Emerging Technology Program

#1134: Modulating Valve for Single Stage Furnace

Final Public Pilot Assessment Report

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The results within this report relate only to the items tested.

Executive Summary

Introduction

As a part of the Nicor Gas energySMART energy efficiency program, the Emerging Technology Program (ETP) assesses new technologies that have the potential to realize natural gas savings for the 2.2 million Nicor Gas customers in Northern Illinois. The Gas Technology Institute (GTI) provides program implementation for the Nicor Gas ETP. This report summarizes the findings of laboratory evaluations for the Modulating Valve for Single Stage Furnace technology and the potential for this technology to provide energy efficiency savings to Nicor Gas residential customers.

Background

Right-sizing heating equipment is crucial to reducing annual operating costs and energy consumption. Air Conditioning Contractors of America (ACCA), an educational institute, develops standards and manuals for HVAC installers. Manual S and Manual J are the two that are applicable to residential HVAC systems. Manual J, Residential Load Calculation, stipulates the heating load calculation for design-day weather conditions. Manual S, Residential Equipment Selection, stipulates the furnace sizing at 1.4 times the calculated heat load. As a result, the selected furnace is oversized. Oversized heating equipment can satisfy heating loads of unusually cold temperatures during the winter. The oversized furnace short cycles for most of the heating season. As such, increasing the duration of cycle times is attractive because it often results in increased efficiencies and gas savings. The Modulating Valve for Single Stage Furnace is a bolt-on device for single-stage furnaces that controls the firing rate of a furnace based on time off between furnace cycles. The Modulating Valve for Single Stage Furnace can make a single-stage furnace operate at a lower firing rate under certain cycle conditions.

Results

The tested Modulating Valve for Single Stage Furnace operated consistently in low-flow mode (at 80% of the total firing rate) when time off between cycles was longer than 9.75 minutes. Similarly, it operated in the high-flow mode when time off between cycles was less than 4.41 minutes. The Modulating Valve alternated between low and high flow periodically between time off cycles of 4.41 minutes and 9.75 minutes. The combustion efficiencies were lower in low-flow operation with the Modulating Valve. Firing rates were modeled to compute annual energy consumption in pre-1980 864-square-foot (sqft) construction in the Chicagoland area. The modeling data showed that the furnace would operate in low-flow conditions for 16% in the heating season. There were no measurable energy savings potentials of the laboratory-evaluated Modulating Valve for Single Stage Furnace.

Next Steps/Recommendations

The furnace's reduced efficiency in low-flow Modulating Valve operations is primarily attributed to combustion chemistry. Further evaluation of this technology is not recommended as the technology does not provide energy savings as intended.

The product has no existing Underwriters Laboratories (UL) or CSA Group certifications. The plan was to certify the Modulating Valve for safety standards after the initial laboratory evaluations. Because the energy savings potentials are not promising, the UL and CSA Group certifications were not carried out.

Background

Residential heating equipment is currently sized by HVAC installers based on the Air Conditioning Contractors of America (ACCA) Manual S, Residential Equipment Selection. It is essential to install properly sized heating equipment to maximize energy efficiency and minimize operating cost. Manual S stipulates the furnace sizing at 1.4 times the calculated heat load. As a result, the selected furnace is oversized. Oversized heating equipment can satisfy heating loads for unusually cold temperatures during the winter. The oversized furnace short cycles for most of the heating season. As such, increasing the duration of cycle times is attractive because it often results in increasing efficiencies and gas savings.

Technologies such as multi-stage and modulating furnaces have been developed to address short-cycling. These furnaces increase the heating cycle duration of the system by reducing the firing rate. Alternatively, an aftermarket Modulating Valve for Single Stage Furnace, a natural gas flow reduction device, is designed to reduce the firing rate in single-stage furnaces. This technology is a bolt-on device that is installed upstream of the gas valve inlet as shown in Figure 1.

