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Condensing Economizers for Efficiency Improvement
and Emissions Control in Industrial Boilers

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ABSTRACT

Condensing economizers recover sensible and latent heat from boiler flue gas, leading to marked improvements in thermal efficiency. These economizers can, in addition, be used to reduce emissions of particulates and sulfur dioxide. This paper summarizes the current commercial status and continuing development efforts with one type of condensing economizer. In this design Teflon[®] covered tubes and enclosure walls are used to handle the corrosive condensate. Flue gas flows around the tubes and feed water, being heated, flows through the inside.

Originally, these economizers were developed only for heat recovery and involved a single heat exchanger. Over 100 of these single-stage economizers are currently in operation in industrial and commercial boiler plants.

In addition to improving thermal efficiency, condensing economizers can also be used to reduce particulate emissions primarily by inertial impaction of particles on tube surfaces, water droplets, and added impactors. Collected particles are then removed with condensate. Water sprays directly on the tubes can be used to enhance particle capture. With coal-firing, tests have shown particle removal efficiencies as high as 98%. To enhance the emissions control potential of condensing economizer technology a two-stage economizer system concept has been developed. Two heat exchanger modules are used. The first is a downflow design and recovers primarily sensible heat from the flue gas. The second is upflow and recovers mostly latent heat. Condensate is collected in a transition plenum between the two stages. This configuration, termed the Integrated Flue Gas Treatment System (IFGT), provides great flexibility for implementing emissions reduction strategies. Particulate emissions can be reduced without impacting sensible heat recovery by recirculating collected condensate to spray nozzles at the top of the second stage heat exchanger. In tests at Brookhaven National Laboratory with heavy oil firing, particulate reductions over 90% and final emission rates on the order of .005 lb/MMBtu are achieved. Adding sorbents to the recirculated condensate reduces sulfur dioxide emissions and SO₂ removal efficiencies over 95 % are achieved. Such economizers are now being offered on a commercial basis. Also, condensing economizers show great potential for the removal of certain air toxics such as mercury and nickel.

Currently, the enhancement of the capture of fine particulates and air toxics are being explored in laboratory development studies at Brookhaven National Laboratory, Babcock and Wilcox Co., and through a major demonstration program at Consolidated Edison Co. of New York Inc., where a 30 MW IFGT unit will shortly be commissioned.

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INTRODUCTION

Condensing economizers are heat exchangers that can be used to improve the efficiency of boilers and furnaces. By diverting all or part of the stack gases through an economizer, it recovers both sensible and latent heat that typically would be wasted. Condensing economizers are being used in residential, commercial and industrial applications.

The specific economizers which are the subject of this paper are configured in a shell and tube design with the flue gases flowing around the horizontal tubes. The heat sink flowing through the tubes can be any liquid or gas, but is usually water. To avoid the detrimental effects of corrosive flue gases the exposed surfaces and copper-nickel tubes are covered with Teflon®. Single stage units of this type have been commercially available for retrofitting to commercial and industrial-sized boilers. The low-grade heat can be used to preheat boiler feedwater, makeup water for steam, combustion air, process water, laundry wash water, etc.

A typical setup of a single stage Condensing Heat Exchanger® (CHX) is shown in Figure 1. This diagram shows a modular unit that can be easily sized and constructed according to its heat recovery requirements. In the case shown, a slipstream of the stack gas is passed into the economizer with the induced draft fan. Water flows countercurrent to the hot flue gas for maximum heat recovery. Water condensed from the flue gas is collected at the bottom of the economizer and can be drained or pumped out for further treatment and disposal, as appropriate. The cooled flue gas is then exhausted through a separate noncorrodible stack or recombined with the hot gases from the existing stack, depending on exit temperature limitations.

In addition to the improved efficiency that can be realized with condensing economizers, it has also been demonstrated that they can be very effective for emissions control. With simple condensing economizers, early tests, discussed in more detail below, showed that a significant fraction of flue gas particulates are captured and drained off with the condensate.

Integrated Flue Gas Treatment System

The potential for emissions removal is greatly advanced by the development of the Integrated Flue Gas Treatment (IFGT) system. Figure 2 shows this system which includes two heat exchanger sections separated by a transition plenum. Flue gas flows down through the first heat exchanger section and is cooled to about the dew point of the water vapor. This gas then passes through the transition plenum and upward through the second heat exchanger where mostly latent heat is recovered. Water sprays can be used in selected locations to enhance particulate capture, and, with the addition of alkali reagents, sulfur oxides can be removed as well. The condensate water can be recirculated through spray nozzles at the top of the second stage and in the interstage plenum. Flue gas enters the IFGT at 300°F - 450°F and exits at about 100°F. A mist eliminator is included as part of this system to reduce water droplet carryover.

