Boiler Flue Gas Energy Recovery System

Test Results and Analysis of Application
for Multi-Residential Buildings

Prepared by

Samuel van Berkel, PEng, MASc
Watershed Technologies Inc.

Prepared for

Carbon Cap Inc.
and
The Atmospheric Fund (TAF)

January 2018

Watershed Technologies Inc. 477A Dupont St., Toronto, Canada, M6G 1Y6
www.watershed.ca Tel: 416-538-7940 Email: info@watershed.ca

Executive Summary

Flue gas recovery (FGR) is a system for retrofitting existing natural gas boilers with air-to-water heat exchangers to recapture the 10-25% of energy that would otherwise be lost in the flue gases. In the case of multi-residential buildings, there is a significant low temperature domestic hot water (DHW) load which can be heated by the flue gases, providing significant recovery potential for both DHW and space heating boilers. Because the FGR heat exchanger is decoupled from the boiler itself, it can provide some efficiency benefits even beyond conventional condensing boilers. This report summarizes the results of a test of the FGR system and provides a brief analysis of the potential application for multi-residential buildings.

The performance test was carried out using a Camus SureFlame atmospheric boiler (600 MBH input) at stable operating conditions and a combustion efficiency of 85%. Domestic cold water was used as the recovery medium through the FGR heat exchanger. Water flow analysis was conducted using an ultrasonic flow meter and portable surface thermometer. Results of the water flow analysis indicate 94.7 MJ/hr of energy recovery. An analysis of airflow and enthalpy through the FGR heat exchanger was also conducted, indicating 95.3 MJ/hr of energy recovery (<1% difference with water flow analysis). The rate of condensation measured also agreed well with the calculated value (8% difference), further validating the airflow model.

Given a boiler natural gas energy input rate of 633 MJ/hr, the resulting energy recovery rate of 95 MJ/hr represents 15% of the total input. Based on the combustion efficiency measurements of 85%, this 15% is roughly equivalent to 100% of the flue gas energy available for recovery.

In theory, the FGR system should be able to recover close to 100% of the available flue gas energy, providing potential natural gas savings of 15-25% for atmospheric boilers. In practice, achieving these results will depend on a number of key factors. Roughly 12% total natural gas energy content can only be captured by low temperature loads such as domestic hot water (DHW). For buildings with a lower DHW to space heating ratio, there may be periods when available space heating energy exceeds the DHW heating load. In these cases other strategies for capturing excess low temperature energy may be beneficial such as preheating ventilation air or adding a stratified DHW preheating storage tank.

Achieving maximum energy recovery will also depend on the sizing of the FGR air-to-water heat exchanger. As the number or size of operating boilers is increased, or as average water temperature through the heat exchanger rises, the size of the heat exchanger will have to be increased or there will be insufficient heat transfer to fully cool the flue gases, resulting in reduced energy recovery.

The FGR system applied to multi-residential buildings has the potential to recover nearly all of the boiler flue gas energy, resulting in gas savings of 15-25% for atmospheric boilers. In practice, there may be some reduction in energy savings due to the availability of low temperature loads, heat exchanger sizing or other operational issues. These issues would be best explored by monitoring an installed application of the FGR system. Ultimately, the costs of installation, operation and maintenance will determine the economic feasibility of the FGR system for multi-residential buildings.

1. Overview

Most buildings in Canada utilize natural gas for heating. Although natural gas contains 37-39 MJ/m³ of energy, 10-25% of this energy is typically lost in the flue gases as hot moist air. Newer condensing boilers have the potential to capture almost all of this energy, but require low temperature operating conditions to achieve full performance. Many existing heating systems, particularly multi residential buildings with baseboard radiators, are designed for high temperature operation. As a result, even condensing boilers only achieve partial flue gas energy recovery in these applications. The reduced benefit of condensing boilers, combined with their significant cost, has lead many multi-residential building owners to continue operating low-efficiency boilers.

Flue gas energy recovery or flue gas recovery (FGR) is a system for retrofitting existing boilers with air-to-water heat exchangers to recapture flue gas energy not captured by the boilers themselves. In addition to potential cost savings over condensing boilers, FGR may be able to provide increased energy savings in applications where traditional condensing boilers have performed poorly. Because the FGR heat exchanger is decoupled from the boiler itself, it can be used to heat a low temperature medium even while the boiler is heating a different, high temperature medium. In the case of multi-residential buildings, there is a significant low temperature domestic hot water (DHW) load which can be heated by the flue gases, providing significant recovery potential for both DHW and space heating boilers.