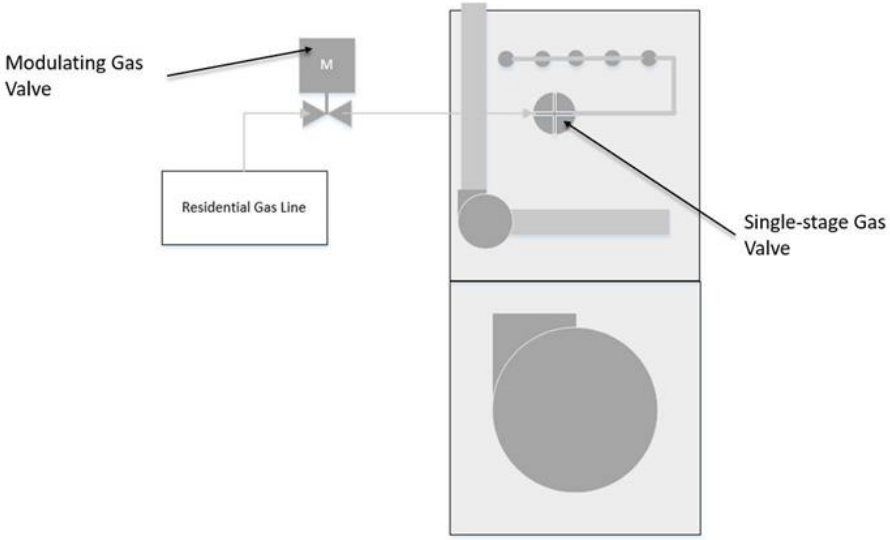

Figure 1 – Schematic of the Modulating Valve for Single-stage Furnaces Installation

The Modulating Valve for Single Stage Furnace device is connected to the gas valve electronic connections to sense the heat call and track the time between the last heat call and next heat call. Based on the time off between cycles, the Modulating Valve selects one of its two stages of operation, low- or high-flow:

1. Low-flow (80% of the total firing rate) is activated only when the time off between the last and next heat calls occurs between 10 minutes to 5 hours.

2. High-flow (100% firing rate) is activated to satisfy the heat calls that occur in under 10 minutes or after more than 5 hours.

The Modulating Valve comes with four valve ports for different furnace size ranges including: 40,000 – 55,000 BTU, 60,000 – 75,000 BTU, 80,000 – 100,000 BTU, and 1055,000 – 120,000 BTU.

Objectives and Testing Methodology

Objective

The following objectives were established as the goals of this project:

- Verify Modulating Gas Valve's two stages of operation
- Validate gas savings potentials

Testing Methodology

A 44MBH 80AFUE Carrier furnace (model # 58PHB) was used for this laboratory evaluation. A baseline comparison was performed to quantify gas savings when the Modulating Valve was installed to a single-stage furnace.

The experimental method employed for this laboratory evaluation is an alternative to ANSI/ASHRAE 103 standard for estimating seasonal furnace performance. The furnace was configured in a laboratory test setup to draw preconditioned air from the lab into the furnace and dump the heated supply air out of the lab. Algorithms developed specifically for this furnace evaluation were used to control the on/off thermostat calls. Data sets of direct energy input and output measurements were collected for furnace operating under incremental part loads, including 1%, 5%, 10%, 15%, 20%, 30%, and continuing at 10% intervals to 100%. For example, a 44MBH furnace operating at 10% part load, would have to deliver 4,400 BTU/hr. The data sets were then used to calculate part-load efficiencies based on energy input and output (thermal efficiencies) and to develop part-load performance curves for the furnace operating with and without the Modulating Gas Valve. In part-load conditions, the test data were collected for four cycles in baseline mode. The test data were collected for 20 cycles in retrofit mode. The data were averaged and used as inputs in the modeling software. Annual heating therms were then calculated using building energy modeling software applying the performance curves together with weather data and hourly load calculations for specific climates and buildings.

Steady state measurements for calculating combustion efficiencies were also collected under the same incremental part loads. Combustion efficiency is a key performance calculation for determining Annual Fuel Utilization Efficiency (AFUE) per the ANSI/ASHRAE 103 standard. It is calculated assuming output energy equals input energy minus the stack losses. Combustion efficiencies for this project were determined by measuring the temperature and oxygen content of the exhaust gases, as well as condensate production while the furnace operated under part-load conditions at steady state.

In the following sections, the test results are presented and discussed.

Test Equipment

Figure 2 identifies the equipment and instruments included in the test setup, delineates the system components and subsystems, and identifies the input and output energy streams for each of the systems tested. The instruments used in the test setup identified in Figure 2 are listed in Appendix A. Data acquisition and calculation methods associated with the instrument measurement points are defined in Appendix B.

Return air to the furnace (entering air temperature) was controlled using two two-row water coils in the duct upstream of the furnace inlet. An air-to-water heat pump was used to supply hot or cold water to the coil at a constant temperature, which was set depending on the laboratory room air and outdoor ambient temperatures. Laboratory room air was conditioned by the main facility HVAC system. During testing, the laboratory was generally kept above 65˚F, so the conditioning coil was used to trim the return air temperature down.