The major flue gas pollutants of interest for commercial system applications are particulates, sulfur dioxide, and air toxics, such as heavy metals. Consolidated Edison

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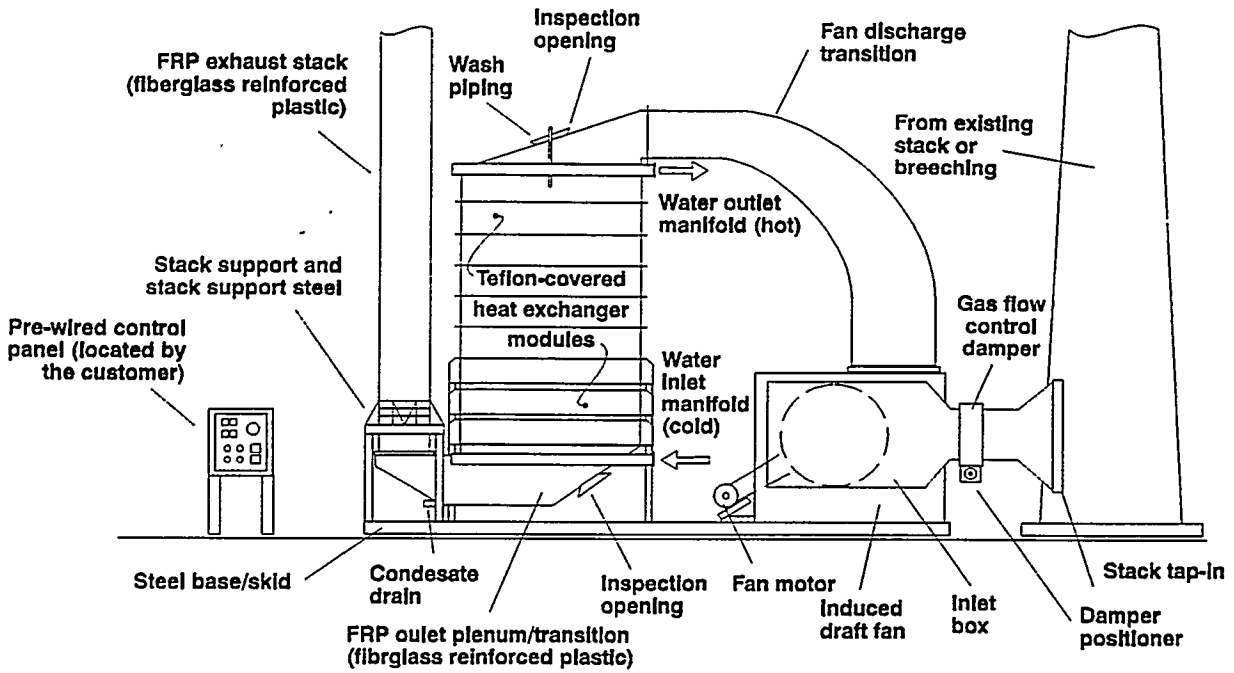


Figure 1. Typical condensing heat exchanger system [1].

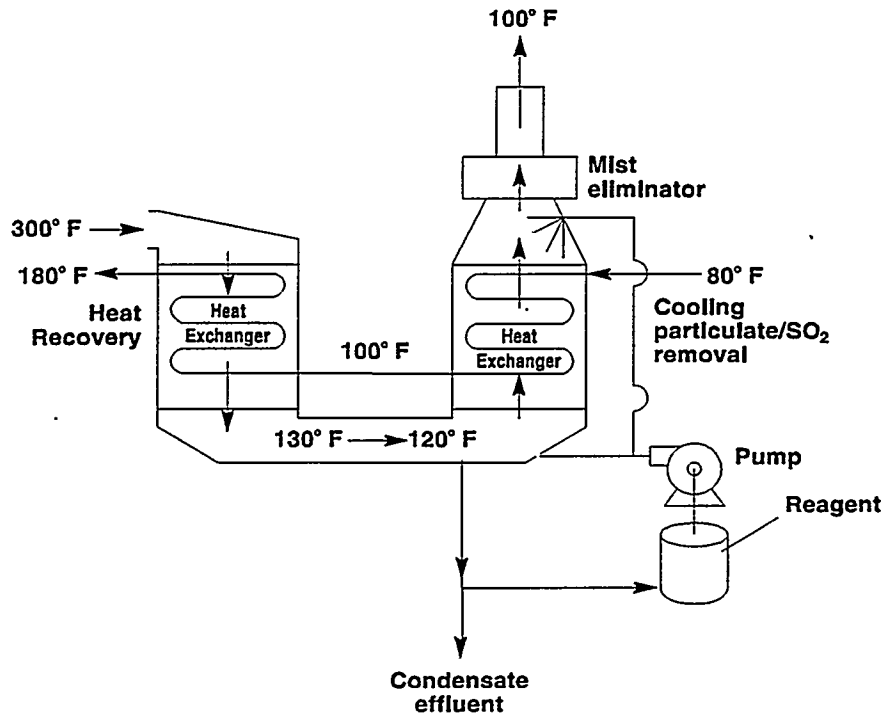


Figure 2. Integrated flue gas treatment system [2].

Company of New York Inc. (Con Edison), Babcock & Wilcox (B&W), and Condensing Heat Exchanger (CHX) Corporation have an extensive program to develop the IFGT technology. Brookhaven National Laboratory (BNL) is currently in its second year of a research partnership with these companies under a Cooperative Research & Development Agreement (CRADA) program funded by the U.S. Department of Energy (DOE).

