A Field Demonstration: Transport Membrane Heat Recovery on Industrial Steam Boiler

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ABSTRACT

Advances in research on heat recovery devices for combustion processes led to the development of a system employing a nano-porous transport membrane condenser and a low-pressure economizer. The heat recovery system employs new materials and techniques to extract latent and sensible heat from previously untapped combustion exhaust streams. This paper presents a result of an assessment on the technology installed on a 250hp steam boiler at a pharmaceutical plant.

The test was conducted at a healthcare facility where the boiler with advanced heat recovery system has been operating for more than two years. The plant operates year round with the relevant boiler operational for about 8,300 hours. Ninety percent (90%) of the natural gas used in the plant is consumed by the two Cleaver-Brooks boilers. The remaining 10% is used for building heating and ventilation and domestic hot water heating. The main purpose of the study was to evaluate the performance of this heat recovery system.

Standard packaged boilers operate at a combustion efficiency around 80%. A standard high-pressure economizer improves the efficiency by about 3%. Depending on firing rate, the advanced condensing membrane and low-pressure economizer added an additional 5-6% efficiency resulting in overall boiler combustion efficiency up to 92%.

Boiler combustion and fuel-to-steam efficiencies were calculated using the indirect stack loss method. Yearly savings due to gas consumption reduction was about $18,000. The cost savings due to water recovery were not evaluated, but the water recovery benefits are obvious and apparent. The unique and state-of-the-art nanotechnology waste heat recovery system is promising and warrants installation in many types of applications.

Introduction

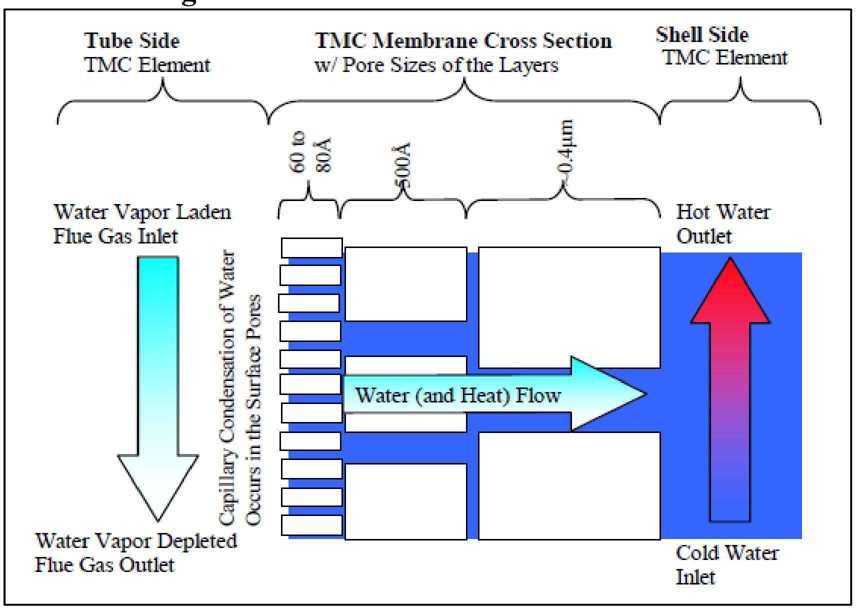
Project Background & Technology

One of the byproducts in natural gas combustion is water vapor in the exhaust stream. This flue gas is a target for heat recovery since it exits at a temperature greater than the makeup water and since water vapor has large latent and sensible heat capacities. Traditional economizers have focused on recovering as much sensible heat as possible through the use of feedwater economizers and condensing economizers. However, large surface areas and special corrosion reducing materials and techniques are required because the flue gas is typically at a relatively low temperature and the water condensate is acidic. Therefore, only a fraction of the sensible heat and none of the water and latent heat were recoverable.

The development of Ultramizer supplies heat recovery capability that is not feasible with current commercially available economizers. The Ultramizer is comprised of three (3) stages of heat recovery: high pressure economizer (HPE), low pressure economizer (LPE), and transport member condenser (TMC). The HPE and LPE function analogously as feedwater economizer and condensing economizer, respectively.

The TMC uses a nano-porous membrane to recover latent heat and condensed water from the boiler's exhaust stream. A ceramic, nano-porous membrane with three pore sizes was created to extract water from the flue gas via capillary condensation transport. As water vapor and flue gas passes through the TMC, water condenses on the walls and is transported to the shell side water flow (see Figure 1). Therefore, a portion of the latent and sensible heat contained in the water vapor is recovered along with the water itself. The water vapor condenses before reaching the saturation point due to capillary condensation, thereby minimizing the creation of acidic conditions. The ceramic developed has been shown to be corrosion-resistant and the capillary condensate prevents exhaust gases from entering the water stream on the shell side of the TMC.