Performance testing of the FGR system was carried out on December 13, 2017 at Carbon Cap's facility in Ancaster, Ontario. This report summarizes the results of that testing and provides a brief analysis of the potential application for multi-residential buildings in Southern Ontario.

2. Performance Testing

The performance test was carried out using a Camus SureFlame atmospheric boiler with a rated input of 600 MBH (633 MJ/hr) and a rated efficiency of 81%. The boiler was run continuously during the test and allowed to reach a stable operating condition before measurements were taken. An FGR heat exchanger with four distinct sections was used for heat recovery, while an axial fan was used to provide airflow through the heat exchanger. Domestic cold water was used as the heat recovery medium. The test configuration is shown in Figure 1, along with measured, calculated and estimated values for temperature, humidity, airflow and energy recovery.

Parameters were measured directly where possible, but a number of assumptions were required:

1. Although a dedicated natural gas meter was installed by the utility (Union Gas), the meter's resolution of 1 ccf (2.83 m³) made its use impractical and the natural gas consumption rate was instead based on the boiler's rated input of 600 MBH (16.4 m³/hr of natural gas).
2. The natural gas composition was based on the typical values published by the utility (Union Gas): 93.9% methane, 4.2% ethane, 0.3% propane, 1.0% nitrogen, 0.5% carbon dioxide and 0.1% other compounds. Similarly, energy content was set at 38.7 MJ/m³. https://www.uniongas.com/about-us/about-natural-gas/Chemical-Composition-of-Natural-Gas
3. The relative humidity (RH) of the ambient indoor air was assumed to be 20%, based on typical indoor levels and the absence of any significant indoor moisture sources (not a major factor in the overall results).
4. The RH of the flue gas downstream of the FGR heat exchanger was assumed to be 100% based on having being cooled below the dew point, generating significant condensation.