DEVELOPMENT PROGRAMS

Brookhaven National Laboratory

The main objective under the current CRADA program is to develop IFGT condensing economizer technology to the point that it will be strongly attractive commercially, providing a viable method of both improving energy efficiency and reducing pollutant emissions from stationary combustion sources. Specifically, the goals are to obtain thermal efficiencies 10% greater than with conventional equipment, sulfur dioxide capture over 95%, and consistent capture of over 90% of particulates with oil firing. In addition, removal potential for selected air toxics and nitrogen oxides will be evaluated and optimized within practical constraints.

As part of the CRADA a two-stage condensing economizer was installed at the BNL Combustion Laboratory in 1994. Tests are conducted with heavy fuel oil firing at rates up to 1 MMBtu/hr (1,000 lb/hr flue gas). Figure 3 shows the configuration of the laboratory setup. This facility includes a cast iron boiler with a maximum capacity of 1.8 MMBtu/hr. The boiler has been configured as a steam boiler to provide for studies of the effects of steam injection into the economizer. Flue gas from the boiler can be either vented through a conventional chimney or sent to the IFGT. The induced draft fan and dampers located downstream of the IFGT allow for independent control of the amount of flue gas entering the IFGT.

BNL is focusing its efforts on exploratory studies aimed at providing better understanding of particle capture mechanisms and development testing of novel concepts for achieving higher levels of particle capture. The BNL work includes determining the effects of boiler load, water sprays to the economizer tube banks, and steam injection on particulate capture across the IFGT condensing economizer. Total mass loading of particulates in the flue gas has been measured at the inlet and outlet of the economizer under various test conditions. Particle size distributions using a cascade impactor have been measured as well.

BNL has also done analysis work to predict heat transfer performance and particulate capture in the condensing heat exchanger. To date, a user-friendly computer program and spreadsheet have been developed that performs heat transfer and pressure drop calculations.

In addition to the two-stage IFGT, BNL also has a single-stage condensing heat exchanger that was used in prior studies funded by the U.S. Department of Energy's Pittsburgh Energy Technology Center. With these small-scale units and the flexibility of operation, BNL is ideally suited for evaluating new hardware configurations and operation concepts that might improve pollutant removal.

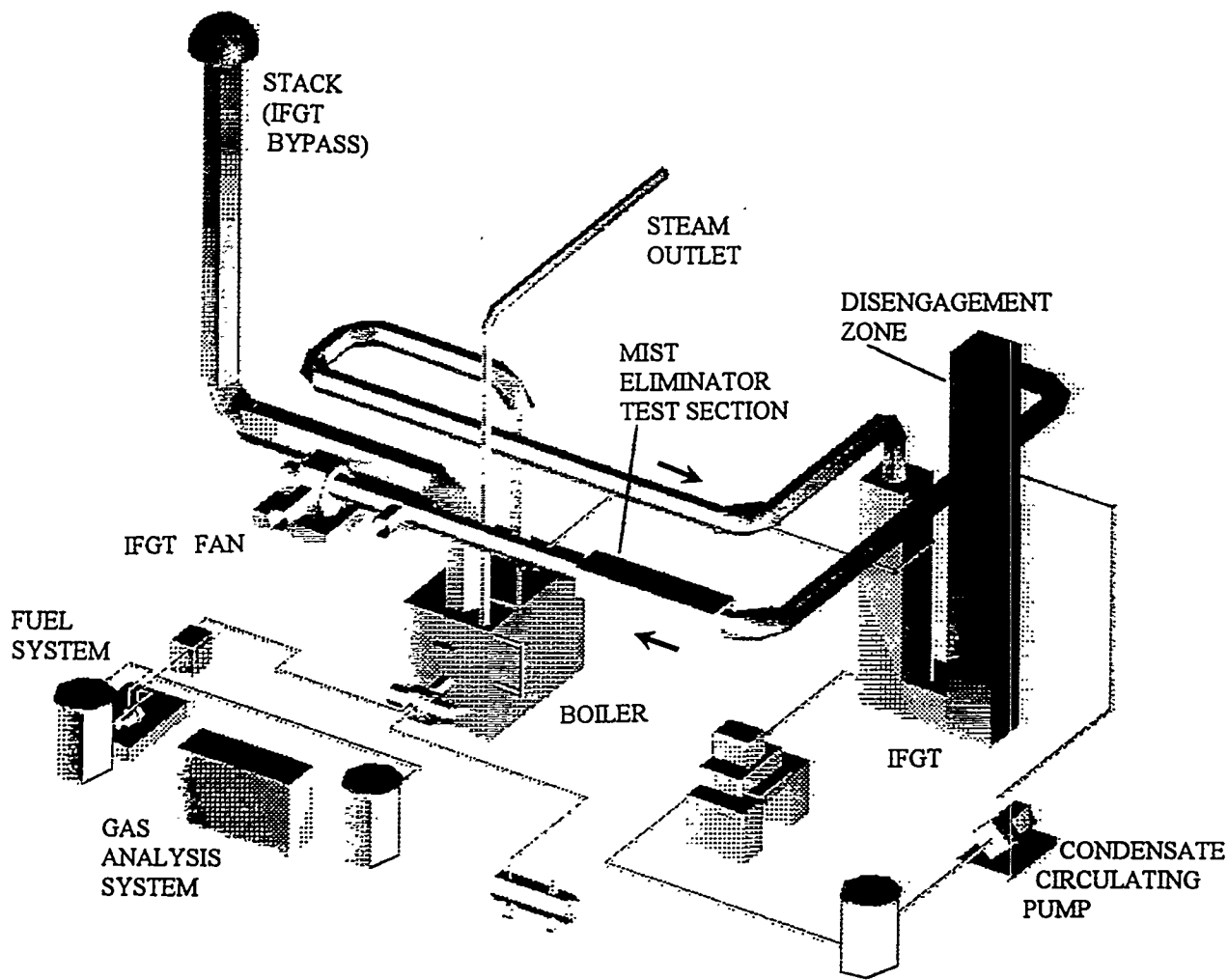


Figure 3. Condensing economizer laboratory at BNL.