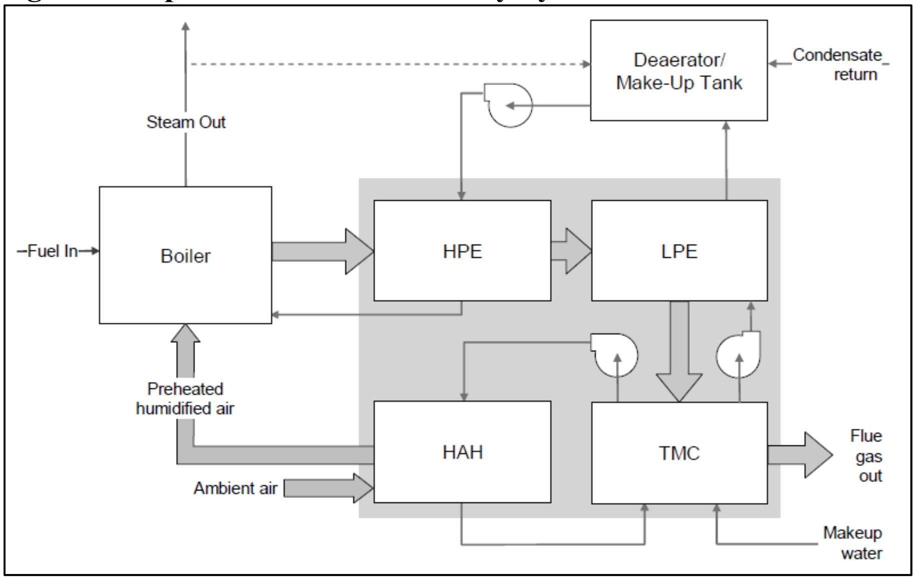
Figure 1. TMC Condensation Schematic



Source: (Gard 2011)

The Ultramizer has been demonstrated in a system containing a HPE, LPE, and humidifying air heater (HAH) as shown in Figure 2. HPEs are common, so the LPE-TMC combination is considered the advanced technology. The HPE uses water from the storage tank to recover some of the sensible heat in the flue gas; the LPE uses water extracted from the TMC to further recover sensible heat at a lower temperature; the TMC recovers condensed water and the associated latent heat; the HAH cycles TMC water to increase the enthalpy of the air used for boiler combustion to increase its efficiency. The technology was developed by a joint collaboration between the manufacturer, a laboratory, and natural gas utilities.

Figure 2. Super Boiler Heat Recovery System Schematic with TMC



Source: (Wang 2013)

