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FLUE GAS RECIRCULATION FOR STOKER BOILERS

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ABSTRACT

Flue Gas Recirculation is a combustion modification process that replaces a portion of the combustion air supply with recirculated flue gases. When flue gas is extracted from the hopper section of the mechanical dust collector, stack particulate emissions are decreased by improved multiclone collection efficiency. The coupling of Flue Gas Recirculation with hopper evacuation provides a convenient means to reduce particulate emissions and dispose of the collected fly ash. Results indicated reductions in stack particulate emissions from baseline conditions of 70 percent with the incorporation of Flue Gas Recirculation. The evaporation rate also improved by 4.5% with the use of Flue Gas Recirculation.

1.0 INTRODUCTION

A persistent problem with stoker-fired boiler is that the fuel and air usually do not have adequate time to mix properly within the fuel bed area. One reason is that a certain mass flow of air in the excess of that required for combustion must be supplied to cool the fuel bed and to prevent the formation of clinkers in the ash. Even use of overfire air and different grate designs have not solved the problem completely. The result is that stoker boilers frequently operate at excess O_2 levels of 10% or higher and produce relatively high amounts of particulate emissions.

The advent of the "energy crisis" and increased concerns about environmental pollution prompted renewed interest in ways to improve the operation of stoker-fired boilers. With thousands of stoker boilers in operation, in the United States, the potential impact was large. Consequently, the U.S. Government and a number of private companies initiated R & D programs aimed at stoker boilers (1), (2), (10).

In the United States, the use of gas recirculation on stoker boilers was not a common technology. However, in Europe where fuel is much more expensive, they have utilized energy saving processes, such as Flue Gas Recirculation, to improve their fuel efficiency. It is used on coal-fired stokers and water-wall incinerators (3).

Starting in the mid-seventy's, the U.S. EPA funded and participated in a number of laboratory and demonstration programs to investigate the application of Flue Gas Recirculation technology to stoker boilers (4), (7), (8), (9), (10). Briefly, these programs sought to improve the air pollution emission performance of stoker-fired boilers without degrading the fuel economy. The emphasis was placed on reducing emissions of particulate matter, smoke (opacity), oxides of nitrogen and oxides of sulfur.

Many combustion modifications, as well as hardware modifications, were evaluated during these programs.

Flue Gas Recirculation was found to be the most cost effective combustion modification for meeting all of the objectives as well as improving boiler fuel economy.

Dramatic reductions in particulate matter emissions were achieved. Reductions of 70% in stack flue gas particulate matter loadings were measured at concurrent opacity readings under 20%.

The culmination of this effort was the installation of a Flue Gas Recirculation system on a 100,000 lb/hr coal-fired spreader stoker at a midwest university. The results were very successful and beyond the program objectives. This particular boiler was steam capacity limited due to clinker formation as a result of firing low-fusion Western Kentucky coal. After the Flue Gas Recirculation system was operational:

- Boiler efficiency was increased between 6% and 7% for almost $150,000 per year fuel savings.
- Boiler steam capacity increased over 40% without clinker formation.
- Excess O_2 was reduced from 10% to 3% at full load.
- Particulate emissions were reduced 40% and stack opacity reduced to 15%.
- NOx emissions were reduced almost 50%.

There are now several Flue Gas Recirculation systems operational.

The Flue Gas Recirculation process requires some amount of customization for each installation since every retrofit is not the same. For example, modifications to the overfire air system are especially important to the technical and economic success of the project. Special attention is also paid to interfacing the Flue Gas Recirculation system with the existing boiler controls.

A Flue Gas Recirculation system will cost less than half the cost of a conventional Hopper Evacuation/Baghouse system.

In some cases, the Flue Gas Recirculation process can result in increased steam capacity. For example, if the boiler is fan limited or particulate or opacity limited such that it can't be operated at maximum steaming rate before running into one of these limits.

The Flue Gas Recirculation produces lower grate temperatures, which prevents fuel bed clinker formation and allows the use of a wider range of lower-fusion fuels.

The following sections discuss the Flue Gas Recirculation process, the specific hardware involved, a review of the operating installations including the particulate reduction and efficiency improvement results that have been achieved.

