Forced Internal Recirculation Burners for Boilers and Process Heating

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ABSTRACT

Burners for gas-fired boilers and process heating applications must meet increasingly stringent emissions requirements, particularly for nitrogen oxides (NO_x). Current regulations for boilers in most U.S. regulatory districts require 30 vppm or less NO_x, and some areas require below 9 vppm.[1] The methods commonly used to achieve these low emissions include low-NO_x burners that utilize external flue gas recirculation (FGR), combustion at high excess air, steam or water injection, or the use of a stack cleanup system such as selective catalytic reduction (SCR). But all of these measures reduce energy efficiency, either by increasing stack losses or by increasing electric power requirements. Stack losses are incurred from increased flue gas volumetric flow which reduces the amount of heat extracted from the combustion products, or, in the case of steam injection, from loss of a portion of the generated steam as latent heat in the stack. Power required for additional or higher-capacity blowers, pumps, and other auxiliary equipment add to the energy costs of the system.

The Gas Technology Institute (GTI), with support from the U.S. Department of Energy Office of Industrial Technologies (DOE-OIT) and from the natural gas industry, has developed a family of ultra-low-NO_x burners using a Forced Internal Recirculation (FIR) approach. (Khinkis, Abbasi, & Cygan, 1994) This burner design moderates flame temperature, and consequently NO_x, by the use of a distributed flame pattern and a metallic insert that uses the kinetic energy of the burner jets to induce a recirculation flow back to the root of the primary flames. The insert also re-radiates a substantial fraction of the combustion energy back to the low-temperature walls of the vessel. These burners have been field-demonstrated at industrial sites up to 60 million Btu/h and have consistently achieved NO_x emissions as low as 9 vppm without external FGR, steam injection, or high excess air (Giaier *et al.*, 1997; Rabovitser, Cygan & Knight, 1999; Cygan *et al.*, 2001). No catalytic cleanup system is required. This approach results in maintaining or even increasing the energy efficiency of the boiler through reduction in the flue gas temperature.

The paper will review the results of three FIR burner field installations and examine the potential and demonstrated energy savings of this approach in comparison with FGR, high excess air, steam injection, and SCR.

Introduction

The demand for ultra-low-NO_x combustion technologies at industrial facilities is increasing. Current regulations by California's South Coast Air Quality Management District require NO_x levels below 30 vppm for existing gas-fired units at or above 2 million Btu/h. New boilers in California and other parts of the U.S. are often limited to as low as 9 vppm

[1] All emissions are corrected to 3% O_2 basis.

NO_x. With expectations of even stricter NO_x emissions limits in the future, boiler operators need cost-effective, low-emissions burners for existing and new equipment.

The methods commonly used to achieve these low emissions include low-NO_x burners that utilize external FGR, combustion at high excess air, steam or water injection, or the use of a stack cleanup system such as SCR. But all of these measures reduce energy efficiency, either by increasing stack losses or by increasing electric power requirements. Stack losses are incurred from increased flue gas volumetric flow which reduces the amount of heat extracted from the combustion products, or, in the case of steam injection, from loss of a portion of the generated steam as latent heat in the stack. Power required for additional or higher-capacity blowers, pumps, and other auxiliary equipment add to the energy costs of the system.

Thus far, the external FGR approach has dominated the 15-30 vppm NO_x retrofit market, and ultra-low-NO_x emissions performance (below 9 vppm) has been demonstrated with very high FGR levels, but burner stability, energy efficiency, and turndown are all compromised, leading to higher costs.

As an alternative to these methods, GTI has developed the Forced Internal Recirculation (FIR) family of burners with funding support from the Gas Research Institute (GRI), U.S. Department of Energy Office of Industrial Technologies (DOE-OIT), Southern California Gas Company, and GTI's Sustaining Membership Program. The main feature of the FIR approach is the distribution of a premixed or partially premixed flame around a metallic insert or "recirculation sleeve" that induces recirculation of combustion products back to the root of the flame. The recirculation sleeve also anchors the flame and radiates to the cold boiler or process heater walls, increasing heat transfer and reducing peak temperatures. In this way, NO_x is drastically reduced without the efficiency penalties incurred by external FGR, steam injection, or high-excess-air combustion. The FIR burner can be applied to a wide range of industrial boilers and process heaters including those used in the paper, chemical, petroleum, food, and steel industries.