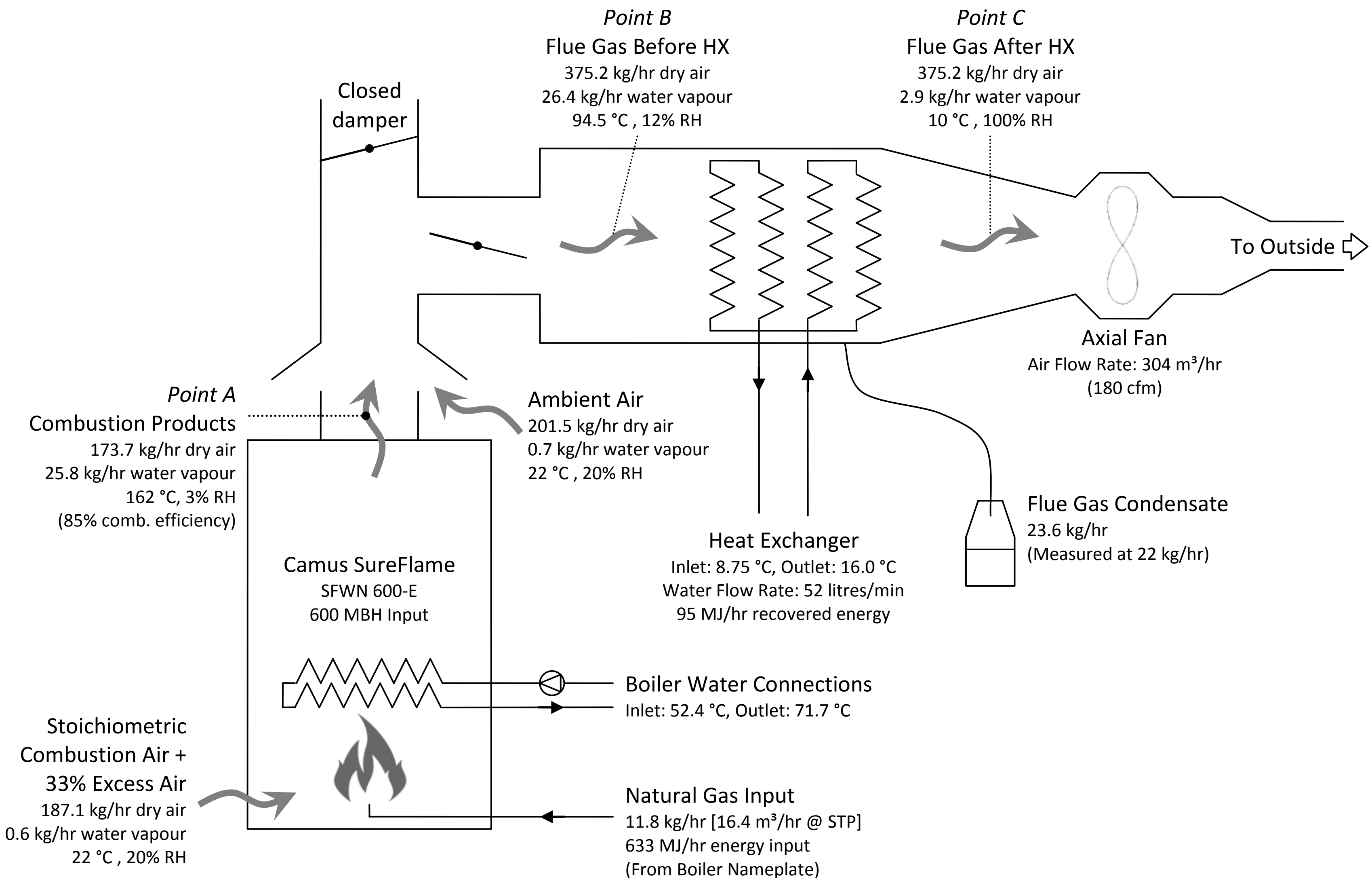


Figure 1. FGR system test configuration and values

Water Flow Analysis

An ultrasonic flow meter was used to measure the flow of water through the FGR heat exchanger. The average flow rate was determined by taking the difference between two water meter readings, approximately 20 min apart. Water temperatures were measured upstream and downstream of the heat exchanger using a Testo 905-T2 surface thermometer on copper pipe. Two sets of temperature readings were taken roughly 10 min apart and averaged. Energy recovered was calculated as shown below:

$Q = c_p \rho q \Delta t$
$Q = (4.18\ kJ/kg/°C)\ (1.0\ kg/L)\ (52.1\ L/min)\ (60\ min/hr)\ (16.0\ °C - 8.75\ °C)$
$Q = 94.7\ MJ/hr$

Where,
Q = rate of energy recovery, MJ/hr
c_p = specific heat of water, 4.18 kJ/kg/°C water
ρ = density of water, 1.0 kg/L
Δt = temperature difference between inlet and outlet, °C

Results of the water flow and temperature measurements through the FGR heat exchanger indicate 94.7 MJ/hr of energy recovery.

Airflow Analysis

Flue gas analysis was performed using a Testo 327 combustion analyzer. Measurements taken indicate a flue gas temperature of 162 °C, 33% excess air and a combustion efficiency of 85%. Based on these values and a natural gas flow rate of 11.8 kg/hr (16.4 m^3/hr), the combustion process resulted in 173.7 kg/hr dry air and 25.8 kg/hr water vapour with an enthalpy rate of 100 MJ/hr (Point A in Figure 1).

A temperature of 94.5 °C was measured upstream of the FGR heat exchanger, after the mixing of combustion air with ambient air through the boiler's vent hood. Based on this temperature measurement and the constituents of the two air sources, the mixed air contained 375.2 kg/hr dry air and 26.4 kg/hr water vapour with an enthalpy rate of 106 MJ/hr (Point B in Figure 1).

A temperature of 10 °C was measured downstream of the FGR heat exchanger, after cooling of the airstream by the water. As this temperature was well below the dew point of the upstream air, 100% RH was assumed downstream of the FGR heat exchanger. Based on this assumption, the cooled air contained 375.2 kg/hr dry air and 2.9 kg/hr water vapour with an enthalpy rate of 11 MJ/hr (Point C in Figure 1).

Comparing enthalpy rates before and after the FGR heat exchanger yields a net change in enthalpy of 95.3 MJ/hr, which agrees with the results of the water flow analysis (<1% difference). Similarly, comparing water vapour flow before and after the FGR heat exchanger yields a net reduction of 23.6 kg/hr, which agrees fairly well with the measured rate of condensate generation of 22 kg/hr (8% difference), further validating the airflow model and results.

Energy Recovery Results

Stoichiometric analysis of the natural gas combustion yields 25.2 kg/hr of water vapour or 56.9 MJ/hr of latent energy (the energy associated with the phase change of water from vapour to liquid). The airflow model indicates 23.6 kg/hr of water vapour are condensed out of the flue gas, which is equivalent to 53.3 MJ/hr or 94% latent energy recovery.