2.0 TECHNICAL DISCUSSION

The use of Flue Gas Recirculation allows the decoupling of the two fundamental requirements of stoker boiler operation. The two requirements are:

1. Sufficient oxygen must be provided to completely burn the fuel and
2. Heat must be removed from the burning fuel bed to prevent the melting of the ash and the formation of slag or clinkers.

The use of the Flue Gas Recirculation provides a diluent to the combustion air so that the oxygen content may be reduced. However, even at reduced oxygen content the combustion air still provides adequate oxygen to completely burn all of the fuel.

The Flue Gas Recirculation also acts to more efficiently cool the burning fuel bed by supplying water vapor that has a greater heat capacity than air alone.

It is the greater heat absorbing capacity that allows the reduction of the excess air in greater than a one-to-one ratio with the rate of Flue Gas Recirculation.

For example, a coal-fired boiler, operating at 100% excess air, may be reduced to 20% excess air with the addition of 30% Flue Gas Recirculation. The gas flow through the fuel bed is reduced from 20 pounds of air per pound of coal in the baseline case to 15 pounds of flue gas and air mixture in the Flue Gas Recirculation case.

It is this reduction in gas flow through the fuel bed that helps to reduce particulate entrainment from the furnace and reduce the burden on the dust collection device.

The Flue Gas Recirculation process operates at much lower excess air in the fuel bed. For this reason, modifications to the overfire air system are necessary to prevent smoke formation at the lower desired stack excess air conditions.

The goal of the overfire air modifications is to improve the mixing of the volatile fuel components coming from the fuel bed and in the overfire air. To achieve this, greatly enlarged overfire air jet nozzles are provided to increase the mass flow of gas in the overfire air. It is this increased mass flow that increases the momentum of the overfire air gas jet to penetrate further into the furnace and provide better mixing.

It is important that while providing this increase in gas flow that the excess air not be increased. If only air were used in the overfire air system then the excess air would increase in the furnace.

This problem is solved by using a flue gas/air mixture in the overfire air system to dilute the oxygen concentration and maintain control over the excess air in the furnace.

The Flue Gas Recirculation system may be configured in several ways to achieve certain desired process objectives (Fig. 1). One such configuration takes the flue gas from the hopper of a mechanical cyclone dust collector. This is the well known "hopper evacuation" or "side stream separation" process. However, instead of having to clean up the side stream with a baghouse or a scrubber, the flue gas is injected into the combustion air in the windbox of the stoker. All the benefits of improved mechanical dust collector performance with hopper evacuation are achieved as well as the benefits of greater fuel economy from the Flue Gas Recirculation.

Taking a portion of the gas from the hopper of the mechanical cyclone dust collector works to prevent the entrainment and re-entrainment of the dust from that section of the dust collector. The hopper evacuation also increases the effective pressure drop across the collecting tubes. This increased pressure drop increases the inertial separating effect by increasing the tangential velocity of the vortex. This greater velocity exerts more "g" force on the particulate, which results in better separation.

One of the most beneficial applications of FGR is the combination with hopper evacuation of the mechanical dust collectors. Significant increases in multiclone collection efficiency have been demonstrated by withdrawing approximately 15 percent of the total flue gas flow directly from the multiclone hopper through a side stream separator. Particulate collection is increased by: (1) increasing the "pull" on captured particulate matter and (2) reducing the re-entrainment of particles from the dust-laden hopper gases into the multiclone exhaust stream and subsequently out the stack.

When combined with FGR, the hopper evacuation stream is mixed directly with the stoker's undergrate combustion air stream, where effective dust collection is achieved by: (1) settling of the large particles, and (2) filtration in the bed. The settling of large particles is due to the dramatic reduction in gas velocities (up to an order of magnitude depending on boiler design) as the undergrate air/recirculated gas stream enters the stoker undergrate and fuel bed. The accumulated ash is then disposed with the normal grate ash.

3.0 RESULTS OF FLUE GAS RECIRCULATION APPLICATIONS

FLUE GAS RECIRCULATION APPLICATION AT THE UPJOHN COMPANY

The Upjohn Company in Kalamazoo, Michigan has the FGR system with the greatest number of hours in service.