FIR Burner Concept

The FIR burner (U.S. Patent No. 5,350,293) combines premixed staged combustion, internal recirculation of first-stage combustion products forced by the kinetic energy of the jet, and heat removal by radiant heat transfer to the lower-temperature combustion chamber walls. One version of the FIR burner is shown in Figure 1. Depending on the application and the end-user requirements, the fuel-air mixing and distribution is achieved in several different ways. Fully premixed, partially premixed, and nozzle-mixed methods have been used for both first and second stages. Recirculation sleeves have been made from various high-temperature alloys with excellent results.

These techniques promote stable, uniform combustion, minimize peak flame temperatures, prevent the formation of high-oxygen pockets, and enhance heat transfer to reduce second-stage combustion temperatures. The result is reduced NO_x formation while maintaining good fuel burnout characteristics.

The FIR burner was originally conceived as an air-staged burner, shown in Figure 2, but the design has evolved for specific boiler requirements to include fuel/air-staged designs. This adaptation has involved a variety of design iterations.

Figure 1. Forced Internal Recirculation Burner

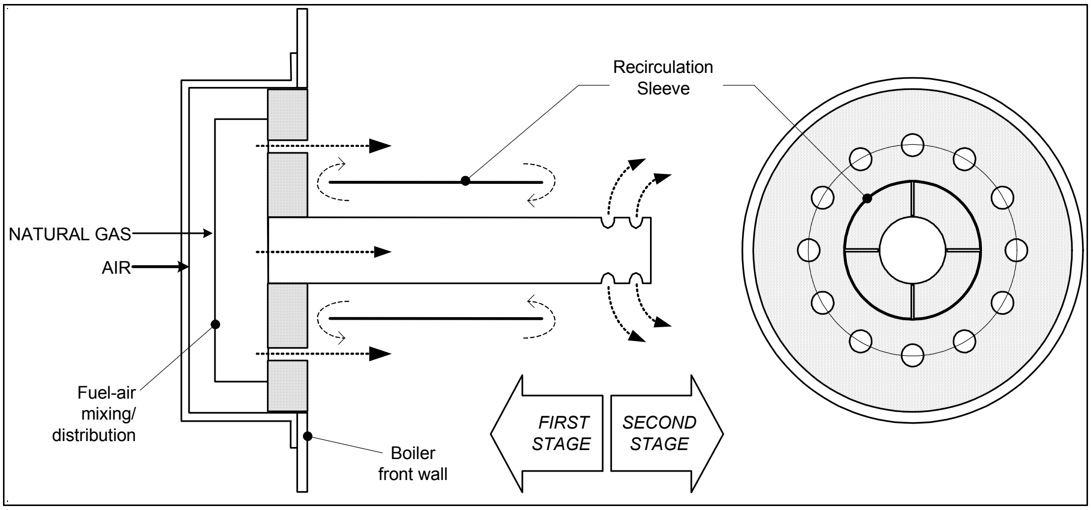
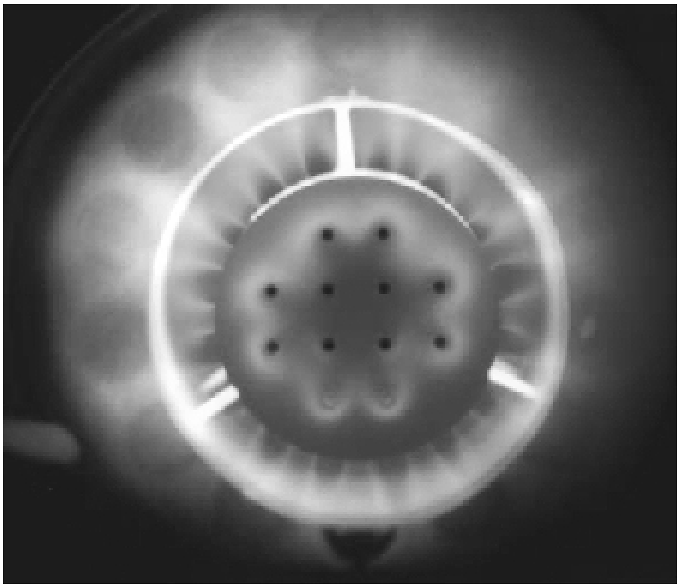


Figure 2. Photograph of Air-Staged FIR Burner Flame



Development of the FIR Burner

GTI (previously IGT) began development of the FIR burner in 1992 as an internal R&D project. The first step was fabrication of a 6-million-Btu/h flexible test burner for proof-of-concept tests on a boiler/heater simulator. Early results were favorable enough to enlist support from GRI and the natural gas industry, and NO_x levels as low as 8 vppm were achieved through design improvements.

