DOE/EE-0217

Assessment of Donlee 3000-Horsepower TurboFireXL Boiler

Industrial boiler found to provide enhanced efficiency, low NO_x emissions for commercial and industrial applications

Technology Installation Review

A case study on energy-efficient technologies

Prepared by the New Technology Demonstration Program

The package boiler concept has been around for more than 60 years, and there are many types available. Boilers provide steam or hot water for industrial and commercial use. The TurboFireXL boiler, shown in the figure below, is a non-traditional boiler that combines firetube and watertube technology. The boiler is housed in a cylindrical body encasing a combustion chamber with watertubes extending along the waterwall. Donlee Technologies developed the design with support from the Gas Research Institute (GRI).

The watertube furnace section is connected to the firetube convective section in the steam drum by a turning box with the waterwall side and end walls. The waterwall tubes have an outlet leading to a top header that is connected to the steam drum and two water inlets from the bottom water header. The turning box end wall contains points to access the watertube furnace section and the steam drum and firetube sections. The single-pass convective section is located in the steam drum. The heat transfer is enhanced between the flue gas and the water in the steam drum by the addition of turbulators (metal gas flow restrictors).

The two-staged combustion coupled with the cyclonic burner is pivotal to the unit's efficiency and low NO_x and CO emissions. The cyclonic swirling flame discharges combustion gases directly into the watertube boiler section. The firing rate and fuel and air allowances are controlled by a microprocessor-based controller and boiler pressure sensor (GRI 1994). A water/steam mixture is formed as the water rises from the bottom water header through the tubes in the boiler wall. The steam drum, designed as a firetube unit, has flue gases flowing through tubes to provide heat transfer to the water in the drum. An economizer utilizes the remaining heat in the flue gas to preheat the boiler feedwater. Water is taken from the steam drum to the header by natural circulation generated by the rising steam/water mixture. A steam quality that is greater than 99.5 % is produced as the steam flows through the separator at the top of the drum.

This *Technology Installation Review* (TIR) describes the TurboFire XL industrial boiler technology and presents information on existing applications, energy-saving mechanisms, installation requirements, and relevant case studies.

TurboFireXL Boiler Photo courtesy of Donlee Technologies

Background

The industrial sector consumed 20,140 TBtu of energy in 1992, which is 37% of the total energy consumption in the United States. Natural gas accounts for 45% of this energy use, and boiler systems are the largest end use in the industrial sector. Boilers account for approximately 40% of all industrial energy consumption for heat and power. Thirty-six percent of boilers use natural gas (EIA 1991). Industrial boilers range in size from 125 to

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2500 horsepower (hp). The watertube and firetube are the two major types of industrial boilers. Firetube boilers are used predominantly in applications requiring pressures below 300 psig and sizes ranging from 100 to 750 hp. The stresses created in the boiler's combustion tube limit the pressure and capacity.

The boiler's combustion gases pass through tubes surrounded by the boiler's water. For high-pressure (up to 850 psig, 750 to 2500 hp) and high capacity (up to 90,000 lb/hr of steam) applications, watertube boilers are used. In watertube boilers, water circulates within externally heated tubes. An advanced gas-fired system that is more fuel-efficient and aids in meeting stricter environmental regulation is needed.

The TurboFireXL boiler, a clean-burning combination watertube/firetube boiler, uses a convective steam drum and incorporates a unique cyclonic burner concept. This report describes results from an evaluation of the performance of Donlee's 3000-horsepower TurboFireXL boiler. The evaluation indicates that the boiler maintained efficiencies greater than 81% down to a 10:1 turndown (minimum-firing) operating on gas and oil. The NO_x and CO_2 emission levels remained significantly lower than the EPA's requirement and those of standard boilers. Emissions were lowest at the minimum-firing load for both fuels.

Technology Description

The TurboFireXL boiler combines watertube and firetube designs with a cyclonic burner and staged combustion system. The major parts of the boiler are shown in Figure 1. Technology information was extracted from the general description section of Donlee Technologies Inc.'s boilers' data manual.

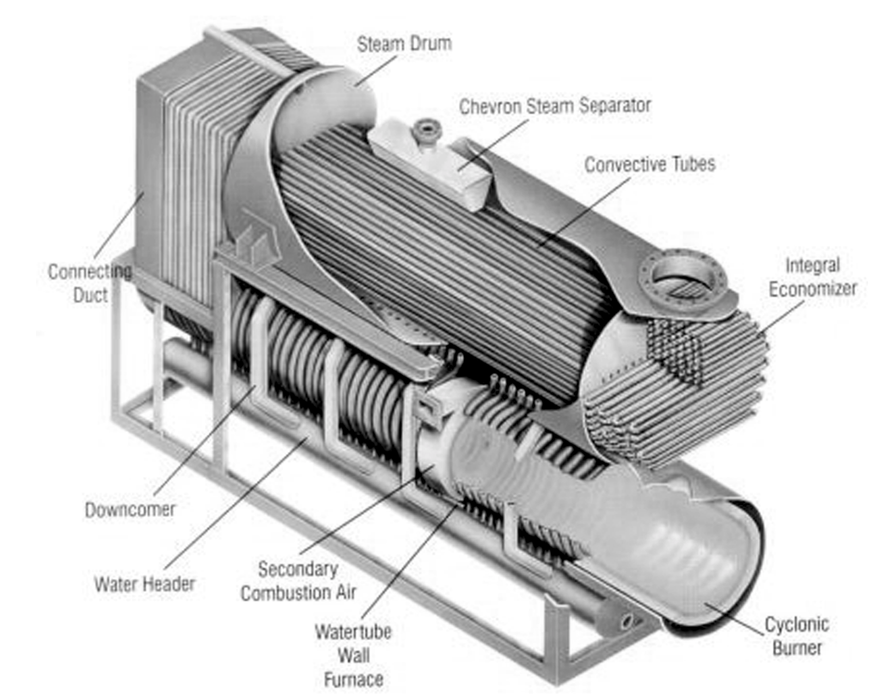

Illustration courtesy of Donlee Technologies

Figure 1. TurboFireXL boiler cutaway.