The first installation at the Upjohn Company was on a 90,000 pound per hour steam, coal-fired spreader stoker. The boiler is located at their research center heating and cooling plant in downtown Kalamazoo.

The FGR installation at the Upjohn Company featured hopper evacuation of the mechanical cyclone dust collector as the source for the FGR. This configuration was chosen since Upjohn was primarily interested in reducing the particulate and opacity emissions at their stack.

The particulate test results on Boiler #5 were very impressive. The average particulate loading of three tests was 0.133 pounds per 1,000 pounds of flue gas, corrected to 50% excess air. This is compared to 0.47 pounds per 1,000 before the FGR modification. This represents a 71% reduction from the baseline case. All the particulate tests were performed with the stack under 20% opacity. Table 1 contains the test results from the #5 boiler. The coal analysis is also given in Table 1.

The Upjohn Company has since installed three more FGR systems in order to bring their other boilers into compliance with the Michigan DNR regulation for particulate and opacity emissions. They now have 360,000 pounds of steam generating capacity with the installed FGR systems.

In order to reduce cost, the Upjohn Company FGR installations did not include any modifications to the overfire air. For this reason, the boilers reach their lowest excess air limit at about 5.0% excess O_2 in the stack before they smoke. Other installations with overfire air modifications, the University of Wisconsin/Madison, have demonstrated lower excess air limits before smoking occurred (12).

The Upjohn Company FGR systems do not use a measurement of the oxygen content in the combustion air/flue gas mixture under the grate for controlling the recirculation rate. Instead, the FGR fan damper controller was slaved, with an adjustable bias, to the forced draft fan damper controller. This system then activates the FGR fan damper in the same way as the FD fan damper opens and closes. This is an acceptable control system however; more flexibility and better efficiency can be achieved with oxygen measurement control systems.

		Boiler #5 Full Load
Test•	1	.098
	2	.141
	3	.160
	Avg.	.133
	Before Avg.	.470

- lb. of particulate per 1,000 lbs. flue gas
- (corrected to 50% excess air)

		% Weight
Ash		10.50
Sulfur		2.70
Hydrogen		4.57
Carbon		63.80
Nitrogen		1.05
Oxygen		7.68
Moisture		9.70
	Total	100.00
Heating Value		11,634 Btu/lb

Table 1. Particulate Emission Results and Coal Analysis for Upjohn Company FGR Installation.