With laboratory success in hand, GTI teamed up with Detroit Stoker Company (DSC), and in 1997, the first field demonstration project was started on a watertube boiler, while a parallel effort with firetube boilers was initiated. Three field demonstrations were completed in partnership with DSC. In 2001, a license was granted to Johnston Boiler Company to market the FIR burner on firetube boilers, and in 2002, a licensing agreement was signed with Coen Company Incorporated to build and sell FIR burners for package watertube boilers. Efforts are continuing to find commercial partners in other markets including field-erected boilers, boilers that utilize gaseous fuels other than natural gas, and process heating applications.

FIR Burner Field Demonstrations

Detroit Stoker Company

A 20-million Btu/h commercial prototype FIR burner, designed and built jointly by GTI and DSC, was tested at the DSC manufacturing facility in Monroe, Michigan. The boiler is used to generate process steam and for heating the 400,000-square-foot facility during the winter months.

Equipment. The host boiler was originally a coal stoker, but was converted to natural gas firing before the beginning of this demonstration. Existing burner controls were integrated with the FIR burner for testing. Water-cooled panels were installed over the refractory floor at the beginning of the demonstration to determine the effect of cooling surface on emissions.

The commercial prototype burner was designed with adjustable geometry to evaluate key design parameters including the primary and secondary air velocities, recirculation insert length, distance between recirculation insert and primary nozzle plane, distance between recirculation insert and secondary air tip, and effect of tertiary air. Figure 3 shows the burner installed at the host site.

Testing. The FIR burner was installed at DSC in September 1997, and testing began with variations in geometry and operational parameters. Two test campaigns were conducted at DSC:

- FIR burner/water-cooled floor – starting in 1997, the boiler included water-cooled panels on the floor, resulting in approximately 80% internal wall coverage by a cooling surface;
- FIR burner/refractory floor – prior to the 1998 heating season, the water-cooled floor panels were removed, resulting in approximately 60% internal wall coverage by a cooling surface.

Data from testing at DSC are summarized in Table 1. With the water-cooled floor, NO_x concentrations ranged from 6.7 vppm at 11 million Btu/h to 8.3 vppm at 5 million Btu/h. Excess air in the stack ranged from 14.9% to 12.1% (3.0% to 2.5% O_2) and maximum CO emissions were 40 vppm, measured at 25% load. Additional tests were performed which included automatic start-up and operation, load swinging from 20 to 100% at regular and increased speed, and boiler shut-down.

Figure 3. 20-Million-Btu/h FIR Burner Installed on DSC Watertube Boiler

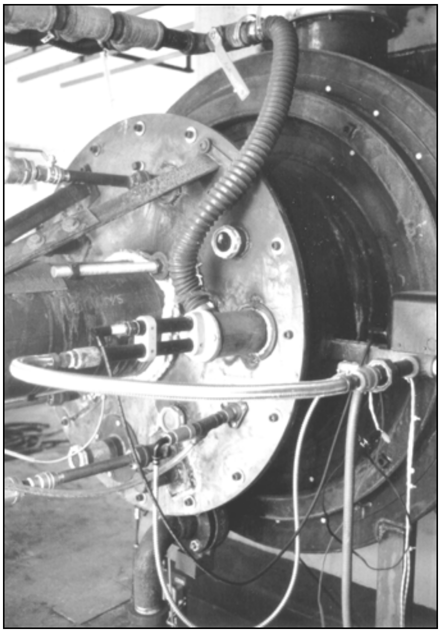


Table 1. Data from 20-Million-Btu/h FIR Prototype Burner at DSC Facility

	Water-Cooled Floor			Refractory Floor		
Firing Rate, million Btu/h	5	11	20	11	15	19
Load, %	25	55	100	55	75	95
O_2, %	3.0	2.5	2.9	3.0	2.8	2.1
NO_x, vppm*	8.3	6.7	7.2	8.0	9.9	8.6
CO, vppm*	40	18	3	10	19	11

* Emissions corrected to 3% O_2

With the refractory floor, NO_x concentrations ranged from 8.0 vppm at 11 million Btu/h to 9.9 vppm at 15 million Btu/h, but with a slightly lower value at maximum fire. It was not possible to test at lower loads because the host facility required steam for heating and manufacturing. Excess air in the stack ranged from 14.9% to 10.0% (3.0% to 2.1% O_2) and CO emissions were consistently below 25 vppm. As before, additional tests were performed which included automatic start-up and operation, load swinging from 55 to 100% at regular and increased speed, and boiler shutdown.