Cyclonic Combustion

Staged cyclonic combustion is executed in a cylindrical refractory burner section by injecting primary combustion air and fuel tangentially at high velocity through nozzle ports. The primary zone of the staged cyclonic burner is fired fuel rich in a combustion process characterized by intense swirl combustion flow and high internal recirculation. Combustion is completed by injecting secondary air through ports in a refractory ring in the waterwall section. The air staging of cyclonic combustion contributes to reducing NO_x emissions in the boiler. Theoretically, fuel rich combustion of well-mixed air and fuel prevents the formation of NO_x in the primary zone, since all the oxygen in the air is burned in the combustion of the fuel. Thus no oxygen is available to react with the nitrogen in the air to form nitrogen oxides. Since fuel rich combustion occurs at reduced flame temperature, the primary combustion temperatures are reduced in the staged combustion. The primary zone reduced gas temperature assists in minimizing the NO_x formation in the secondary stage.

In the primary zone burner, combustion air and fuel are mixed using a cross flow nozzle. The mixing is further improved by the enhanced recirculation induced by the refractory target orifice located at the secondary air injection ring. By injecting secondary air into the target orifice, good mixing of secondary air with the primary zone gases is accomplished. Low CO emissions and low excess air over a high turndown range (10:1) can be realized due to the proper mixing in the staged cyclonic burner. The turndown is the ratio between full load output and minimum load output. Having a high turndown reduces the frequency of on/off cycling.

NO_x formation is further reduced by the steam injection system (up to 80% possible reduction) located in the staged cyclonic burner. The steam is injected with natural gas into the primary zone of the burner and causes a lower local flame temperature. The injection of a small amount of steam (less than 0.05 lb of steam per ft^3 of fuel flow) achieves NO_x emissions < 25 ppm and slightly reduces the boiler efficiency (typically—3–10%). For oil firing, steam is injected through the swirler and annulus area of the oil gun. Other industry methods of NO_x reduction are low excess air (natural gas fuel only—5-10% reduction), flue gas recirculation (60–70% reduction), and selective catalytic reduction (SCR—up to 90%).

The cyclonic combustion has a significant convective heat transfer component resulting from the swirling cyclonic flow, which increases the heat transfer. This increased heat flux reduces the surface area needed to generate the required steam.

Watertube Wall Boiler

The waterwall boiler section is a cylindrically shaped container. It contains 2-inch-diameter waterwall tubes on 3-inch center-to-centers. A gas-tight design for the high-pressure operation and containment of flue gases is achieved by waterwall tubes continuously seal-welded to a fin membrane. The watertubes form a wishbone configuration with one outlet connection for steam/water mixture to a steam drum and two inlet connections for water from a bottom water header. The wishbone configuration promotes circulation of the steam/water mixture in the membrane tubes to the steam drum. The bottom water header is protected from the flame impingement by removable cast refractory blocks.

The refractory burner section is flanged to the watertube wall. The secondary air section is seal-welded to the watertube wall. The target orifice in the waterwall is attached in the secondary air section. A turning box with watertube side walls and end walls connects the watertube boiler section and the firetube section in the steam drum. The turning box waterwall tubes also have a wishbone configuration with an outlet to a top header that connects with the steam drum and two water inlets from the bottom water header. A man-way to access the watertube boiler section is located at the end wall of the turning box. In addition, there are two viewing ports; one port gives a view of the flame from the burner and the other provides a view of the furnace and flame from the rear turning box.

Turning Box and Economizer

The watertube wall design of the sides of the turning box between the waterwall section and the steam drum provides additional heat transfer surfaces from the flue gas to the water-steam mixture (which increases boiler efficiency) and reduces refractory.

Standard and optional economizers are available based on site requirements. The standard economizer is a finned tube integral design, incorporating several parallel serpentine coils, connected to common top and bottom headers. The inlet and outlet of each coil are welded to a curved plate, and the plate is fitted onto the shell. Spacers that provide additional support and maintain spacing for the flue gas are welded between the elbows of each economizer coil. The flue gas is prevented from bypassing the economizer by flow diverters. A superheater, consisting of a compact serpentine tube array, is located in the turning box. The superheater is optional but helps produce higher overall steam generation efficiencies.

Burner and Steam Drum

The burner chamber has 10 to 14 air ports depending on the boiler size. The cyclonic burner has a cross-flow nozzle mixing design. Ports for the pilot, flame scanner, and optional oil-firing nozzle are in the burner front cover. The secondary air ports are located in the target orifice and the ports are tangential to the inner diameter of the orifice.

The internal components of the steam drum include a steam separator and convective tubes with option for a chemical feed and surface blowoff system. The convective tube bank further heats the steam/water mixture before releasing it to the steam outlet through the steam separator at the top of the drum. The separator is installed against the crown of the steam drum to provide maximum water/steam disengagement height. Typically, the internal surface of the convection tubes is ribbed to promote heat transfer. The diameter of the tubes is 2.5 inches for 30,000 lb/hr and 3 inches for 65,000 lb/hr and 100,000 lb/hr boiler units.