In addition to the latent energy recovered, 42.1 MJ/hr of sensible energy was captured from the airstream (the energy associated with the change in temperature of the air and water vapour). Because the flue gases were cooled below the ambient air temperature of 22 °C, additional sensible energy was captured from the ambient air resulting in an apparent sensible recovery of more than 100%.

Given a boiler natural gas energy input rate of 633 MJ/hr, the resulting total sensible and latent energy recovery rate of 95.3 MJ/hr represents 15% of the total input. Based on the combustion efficiency measurements of 85%, this 15% is roughly equivalent to 100% of the flue gas energy available for recovery (although it is actually 94% of the flue gas latent energy, 100% of the flue gas sensible energy and small amount of additional sensible energy from the ambient air).

3. Application for Multi-Residential Buildings

In theory, the FGR system should be able to recover close to 100% of the available flue gas energy from both space heating and DHW boilers. The potential natural gas savings will depend on the existing boilers' combustion efficiency, with less-efficient atmospheric boilers providing the greatest opportunity (potential savings of 15-25%) and more-efficient forced draft and condensing boilers providing a smaller opportunity (potential savings of 5-15%).

In practice, achieving these results will depend on a number of key factors. The temperature of water circulated through the FGR heat exchanger has an impact on the amount of energy recovered from the flue gases. The FGR system test was performed in December and utilized domestic cold water at 8.75 °C. Due to seasonal changes in ground temperature, summer domestic cold water temperatures are slightly higher. Using the same boiler operating parameters as the test case and assuming an average summer domestic cold water temperature of 14 °C, the maximum energy recovery would be reduced by roughly 5% (equivalent to a 0.8% increase in boiler energy use).

A significant portion of the flue gas energy can only be recovered by reducing the flue gas temperature below the dew point (typically around 55 °C). For many multi-residential buildings, particularly those heated with baseboard radiators, hot water return temperatures will be above 55 °C for the colder portions of the heating season. In these scenarios the remaining sensible energy and all of the latent energy (roughly 12% total natural gas energy content) can only be recovered by low temperature loads such as DHW. For discussion purposes, this portion of the energy will be referred to as the "low temperature energy".

Fortunately, for most multi-residential buildings the ratio of DHW heating load to space heating load is high enough that there is sufficient DHW heating load to absorb the low temperature energy under most circumstances. For buildings with a lower DHW to space heating ratio, there may be periods when available space heating energy exceeds the DHW heating load, particularly cold nights when space heating peaks but DHW consumption is at a minimum. There may be a drop in flue gas energy recovery during these periods.

Figure 2 illustrates hourly DHW and space heating loads for a Toronto multi-residential building for a one-week period in December 2017. The available energy from space heating recovery represents the 12% of energy expended for space heating that can only be absorbed by low temperature loads such as DHW.