The FIR burner at DSC has been in unattended operation for over four years, and has logged over 10,000 hours with high reliability and no deterioration of performance.

Vandenberg Air Force Base

A 2.5-million-Btu/h commercial prototype FIR burner, designed and built jointly by GTI and DSC, was tested at the Vandenberg Air Force Base (VAFB) in Santa Barbara County, California.

Equipment. A 4-million-Btu/h Kewanee firetube boiler, shown in Figure 4, was selected for retrofit demonstration of the FIR burner. The boiler, is used to generate process steam and heat for the officers' dining facility at the base, was oversized for its site requirements, and so was de-rated to 2.5 million Btu/h for this demonstration.

The VAFB commercial prototype burner was designed and fabricated as a scaled-down version of the air-staged laboratory burner.

Testing. The FIR Burner was pre-tested on a 20-inch-ID boiler simulator in GTI's Combustion Laboratory, and then shipped to the field test site for installation. The test program consisted of two campaigns:

- Baseline testing – baseline data was obtained from the boiler with its existing conventional Kewanee burner;
- FIR burner/air staging – shakedown and parametric performance testing of the FIR burner, which took place during January-April 1999.

Results of the field demonstration are summarized in Table 2.

Figure 4. 2.5-Million-Btu/h FIR Burner Installed on Vandenberg AFB Firetube Boiler

Table 2. Data from 2.5-Million-Btu/h FIR Burner at Vandenberg AFB

Firing Rate, million Btu/h	0.5	1.0	1.5	2.0
Load, %	22	40	60	80
O_2, %	4.5	3.4	3.5	2.3
NO_x, vppm*	9.8	13.3	14.4	17.2
CO, vppm*	11	13	7	13

* Emissions corrected to 3% O_2

- At baseline conditions with the original burner, NO_x emissions ranged from 45 to 80 vppm;
- With the FIR burner, NO_x ranged from 9.8 vppm at 0.5 million Btu/h to 17.2 vppm at 2.0 million Btu/h a 75% reduction compared to baseline levels; tests at higher firing rates were not possible due to limited steam demand;
- Excess air in the stack ranged from 24.5% (4.5% O_2) at 0.5 million Btu/h to 11.0% (2.3% O_2) at 2.0 million Btu/h;
- CO emissions were stable at <15 vppm across the load range;
- Testing at firing rates above 2.0 million Btu/h was not possible because of limited steam demand.

The FIR burner has been in continuous operation at the Base, in fully automatic mode, since April 1999.

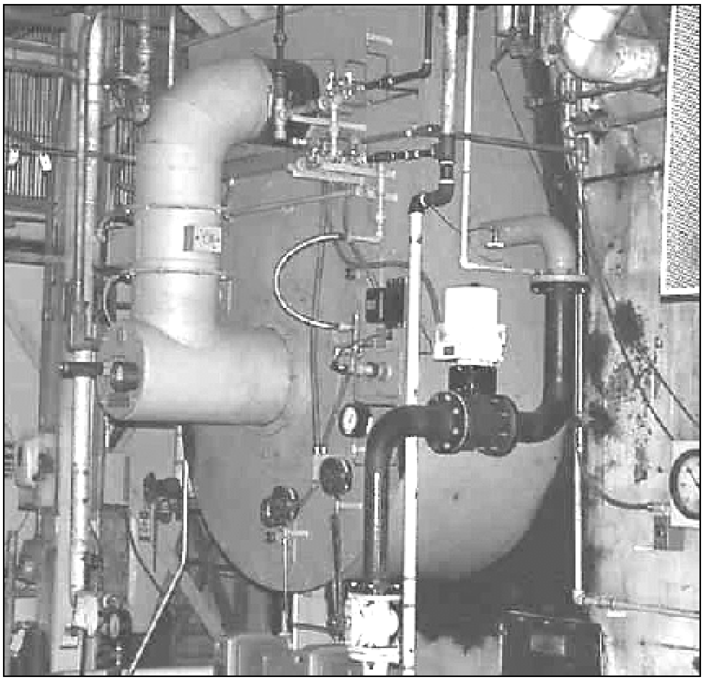
Southern California Brewery

GTI and DSC designed and built a 60-million-Btu/h commercial prototype FIR burner for demonstration at a commercial brewery in Southern California. The site included four identical boilers to provide process steam, two of which were generally in operation to handle normal load swings. All four boilers had been previously fitted with low-NO_x (30 vppm) gas burners using external FGR to comply with regional regulations. The boilers were also equipped with individual CEM's for monitoring NO_x, CO, and stack oxygen.