Case Studies

TurboFireXL boilers can be used in any application where traditional boilers have been used. This advanced natural-gas-fired boiler was developed for industrial and commercial use. This section briefly highlights three applications where the TurboFireXL boilers are being used. The first installation is a 1000-hp TurboFireXL field test unit at Knouse Foods' Peach Glen facility in Pennsylvania installed in 1992. Knouse uses its boiler for the sterilization of fruit and for heating the plant and administrative offices. The boiler produces 34,500 lb/hr of steam at a pressure of 125 psig with steam quality greater than 99.5%. The steam quality exceeds the clean steam specifications of the food processing industry. The boiler heats the entire building when it is operating at 75% output and is saving $400/day in heating costs during peak period of operation and up to $90,000 annually on steam generation. The boiler is supplying the function that two traditional boilers supplied in the past. The Knouse boiler operates at an average efficiency of 85% over a turndown ratio of 10 to 1 with full modulation. The integral economizer of the boiler helps meet the efficiency requirements. Boiler start-up takes 30 to 45 minutes.

The second boiler is located at a paper mill owned by Cascades Niagara Falls, Inc., in New York. The 1800-hp boiler was installed in 1993 primarily as a steam source (60,000 lb/hr of steam). The third is a 3000-hp unit (100,000 lb/hr of steam) that has been constructed for SCM Chemicals in Ashtabula, Ohio. The unit is designed to operate at 250 psig and produce superheated steam at above 600°F (GRI 1994; Donlee).

Energy-Saving Mechanisms and Benefits

Industrial steam boilers consumed 2.6 quads (~30%) of the 8.9 quads of natural gas consumed in the United States in 1994. Industrial boilers range in size from 125 to 2500 hp. The watertube and firetube are the two major types of industrial boilers. Firetube boilers are used predominantly in applications requiring pressures below 300 psig and sizes ranging from 100 to 750 hp. The stresses created in the boiler's combustion tube limit the pressure and capacity. The boiler's combustion gases pass through tubes surrounded by the boiler's water. For high-pressure (up to 850 psig, 750 to 2500 hp) and high-capacity (up to 90,000 lb/hr of steam) applications, watertube boilers are used. In watertube boilers, water circulates within externally heated tubes. An advanced gas-fired system that is more fuel-efficient and aids in meeting stricter environmental regulations is needed. The TurboFireXL boiler, a combination watertube/firetube boiler, uses a convective steam drum and incorporates a unique cyclonic burner concept.

The Donlee Technologies TurboFireXL models are packaged compact units. The boiler capacity ranges from 1000 to 3000 hp providing 34,500 to 100,000 lb/hr of steam at pressures up to 650 psig. Its compactness reduces the space requirement and lowers the installation costs. The cyclonic swirling flame provides superior mixing of fuel gas and combustion air while furnishing high convective heat transfer. The boiler offers a quick start-up and maintains high efficiency during rapid response load change and low emissions of nitrogen oxides (NO_x ≤ 30 [gas], 59 [oil] parts per million [ppm]) and carbon monoxide (CO ≤ 20 [gas] 31 [oil] ppm). The low NO_x emission level meets stricter requirements by some states. The unit provides good steam quality (99.5%) and the boiler efficiency remains above 81% during fall capacity down to 10% of rated capacity.

Federal Sector Potential

Technology Screening Process

A feasibility assessment is needed to justify the hardware required at targeted sites. Assessment activities may include the following:

- Determine relevant specifications (thermal, physical, environmental, operational, and economical) of the TurboFireXL boiler.
- Collect energy expenditure, emissions, time-dependent energy (steam) usage.
- Survey facilities where boilers will be used and devise site-selection criteria.
- Conduct life-cycle analyses using the boiler technology.
- Develop test and implementation plans for boilers.

Costs and Installation

Donlee manufactures three packaged boilers, and their costs are $250,000 (1000 hp), $370,000 (1800 hp), and $590,000 (3000 hp). The installation cost varies based on the site conditions from $50,000 to $100,000 (1000 hp), $100,000 to $150,000 (1800 hp), and $150,000 to $200,000 (3000 hp). Hence, the total installation cost varies from $300,000 to $790,000.

Technology Performance

Knouse Foods' Peach Glen facility in Pennsylvania is a fruit processing company that uses steam primarily to process, heat, and sterilize fruit. Also, the company uses steam for clean-up and to heat the plant and administrative offices. The steam requirement is 35,000 lb/hr operating at 125 psig with an 8 to 1 or greater turndown. A 1000-hp TurboFireXL was installed in 1992 with a 25 1/2-inch-diameter stack

After four years of operation, yearly inspections of the boiler revealed no watertube problems. The high circulation in the watertubes limits the potential for corrosion. In addition, the startup time was reduced from 3 hours to 30 to 45 minutes. The boiler complies with environmental safety regulations in the Clean Air Act Amendments of 1990. The NO_x emissions level was maintained at less than 30 ppm attributed to the boiler cyclonic burner technology. A cyclone of swirling flames and hot gases is formed in the boiler's furnace creating an optimum mix of fuel and air. Injecting steam into the combustion zone reduces NO_x formation further and eliminates the need for a NO_x removal system can.

Two problems were encountered after the boiler was installed. The first problem was the high level of noise generated by the fan. The 100-hp fan required insulation to reduce the noise to a tolerable level. Cycling of the boiler during low steam demand periods was the second problem. This occurred during weekends during process down time and low space heating requirements.

The problem was resolved by decreasing the low firing rate and attaining maximum turndown capacity. Another change made was adding a single element control that used a differential pressure transducer to further control feedwater. The control helped to regulate boiler water in the steam drum more evenly during rapidly changing steam demand. Over the five years period the boiler has been operating, it has revealed that it can respond in seconds to changes in load demand from 8,000 to 32,000 lb/hr throughout the day without damaging the boiler. Also, throughout load demand the steam quality (99.5%) is maintained.