Project Organization

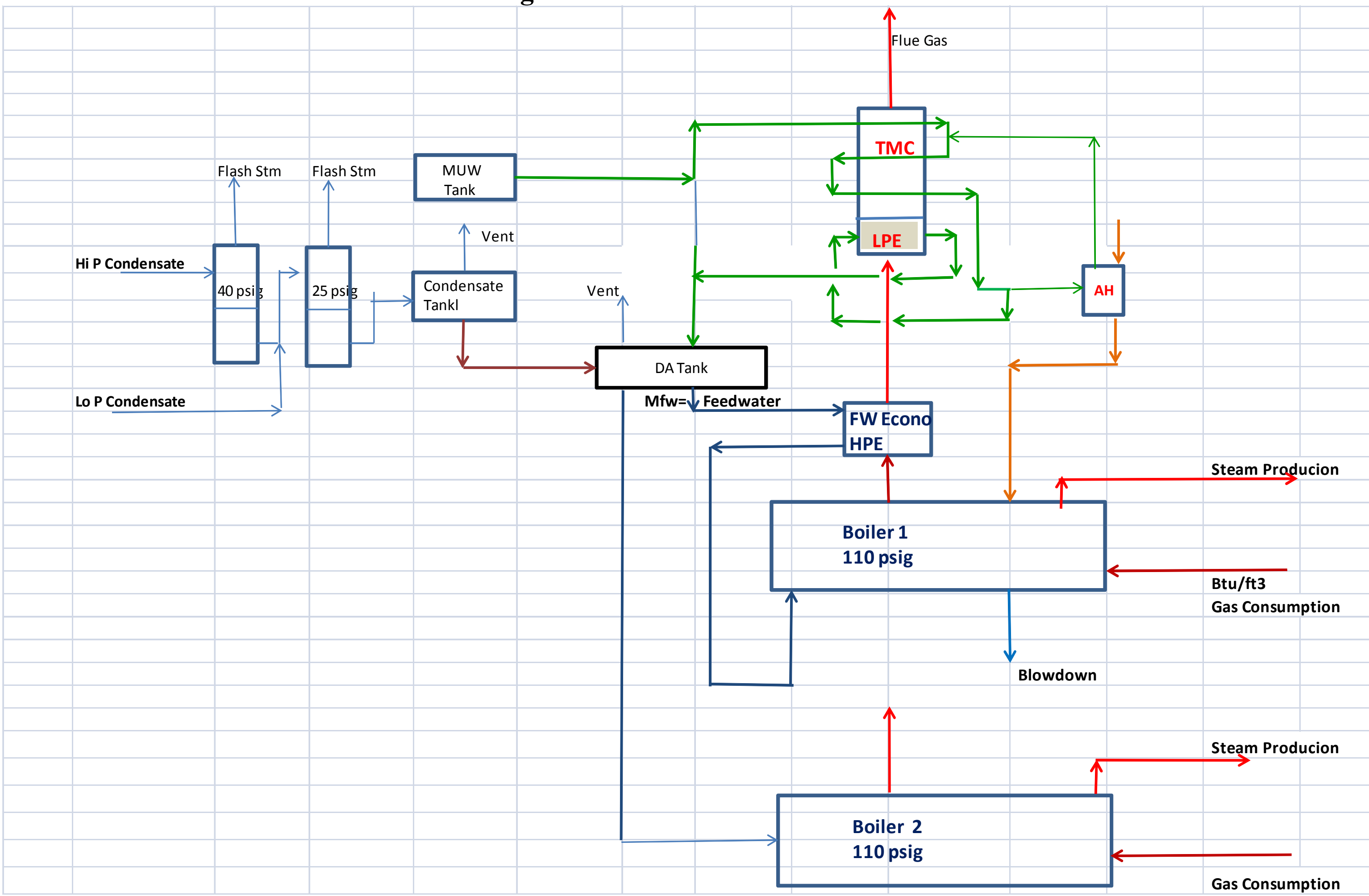
Project Objective

The objective of this study was to evaluate the performance of the TMC-based flue gas heat recovery system installed on a steam boiler. The heat recovery system was comprised of the components listed above: an HPE, LPE, TMC, and HAH. The primary objectives were to establish the combustion and fuel-to-steam efficiency gains due to the HPE/LPE/TMC package. The study was performed to verify or refute previous results and to gain a more complete understanding of the benefits of the Ultramzier system.

Test Site Description

The advanced heat recovery system was installed on a Cleaver-Brooks 250 bhp steam boiler at a healthcare facility in southern California. A second Cleaver-Brooks 250 bhp boiler without any heat recovery system is also located at the site, in the same boiler room. The two-boiler system with the TMC heat recovery system on Boiler 1 is shown schematically in Figure 3.

Figure 3. Boiler Plant Schematic



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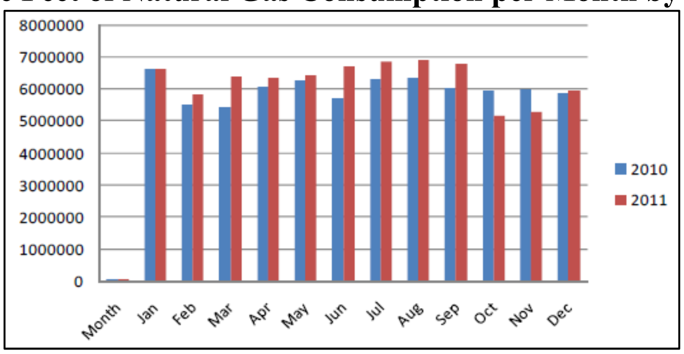
The recovered condensate from the TMC is supplied to the de-aerator as a portion of the boiler make up water (MUW). Prior to the Ultramizer instalaltion, it was estimated that the total boiler water was about 20-25% MUW.

The water from the de-aerator tank is pumped through the HPE to be pre-heated before entering the boiler. The flue gases from Boiler 1 pre-heat the feed water in the HPE, heat the TMC condensed water in the LPE, and then water vapor condenses at a low temperature in the TMC capillaries. Water condensed in the TMC is also used in the HAH to preheat the combustion air and supply to the de-aerator tank. Boiler 2 is fed by the same de-aerator tank but does not have a heat recovery system in place. Since the feedwater in the de-aerator tank is partly comprised of TMC-recovered water, both boilers receive water at elevated temperatures. The water delivered to Boiler 1 is heated further by the HPE; the water delivered to Boiler 2 is not.