Equipment. The selected boiler is an E. Keeler D-type watertube boiler with approximately 48,000 lb/h steam capacity. After a conversion permit from the South Coast Air Quality Management District was granted, the original low-NO_x burner was removed and the boiler was retrofitted with an FIR burner. The 60-million-Btu/h commercial prototype burner, shown in Figure 5, was designed cooperatively by GTI and DSC and fabricated by DSC.

The burner was configured to use the host site's existing combustion controls. The burner package includes a blower and fuel control valve, and initially used the existing FGR controls for secondary air trim. Various modifications were made to the original burner design, which will be described below.

Figure 5. 60-Million-Btu/h FIR Burner on California Brewery Watertube Boiler



Testing. The field testing was divided into three campaigns:

- Baseline testing – baseline data obtained from the boiler with its existing burner, a Faber low-NO_x burner utilizing external FGR;
- FIR burner/air staging – shakedown and parametric performance testing of the FIR burner in its initial configuration during September-December 1999;
- FIR burner/fuel-air staging – testing of the burner after significant modifications to mitigate high CO emissions related to short-circuiting across the tangent tube wall separating the furnace from the convective pass of the boiler; these tests were conducted during July-October 2000.

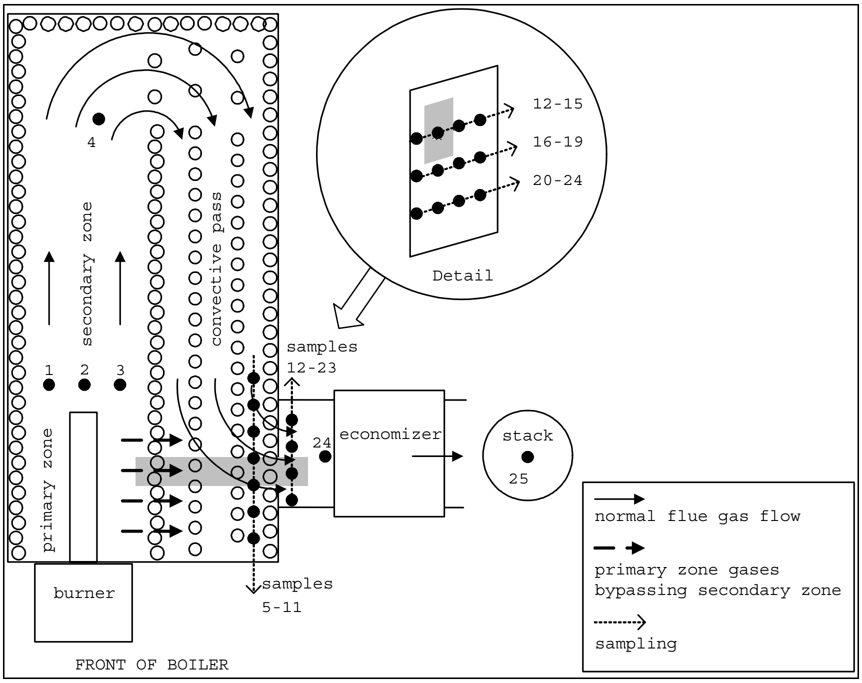
Testing with the previous burner to establish a performance baseline confirmed that external FGR up to 60% of total flue gas was required to hold NO_x below 30 vppm in compliance with the facility air permit. CO emissions were in the range of 150 to 180 vppm.

The existing burner was removed and replaced with the FIR burner in August 1999. Shakedown of the FIR burner confirmed stable operation from 12 to 60 million Btu/h and NO_x levels were as low as 9.2 vppm. However, CO emissions were very high (~900 vppm). It was believed at the time that the high CO levels were a result of poor mixing in the secondary zone, and design changes were implemented accordingly. The team implemented three modifications to the secondary air tip design for enhanced mixing and additional CO burnout, added a register to control the amount of primary air, and modified the primary nozzle design to obtain more uniform combustion. Despite these changes, stack emissions were still too high (13.6 vppm NO_x and >1000 vppm CO). Sampling of the fuel-air mixture at four locations in the primary distribution plenum and analysis by gas chromatography (O_2,

N_2, and CH_4) showed good uniformity, ruling out poor fuel distribution as a source of problems.

