multistage, cascade impactor which adapts to the EPA sampling train was used to measure size distribution of particulate emissions. With simultaneous sampling at the various locations the removal efficiencies with respect to particle size under different operating conditions was determined.

Some of the data was collected with coal-water slurry firing. At the low firing rates at which these studies were performed atomizer pluggage was a particular concern. Several air-atomized nozzles were tested. The most consistent performance was obtained using an "Aero" nozzle supplied by Delavan Inc. Coal water slurry was strained through a 16 mesh screen and then fed to the atomizer using a peristaltic pump.

The boiler used is a sectional cast iron hot water boiler, manufactured by Peerless Industries, Inc., and has a capacity rating of 586 kW (2,000,000 Btu/hr). However, all of the tests, were done at a firing rate of 82 kW (280,000 Btu/hr) or less. These lower firing rates were used simply to match the economizer capacities used. In the oil-fired case, No. 2 fuel oil was burned with a pressure atomized flame retention head burner. At such low firing rates maintaining the desired flue gas temperatures required that the boiler unit be modified such that the combustion area including most of the top section was lined with refractory boards. In addition, most of the boiler heat exchanger sections were blocked with refractory material and only several of the passages remain open. The amount of heat exchanger surface which was effective could be adjusted to trim boiler exit temperature.

Combustion gases leaving the boiler were directed through the condensing economizer and then exhausted outside with an induced draft fan, or a side wall power venter. A bypass system with dampers was set up as part of the flue piping to control the volume of flue gas entering the economizer. Flue gas velocities were measured at the inlet and outlet of the condenser with a standard pitot tube.

The burner arrangement used to fire the coal water slurry includes a direct-fired air preheater which burns kerosene. In some of the coal water slurry tests this burner was used to preheat the combustion air to 120 C (250 F). Under these conditions the oxygen content of the vitiated combustion air is about 19.5%. Strong burner swirl is achieved using axial swirl vanes at the burner head. Typical pressure drop across this head is 750 Pa (3 inches of water). The burner can also directly co-fire No. 2 fuel oil using a pressure atomizer adjacent to the air-atomized slurry nozzle. This was used for initial warm-up of the combustion chamber refractory liner and the boiler itself. During some of the combustion tests with coal water slurry the No. 2 oil was co-fired to assure stable conditions at the economizer. In the experimental work both air- and water- cooled condensing economizers, built by Condensing Heat Exchanger Corp., have been evaluated. These are cross-flow tube type heat exchangers with flue gas passing outside of the Teflon-covered metal tubes. Construction details can be found in reference 5.

Thermal Efficiency Prediction

The method developed by Colburn and Hougen^[6] has been used to calculate the latent and sensible heat transfer rates, the water vapor condensation rates and the temperature profiles through the heat exchangers. This general method for evaluating the condensation of a single vapor from a non-condensable gas has been specifically applied by others to flue gas condensing economizers.^[7] Predictions of the thermal performance of both the air and water-cooled economizers used in this project to date have been reported earlier.^[8,9]

In the case of the air-cooled economizer condensation of water was found to begin relatively late in the economizer. The overall condensation rate could be increased considerably by presaturating the flue gas with water vapor but at some thermal efficiency sacrifice. The water-cooled economizer was designed for higher gas velocities and pressure drop. Condensation rates are considerably higher.

Particulate Removal Prediction

Particle removal is dependent primarily upon the following unit mechanisms: (1) inertial impaction on the tubes, (2) interception, (3) diffusion, (4) particle growth due to nucleation and condensation of water vapor, and (5) thermophoresis. In any practical heat exchanger these are affected by factors including: flue gas temperature and moisture content, heat exchanger surface temperature, excess air, total surface area, gas side pressure drop, and heat exchanger configuration.

For each mechanism discussed above a collection efficiency can be defined. A combined collection efficiency due to all the effects for a single tube can then be found and then used in relationships to evaluate the total collection for the n-rows of the heat exchanger. The predicted collection efficiency, considering four of the listed mechanisms, for both the air- and the water-cooled economizers have been evaluated. For flyash particle resulting from coal combustion, the dominant capture mechanism is inertial impaction. Diffusion is negligible and thermophoresis can only be important for the smallest particles when the difference between the flue gas temperature and the tube surface temperature is very high. For condensation particle growth to occur, the flue gas must be supersaturated somewhere in the boundary layer. Analysis done during this project has shown that this is not likely to occur even when the flue gas contains water upstream of the economizer.