Babcock & Wilcox

B&W and CHX Corporation are undertaking an extensive program to further develop the IFGT technology for emission control applications. B&W is involved with the marketing, manufacture and development testing of condensing heat exchangers. Both the single-stage heat recovery and IFGT units are now available for industrial, commercial and utility customers.

B&W's development efforts are currently focused on the applications of the IFGT for fuels such as coal, Orimulsion^{®†}, and waste fuels. Their Research and Development Division in Alliance, Ohio is equipped with an IFGT pilot unit (5,000 lb/h flue gas) connected to their Small Boiler Simulator (SBS) test facility, which has a capacity of 6 MMBtu/hr. Figure 4 shows the SBS facility which can evaluate various combustion and pollution abatement processes. It has the capability of handling pulverized coal, liquid and gaseous fuels, as well as other solid fuels. This facility also has other flue gas cleanup devices (baghouse, dry scrubber, etc.)

The testing work at the B&W facility is aimed at application-specific development work. It is well equipped to conduct pollutant removal tests in conjunction with other commercial devices, and with a wide variety of fuels. Studies performed by BNL can also be confirmed here to evaluate expected performance on a larger scale and to assist with final configuration design.

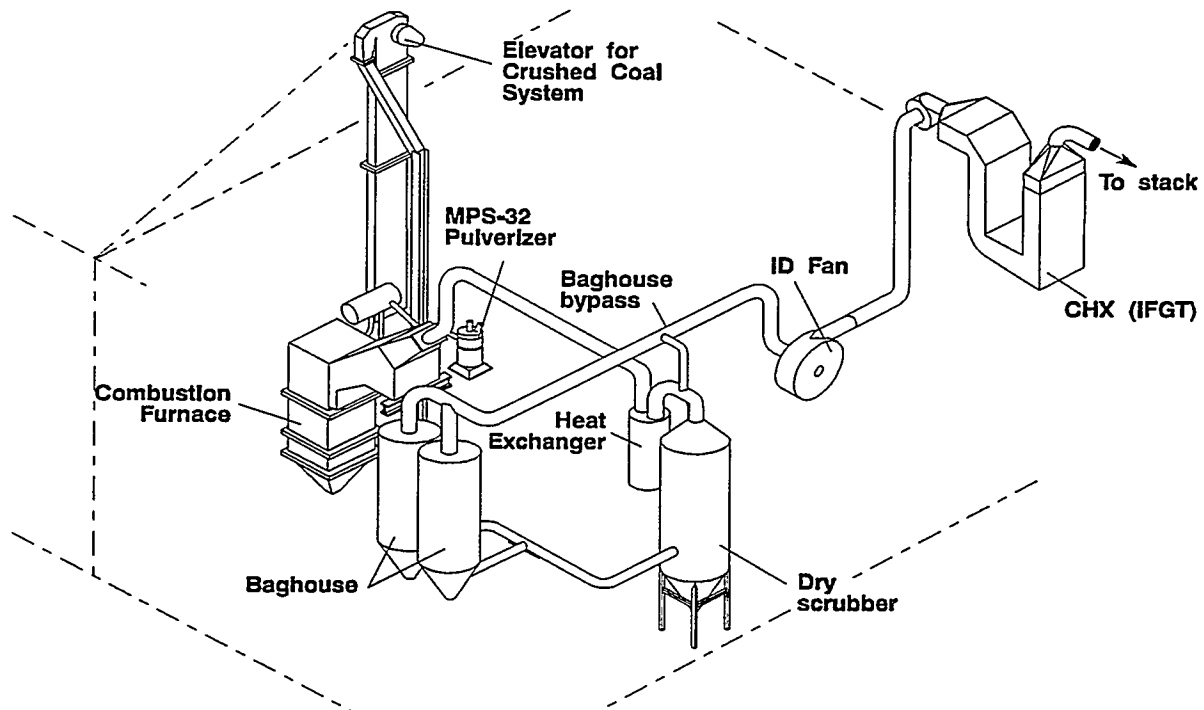


Figure 4. Small Boiler Simulator and Condensing Heat Exchanger test facilities at the Babcock and Wilcox Alliance Research Center [3].

†Orimulsion is a water-based bitumen emulsion produced in Venezuela. It has a high water content, which can lead to lower boiler efficiency, has a higher sulfur content and greater particulate emissions than most fuel oils.

Consolidated Edison

Con Edison has been actively working with CHX Corporation, the original developer of the Teflon coated economizer, to improve and demonstrate this technology. Since 1992, Con Edison has been operating a full-scale single stage economizer at its 74th Street Cogeneration Station in New York City. With this equipment a heat rate improvement of 800 Btu/kWh has been realized.

