ENERGY EFFICIENCY AND EMISSION REDUCTION OF TPM, $PM_{2.5}$, AND SO_2 FROM NATURAL GAS AND FUEL OIL FIRED BOILER EXHAUSTS

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1.0 ABSTRACT

Fully 8% of all of Canada's energy consumption occurs in gas and fuel oil fired boilers in commercial and institutional facilities[1], with proportional amounts of greenhouse gases, particulate matter, and other pollutants. Recently particulate matter, and in particular that smaller than 2.5 microns ($PM_{2.5}$) has garnered specific attention due to attributed health effects as demonstrated by associated increased hospital admissions and emergency room visits—and even to death from heart or lung diseases[2].

The pollution control hierarchy places pollution prevention well above end of pipe pollution control, so reducing energy consumption is the primary way to approach reducing this significant portion of the world's emissions. In addition, energy conservation meets the most fundamental requirement for a successful large scale emission reduction program – that being a return on investment (ROI) for an emission reduction project.

Condensing heat recovery technologies can easily provide boiler plant efficiency improvements of 10% to 20%, with a directly proportional decrease in all $PM_{2.5}$, greenhouse gases, and other pollutants. In addition, direct contact condensing heat recovery units (which are wet scrubbers designed for heat recovery applications) can simultaneously provide significant end of pipe reduction in total particulate matter (TPM), $PM_{2.5}$, and SO_2 emissions.

This paper describes a verification program conducted on an existing installation at the Stratford General Hospital in Stratford, Ontario. During normal winter (high load) operation of the boiler plant equipped with a FLU-ACE® direct contact condensing heat recovery system, the impact of the system on the boiler plant energy efficiency, and the end of pipe reduction of TPM, $PM_{2.5}$, and SO_2 were simultaneously measured during firing of natural gas and #2 fuel oil.

This paper presents the method and results of this verification program.

2.0 SITE AND PROCESS DESCRIPTION

The Stratford General Hospital is a medium sized community hospital located in Stratford, Ontario, that provides public health care services to the surrounding community.

The hospital site is equipped with a central heating plant ("CHP") facility, which contains three (3) natural gas fired 300 BHP steam boilers, which can also be operated with #2 fuel oil as the back-up fuel for peak winter conditions. Exhaust gases from all three boilers are routed to a single FLU-ACE® Condensing Heat Recovery System, which is a packed wet scrubber designed for low grade heat recovery. The boilers and the heat recovery unit were all installed as a single project and are all controlled through a single Johnson Metasys control system.

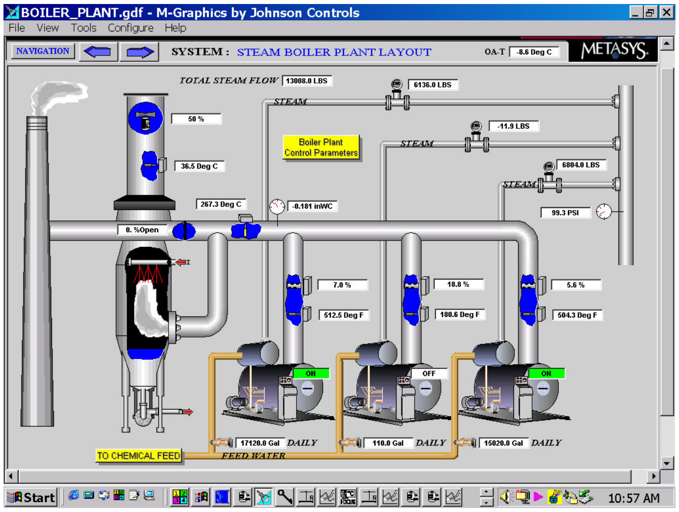

Figure 1 – Control Screen Snapshot

A snapshot of a control screen from the Johnson Controls Metasys control system at the Stratford General Hospital, is provided in Figure 1, showing the boilers and the condensing heat recovery unit. It also provides typical operational data from a moment during the test program.

Measurements were taken simultaneously at the inlet of the FLU-ACE® (which is the outlet of the boilers), and at the outlet of the FLU-ACE® (exhaust to atmosphere) to determine removal efficiency of PM, $PM_{2.5}$, and SO_2. At the same time Metasys boiler plant performance data was collected to track the efficiency of the boiler plant.

A process schematic is provided in Figure 2 showing more clearly the operation of the combined heat recovery and pollution control system.