The plant consumes about 73.6 million cubic feet of natural gas annually. The monthly gas consumption by billing data is shown in Figure 4. Note that the heat recovery system was in place for all these months.

Figure 4. Cubic Feet of Natural Gas Consumption per Month by Boiler Facility



Testing and measurements were performed in early May of 2012 and load duration curves were established for each boiler. It was assumed that these load curves represent typical operation of the plant. Therefore, these profiles were used to determine average operating conditions for each boiler. These average operating conditions were used during the analysis to calculate average boiler efficiencies. Boiler 1 and Boiler 2 operate for about 8,300 and 6,430 hours per year, respectively. The boiler operating conditions and load duration curves are shown in Figure 5 and Table 1.

Figure 5. Load Duration Curves for Each Boiler Over May 1 And 2

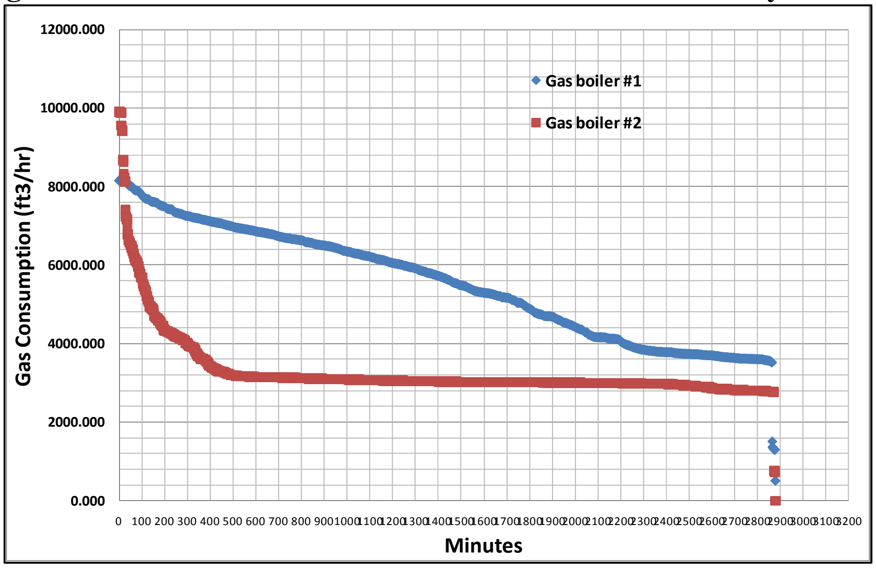


Table 1. Estimated Average Yearly Operating Conditions

	Boiler 1	Boiler 2
Yearly Operating Time [hours]	8300	6430
Avg. Firing Rate [%]	54%	31%
Yearly Gas Consumption [MMCF]	46.0	20.3

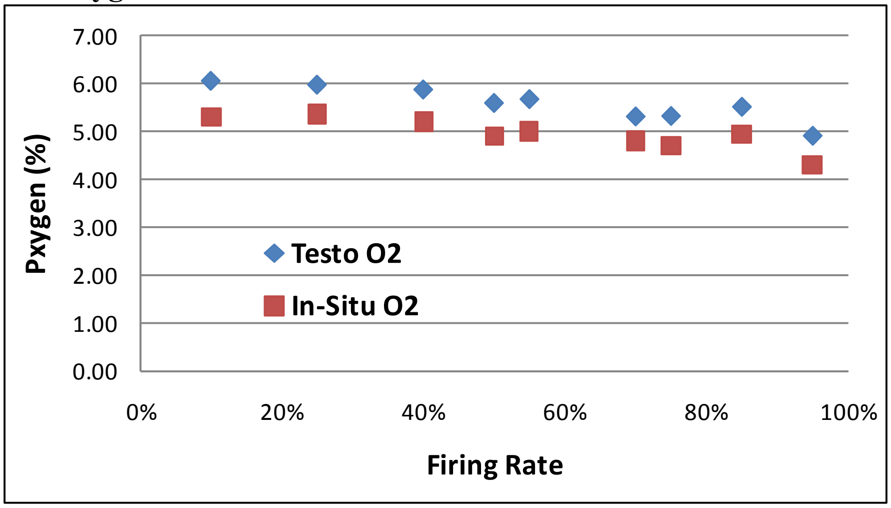
Monitored Data Points & Metering Equipment