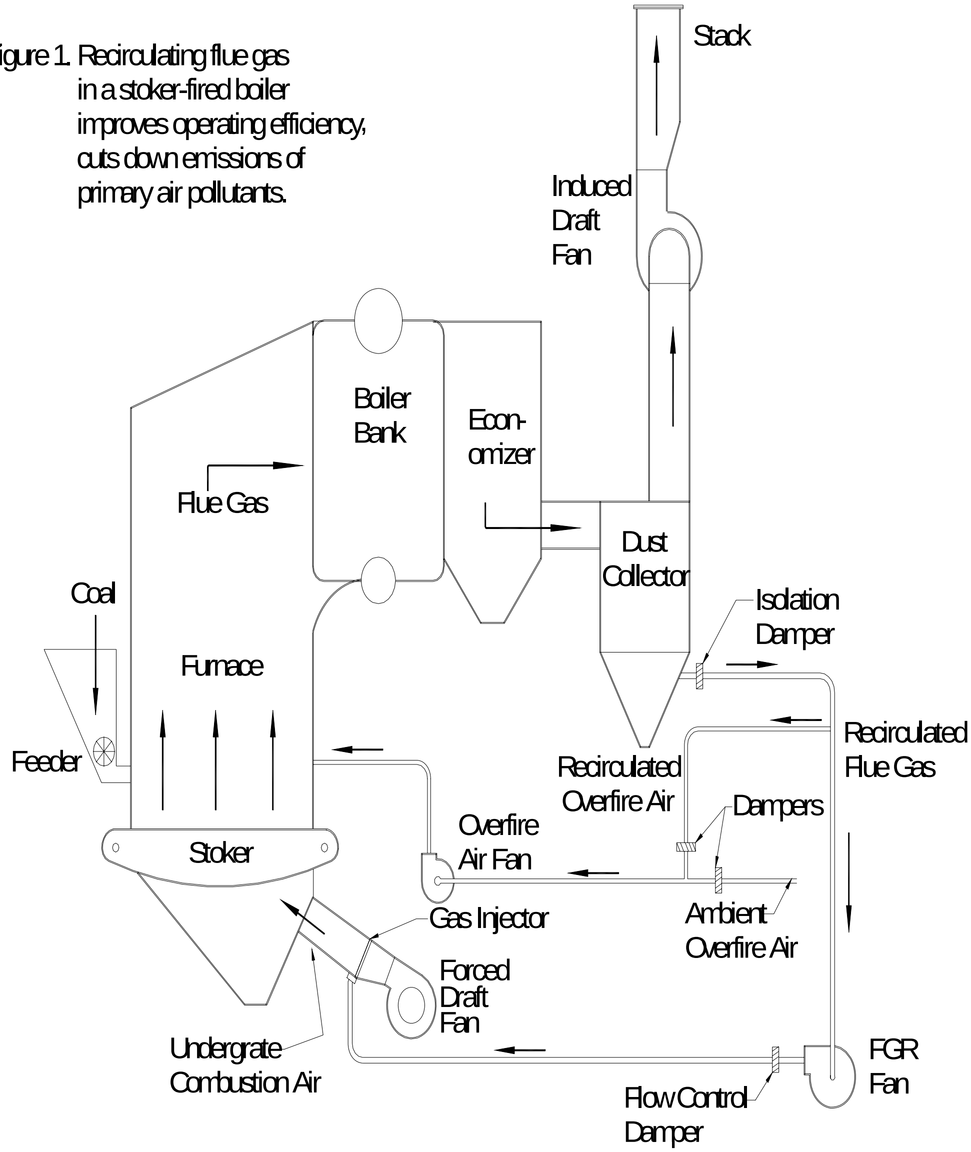
Even with this system the Upjohn Company is realizing impressive coal savings with the FGR system. The reduction in excess resulted in a 4.5% improvement in evaporation rate on boilers #5 and #6. The measurements were made over a twelve-day period. Measurement was made of the evaporation rate over four days with the FGR systems running. The rate was 10.81 pound of steam per pound of coal. The systems were turned off for the next four days and the evaporation rate dropped to 10.29 pounds of steam per pound of coal. The FGR systems were then turned on and measurements made over the next four days when the evaporation rate improved to 10.76 pounds of steam per pound of coal.

These impressive fuel savings are an added benefit to the dramatic particulate reductions that were achieved at the Upjohn Company. Upjohn now has four 90,000 pph stoker boilers equipped with FGR.

3.2 FGR APPLICATION AT THE WASHINGTON STATE CORRECTION CENTER IN SHELTON, WA.

A series of particulate emissions tests were conducted on Boiler #3, located at the Washington State Correction Center in Shelton (Reference 5). The objective of these tests was to evaluate the use of FGR in combination with multiclone hopper evacuation to reduce stack particulate emissions below the OAPCA Regulation 1 limit of 0.10 gr/DSCF (12 percent

Figure 1. Recirculating flue gas in a stoker-fired boiler improves operating efficiency, cuts down emissions of primary air pollutants.



CO_2). Previous tests on this unit had demonstrated particulate emissions well in excess of Regulation 1 requirements.

The test boiler was a Babcock and Wilcox balanced draft, two drum integral furnace fired by two Detroit Roto-Stokers onto a Type CC reciprocating grate. The design rating of the boiler was 20,000 pounds steam per hour at 120 psig. The boiler was equipped with two Western Precipitation-Type 9V6R12 size 10-2 multiclones.

During the test series, the boiler fired coal obtained from Centralia, Washington. The coal had been twice washed to remove clay impurities and screened to limit fines content. The coal contained approximately 14.5 percent ash, 25 percent moisture, 1.2 percent sulfur and had a heating value of approximately 7800 Btu/lb. Use of this low grade coal limited boiler output to approximately 12,000 pounds steam per hour due to grate bed build-up and excessive combustibles in the bed refuse. Tests were conducted primarily at a load of 10,500 pounds steam per hour.