The project team then began a detailed sampling campaign to determine the origin of high CO, as shown in Figure 6. Sampling at three locations about 14 inches downstream of the secondary air tip (pts 1-3) showed much lower CO levels (70-380 vppm) than the stack. Another sampling probe inserted from the back of the boiler 6 feet into the combustion chamber (pt 4), showed very low CO levels (4-6 vppm). But sampling at locations just upstream of the economizer (pt 24) and at the transition to the economizer still revealed CO levels ranging from several hundred to several thousand vppm. Based on these findings, we concluded that CO-rich combustion gases from the substoichiometric primary zone were bleeding though the tangent-tube boiler wall separating the combustion chamber from the convective pass. This was confirmed by sampling inside the convective pass (pts 5-11) and in the transition duct from the convective pass to the economizer inlet (pts 12-23).

Figure 6. Sampling to Determine Source of High Stack CO Levels



To reduce the wall leakage, 1/4-inch steel rods were stitch-welded between the tangent tubes, and the remaining gaps were filled with trowelable refractory. This measure reduced stack CO by about 90%, but CO levels were still in the range of 300-500 vppm. Clearly, a permanent burner-based solution was needed.

This need was addressed by reconfiguring the burner to a design with lean first-stage combustion—so-called *Fuel/Air Staging*. GTI and DSC modified the prototype burner, and field testing resumed from July through October 2000. The burner operated smoothly from 15 to 60 million Btu/h, and NO_x and CO emission targets were met at 18 to 60 million Btu/h as indicated by the data in Table 3. CO emissions at the lowest load (15 million Btu/h) continued to be slightly above the 30 vppm target, but were well within the site permit requirement of 400 vppm.

Table 3. 60-Million-Btu/h FIR Burner Performance with Fuel-Air Staging (Oct 2000)

Firing Rate, million Btu/h	15	31	41	51	60
Load, %	25	52	68	85	100
O_2, %	4.6	4.6	4.5	5.0	5.7
NO_x, vppm*	7.4	7.0	8.6	8.5	7.7
CO, vppm*	60	5	6	3	2

* Emissions corrected to 3% O_2

This performance represents a 65% NO_x reduction and a 96% CO reduction compared to the previous (baseline) burner, *without* the use of external FGR. Furthermore, after comparing stack temperatures and fan power demand, and accounting for the slightly elevated excess air requirement for optimal FIR operation, the net energy efficiency improvement was about 1.0%, which was attributed to the elimination of external FGR.

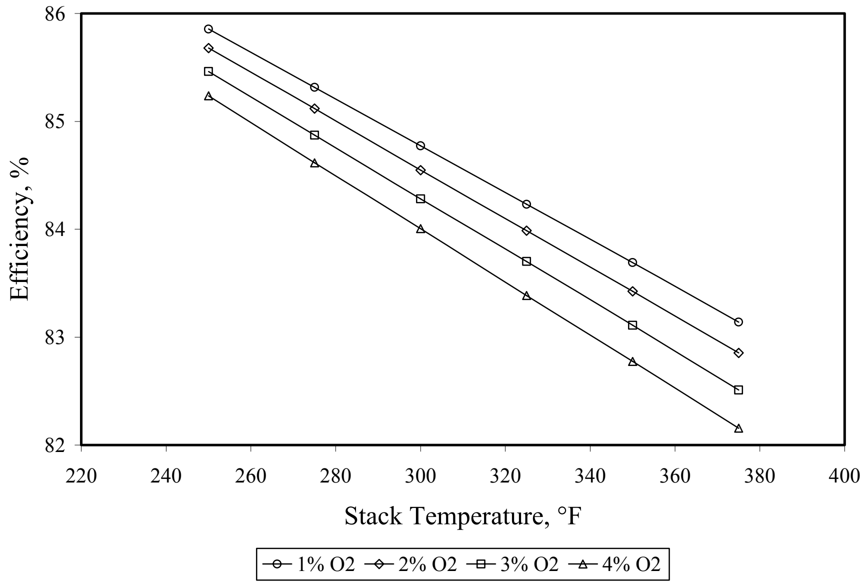
The 60-million-Btu/h prototype FIR burner has been operating in automatic regime since July 20, 2000, providing steam for plant operations. The brewery was satisfied with the FIR burner performance and decided to purchase the burner. A permit was obtained from the South Coast Air Quality Management District for continuing burner operation, and ownership of the burner was transferred to the host site in September 2001. The host site reports no problems with the FIR burner, and has been using Boiler No. 3 for baseload steam generation because of its low emissions and stable performance.