Monitoring of the flue gas components, natural gas consumption, steam flows, firing rate, and flow temperatures were necessary for a thorough analysis of boiler performance. Measurements were taken using the pre-installed DAS, a Testo 350 combustion analyzer, Fluke digital thermometer, strap-on ultrasonic flowmeter, in-line gas meter, and the in-situ devices connected to the Hawk boiler room control panels. Data was either manually recorded or printed, as available. In general, calibrated, hand-tool data was used to confirm the accuracy of DAS and control panel data so that a rigorous analysis using available data points could be performed.

The steam flow readings from the control panel were compared with the two-day average from the DAS and the projected steam production as calculated by analysis of flue gas and gas meter data. The gas consumption data recorded by the DAS was accurate when compared to the manual readings from the dedicated gas meter for each boiler. The steam production reported by the control panel was 18% below the accurate calculation of steam flow based on flue gas data. It appears that the steam measurements from the sensors are out of range and fluctuate enough to warrant re-calibration. This would ensure accurate steam production readings for future use.

After accounting for the difference in oxygen reading methods between the on-board control panel and flue gas analyzer, the control panel gas component data was shown to be reliable. Figure 6 shows the comparison between the in-situ sensor and portable flue gas analyzer excess oxygen measurements. Since the portable analyzer measurements are expected to be slightly higher, the comparison suggests that the in-situ flue gas component measurements are accurate and reliable.

Figure 6. Excess Oxygen Measurements in the Flue Gas for Both Measurement Systems



The water flow and temperature measurements taken by the in-situ system were compared with a calibrated temperature sensor and ultrasonic flowmeter. Unfortunately, the ultrasonic flowmeter data fluctuated uncontrollably during each test and did not provide usable results. This was perhaps due to rapidly changing water levels in the de-aerator tank or a malfunctioning meter. The temperature measurements were confirmed accurate.

Table 2. List of Data Points

Data Point Name	Equipment Description
Condensate Tank Outlet Temperature	Thermocouple
TMC Inlet Water Temperature (from MUW)	Thermocouple
TMC Inlet Water Flowrate (from MUW)	Inline flowmeter
TMC Inlet Water Temperature (from HAH)	Thermocouple
TMC Inlet Water Flowrate (from HAH)	Inline flowmeter
TMC Inlet Flue Gas Temperature	Thermocouple
Exit Stack Temperature	Thermocouple
LPE Outlet Water Temperature	Thermocouple
LPE Outlet Water Flowrate	Inline flowmeter
LPE Inlet Flue Gas Temperature	Thermocouple
HAH Inlet Water Temperature	Thermocouple
HAH Inlet Air Temperature	Thermocouple
HAH Outlet Air Temperature	Thermocouple
HPE Inlet Water Temperature	Thermocouple
HPE Outlet Water Temperature	Thermocouple
HPE Outlet Water Flowrate	Inline flowmeter
HPE Inlet Flue Gas Temperature	Thermocouple
Boiler Steam Flowrate	Inline flowmeter
Boiler Gas Consumption	SoCal Gas Billing Meter
Flue Gas Components (O_2, CO, and NOx)	Testo 350 Combustion Analyzer

Test Procedure

Analyses of combustion and fuel-to-steam efficiency were performed. The testing was conducted over two consecutive days. Boiler 1 was tested in the arrangement shown in Figure 2 while Boiler 2 had no recovery system. Again, it should be noted that both boilers received boiler feedwater from the same de-aerator tank where the recovered water was delivered.

Boiler 1 was put in manual control mode during data collection to ensure data were recorded under steady state conditions. Boiler 2 operated in auto-control mode to maintain the load demand. Boiler 1 was tested from low fire (10%) to high fire (95%) in increments of 15%. The combustion test was repeated on the second day in increments of 25% for additional data points.

The firing rates were set on the onboard PLC control. It should be noted that the % firing rate shown on the control panel did not correspond with the % of rated capacity firing rate. For example, a 10% firing rate does not mean that the boiler was consuming 10% of the maximum rated input capacity. The firing rates were programmed based on boiler characterization curves that reflect the scale of the performance. As was determined, a 10% firing rate actually corresponded to about 30% of rated input. Results are presented for both firing rate settings and actual rates.

Data Analysis Methods

Two methods for boiler efficiency calculations were used: an indirect method and a direct method. The indirect method uses stack losses to determine the combustion efficiency while the direct method uses energy and mass balance approaches to calculate efficiency.