To achieve 30 percent hopper evacuation, it was necessary to exhaust 2,500 ACFM of flue gas from the two multiclone hoppers. Duct work was fabricated from commercial round galvanized steel, connected to the existing manholes on the multiclone hoppers and arranged with dampers so that evacuated gases could either be discharged out the window to atmosphere or introduced into the boiler combustion air at the forced draft fan outlet. A stainless steel pressure blower designed to handle dirty gases at high temperatures was used to recirculate the flue gas. Flow was regulated by a series of dampers.

Particulate mass loading measurements were made simultaneously at the boiler outlet upstream of the multiclone and were also made at the boiler outlet. Two four inch sample ports were installed in the boiler exhaust duct just downstream from the last boiler convective pass. A port located at the rear base of the duct allowed a traverse perpendicular to the flow stream to determine boiler exhaust (multiclone inlet) velocity, temperature and O_2 distribution. Particulate mass loading measurements were made through this sample port using an instream Alundum filter thimble following ASTM procedures. The second boiler outlet sample port was positioned on top of the exhaust duct to allow direct penetration into the exhaust stream. Particle size measurements were made through this sample port using an MRI Model 1502 Inertial Cascade Impactor equipped with a cone nozzle and positioned in the center of the exhaust stream.

Stack particulate samples were obtained through two existing three inch sample ports near the stack outlet. Particulate mass loadings were determined using a Joy Portable Effluent Sample designed to the specifications for EPA Method 5. Sampling was conducted using a 12-point, two diameter, equal area traverse.

The test program consisted of eleven tests. Table 2 presents a summary of the test conditions and comparative data for the boiler outlet mass and particle size and stack mass emissions results. Comparative test conditions have been grouped into the five major test categories as follows:

- As found
- Baseline (tuned-up) multiclone
- Multiclone hopper evacuation
- Multiclone hopper evacuation with FGR
- Reduced load with multiclone hopper evacuation and FGR

Tests conducted at all but the last condition were made at a load of 10,500 lb/hr. Although boiler firing and flue gas conditions were similar for all tests, significant variations in the boiler outlet mass loadings were measured ranging from 0.34 to 0.80 gr/DSCF (12 percent CO_2). Several operating factors (coal fineness, bed condition, etc.) could have accounted for these differences, but were not identified as part of the test program. Boiler outlet particle size distribution measurements, however, were consistent between the test runs with approximately 70 percent in the first size cut (18 micron) and 20 percent in the second (9 micron). The balance was collected on the final impactor filter (0.3 micron). Data for all impactor runs is presented in Table 3.

Stack particulate levels were reduced from an "as found" condition (without multiclone hopper evacuation) of 0.25 gr/DSCF to approximately 0.1 gr/DSCF by cleaning and balancing the multiclones. Multiclone collection efficiency increased from 66 percent to approximately 80 percent. Tests conducted with the clean multiclone (Test 3, 6 and 7) resulted in stack emission at the Regulation 1 limit.

During the next test series (Tests 4, 5 and 8), the temporary duct work was attached to the multiclone hopper, the dampers adjusted to withdraw 10 to 20 percent of the flue gas from the hopper and the particle laden gases discharged out the window. Under these operating conditions, the multiclone collection efficiency increased to approximately 85 percent, reducing stack particulate levels to approximately 0.07 gr/DSCF (12 percent CO_2). Peak multiclone efficiency (88 percent) was obtained during Test 5 with the hopper evacuation rate at 16 percent of the total flue gas flow.

The ductwork dampers were then arranged so as to discharge the hopper evacuation gases into the forced draft discharge to incorporate the FGR process. Approximately 19 percent of the total exhaust gases were recirculated into the undergrate combustion air stream. A further decrease in particulate emissions to 0.06 gr/DSCF was observed. Hopper evacuation in combination with increased gas flow through the multiclone increased collection efficiency to 90 percent. Sustained operation with FGR at 10,500 lb/hr was maintained for 24 hours.