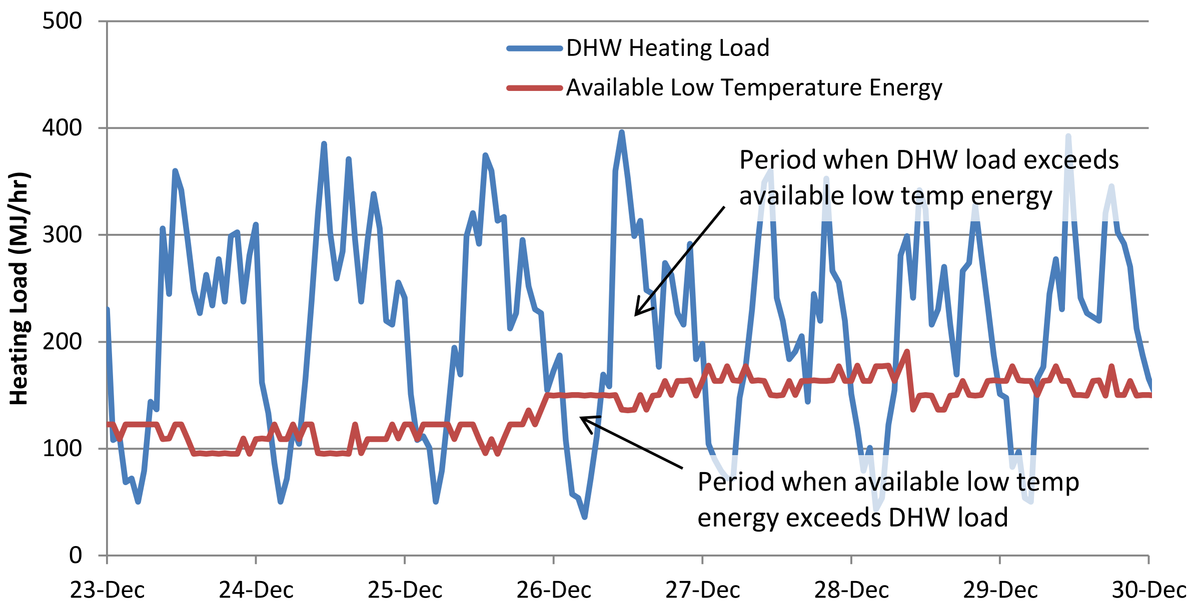


Figure 2. DHW heating load and available energy recovery from space heating system.

In the example in Figure 2, the available low temperature energy exceeds the available DHW load for brief periods each night, with the difference increasing as space heating load rises. Even so, the overall effect is only a 10% reduction in total low temperature energy recovery (equivalent to a 1.2% increase in boiler energy use) for a relatively cold week (average temp -10.5 °C). For this example, the overall impact on annual savings is likely negligible.

For buildings where the ratio of DHW to space heating load is lower and the impact on annual savings is more significant, there may be other strategies for capturing excess low temperature energy. These include preheating ventilation air or adding a stratified DHW preheating tank to store recovered low temperature energy during the night for use during the morning peak. The economic feasibility of these measures will vary widely by building, depending on the physical layout of existing systems and potential energy to be recovered.

Achieving maximum energy recovery will also depend on the sizing of the FGR air-to-water heat exchanger. The test was conducted using a heat exchanger that was sufficiently sized for the boiler and water temperature, allowing the flue gas to be cooled to within 1.5 °C of the inlet water temperature. As the number or size of operating boilers is increased, or as average water temperature through the heat exchanger rises, the size of the heat exchanger will have to be increased or there will be insufficient heat transfer to fully cool the flue gases, resulting in reduced energy recovery. The optimal heat exchanger sizing will balance the increasing cost of a larger heat exchanger with decreasing energy savings at each increment, and will likely sacrifice a small reduction in energy recovery during periods of maximum boiler output for reduced installation cost.

Although likely small, the FGR system will require additional electrical energy for both the flue gas fans and pumps to circulate water through the heat exchanger. This electrical energy should be discounted from any natural gas savings.

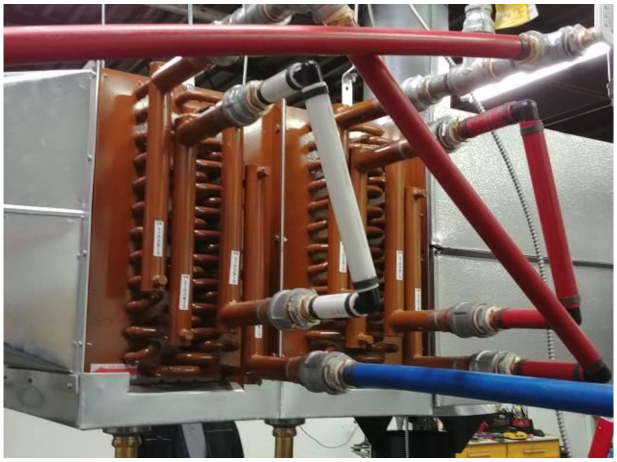
4. Conclusions

The FGR system applied to multi-residential buildings has the potential to recover nearly all of the boiler flue gas energy, resulting in gas savings of 15-25% for atmospheric boilers (less for more efficient forced draft or condensing boilers). In practice, there may be some reduction in energy savings due to the availability of low temperature loads, heat exchanger sizing or other operational issues. These issues would be best explored by monitoring an installed application of the FGR system, including thermal metering of the heat exchanger and boiler output, and energy monitoring of the boiler natural gas consumption and fan and pump electricity consumption.

There are a number of issues that are beyond the scope of this report including installation, operation and maintenance, as well as regulatory approvals and safety. All of these factors will impact project costs, and ultimately determine the economic feasibility of the FGR system for different multi-residential buildings.

Testing Photos

Test setup including Camus boiler, venting, FGR heat exchanger, fan and connections.
(Laars boiler in background not used in test.)



FGR heat exchanger and connections

Water temperature measurements

Union Gas meter (ccf)

Ultrasonic water meter

Combustion analyzer output

Condensate measurement