Potential for Energy Savings

The main goal of FIR burner development has always been emissions reduction. However, the burner is designed also with energy efficiency in mind. In a boiler, the primary energy loss is in the stack gas, which carries both sensible and latent heat out to the atmosphere. For any given fuel, the energy efficiency can be directly calculated from the stack gas volumetric flow and the stack temperature. The stack gas flow can in turn be calculated from the stack O_2, as shown in Figure 7 for natural gas.

For any given boiler, the use of FGR will increase total mass flux through the system up to the FGR takeoff, and accordingly decreasing residence time of hot gases in the furnace and convective pass, and decreasing radiative heat transfer because of the lower flame emissivity. While there is a competing effect from increased convective heat transfer from the higher mass flux, the net effect will generally be an increase in the stack temperature and lower fuel efficiency (EPA 1992). In addition, the use of FGR increases the back pressure and consequently the fan horsepower requirement, which increases electricity cost. Forced FGR requires an additional fan and its associated capital cost. Induced FGR, the preferred method for most manufacturers, does not require a separate fan but does increase the load on the main combustion air fan with its consequent energy (and possibly equipment) costs.

Figure 7. Energy Efficiency as a Function of Stack Temperature and Oxygen



Other methods that are used to reduce NO_x also incur energy penalties. Some ultra-low-NO_x burners use high excess air (>7% stack O_2) to achieve NO_x below 9 vppm. This method, while effective, reduces energy efficiency because of the increased flue gas volume and also increases the fan load because of the high air requirement. Direct water or steam injection have also been used. The added water vapor reduces flame temperature and increases jet velocity, resulting in lower NO_x emissions, but water injection consumes a portion of the energy released by combustion because of its high latent heat of vaporization, which is not recovered downstream of the boiler. Steam injection does not steal energy directly from the flame, but steam is the product of the boiler, and each 1% of steam diverted to the combustion system represents a 1% loss of energy efficiency. Adding water vapor to the flue gas may also present problems in installations where stack temperatures must be carefully controlled to avoid condensation and the attendant corrosion problems (EPA 1992).

Table 4 shows the estimated performance of a conventional burner with each of these modifications, assuming that dilution to a certain theoretical adiabatic flame temperature would result in the same level of NO_x formation regardless of the type of diluent (flue gas, air, or water vapor) used. Although this is a gross simplification of complex NO_x formation chemistry, the analysis shows that boiler efficiency can be significantly degraded. The table shows that FGR would result in the least reduction in efficiency, about 1.6%, while steam injection would result in the largest reduction, about 20.1%.

Finally, catalytic methods—chiefly SCR—can be used to reduce NO_x to very low levels. However, SCR requires a significant capital investment, requires the storage and use of chemicals (ammonia or urea) in the boiler house which may require added safety precautions and facility management, restrict the operational flexibility of the boiler because of the strict flue gas temperature and velocity requirements to operate within specified limits, and also incur additional costs in the form of catalyst purchase, chemical purchase, and electricity for pumps.

Table 4. Comparison Table for Diluents Options (Constant Steam Production)

	Unmodified burner	FGR	High excess air	Water injection	Steam injection
Adiabatic temp, °F	3360	2820	2820	2820	2820
FGR %	0	31	0	0	0
Excess air ratio	1.10	1.10	1.45	1.10	1.10
Water injected, lb/h	0	0	0	750	0
Steam injected, lb/h	0	0	0	0	1191
Flue gas temp, °F	500	560	530	525	520
Boiler efficiency, %	88.2	86.6	84.4	77.0	68.1

The FIR burner offers a relatively simple alternative to these NO_x control methods that does not reduce energy efficiency, and may in some cases actually increase energy efficiency slightly because of the enhanced heat transfer to the furnace walls. The burner does not require special sensors or advanced controls and can usually be retrofitted to existing burner controls.

This project demonstrates that combustion system research and development can deliver effective approaches to reduce boiler emissions without resorting to methods that compromise energy efficiency.

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