Technology Demonstration

A technology demonstration project on a TurboFireXL boiler (3000 hp) was conducted at the Donlee facility, York, Pennsylvania, for Lockheed Martin Energy Systems, Inc., Oak Ridge, Tennessee, on April 22 and 23, 1999. The objectives of the project were to measure the environmental impact and efficiency performance of the boiler. The combustion of natural gas and No.2 oil in boilers results in the following nine emissions: nitrogen, oxygen, water, carbon dioxide, particulate, carbon monoxide, nitrogen oxide, sulfur oxides, and volatile organic compounds. The latter five emissions are classified as pollutants. These pollutants were measured by sampling the boiler stack exhaust while operating at minimum, 25%, 50%, 75%, and 100% loads except for the particulate which was measured at 100% using natural gas and 50% and 100% using No.2 oil. The percent load on the boiler was based on fuel flow. Envisage Environmental conducted emission sampling, and Schmidt Associates performed ASME efficiency test concurrently to emission sampling.

Emissions Results

The sample collection and analysis techniques utilized for emission tests were performed in accordance with USEPA Reference test methods 1, 2, 3, 4, 5, 7E, 10, and 25A, which are listed in the box on the following page. Sample points were at two separate traverses located at 1, 2.9, 5.2, 7.8, 11, 15.7, 28.3, 33, 36.2, 38.8, 41.1, and 43 inches in from the inner wall of the 44-inch-diameter stack. Therefore, there was a total of 24 points, twelve at each traverse. Estimates of EPA AP-42 emissions for natural gas and No. 2 fuel oil are presented in Table 1. The emissions were sampled every minute and averaged over the periods shown in Table 2.

Natural gas-fired emission test results are shown in Tables 2, 3, and 9 (see Appendix A). The gas-fired results reveal NO_x emissions ≤ 30.3 ppm for the five firing loads tested. These results are nearly analogous to the manufacturer's predicted NO_x emissions of less than 30 ppm, which is significantly less than EPA AP-42 factors of 112 ppm, as shown in Table 2 and Figure 2. The highest emissions level was recorded at 100% load (30.3 ppm) while the lowest

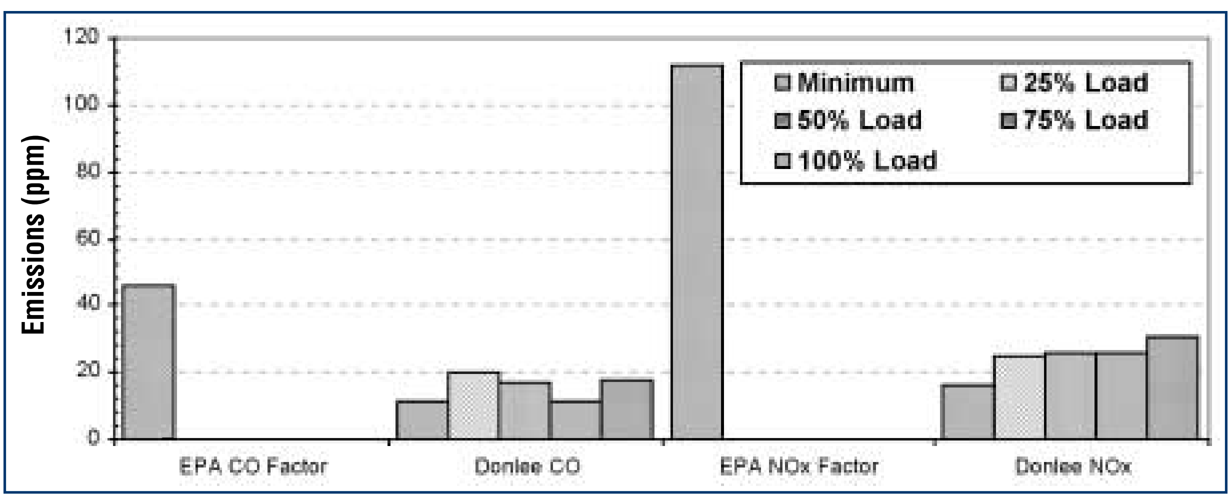

***Figure 2**. TurboFireXL emissions versus EPA factors (natural gas).*

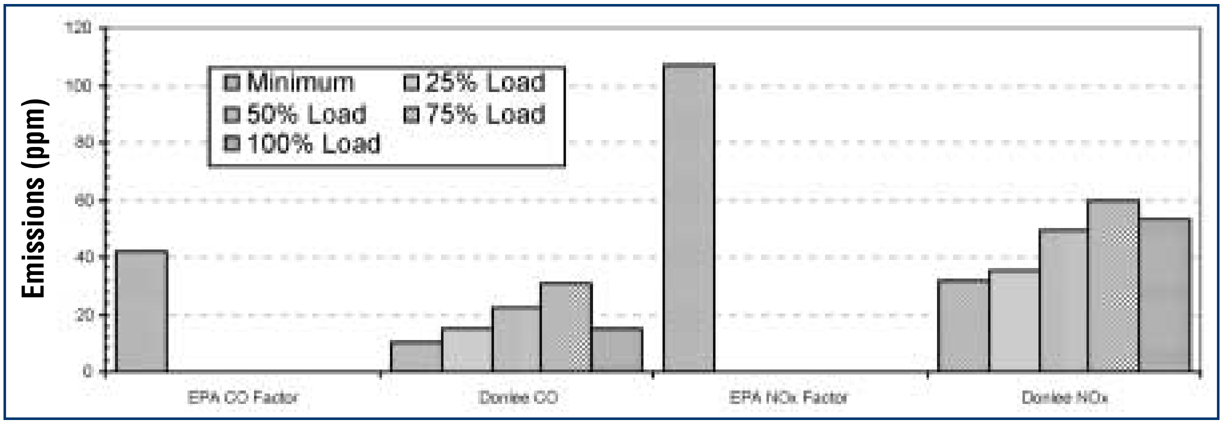

Figure 3. TurboFireXL emissions versus EPA factors (No. 2 oil).