Furnace leaving air temperatures were measured using a nine-point horizontal thermocouple array. Leaving airflows were also measured at the same nine points. From previous forced-air testing, it was found that temperatures, and airflow measurements have distinctly similar gradients across the horizontal measurement plane.

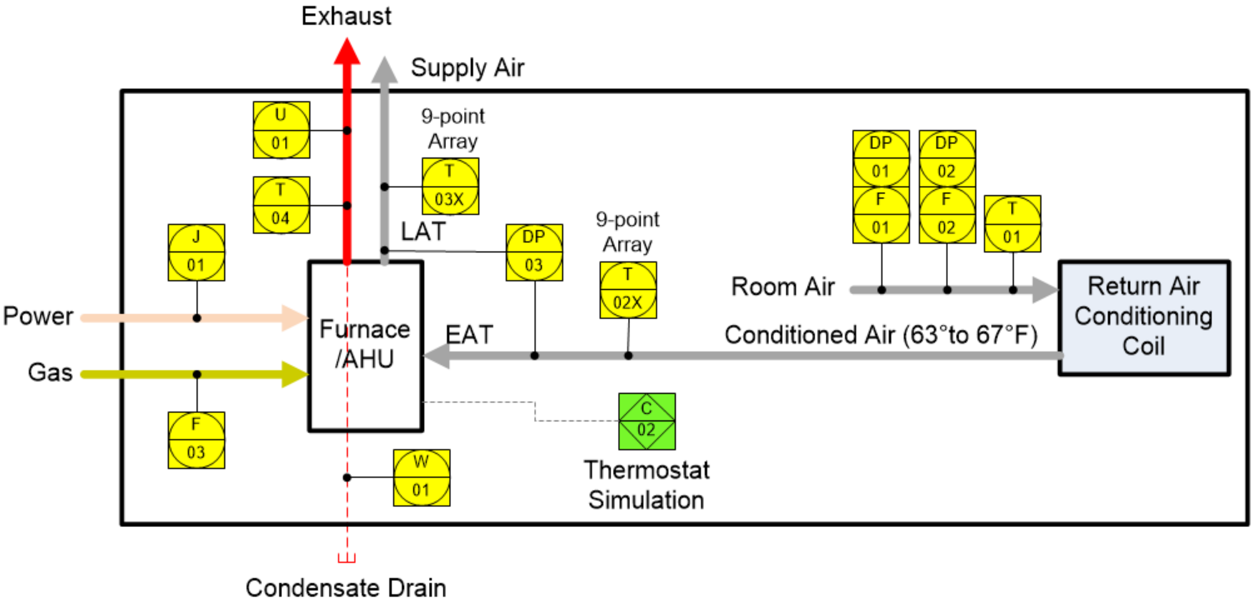

Figure 2 – Test Setup Diagram

Results and Discussion

The Modulating Valve's two stages of operations were identified in the part-load test. Figure 3 demonstrates that the Modulating Valve used the low-flow consistently up to 15% part load and the high-flow stage consistently from 30% to 100% part loads. At 20% part load, the Modulating Valve used a mix of low-flow and high-flow operation. The Modulating Valve retrofitted furnace operated consistently in the low-flow mode when time off between cycles was longer than 9.75 minutes. Similarly, it operated in the high-flow mode when time off between cycles was less than 4.41 minutes.