In 1993, Con Edison installed and tested a pilot-scale two-stage IFGT at its Ravenswood Steam Station. The IFGT unit treated a 25,000 lb/hr flue gas slipstream from the residual oil-fired boiler. Sulfur oxide removal tests were conducted using a reagent of soda ash and condensate. As an SO₂ removal device, the condensing economizer has significant advantages over a conventional scrubber because it can simultaneously recover energy thereby improving efficiency and economics.

Recently, Con Edison has installed a new full-scale IFGT facility that can handle 275,000 lb/h of flue gas (100 MMBtu/h) at their Ravenswood Steam Station. This is the largest unit to be tested and will be used to demonstrate the IFGT technology and pollutant removal capability on a commercial scale. Performance evaluations will be done on low ($\leq 0.3\%$) and high sulfur fuel oils. The use of fuel oil with a sulfur content greater than 0.3% will require prior approval from the New York State Department of Environmental Conservation (NYSDEC) and New York City Department of Environmental Protection (NYCDEP). Measurements in the flue gas will be made for particulates, SO₂ and SO₃, chromium, nickel, and mercury.

PARTICULATE REMOVAL

In a condensing economizer particulates can be removed from the combustion gases along with water vapor. The captured particulates are then drained out with collected condensate for disposal. There are several mechanisms by which particulates can be transferred from the gas to the condensing water in an economizer including:

- Inertial Impaction - particles may impact on economizer tubes, water drops, or potentially on other impactors which may be added to the economizer system.
- Interception - when particles follow streamlines around impactors but come closer than one particle radius away from the impactor surface they can be captured by the mechanism of interception.
- Diffusion - particles may move to surfaces by simple brownian diffusion. Particle diffusivity decreases greatly as particle diameter increases and so this mechanism is most important for the smallest particles.
- Thermophoresis - in a temperature gradient, particles have greater momentum transfer from molecules on the hot side than on the cold side. This results in a driving force on the particle in the direction of decreasing temperature. It has been shown that thermophoresis can greatly increase the rate of diffusion of small particles to tube surfaces in coal combustion systems [4].

- Condensation Growth - If the gas is supersaturated locally with respect to water vapor, condensation of water may occur directly on particles, increasing their mass and improving the possibility that they may be removed by inertial impaction.

In addition to these mechanisms which promote the capture of particles in a condensing economizer there are mechanisms which can "create" particles in these systems:

- Condensation from gas phase - As flue gas cools in the economizer particulates may be formed as some species condense from flue gas. This may include sulfuric acid aerosol.
- Carryover from sprays - sprays used in condensing economizers will contain some very fine drops which may be carried out of the system. If these sprays contain dissolved or suspended solids they can contribute to the measured particulate emissions as the water evaporates either in the ducts or in the particulate sampling train.

Early field measurements of particulate removal across a single-stage economizer on a commercial boiler firing #6 fuel oil, showed removal efficiency to be 70% [5]. This unit was installed only for heat recovery. Continuous water sprays on the tubes were not used and there was no SO₂ control.

Studies of particulate removal across a single stage economizer were also conducted at BNL for coal-water slurry applications [6]. These economizers were being considered for use with coal-water slurries because of the relatively high flue gas latent heat losses associated with these fuels. Two experimental arrangements were used in these studies including oil-firing with injection of flyash upstream of the economizer and direct coal-water slurry firing. With the coarse particulate from coal slurry firing economizer particulate removal efficiency without the addition of water sprays to the economizer was as high as 95%. With the addition of water sprays removal efficiency increased to as high as 98%. In these single-stage economizers the addition of the water spray adversely affects heat recovery. This impact is avoided with the use of recirculated condensate in the two-stage IFGT design described earlier.

As a part of this study analysis was done to evaluate the relative contribution of each of the removal mechanisms discussed above. It was concluded that simple inertial impaction and interception were the most important mechanisms. Diffusion, enhanced by thermophoresis is the most important mechanism for the very fine particles but this mechanism does not usually contribute greatly to the overall removal efficiency. Conditions in the economizer were not found to be suitable for creating supersaturated water vapor and direct condensation growth. Figure 5 shows the measured removal efficiency as a function of particle diameter from these tests. Also shown in this figure is a prediction, based on a model developed at BNL, for particle removal based on impaction and interception by the economizer tubes. The general shape of the removal curve is consistent with the inertial separation mechanism although the actual performance is considerably better than predicted. This implies that the condensate and spray drops produced within the economizer are important impaction sites.