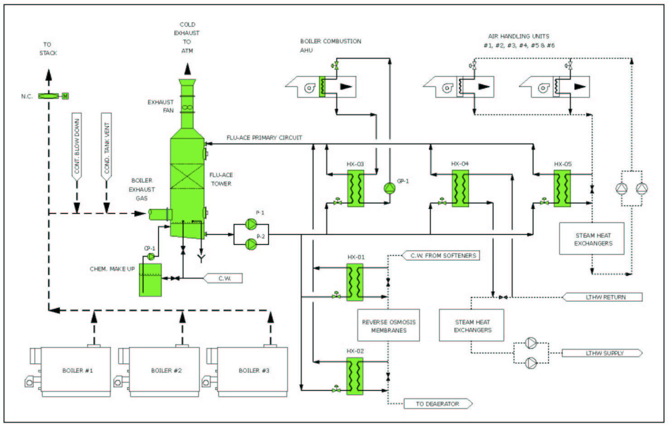

Figure 2 – Process Schematic

The combined boiler total "peak winter season" (maximum monthly average) recorded steam output is 18,000 lb steam/h @ 90 psig.

The sampling program was conducted during firing of #2 fuel oil (3 tests) and natural gas (3 tests). The tests were completed during high load (normal winter) operating conditions, firing boilers #1 and #3, with the plant producing between 8,080 and 20,130 lbs/hr of steam, at an average of 12,610 lbs/hr. Hourly average plant and individual boiler steam production, exhaust gas temperature, and % oxygen data, were gathered for the entire period of the testing.

3.0 METHODOLOGY

3.1 Energy Efficiency Verification

The energy efficiency improvement resulting from the operation of the condensing heat recovery unit was tracked during all tests using Johnson Controls Metasys control system. The measured exhaust gas temperature, steam production, and % oxygen (%O_2) were tracked during all tests on each fuel. Standard and accepted combustion calculations were applied[3,4]. The exhaust gas temperature, combustion air temperature, and %O_2 were used to determine excess combustion air and to calculate:

Sensible (dry) heat loss – the heat available in the exhaust gas due to its temperature, it is dependent upon the fuel composition, the excess air level, and the difference between the exhaust gas temperature and the combustion air temperature, the sensible heat loss for natural gas combustions is:

[1] % Sensible Heat Loss = $M_{DG}/Q \times C_p \times (T_E-T_C) / 10^4$

Where: M_{DG}/Q is the lb dry exhaust gas / 10^6 Btu gas burned;
C_p is the heat capacity of the gas (Btu/lb °F);
T_E is the stack exhaust temperature (°F);
T_C is the combustion air temperature (°F).

Latent heat loss – the latent heat contained in the flue gas due to the creation of water vapour (steam) from the combustion of hydrogen in the fuel. It is dependent upon level of moisture in the flue gas formed from the combustion of hydrogen. The loss consists of heat of evaporation plus superheat, and as such it depends upon hydrogen content in the fuel, stack exhaust temperature, and combustion air temperature:

[2] % Latent Heat Loss = $M_W/Q \times (1089-T_C+0.46 \times T_E) / 10^4$

Where: M_W/Q is the lb water formed / 10^6 Btu gas burned.

Note the equation above is only valid above the dew point of the exhaust gas, and does not apply in the condensing regime. Assuming modern burners with low CO concentrations in the exhaust, the sum of [1] and [2] represents the heat lost in the flue gas. For the purpose of this study the blowdown and radiation losses were considered constant (with regards to impact of the heat recovery system) and not relevant to the efficiency increase, and so efficiency has been expressed as:

[3] Boiler Plant Thermal Efficiency = 100%-[1]-[2]

In truth the actual boiler plant efficiency will be some 3% to 5% lower due to radiation and blowdown losses.

The efficiency increase due to the operation of the condensing heat recovery unit was calculated as the Boiler Plant Thermal Efficiency based on the %O_2 and temperature of the exhaust gas before the FLU-ACE® (efficiency of boiler plant without heat recovery unit) and after the FLU-ACE® (efficiency of boiler plant with heat recovery).

3.2 TPM, $PM_{2.5}$, and SO_2 Reduction Verification

Sampling and analytical methodologies for the emissions test program can be separated into four categories as follows:

1. Measurement of gas velocity, molecular weight, and moisture content;
2. Measurement of filterable and condensable PM emissions;
3. Measurement of filterable $PM_{2.5}$ emissions;
4. Measurement of sulfur dioxide content in gas stream.