The final test included FGR at a reduced load of 7,000 lb/hr recirculating approximately 30 percent of the flue gases. This test concluded approximately 36 hours of continuous FGR operation on the boiler.

No detrimental impacts on boiler operation, firing or bed conditions were noted during the 36 hour FGR test run. Refuse ash conditions off the grate appeared to be similar to that under normal firing conditions. No appreciable clinker formation delayed burning on the grate or in the ash pit or increased CO emissions were observed. FGR also allowed a reduction in overall excess air of approximately 25 percent corresponding to an increase in boiler efficiency of 3 percent.

It should be noted that application of FGR was limited to the undergrate air only for purposes of demonstrating the particulate control potential on the Shelton boilers. Complete application of FGR would also include evaluation of the need for modification to the overfire air supply system. While 18 percent recirculated to the undergrate air would appear to provide satisfactory operation of both the bed combustion conditions and multiclone collection efficiency, the quantity of recirculated gas into the overfire air together with modification to the size and location of overfire air jets must be determined independently on the basis of fuel firing and furnace design characteristics. Proper application of the synergistic effects of recirculated gas to both combustion air streams is a key element of FGR on coal-fired stokers.

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TABLE 2. PARTICULATE EMISSIONS SUMMARY

Objective	Test	Boiler Outlet (gr/DSCF @ 12% CO_2)	Stack (gr/DSCF @ 12% CO_2)	Multiclone Collection Efficiency	Boiler Outlet Particle Sixe
As Found	1	0.780	0.255	67.3%	
	2	0.644	0.229	64.4%	75% > 10μ
	Avg.	0.712	0.242	66.0%	
	3	0.351	0.095	72.9%	72% > 10μ
Cleaned Multiclones	6	0.476	0.091	80.9	
	7	0.711	0.114	84.0%	71% > 10μ
	Avg.	0.513	0.100	80.5%	
Multiclone Hopper Evacuation	4	0.388	0.068	82.5%	68% > 10μ
	5	0.510	0.063	87.6%	77% > 10μ
	8	0.475	0.069	85.5%	
	Avg.	0.458	0.067	85.4%	
Multiclone Hopper Evacuation w/ FGR	9	0.803	0.062	92.3%	71% > 10μ
	10	0.341	0.052	84.8	71% > 10μ
	Avg.	0.572	0.057	90.0	
Reduced Load Teat	11	0.342	0.051	85.1	64% > 10μ

TABLE 3. BOILER OUTLET CASCADE IMPACTOR RESULTS
Particulate Size Distribution

Impactor	Mean Particle	2		3		4		5		7		9		10		11	
Stage	Diameter (μ)*	mg	%	mg	%	mg	%	mg	%	mg	%	mg	%	mg	%	mg	%
1	18.0	82.7	75.4	100.5	72.6	61.3	68.1	74.6	77.1	66.4	71.4	62.6	70.9	160.3	70.6	68.3	64.1
2	9.0	18.4	16.8	26.6	19.2	15.8	17.6	15.9	16.4	14.4	15.9	10.7	12.1	52.6	22.9	26.1	24.5
3	3.5	2.8	2.6	2.0	1.4	4.7	5.2	0.5	0.5	4.2	4.6	10.0	11.3	9.5	4.1	6.9	6.5
4	1.5	0	0	0	0	0.8	0.9	0	0	0.8	0.9	0.8	0.9	0.7	0.3	2.1	2.0
5	0.8	0	0	0.2	0.1	0.8	0.9	0	0	0.4	0.4	0	0	0	0	0.3	0.3
6	0.35	0	0	0.9	0.7	0.6	0.6	1.1	1.1	0.6	0.7	0	0	0	0	0.2	0.2
Filter	<0.3	5.8	5.3	8.4	6.1	6.0	6.7	4.7	4.9	5.5	6.1	4.1	4.6	3.8	1.7	2.6	2.4
Mass Loading (gr/DSCF @ 12% CO_2)		0.422		0.523		0.590		0.582		0.607		0.433		1.126		0.632	

*Sample flow rate of 2.0 CFM at duct conditions