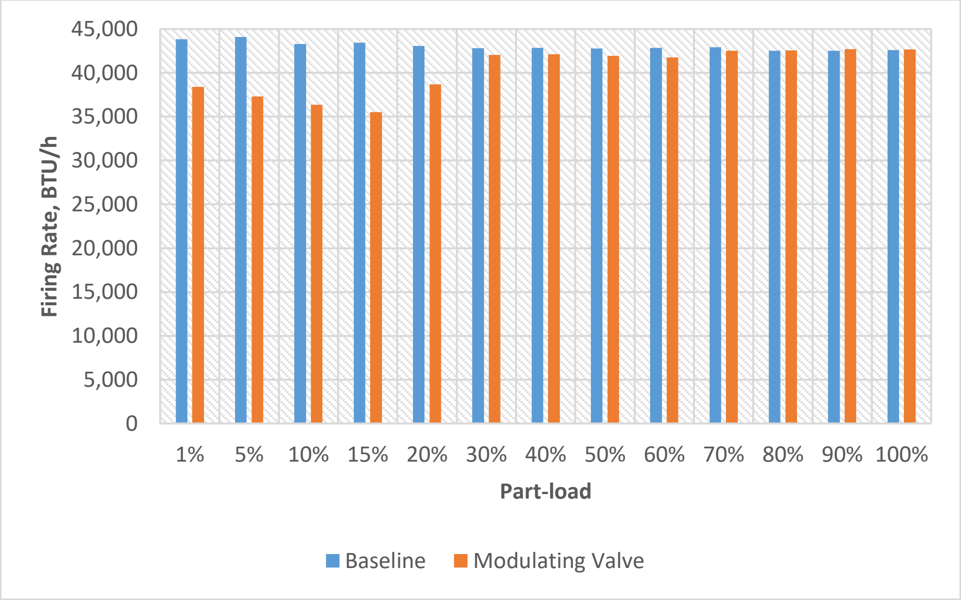

Figure 3 – Firing Rates in the Part-load Test

The evaluated Modulating Valve can interface only with gas valves that operate with 2-wire systems such as White Rodgers valves found in Carrier and Rheem furnaces. However, 3-wire systems are often implemented in Honeywell single-stage valves that are used by Trane and Goodman furnaces. This is a limitation of this technology's compatibility.

Appendix C lists the performance evaluation curves associated with the baseline and Furnace with the Modulating Valve. The performance curves data were used as inputs for the building energy modeling software to quantify gas consumption and operation cost. The annual gas consumption, and gas and net operational costs (gas and electric) are listed in Table 1. The performance between baseline and the Modulating Valve retrofit was within +/-2%. It was predicted that the Modulating Valve's low-flow mode would be active for 16% of the heating season for a pre-1980 building construction of 864-sqft in Chicago IL. No significant gas consumption difference was found at 20% part-load condition between the baseline and the Modulating Valve retrofit, as shown in Table 2.

Table 1 – Annual Gas Consumption, and Gas and Net Operational Costs in an 864-sqft Home in Chicago, IL

Variable	Baseline	Retrofit
Annual Gas Consumption MMBTU	62.02	61.98
Annual Gas Cost, $	493.34	493.33
Annual Net Operational Cost, $	580.17	581.65

Table 2 – Annual Gas Consumption for Part Load Less than 20% in an 864-sqft Home in Chicago, IL

Part-loads Less Than 20%	Baseline	Retrofit
Annual Gas Consumption MMBTU	10.07	10.10

These results are not surprising based on the research literature. Alex et al. compared two-stage to single-stage furnaces in the 2006 ACEEE Summer Study. They demonstrated that two-stage furnaces have no significant efficiency gains in comparison to single-stage furnaces using two test methods as shown in Figure 4.

Similarly, GTI’s 24-hour Low Capacity Heating Testing study compared efficiencies of modulating, single- and two-stage furnaces. The test results of this test suggest that two-stage furnaces efficiencies are not superior to the single-stage furnace, as shown in Figure 5.

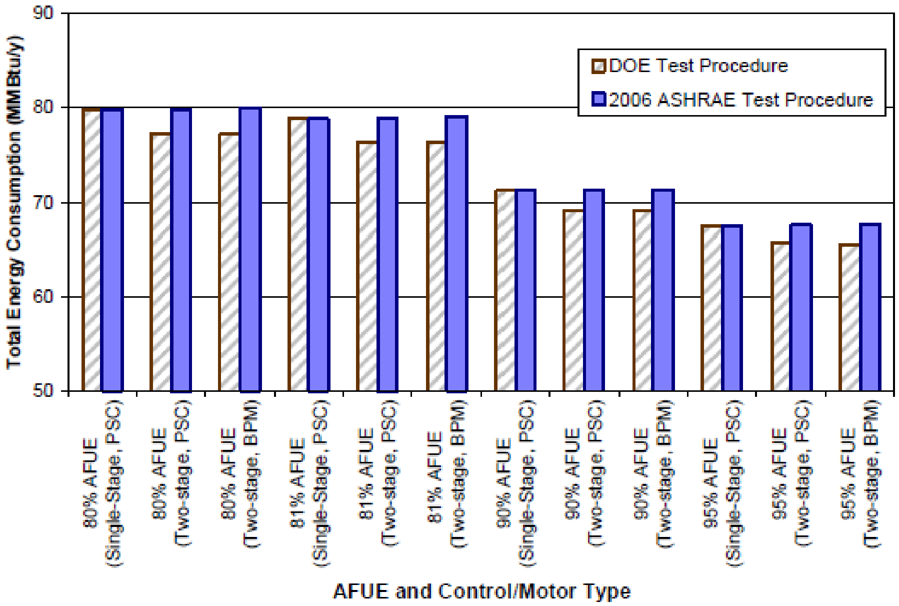

Figure 4 – Total Energy Consumption at Various AFUE Levels in Single- and Two-stage Furnaces