Results

As a result of the importance of inertial impaction in particle capture, anything which leads to increased gas velocity and pressure drop improves total collection efficiency. The water-cooled economizer studied has a smaller minimum flow area than the air-cooled economizer and velocities roughly five times greater. Removal efficiency in the air-cooled economizer was determined to vary from 42% to 66%, while in the water-cooled economizer, removal efficiency was over 90%. Increasing the firing rate and gas flow through the economizers increases pressure drop and removal efficiency. Table 1 provides a summary of results obtained with the water-cooled economizer with a 5" of water pressure drop.

To evaluate effects of the addition of water vapor to the flue gas upstream of the economizer, tests were conducted with flue gas water vapor contents ranging from 10 to 20% (volume). In these tests, the overall particle removal efficiency was nearly independent of flue gas water vapor content. In addition, pre-saturating the gas in this way reduces heat transfer rates in the economizer. The system thermal efficiency penalty is about 1%. Adding water sprays directly within the economizer, in contrast, was found to improve particle removal. This might be used very effectively to obtain high removal efficiency at lower boiler loads where economizer pressure drop is reduced. As with water addition upstream of the economizer, water sprays in the heat exchange tube bank carry a heat transfer penalty.

All of the above results have been with oil-firing and spray-dried flyash. In tests with direct coal-water slurry firing, particle removal efficiencies ranged from 85 to 92% with gas-side pressure drops about 4.6-in. of water. Again with water sprays directly on the tube bank, marked improvements were observed with particle removal efficiencies of about 94%.

Run	13	14
Firing Rate, kW (Btu/hr)	82 (280,046)	82 (280,046)
Particulate concentration at the inlet of economizer, gm/dscm	0.544	0.378
Particulate concentration at the outlet of economizer, gm/dscm	0.01	0.014
Particulate removal efficiency across economizer, %	98	96
Particulate concentration at the outlet of induced draft fan, gm/dscm	0.007	0.006
Overall particulate removal efficiency across system, %	98.6	98
Water vapor content at the inlet of economizer, %	11	10
Water vapor content at the outlet of economizer, %	5	5
Flue gas temperature at the inlet of economizer, C (F)	205 (401)	205 (401)
Flue gas temperature at the outlet of economizer, C (F)	51 (124)	52 (126)

Table 1. Summary of Results of Tests with Water-cooled Condensing Economizer.
All Tests with Oil-firing, Spray-dried Flyash, Firing Rate of 82 kW (280,000 Btu/hr).
No additional Water Sprays used.

DISCUSSION

Results of the experimental work have shown that inertial capture of particles is the most important mechanism. Specifically, this is supported by 1) the shape of the removal fraction/particle size curves, 2) higher removal efficiency with higher velocity and pressure drop. This is certainly consistent with predictions. However, the actual particulate removal performance of the economizers has consistently been better than predicted. This may be due to inertial impaction of flyash on condensate drops falling from tubes. An estimate of the potential importance of this effect has been made using assumptions about drop size and concentration in the gas phase. Results are shown in Figure 2 and indicate that such impaction could be very important. In future condensing economizer designs, it may be practical to enhance this effect by "seeding" the economizer with small diameter impactors. An evaluation of this concept can be found in Reference 5.

Conclusions

A number of detailed conclusions can be drawn from the studies conducted during this project. Perhaps the most important is that condensing economizers can be used to control particulate emissions from coal water slurry-fired boilers. Particulate removal efficiencies as high as 98% were achieved in this study. For future improvements in the capture of flyash particles enhancing inertial collections through combinations of increased maximum gas velocity in the tube bank, directed water sprays within the heat exchanger and possibly added small diameter impaction sites are suggested.

Figure 2. Prediction of particulate capture on condensate drops within the condensing economizer. Comparison with both predicted capture on heat exchanger tubes and observed results.

PLANS

BNL is currently planning to begin a Cooperative Research and Development Agreement project with Babcock and Wilcox Co., Condensing Heat Exchanger Corp., and Consolidated Edison Company of New York. Under this agreement, BNL will continue development studies with DOE support and emphasis on removal of trace pollutants, SO_2 capture, and a two-stage economizer concept. Babcock and Wilcox will also undertake development work at their Alliance Research Center. Consolidated Edison will conduct a demonstration project at their Ravenswood generating station. All groups involved will participate in planning and review of development efforts.

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