level was at low load (16.3 ppm). Table 3 reveals an NO_x emission rate of less than 0.004 lb/MMBtu (EPA) for all firing loads. This is substantially less than EPA's emission limit of 0.86 lb/MMBtu (EPA) for cyclone boilers. The manufacturer predicted CO emissions to be less than 50 ppm, and the tests revealed actual CO emissions to be less than 21 ppm, which is substantially lower than the Table 1 and Figure 2 factor of 46 ppm and the predicted value. The highest CO emissions level was at 25% load (20.5 ppm) and the lowest was at minimum load (11.1 ppm). Other manufacturers' comparable boilers generate emissions levels of approximately 100 ppm operating conventionally and less than 40 ppm with flue gas recirculation. These comparable boilers can be retrofitted with selective catalytic reduction (SCR) units to reduce the emissions level to below 20 ppm, but the SCR unit is expensive (Donlee and Cleaver Brooks). In comparing the emissions of other pollutants in Tables 2 and 3 (VOCs and particulate) to EPA's factors in Table 1, these pollutant emissions are considerably less than EPA's factor limits.

No. 2 fuel oil results are presented in Tables 4, 5, and 10 (see Appendix A), and graphically depicted in Figure 3. NO_x emissions levels varied from 31.2 ppm to 59.2 ppm. The 75% load yields the highest emissions level, and the minimum load yields the lowest emissions level. The maximum NO_x emissions rate was 0.008 lb/MMBtu (Table 5), which is significantly less than EPA's limit of 0.86 lb/MMBtu for cyclone boilers (EPA). The pollutants generated (Tables 4 and 5) are all noticeably below EPA's emission factors for fuel oil shown in Table 1. The CO emissions remained less than 31 ppm, which is smaller than the manufacturer's projection of less than 50 ppm.

Performance Results

The boiler efficiency represents the difference between the energy input and output. The boiler efficiency was computed by utilizing ASME Power Test Code, PTC 4.1, for determining the fuel-to-steam efficiency applying the heat loss method. The adjustments for the injected steam used for NO_x control was the only deviation from the ASME PTC 4.1 method. In all cases except one, the injected steam enthalpy was greater than the flue gas moisture enthalpy, resulting in a slightly higher efficiency.

USEPA Reference Test Methods

USEPA Method 1	Sample and velocity traverses for stationary sources
USEPA Method 2	Determination of stack gas velocity and volumetric flow rate
USEPA Method 3	Gas analysis for carbon dioxide, oxygen, excess air, and dry molecular weight
USEPA Method 4	Determination of moisture content in stack gases
USEPA Method 5	Determination of particulate emissions from stationary sources
USEPA Method 7E	Determination of nitrogen oxides emissions from stationary sources (instrumental analyzer procedure)
USEPA Method 10	Determination of carbon monoxide emissions from stationary sources (instrumental analyzer procedure)
USEPA Method 25A	Determination of total gaseous organic concentrations using a flame ionization analyzer

The heat loss method is a heat balance efficiency, which accounts for all the heat losses of the boiler by subtracting from 100 percent the total percent of stack, radiation, and convection losses. The stack temperature indicates moisture loss and heat carried away in the dry flue gases. Lower stack temperature reveals more effective heat exchange and higher fuel-to-steam efficiency. Air flow across (convection) and heat radiating (radiation) from the boiler are essentially constant throughout the firing range of a boiler.

Some other key factors that affect the boiler efficiency are excess air and ambient air temperature. Excess air is additional air supplied to the burner above that required to complete combustion. Although this excess air is needed to ensure sufficient air to maintain safety, it reduces the boiler efficiency by extracting potential energy that could be used for heating water. A minimum of 15% excess air is recommended. In this demonstration project, the excess air ranged from 30.35% at minimum load to 6% at 100% load using natural gas and 76.34% at minimum load and 17.20% at 100% load using No. 2 oil (see Tables 6 and 7, Figure 4). The data reveals the effect that increasing the percent of excess air has on the efficiency. The efficiency drops by 3.52% when the excess air is increased from 6 to 30.35% using natural gas and 3.94% using No.2 oil. These efficiency reductions are also influenced by the increased percentage of steam injected. Even though the percent of excess air is greater than 15% for all No.2 oil loads, the boiler efficiency remains above 80%. Conventional boilers have approximate 80% efficiency at high-load, but efficiency typically decreases with turndown.

The predicted efficiency was 82% ± 1% from 25 to 100% load firing natural gas, but as seen in Table 6, the test results exceeded the predicted efficiency. The largest sources of losses were due to stack temperature (dry gas heat) and moisture from combustion of hydrogen. The fuels had 12.19% (No.2 oil) and 23.85% (natural gas) hydrogen, as shown in Table 8. Therefore, No.2 oil incurs less loss due to the combustion of hydrogen, which results in higher No.2 oil boiler efficiencies.

Manufacturer

Donlee Technologies Inc., 693 North Hills Road, York, Pennsylvania 17402-2211.