Measurements were taken simultaneously at the inlet of the FLU-ACE® (which is the outlet of the boilers), and at the outlet of the FLU-ACE® (exhaust to atmosphere) to determine removal efficiency of PM, $PM_{2.5}$, and SO_2, by an independent third party (BTEC/Valley Environmental Services), using the following methods:

3.2.1 Exhaust Gas Velocity, Molecular Weight, and Moisture Content

Measurement of exhaust gas velocity, molecular weight, and moisture content was conducted using the following reference test methods codified at Title 40, Part 60, Appendix A of the Code of Federal Regulations (40 CFR 60, Appendix A):

- Method 1 - “Location of the Sampling Site and Sampling Points”
- Method 2 - “Determination of Stack Gas Velocity and Volumetric Flowrate”
- Method 3 - “Determination of Molecular Weight of Dry Stack Gas”(Fyrite)
- Method 4 - “Determination of Moisture Content in Stack Gases”

3.2.2 Particulate Matter (USEPA Method 5/202)

40 CFR 60, Appendix A, Method 5, “Determination of Particulate Emissions from Stationary Sources” and 40 CFR 60, Appendix A, Method 202, “Determination of Condensable Particulate Emissions from Stationary Sources” was used to measure PM concentrations and calculate PM emission rates. Triplicate 60-minute (or greater for natural gas) test runs were conducted for each source and fuel type.

3.2.3 Particulate Matter ($PM_{2.5}$) (USEPA Method 201a)

40 CFR 60, Appendix A, Method 201a, “Determination of PM_{10} Emissions” with a $PM_{10/2.5}$ cyclone with in stack filter and was used to measure filterable $PM_{2.5}$ concentrations and calculate $PM_{2.5}$ emission rates.

3.2.4 Sulfur Dioxide (USEPA Method 6C)

The sulfur dioxide content of the gas stream was evaluated according to procedures outlined in Title 40, Part 60, Appendix A, Method 6C. The SO_2 content of the gas stream was measured using a Western Research SO_2 gas analyzer.

Data was recorded at 4-second intervals on a PC equipped with Labview® II data acquisition software. Recorded SO_2 concentrations were averaged over the course of each test.

4.0 RESULTS

4.1 Energy Efficiency Verification

Based on the calculation method detailed above, the Boiler Plant Thermal Efficiency for the duration of the tests is shown in Table 1 and Figure 3 below.

Test	Before FLU-ACE (%)	After FLU-ACE (%)	Improvement (%)
Natural Gas	78%	95%	17%
#2 Fuel Oil	81%	95%	14%

Table 1 – Boiler Plant Thermal Efficiency Improvement

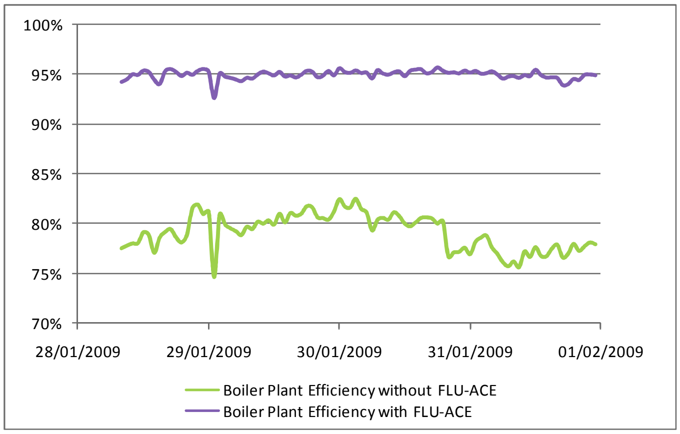

Figure 3 – Boiler Plant Thermal Efficiency during Test Period

4.2 “End of Pipe” Emission Removal

Based on the measurement method detailed above, the emissions measured at the inlet and outlet of the FLU-ACE®, and the emission reduction achieved, during natural gas and #2 fuel oil combustion, are shown in Table 2.