Indirect Method

The indirect method uses gas flue stack data to calculate heat losses. The method follows ASME PTC 4.1 procedure for combustion and fuel-to-steam efficiency. Data such as dry gas loss, hydrogen gas loss due to formation of H_2O, and CO, and combustible losses are required. These losses are then substracted from 100% to obtain an efficiency drop from 100%.

$$\boldsymbol{\eta_c = 100 * \frac{Q_{gas} - \sum Stack\ Losses}{Q_{gas}}}$$

where η_c is the percentage combustion efficiency, Q_{gas} is the energy delivered to the boiler, and *Stack Losses* are the energy losses described above. The ASME procedure establishes a method for deriving fuel-to-steam efficiency by subtracting set percentages of inputs as radiation and boiler blow down losses from the combustion efficiency.

$$\boldsymbol{\eta_{fts} = \eta_c - .005Q_i - .03FW}$$

where Q_i is the input rating and *FW* is the feedwater flow.

The flue gas data collected for the indirect method was also used to determine yearly operation, efficiencies, and other parameters using Enbridge Industrial eTools. The model uses plant parameters to determine operating conditions and efficiencies using an indirect method.

The model has the ability to add a HPE component so that the analysis can separate gains due to the HPE and TMC-LPE advanced heat recovery components. The annual gas consumption obtained from SoCalGas billing data was used as a guideline to establish gas consumption profiles. The steam production was calculated from the measured flue gas analysis and measured gas consumption data.

Direct Method

The direct method uses an energy and mass balance approach with a control volume around the HPE and boiler. Thus the inlet and outlet flows and temperatures can be used to determine combustion and fuel-to-steam efficiencies using the following.

$$\eta_{fts} = \frac{\dot{m}_s h_s - \dot{m}_{fw} h_{fw}}{\dot{Q}_{gas}}$$

where $\dot{m}$ is the mass flowrate, *h* is enthalpy, *s* designates steam, and *fw* designates feedwater.

Results

The combustion and fuel-to-air efficiencies of each boiler and the combined system were calculated to determine the gains due the addition of a HPE and the advanced TMC-LPE module. The various methods described above were used where appropriate and applicable.

Boiler Efficiency With and Without an HPE - Indirect Method

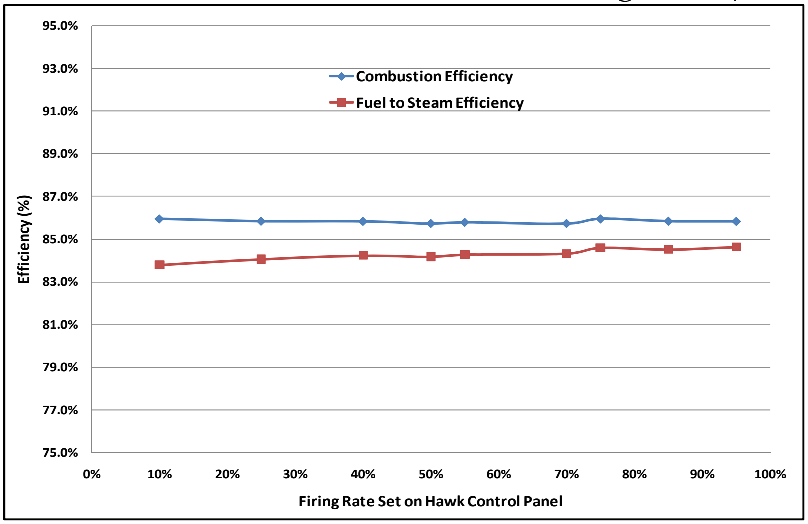
The boiler system combustion and fuel-to-steam efficiencies were calculated using the indirect, stack loss method. These were determined for the entire range of tested firing rates. The steam production and efficiencies for each boiler and the combined system are listed in Table 3 below. The indirect stack loss method was used in conjunction with the Enbridge Industrial eTools boiler model. This model has the ability to incorporate a HPE heat exchanger. Thus, the benefits of the HPE and TMC-LPE systems can be separately analyzed.