Performance tests of a pilot IFGT system were conducted in 1992 with an industrial boiler firing No. 6 fuel oil. The pilot unit used a slipstream of the flue gas from the 14,000 lb/hr boiler. In

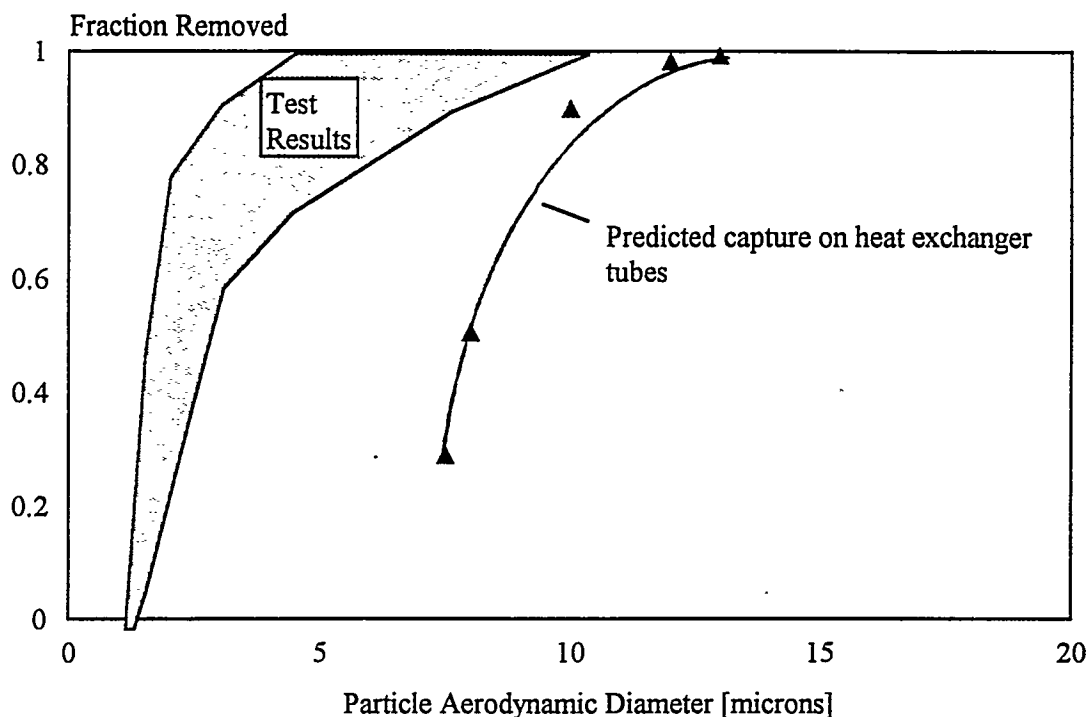


Figure 5. Results of studies with single stage condensing economizer and coal-slurry firing. Particle removal as a function of size, test results and prediction for capture by impaction and interception on tubes.

these tests particulate removal efficiency averaged 89.6% [3]. Performance testing with an IFGT unit has also been done at the Ravenswood Steam Station of Consolidated Edison. The IFGT treated a 25,000 lb/hr flue gas slip stream. Overall particulate removal efficiency was lower than in earlier tests, primarily because of very low inlet particulate loading. The particulate emissions after the IFGT were 0.005 lb/MMBtu.

In work at the Alliance Research Center, Babcock and Wilcox has conducted studies with coal - an upgraded lignite blend, and Orimulsion. The upgraded lignite coal blends consisted of upgraded North Dakota lignite coal blended with a Powder River Basin coal. Testing has been done in two modes: the condensing mode, in which condensate is not recirculated to spray nozzles and the only liquid in the two stage system is the water condensed from the gas and the IFGT mode, where sodium bicarbonate reagent is added to collected condensate before recirculating to spray nozzles. With coal firing particulate removal efficiency in the two stage unit was measured at 89% in the condensing mode. The mass median diameter of the entering flyash with coal firing was measured to be about 12 microns. With Orimulsion firing the overall particulate removal efficiency was much lower, 7%. The very poor removal efficiency with Orimulsion might be attributed to the size distribution of inlet particulates. The mass median diameter of the Orimulsion flyash is about 0.5 microns. However, the smaller size is not seen as the only factor. Examination of size removal vs. diameter curves with Orimulsion shows worse

collection efficiency than with coal for the same particle diameter. Differences in particulate characteristics are apparently important factors here. The Orimulsion ash is hygroscopic and it will adsorb water as it passes through the heat exchanger, resulting in an increase in particulate mass and size [3].

With coal-firing overall particulate removal efficiency in the IFGT mode of operation was lower (81%) than in the condensing mode. The expected reason for this is the carryover of small droplets from the reagent sprays into the exhaust ducts. These droplets evaporate either in the ducts or in the particulate sampling system and the residual solids contribute to measured particulates.

Recent work at BNL involves the two stage IFGT unit and residual oil firing. Work to date has included studies of the effects of water spray location within the IFGT, boiler load effects, and steam injection. The injection of steam into the transition section of a condensing economizer can create supersaturated conditions which may promote the growth of particles too small to be collected by inertial impaction into a size range large enough for capture in the second stage. Recently Sun [7] and Sun et al [8] used steam injection in the design of a "Condensational Growth Particle Scrubber" for a wastewater treatment plant. In the IFGT configuration latent heat of steam injected in the transition section can be recovered in the second stage.

Figure 6 provides a summary of some the results of some basic testing with the IFGT at BNL. These tests were done in the condensing mode - reagents for SO₂ control were not added. Details of the test conditions are provided in Tables 1 and 2 corresponding to two different load conditions. Generally, the benefits of steam injection and water sprays are seen to be similar and most significant under conditions of low boiler load. Without water sprays or steam injection (baseline conditions) particulate removal efficiency decreases with load - an expected result of the dominant influence of inertial impaction on particle capture. Outlet particulate loadings of .03 lb/MMBtu are typically obtained at baseline operating conditions and this can be compared with the US EPA New Source Performance Standard for industrial boilers of .1 lb/MMBtu.