Test	Parameter	Inlet (lb/hr)	Outlet (lb/hr)	% Removal
Natural Gas	Total Particulate Matter	0.05	0.03	46%
	Filterable $PM_{2.5}$	0.03	0.01	70%
	Condensable $PM_{2.5}$	0.04	0.02	60%
	Total $PM_{2.5}$	0.07	0.02	74%
	SO_2	0.01	-	88%
#2 Fuel Oil	Total Particulate Matter	0.27	0.11	56%
	Filterable $PM_{2.5}$	0.10	0.09	7%
	Condensable $PM_{2.5}$	0.13	0.03	75%
	Total $PM_{2.5}$	0.24	0.13	44%
	SO_2	1.97	-	>99%

Table 2 – Measured Emission Levels and Reductions for #2 Fuel Oil and Natural Gas Combustion

5.0 DISCUSSION

5.1 Energy Efficiency Verification

The results of the energy efficiency verification are not surprising. It is well known that given the appropriate low grade heat users (domestic hot water and space heating in this case) that condensing heat recovery technology, and even condensing boilers, can provide well over 90% thermal efficiency, even as high as 98% and 99% during full load periods. The data gathered during these tests simply verifies this, demonstrating 95% efficiency (only 5% combustion losses) as defined in this report.

Figure 4 shows how the efficiency as defined in this report correlates with the flue gas exhaust temperature for the average natural gas combustion conditions at the Stratford Hospital over the period of the tests (6.7% O_2, 142%

combustion air). It shows the pre- heat recovery (497 °F) and post-heat recovery (99 °F) operating points. The sharp increase at roughly 130 °F is the dew point, and demonstrates where condensing systems can begin to recover the latent heat loss by condensing the water vapour formed during combustion.

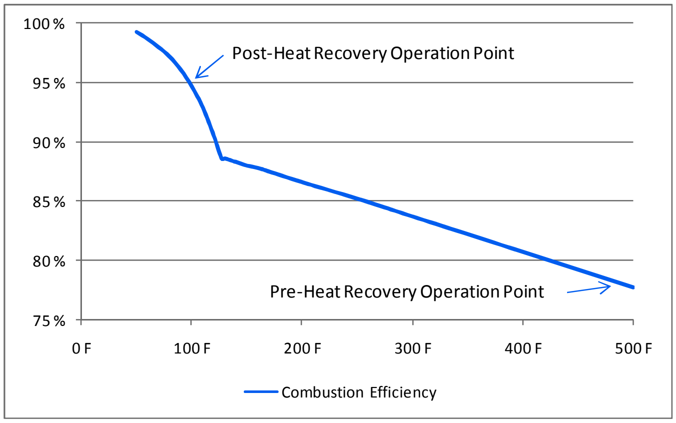

Figure 4 – Boiler Plant Thermal Efficiency vs. Exhaust Gas Temperature (6.7% O_2, 142% combustion air)

The energy efficiency was largely tracked simply to allow for proper reporting of combined energy efficiency and environmental performance.

5.2 "End of Pipe" Emission Removal

The emission reductions are perhaps somewhat less expected and more interesting, but predictable to some degree.

The results (Table 2) clearly demonstrate excellent (average 68%) removal of condensable $PM_{2.5}$, which according to the USEPA AP42[5], should all be considered PM_1, as well as $PM_{2.5}$. But there is significantly lower removal of physical (non-gaseous at point of emission, filterable) $PM_{2.5}$.

The lower removal of physical (filterable) $PM_{2.5}$ (particularly on oil) was expected. From the USEPA AP42[5] "Because natural gas is a gaseous fuel, filterable particulate matter emissions are typically low. Particulate matter (PM) from natural gas combustion has been estimated to be less than 1 micrometer in size. Particulate matter is composed of filterable and condensable fractions, based on the EPA Method 5. Filterable and condensable emission rates are of the same order of magnitude for boilers; for residential furnaces, most of the PM is in the form of condensable material." This is not identical, but is similar for #2 fuel oil (large condensable PM fraction). Wet scrubbers, including the FLU-ACE®, remove PM quite effectively. The PM removal increases with pressure drop and PM size, but decreases dramatically as particle size drops below 1 micron. For PM_1, which implies particulate matter smaller than 1 micron common references[6,7] estimate removals of roughly 50% to 75% at 2 microns, and negligible removal below one micron, with typical packed scrubbers.

Based on this one can surmise:

1. The physical (filterable) PM is largely less than 1 micron in diameter, and as such, is too small for appreciable removal of a physical particle in a low pressure drop packed wet scrubber;
2. The PM is largely condensable, and as such, lends itself well to removal in a heat recovery wet scrubber due to the condensing action, which reduces the exhaust temperature to below the dew point of water and of some heavy fractions of the fuel (which largely make up the PM from natural gas exhaust).