Table 3. Total Plant Plant Production and Efficiencies

	Boiler 1	Boiler 2
Average Gas Consumption [MMBtu/hr]	5.658	3.214
Average Steam Producion [pph]	4,788	2,615
Combustion Efficiency at Boiler Outlet [%]	82.5%	83.2%
Combustion Efficiency at HPE Outlet [%]	85.7%	N/A
Fuel-to-Steam Efficiency at HPE Outlet [%]	84.3%	81.1%
	Total Plant (Both Boilers)	
Average Steam Production [pph]	6,456	
Total Yearly Steam Production [lb]	56,555,178	
Average Plant Fuel-to-Steam Efficiency [%]	83.3%	
Average MUW Flow [pph]	2,324 (36% of total)	

The combustion and fuel-to-steam efficiencies at all operating points (10% to 95% firing rate) for Boiler 1 are plotted in Figure 6. The boiler operates at relatively constant efficiency due to good air-fuel ratio management across all firing rates. The efficiency is lowest at the lowest firing rates due to increased radiation losses.

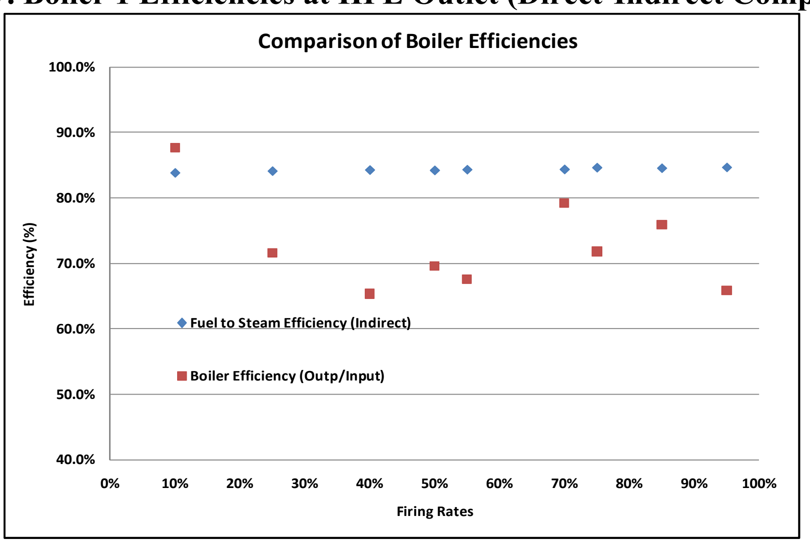
Figure 6. Boiler 1 Efficiencies at HPE Outlet for all Firing Rates (Indirect Method)



Boiler Efficiency With and Without an HPE - Direct Method

The fuel-to-steam efficiencies for Boiler 1 were calculated using the direct, input-output method with a control volume containing the boiler and HPE. This method is dependent upon steam production and water flow measurements. In comparison to the indirect method which uses an ASME prescribed procedure, the efficiency varies wildly across firing rates and even within individual tests as seen in Figure 7. This suggests that the in-situ steam sensors are unstable or not calibrated properly. Therefore, this data was not used further. It is recommended that these measurement systems be inspected and re-calibrated.

Figure 7. Boiler 1 Efficiencies at HPE Outlet (Direct-Indirect Comparison)



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LPE and TMC Efficiency Gains – Indirect Method

The added efficiency gains realized from the LPE-TMC package were determined using the heat recovery calculated using the indirect, stack loss method and simple energy and mass balances around the two components. The balances included heat delivered from the flue gases to two heat sinks: the boiler make-up water and the HAH water re-circulation loop. The amount of heat delivered by the flue gases was calculated using the flowrate, sensible heat, and latent heat recovered across the LPE and TMC. The data for this analysis was gathered on May 2 for firing rate settings of 25%, 50%, 75%, and 95%. Note that in the installed configuration, the TMC is split into multiple tube-shell banks: Bank A sees MUW while Banks B and C see combined MUW and HAH recirculating water.