In on-going research work at BNL under the CRADA program, emphasis is being placed on improving the capture of very fine particulates through the addition of plastic fiber mesh pads at the outlet of the economizer second stage. These pads must be operated with a water spray nozzle to prevent plugging. Current work involves evaluation of the effects of pad thickness and fiber diameter on pressure drop, flooding limits, and particulate capture. With a pressure drop of 2 inches of water pressure across the mesh pad overall removal efficiency is over 96% with residual oil firing and the outlet particulate loading is 0.004 lb/MMBtu. The pads used in this test had a fiber diameter of 0.016 inches and void fraction of 96%.

Table 1. Test Results with IFGT at BNL Under Moderate Load Conditions

Operating Condition		Baseline (no water sprays or steam)	Water spray on second stage	Water spray plus steam injection
Pressure drop across the economizer	inches of water	2.1	2.1	2.1
Flue gas flow at the economizer inlet	lb/hr	838	842	811
Gas temperature at the economizer inlet	F	452	446	469
Gas temperature at the economizer outlet	F	72	76	89
Flue gas oxygen at the economizer inlet	%	4.8	5.5	5.0
Particulates before the economizer	lb/MMBtu	.215	.176	.201
Particulates after the economizer	lb/MMBtu	0.032	0.024	0.017
Economizer particulate removal	%	85	86	91

Table 2. Test Results with IFGT at BNL Under Low Load Conditions

Operating Condition		Baseline (no water sprays or steam)	Water spray on second stage	Water spray plus steam injection
Pressure drop across the economizer	inches of water	0.57	0.62	0.77
Flue gas flow at the economizer inlet	lb/hr	447	435	426
Gas temperature at the economizer inlet	F	385	379	410
Gas temperature at the economizer outlet	F	67	71	94
Flue gas oxygen at the economizer inlet	%	5.7	5.2	6.0
Particulates before the economizer	lb/MMBtu	0.166	0.210	0.162
Particulates after the economizer	lb/MMBtu	0.057	0.040	0.010
Economizer particulate removal	%	66	81	94

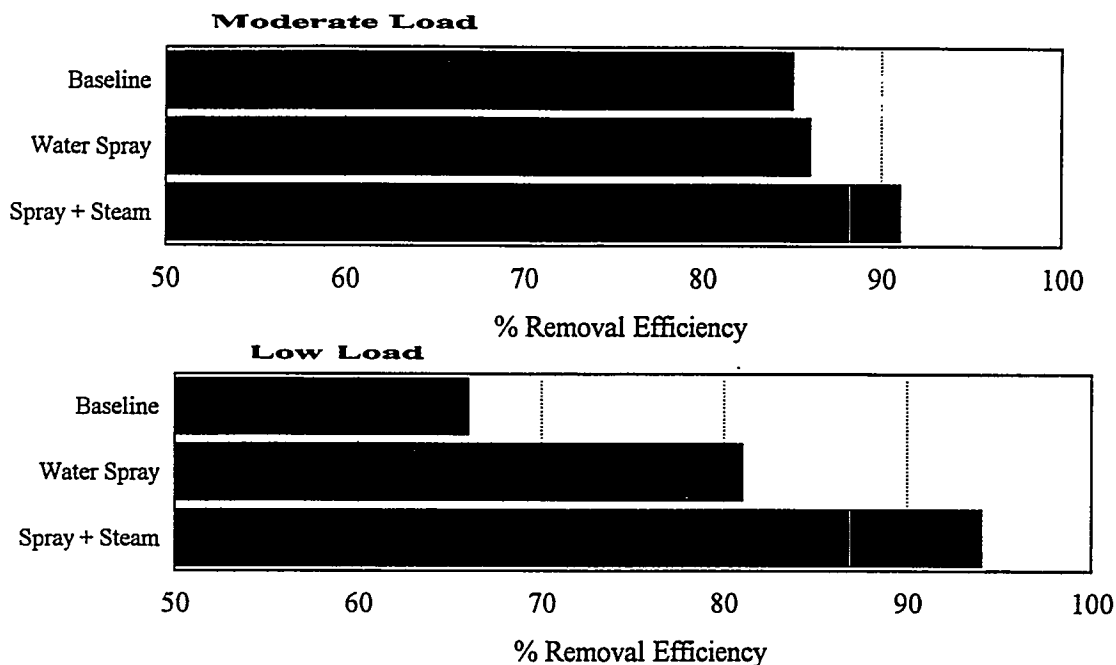


Figure 6. Results of selected basic tests at BNL with two stage condensing economizer. Boiler firing No. 6 fuel oil.

SULFUR DIOXIDE REMOVAL

Sulfur dioxide removal tests have been performed on a number of pilot sized IFGT units with different fuels. Tests performed on a pilot unit at Morgan Linen Company in Menands, New York burning a 1.5% sulfur No. 6 fuel oil achieved an average SO₂ removal efficiency of 99%. Similar tests performed in 1993 on the larger IFGT pilot unit at Consolidated Edison's oil fired Ravenswood plant achieved an SO₂ removal efficiency over 98%. Sodium bicarbonate was the alkali reagent used for these tests.