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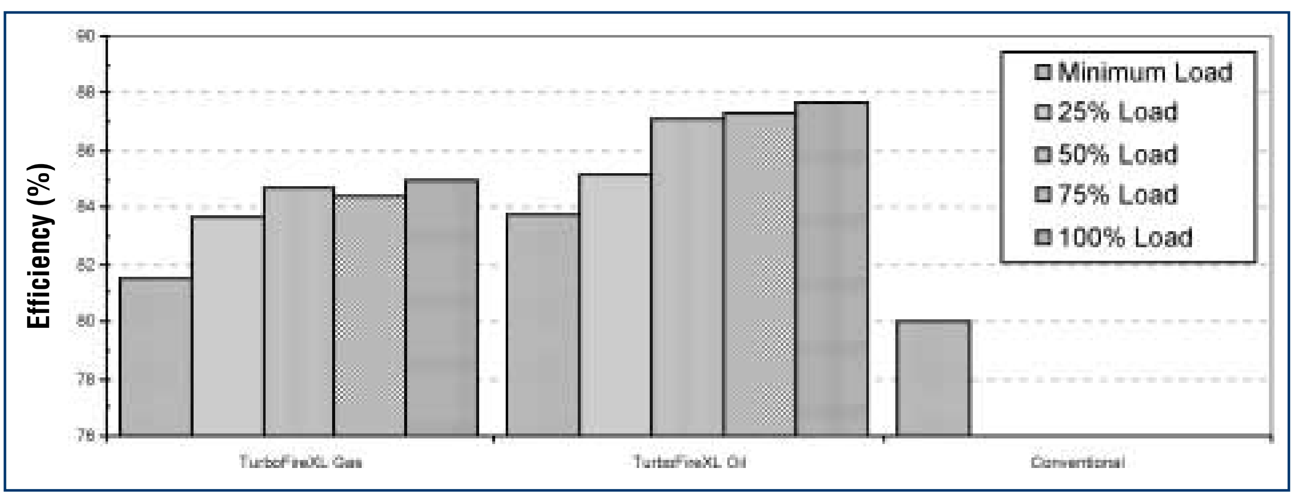

Figure 4. TurboFireXL boiler efficiency.

Appendix A

***Table 1**. AP-42 Uncontrolled Emission Factors (10-100 MMBtu/hr Boilers, Cleaver Brooks).*

Fuel	Units	Particulate	SO_2 [SO_3]	CO	NO_2	VOCs Nonmethane	VOCs Methane
Natural Gas	lb/MMBtu	0.00095-0.0048	0.00057	0.033	0.133	0.0027	0.0029
	ppm	na	0.34	46	112	6.8	7.3
Fuel Oil	$lb/MMBtu_{residual}$	0.649(%S)+0.0195	1.02(%S) [0.013(%S)]	0.0325	0.357	0.0018	0.0065
	$lb/MMBtu_{distillate}$	0.0143	1.01(%S) [0.013(%S)]	0.0325	0.143	0.0014	0.0004
	$ppm_{residual}$	na	549(%S) [7(%S)]	42	273	3.6	13
	$ppm_{distillate}$	na	544(%S) [7(%S)]	42	107	2.8	0.8

Table 2*. Emissions Laboratory Summary Data (Natural Gas Fired).*

Date: April 22, 1999	Symbol (Units)	Minimum Load	25% Load	50% Load	75% Load	100% Load
Sampling Time	t (minutes)	45.0	40.0	40.0	40.0	60
Barometric Pressure	Pb (in. Hg)	29.97	29.97	29.97	29.97	29.97
Static Pressure	Pg (in. H_2O)	-0.06	-0.05	-0.15	-0.17	-0.17
Stack Pressure	Ps (in. Hg)	29.97	29.97	29.96	29.96	29.96
Gas Meter Volume	Vm (ft^3)	32.18	28.51	28.33	28.07	54.54
Stack Area	A (ft^2)	10.56	10.56	10.56	10.56	10.56
Nozzle Diameter	Dn (dec. in.)	na	na	na	na	0.32
"Y" Factor		0.994	0.994	0.994	0.994	0.994
Meter Temperature	(^oF)	67.9	82.2	80.4	78.6	72.5
	Tm (^oR)	527.9	542.2	540.4	538.6	532.5
Stack Temperature	(^oF)	217.5	181.5	228.0	247.1	248.29
	Ts (^oR)	677.5	641.5	688.0	707.1	708.29
Velocity Head (SQRT)	P (in. H_2O)	0.166	0.251	0.446	0.731	0.8
Orifice Pressure	H (in. H_2O)	1.66	1.66	1.66	1.66	3.01
Carbon dioxide	CO_2 (%)	6.8	9.3	10.4	10.3	10.8
Oxygen	O_2 (%)	8.9	4.4	2.5	2.8	1.8
Carbon monoxide	CO (%)	0.0	0.0	0.0	0.0	0
Nitrogen	N_2 (%)	84.3	86.3	87.1	87.0	87.4
Pitot Coefficient	Cp	0.84	0.84	0.84	0.84	0.84
Water Collected	Vlc (ml)	192.8	191.8	160.1	162.1	258.5
Sample Weight:	Mn					
Probe	(g)	na	na	na	na	0.0064
Filter	(g)	na	na	na	na	0.0081
Impingers	(g)	na	na	na	na	0.1074
NO_x	(ppm)	16.3	25.3	25.6	26.0	30.3
VOC as Propane	($ppm_{propane}$)	0.0	0.1	0.0	0.1	0.1935
VOC as Carbon	(ppm_{carbon})	0.0	0.4	0.1	0.4	0.5805
CO	(ppm)	11.1	20.5	16.9	11.5	17.5
O_2	(ppm)	89,000	44,000	25,000	28,000	18,000

Table 3. Gas Fired Total Emission Rate (Moisture and Particulate).