Table 4. LPE and TMC Water, Heat Recovery, Efficiency Gains

Average Adjusted Firing Rate [%]	40%	49%	62%	78%	Average
Hawk Panel Firing Rate Setting [%]	25%	50%	75%	95%	Average
Recirc Water Flow [pph]	4,270	4,095	3,980	4,050	4,099
TMC Bank A Flow - MUW [pph]	1,320	2,625	2,745	2,605	2,324
TMC Bank B&C Flow – MUW & Recirc Water [pph]	5,590	6,720	6,725	6,655	6,423
Avg TMC Water Flow [pph]	4,167	5,355	5,398	5,305	5,056
Flue Gas Temp – LPE inlet [F]	245.6	251.4	259.4	267.3	251.6
Flue Gas Temp – TMC exit [F]	122.5	122.1	121.8	125	123.1
Heat recovered by LPE/TMC [MBtu/hr]	230.9	289.7	381.7	429.3	307.2
Natural Gas Consumption [MMBtu/hr]	4.190	5.115	6.486	8.201	5.544
Stack Losses out of HPE [MMBtu/hr]	0.596	0.729	0.934	1.190	0.791
Heat Recovered by LPE/TMC [MMBtu/hr]	0.231	0.290	0.382	0.429	.0307
Flue Gases Heat Loss at TMC outlet [MMBtu/hr]	0.365	0.440	0.552	0.796	0.484
Combustion Efficiency at HPE Outlet [%]	85.8%	85.7%	85.6%	85.5%	85.7%
Combustion Efficiency at TMC Outlet [%]	91.3%	91.4%	91.5%	90.7%	91.3%
Combustion Efficiency Gains across LPE/TMC [%]	5.5%	5.7%	5.9%	5.2%	5.6%

On average, the LPE-TMC combination recovered about 307,172 Btu/hr (3.07 therms/hr) of energy from the flue gases, resulting in a natural gas savings of 6.4% of the gas consumed by Boiler 1. This savings is realized by raising the MUW temperature from 77.8 °F to 179.8 °F and increasing the combustion air from 80 °F to 123 °F. These savings are on top of savings realized by the HPE. The annual gas savings due to the LPE-TMC package is about 2,550 MMBtu (25,500 therms) for a yearly runtime of 8,300 hours. For a natural gas cost of $7.00/MMBtu, the total yearly savings is roughly $17,850. The LPE and TMC combined to raise the combustion efficiency by about 5.6%, on average. Of that 5.6% gain, about 2.5% is attributable to the TMC and 3.1% to the LPE.

A heat and mass balance showed that the amount of heat delivered and recovered at the mid-firing rate are within 2%. This suggests that the flowmeter readings are accurate for the mid-firing rates. For other firing rates, the measured values for recovered heat are generally lower, suggesting some error in MUW flow readings. This error is probably caused by fluctuating readings of MUW flow, as mentioned earlier in the report. The comparison based on average values of all tests is within 4%, suggesting that the measurement errors caused by fluctuations in the MUW water flow cancel out when values are integrated over a long period of time.

Added Benefits

In addition to energy and water savings, the gas analyzer showed NOx reduction in the exiting flue gases as shown in Table 5.

Table 5. LPE and TMC Water, Heat Recovery, Efficiency Gains

	Average Actual NOx [ppm]	Average NOx Corrected to 3% Excess O_2 [ppm]
Boiler 1	8.33	9.73
Boiler 2	23.5	25.3

Discussion

The measurement and analysis has shown that the transport membrane condensing heat recovery system is a very effective gas saving measure for commercial boilers. The HPE, LPE, TMC, and HAH are all viable strategies for increasing boiler system efficiency on systems with low condensed return. The field test showed added savings for each component. The combined increase in combustion efficiency for all added measures was about 8.8%. Since HPEs are often used without TMC and LPE systems, the savings realized from each component alone was calculated. These efficiency increases are listed in succession in Table 6. Due to the heavy demand of these large boilers, the cost savings is significant. The average yearly savings realized from the LPE and TMC alone were estimated to be almost $18,000.

Table 6. LPE and TMC Water, Heat Recovery, Efficiency Gains

	Boiler 1	Boiler 2
Combustion Efficiency at Boiler Outlet	82.5%	83.2%
Combustion Efficiency at HPE Outlet	85.7%	N/A
Fuel-to-Steam Efficiency	84.3%	81.1%
Combustion Efficiency at TMC Outlet	91.3%	N/A

The results of the field test are encouraging and warrant further investment in the technology. It is already designated for commercial production and a CEC report recently studied the technology as applied to non-steam generating plants. The system is adaptable to other applications such as lime kilns, pet food drying, dry cleaning, and many other processes that use large-scale natural gas combustion. The installed system used in this study has been in operation for more than two years with no major problems. This suggests that the system is matured and ready for commercialization.

The market impacts have been discussed elsewhere but a broad impact study and further analysis should be considered as the product advances towards market penetration. Savings will be dependent upon plant operating conditions, yearly operation times, and secondary use possibilities for waste heat recovery. Further study should include installation of well-controlled and calibrated in-situ sensors so that results can be assured accurate and reliable. The results presented here were derived from in-situ measurements that were compared with spot measurements as the equipment and system allowed. The authors are confident that the results accurately represent the savings in the tested conditions and confirm that the technology is an effective gas saving measure.

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