B&W's IFGT pilot unit was used to perform SO₂ removal tests using flue gas from burning upgraded lignite coal blends and Orimulsion. The coal blends contained about 0.5% sulfur. Orimulsion, an emulsion of bitumen and water, contains about 2.8% sulfur in the fuel. Sodium carbonate was used as the IFGT alkali reagent. The SO₂ removal performance of the pilot unit was evaluated for each fuel over a range of liquid to gas ratios (L/G, gallons/1000 ft³). At an L/G of 10, the SO₂ removal efficiency was about 98% for both fuels. Forced oxidation systems using limestone typically operate at an L/G of 100 to obtain similar removal efficiencies.

Most of the pilot IFGT testing to date used either sodium carbonate or sodium bicarbonate as the reagent. Alkali metals, such as sodium, are ideal because they are very reactive and soluble in water compared to alkaline earth materials, like calcium and magnesium. The cost for sodium reagent may be prohibitive, however, for applications where the sodium usage is high and the

spent sorbent is thrown away. A number of other solution scrubbing processes may also have potential for use with an IFGT. These include the Wellman-Lord process, lime dual alkali process, amine processes, limestone dual alkali process, and magnesium based processes. None of these processes have been tested with an IFGT. One constraint is that the solids content of the alkali reagent spray should be low to prevent abrasion of the Teflon covering on the tubes. The SO₂ removal efficiency, the disposal and recycling of waste, and system economics need to be considered for any new reagent.

For many industrial applications, an IFGT can be efficiently integrated into the process. A recent example of this is an IFGT that was purchased for Weyerhaeuser's pulp and paper plant in New Bern, North Carolina. The IFGT unit will recover heat and treat 100% of the flue gas from a 45 MW package boiler that burns a mixture of # 6 fuel oil and waste gas. The waste gas contains hydrogen sulfide which is converted to sulfur dioxide during combustion. The alkali reagent that will be used in the IFGT is sodium hydroxide which is available at the plant. The IFGT will remove 95% of the sulfur dioxide and produce 18 tons/day of sodium sulfite which will be used as make up for purchased salt cake used in the pulp and paper plant. For this application, the IFGT system is more competitive than conventional wet FGD technology - total annualized cost is lower by about \$1 million/year and installation and capital costs are lower by about \$6 million.

AIR TOXICS REMOVAL

IFGT air toxics removal performance tests have been performed for a number of fuels. The pilot tests performed at Morgan Linen using flue gas from a No. 6 fuel oil yielded removal efficiencies of 20% for nickel, 11% for chromium, 36% for lead, 84% for mercury, 14% for cadmium, and 25% for zinc.

Mercury removal tests were also performed on the B&W pilot IFGT unit while burning the upgraded lignite coal blends. For the combustion test conditions in the SBS, approximately 80% of the mercury in the coal partitioned with the particulate phase, while 20% was in the gas phase. In the gas phase, 80% of the mercury was in the ionic form and the balance was in the elemental form, which is in the range measured in studies of utility boilers. The reagent spray in the IFGT provided nearly complete removal of the ionic mercury. Gas phase mercury removal was 53 - 58% in the IFGT. The removal of the particulate mercury in the pilot IFGT parallels the particulate removal, 81 - 89%. The total mercury removal for the pilot IFGT was 69%.

FUTURE WORK

The U. S. Department of Energy (DOE), the Ohio Coal Development Office (OCDO), and the Electric Power Research Institute (EPRI) are currently providing support to determine the pollutant removal capabilities of the IFGT on flue gas generated from coal combustion. Phase I of this test program will focus on the removal efficiencies of the IFGT for a variety of pollutants controlled, or under consideration for control, under Title III of the Clean Air Act. Pollutant removal tests will be conducted on B&W's pilot scale IFGT using flue gas supplied by the 6 million Btu/hr Small Boiler Simulator shown in Figure 4. Tests will be conducted on up to four different coals. The identified pollutants of interest are particulate matter (PM₁₀ in particular), SO₂, NO_x, HCl, HF, Hg (total and speciated forms) and other trace elements. Additionally, the

ability of the IFGT to remove ammonia from the flue gas will be evaluated as a means of reducing ammonia slip, thereby, enabling greater NO_x removal in SCR systems than is currently achievable.

A one-year exposure test will also be conducted at the Electric Power Research Institute (EPRI) Environmental Control Technology Center (ECTC) as part of this test program. The ECTC uses a flue gas slip-stream from the coal-fired Kintigh Station power plant of New York State Electric Generating Corporation. A small condensing heat exchanger will be installed at the ECTC and exposed to flue gas at typical operating conditions for a one year period of time. Periodic inspections will be conducted to evaluate incremental and cumulative erosion and wear of the Teflon[®] covered tubes due to flyash abrasion.

SUMMARY

Condensing economizer offer an exciting opportunity to improve thermal efficiency and reduce pollutant emissions in a single unit. Studies done to date have indicated that these economizers can remove particulates larger than a few microns. Development work in progress is aimed at improving the capture of smaller particulates. The potential of these economizers has also been established for sulfur dioxide removal although additional application studies with sorbent systems of interest to potential users need to be done. Preliminary results also show that these economizers have potential for removing at least some air toxics and work is in progress to better understand and develop this potential.

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