The results seem to strongly validate this speculation, showing excellent condensable $PM_{2.5}$ removal and limited filterable $PM_{2.5}$ removal.

5.3 Total Emission Reductions

Directly multiplicative to the end of pipe reduction is the pollution prevention benefit. By burning an average 14% (#2 fuel oil) to 17% (natural gas) less fuel, the emissions of all contaminants including all PM, greenhouse gases, SO_2, and NO_x are proportionally reduced. This results in the following per cent and absolute reductions in emissions if we project the tested operating conditions over the entire year (Table 3).

Test	Parameter	% Reduction
Natural Gas	Total Particulate Matter	55%
	Filterable $PM_{2.5}$	75%
	Condensable $PM_{2.5}$	67%
	Total $PM_{2.5}$	78%
	SO_2	90%
	CO_2, Greenhouse Gases, NOx	17%
#2 Fuel Oil	Total Particulate Matter	63%
	Filterable $PM_{2.5}$	20%
	Condensable $PM_{2.5}$	79%
	Total $PM_{2.5}$	52%
	SO_2	>99%
	CO_2, Greenhouse Gases, NOx	14%

Table 3 – Total Emission Reductions for #2 Fuel Oil and Natural Gas Combustion

6.0 CONCLUSIONS

The conclusions that can be reached are as follows:

1. Using condensing heat recovery technology, properly designed boiler plants and infrastructure can often, if not typically, operate at 95% efficiency (only 5% combustion losses) as defined in this report - this represents a 17% improvement in the natural gas combustion efficiency and a 14% improvement in the combustion efficiency of #2 fuel oil due to the use of condensing heat recovery;

2. The “end of pipe” reduction (scrubbed emissions) of the FLU-ACE® when recovering energy from natural gas fired boiler exhausts were verified as 46% TPM, 70% filterable $PM_{2.5}$, 60% condensable $PM_{2.5}$, 74% total $PM_{2.5}$, and over 88% SO_2;
3. The “end of pipe” reduction (scrubbed emissions) of the FLU-ACE® when recovering energy from #2 fuel oil fired boiler exhausts were verified as 56% TPM, 7% filterable $PM_{2.5}$, 75% condensable $PM_{2.5}$, 44% total $PM_{2.5}$, and over 99% SO_2;
4. The breakdown of PM provided by the detailed level of testing clearly shows the limited effectiveness of the system of physical (filterable) $PM_{2.5}$, (38% average removal) and the increased effectiveness on condensable $PM_{2.5}$ (68% average removal);
5. Including the emission reductions from pollution prevention (fuel use reduction) the total emission reduction can be summarized as (averaged across the natural gas and oil test results) 59% TPM, 48% filterable $PM_{2.5}$, 73% condensable $PM_{2.5}$, 65% total $PM_{2.5}$, over 95% SO_2, and 15% CO_2, NO_x, and other toxics and greenhouse gases.
6. This level of emission reduction through combined pollution prevention (fuel use avoidance) and “end of pipe” control in a single technology, can be provided in many cases with an ROI attractive to most institutional and commercial facilities, for new construction or retrofit.

7.0 REFERENCES

[1] John Cuddihy, Christopher Kennedy, and Philip Byer “Energy use in Canada: environmental impacts and opportunities in relationship to infrastructure systems”, Can. J. Civ. Eng. 32: 1–15, 2005 NRC Canada;

[2] USEPA, “Particle Pollution and Your Health”, EPA-452/F03-001, U.S. Environmental Protection Agency, September 2003;

[3] Friedrich, F.D., and Hayden, C.S., “A Combustion Handbook for Canadian Fuels Volume 2 – Gaseous Fuels”, Canadian Combustion Research Laboratory, Mines Branch Monograph 879;

[4] Friedrich, F.D., and Hayden, C.S., “A Combustion Handbook for Canadian Fuels Volume 1 – Fuel Oil”, Canadian Combustion Research Laboratory, Mines Branch Monograph 877;

[5] USEPA AP42, Fifth Edition, “Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources”, U.S. Environmental Protection Agency, January 1995;

[6] Ralph J. Strigle, “Packed Tower Design and Applications”, Second Edition, 1994;

[7] Perry et. al., “Perry’s Chemical Engineering Handbook”, 6th Edition, 1984.