Total Emissions	Minimum Load	25% Load	50% Load	75% Load	100% Load
Particulate					
lb/MMBtu	na	na	na	na	0.00067
lb/hr	na	na	na	na	0.72194
grains/dscf	na	na	na	na	0.00410
Nitric Oxides					
lb/MMBtu	0.0035	0.0040	0.0036	0.0037	0.0041
lb/hour	0.4915	1.1521	2.0634	3.3749	4.4593
lb/dscf	1.94E-06	3.02E-06	3.06E-06	3.10E-06	3.62E-06
Total VOC's					
lb/MMBtu	0.00E+00	1.49E-05	5.27E-06	1.34E-05	2.05E-05
lb/hour	0.0000	0.0043	0.0030	0.0121	0.0222
lb/dscf	0.00E+00	1.13E-08	4.46E-09	1.11E-08	1.8E-08
Carbon Monoxide					
lb/MMBtu	1.46E-03	1.96E-03	1.45E-03	1.00E-03	0.001447
lb/hour	0.2041	0.5681	0.8289	0.9102	1.5674
lb/dscf	8.07E-07	1.49E-06	1.23E-06	8.36E-07	1.27E-06
System Flow Rates					
ft/sec	10.92	16.11	29.36	48.89	53.13
ACFM	6,919	10,204	18,604	30,974	33,660
DSCFM	4,218	6,356	11,251	18,153	20,543
Moisture Content (%Volume)	21.90	24.43	21.30	21.61	18.23
Sample Location Temp. (^{o}F)	218	182	228	247	248

__Table 4__. Emissions Laboratory Summary Data (No. 2 Oil Fired).

Date: April 23, 1999	Symbol (Units)	Minimum Load	25% Load	50% Load	75% Load	100% Load
Sampling Time	t (minutes)	35	35	60.0	35	30.0
Barometric Pressure	Pb (in. Hg)	29.91	29.91	29.91	29.91	29.91
Static Pressure	Pg (in. H_2O)	0.02	0.03	0.00	0.00	0.00
Stack Pressure	Ps (in. Hg)	29.91	29.91	29.91	29.91	29.91
Gas Meter Volume	Vm (ft^3)	26.69	25.55	41.88	25.50	45.10
Stack Area	A (ft^2)	10.56	10.56	10.56	10.56	10.56
Nozzle Diameter	Dn (dec. in.)	na	na	0.32	na	0.32
"Y" Factor		0.996	0.996	0.996	0.996	0.996
Meter Temperature	(^oF)	60.1	58.9	59.1	57.9	63.5
	Tm (^oR)	520.1	518.9	519.1	517.9	523.5
Stack Temperature	(^oF)	152.8	182.6	251.7	255.8	259.8
	Ts (^oR)	612.8	642.6	711.7	715.8	719.8
Velocity Head (SQRT)	P (in. H_2O)	0.260	0.334	0.510	0.963	1.350
Orifice Pressure	H (in. H_2O)	1.80	1.80	1.57	1.80	8.03
Carbon dioxide	CO_2 (%)	5.9	6.2	8.1	8.6	9.8
Oxygen	O_2 (%)	10.5	9.8	6.6	5.6	3.6
Carbon monoxide	CO (%)	0.0	0.0	0.0	0.0	0.0
Nitrogen	N_2 (%)	83.6	84.0	85.3	85.8	86.6
Pitot Coefficient	Cp	0.84	0.84	0.84	0.84	0.84
Water Collected	Vlc (ml)	82.6	87.2	193.3	109.8	216.7
Sample Weight:	Mn					
Probe	(g)	na	na	0.0062	na	0.0079
Filter	(g)	na	na	0.0081	na	0.0440
Impingers	(g)	na	na	0.4858	na	0.1979
NOx	(ppm)	31.2	35.8	48.9	59.2	53.3
VOC as Propane	($ppm_{propane}$)	0.0	0.1	0.9	0.1	0.5
VOC as Carbon	(ppm_{carbon})	0.0	0.3	2.7	0.3	1.5
CO	(ppm)	10.0	15.1	22.0	31.0	14.8
O2	(ppm)	105,000.0	98,000.0	66,000.0	56,000.0	36,000.0

Table 5. No. 2 Oil Fired Total Emission Rate (Moisture and Particulate).

Total Emissions	Minimum Load	25% Load	50% Load	75% Load	100% Load
Particulate					
lb/MMBtu	na	na	0.00112	na	0.00310
lb/hour	na	na	0.58	na	5.10
Grains/dscf	na	na	0.0052	na	0.0173
Nitric Oxides					
lb/MMBtu	0.00777	0.00837	0.00889	0.01004	0.00800
lb/hour	1.7035	2.4305	4.6227	10.6353	13.1648
lb/dscf	3.72E-06	4.27E-06	5.84E-06	7.07E-06	6.36E-06
Total VOCs					
lb/MMBtu	0.00E+00	1.73E-05	1.28E-04	1.26E-05	5.84E-05
lb/hour	0.0000	0.0050	0.0665	0.01	0.0961
lb/dscf	0.00E+00	8.85E-09	8.41E-08	8.85E-09	4.65E-08
Carbon Monoxide					
lb/MMBtu	1.52E-03	2.15E-03	2.43E-03	3.20E-03	1.35E-03
lb/hour	0.3328	0.6239	1.2654	3.3892	2.2246
lb/dscf	7.27E-07	1.10E-06	1.60E-06	2.25E-06	1.08E-06
System Flow Rates					
ft/sec	15.99	21.07	34.05	64.30	90.52
ACFM	10,128	13,350	21,574	40,740	57,355
DSCFM	7,634	9,477	13,193	25,076	34,477
Moisture Content (%Volume)	12.50	13.59	17.55	16.53	18.03
Sample Location Temp (°F)	153	183	252	256	260

Table 6. Natural Gas Efficiency Test Results.

Load %	% Excess Air	% Boiler Efficiency	% Steam Injection Loss
Minimum Load	30.35	81.48	+0.22
25	18.90	83.65	+0.15
50	9.70	84.66	+0.06
75	10.65	84.43	+0.01
100	6.00	85.00	+0.03

Table 7. No. 2 Oil Efficiency Test Results.

Load %	% Excess Air	% Boiler Efficiency	% Steam Injection Loss
Minimum Load	76.34	83.74	+0.10
25	67.12	85.19	+0.07
50	25.16	87.09	+0.02
75	20.52	87.29	-0.01
100	17.20	87.70	+0.001

***Table 8**. Fuel Ultimate Analysis (As Received).*

Product	No. 2 Oil	Natural Gas
Carbon (%Wt)	85.44	73.42
Hydrogen (%Wt)	12.19	23.85
Sulfur (%Wt)	0.60	0.00
Oxygen (%Wt)	1.21	2.02
Nitrogen + Chlorine (%Wt)	0.43	0.70
Ash (%Wt)	0.03	0.00
Moisture (%Wt)	0.10	0.00
Heat of Combustion (Btu/lb)	18,765	22,936
Heat of Combustion (Btu/ft^3)	—	1034
Heat of Combustion (Btu/gal)	149,141	—

***Table 9**. Detailed Gas Fired Emission Test Results (Moisture and Particulate).*

	Symbol (Units)	Minimum Load	25% load	50% load	75% load	100% load
Time of Day		11:35	16:25	17:34	18:39	20:36
		12:20	17:15	18:14	19:19	21:55
Gas Volume-dry, std.	Vmstd (ft^3)	32.37	27.92	27.84	27.68	54.57
Condensate Vapor Vol.	Vwstd (ft^3)	9.08	9.03	7.54	7.63	12.17
Gas Stream Moisture	Bws (vol. dec)	0.2190	0.2443	0.2130	0.2161	0.1823
Mol.Wt-flue gas (dry)	Msd (lb/lb mo.)	29.44	29.66	29.76	29.75	29.80
Mol.Wt-flue gas (wet)	Ms (lb/lb mo.)	26.94	26.81	27.26	27.21	27.65
Flue Gas Velocity	Vs (ft/sec)	10.92	16.11	29.36	48.89	53.13
Flue Gas Volume-Actual	Qs (acfm)	6,919	10,204	18,604	30,974	33,660
Flue Gas Volume-Std.	Qs (dscfm)	4,218	6,356	11,251	18,153	20543
Concentrations	Cs					
Probe	(gr/dscf)	na	na	na	na	0.0018
Filter	(gr/dscf)	na	na	na	na	0.0023
Total Particulate	(gr/dscf)	na	na	na	na	0.0041
NO_x	(lb/dscf)	1.94E-06	3.02E-06	3.06E-06	3.10E-06	3.62E-06
VOC	(lb/dscf)	0.00E+00	1.13E-08	4.46E-09	1.11E-08	1.8E-08
CO	(lb/dscf)	8.07E-07	1.49E-06	1.23E-06	8.36E-07	1.27E-06
Emission Rate	E					
Probe	(lb/hr)	na	na	na	na	0.3187
Filter	(lb/hr)	na	na	na	na	0.4033
Total Particulate	(lb/hr)	na	na	na	na	0.7219
NO_x	(lb/hr)	0.4915	1.1521	2.0634	3.3749	4.4593
VOC	(lb/hr)	0.0000	0.0043	0.0030	0.0121	0.0222
CO	(lb/hr)	0.2041	0.5681	0.8289	0.9102	1.5674
Isokinetic Rate	I (%)	na	na	na	na	83.21

***Table 10**. Detailed No. 2 Oil Fired Test Results (Moisture and Particulate).*

	Symbols (Units)	Minimum Load	25% Load	50% Load	75% Load	100% Load
Time of Day		09:03	10:05	11:36	13:30	15:21
		09:48	10:45	13:00	14:05	15:51
Gas Volume-dry, std.	Vmstd (ft^3)	27.20	26.11	42.75	26.11	46.37
Condensate Vapor Vol.	Vwstd (ft^3)	3.89	4.10	9.10	5.17	10.20
Gas Stream Moisture	Bws (vol.dec)	0.1250	0.1359	0.1755	0.1653	0.1803
Mol.Wt-flue gas (dry)	Msd (lb/lb mo.)	29.37	29.38	29.55	29.60	29.71
Mol.Wt-flue gas (wet)	Ms (lb/lb mo.)	27.95	27.84	27.53	27.68	27.60
Flue Gas Velocity	Vs (ft/sec)	15.99	21.07	34.05	64.30	90.52
Flue Gas Volume-Actual	Qs (acfm)	10,128	13,350	21,574	40,740	57,355
Flue Gas Volume-Std.	Qs-Std (dscfm)	7,634	9,477	13,193	25,076	34,477
Concentrations	Cs					
Probe	gr/dscf	na	na	0.0022	na	0.0026
Filter	gr/dscf	na	na	0.0029	na	0.0146
Total Particulate	gr/dscf	na	na	0.0052	na	0.0173
NO_x	lb/dscf	3.72E-06	4.27E-06	5.84E-06	7.07E-06	6.36E-06
VOC	lb/dscf	0.00E+00	8.85E-09	8.41E-08	8.85E-09	4.65E-08
CO	lb/dscf	7.17E-07	1.10E-06	1.60E-06	2.25E-06	1.08E-06
Emission Rate	E					
Probe	lb/hr	na	na	0.25	na	0.78
Filter	lb/hr	na	na	0.33	na	4.33
Total Particulate	lb/hr	na	na	0.58	na	5.10
NO_x	lb/hr	1.7035	2.4305	4.6227	10.64	13.1648
VOC	lb/hr	0.0000	0.0050	0.0665	0.0100	0.0961
CO	lb/hr	0.3328	0.6239	1.2654	3.3900	2.2246
Isokinetic Rate	I (%)			101.7		84.4

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