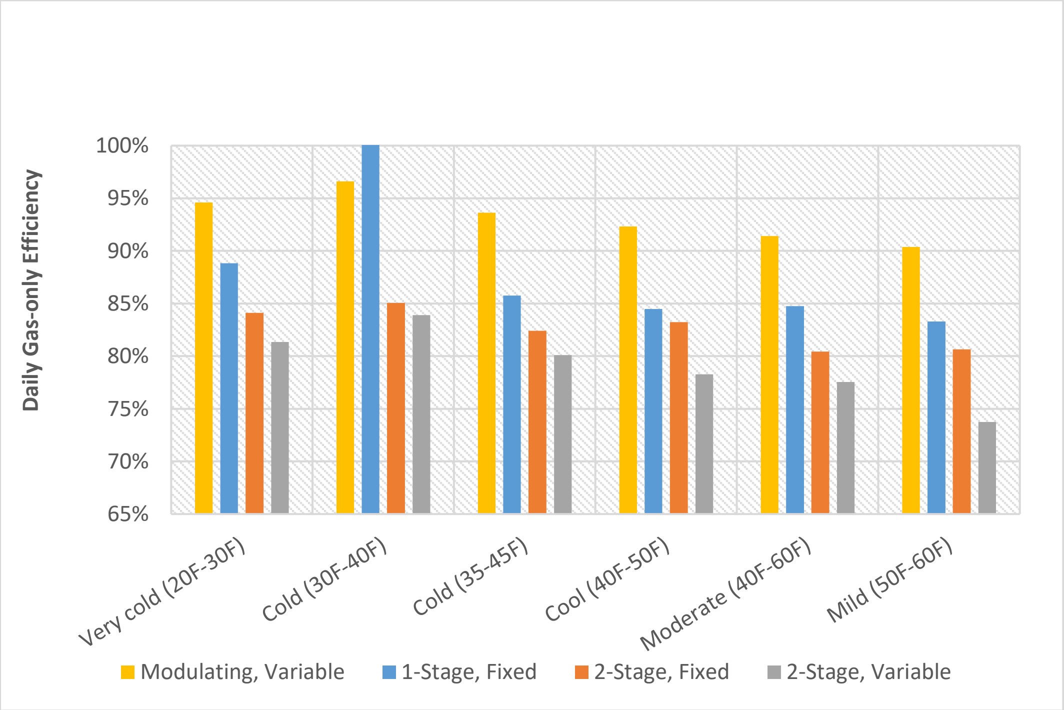

Figure 5 – Daily Gas Efficiency for Modulating, Single- and Two-stage 45MBH Furnaces

GTI performed additional tests at various firing rates to demonstrate the effects on furnace efficiency. Figure 6 shows the gas consumption of the furnace when cycling at 5%, 10%, 15%, 20%, 30%, and 100% load capacities at three firing rates. The data show the efficiency of the furnace was reduced when the designed firing rate was reduced. Figure 7 shows the consequences of reducing the designed firing rate of the furnace. The combustion oxygen increases as the firing rate is reduced in a single-stage furnace. The flame size and the temperature are reduced with negative impacts on the designed heat transfer in the primary furnace coil. As such, the new fully-modulating and two-stage furnaces overcome this draw back by properly regulating the ideal combustion chemistry to maximize gas efficiency.

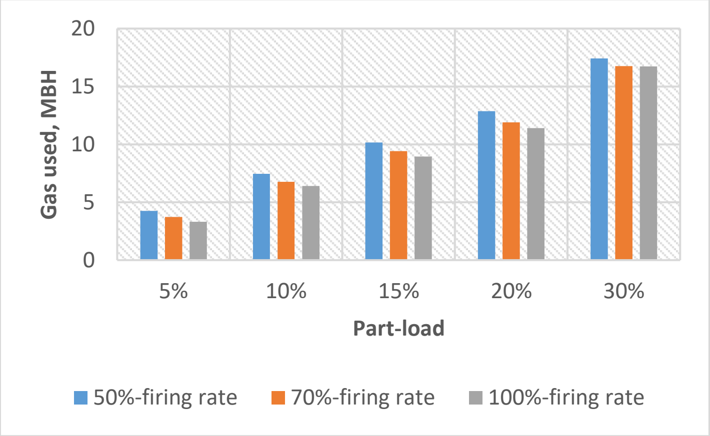

Figure 6 – Gas Consumption at Part Loads using 50%, 70%, and 100% Designed Firing Rate

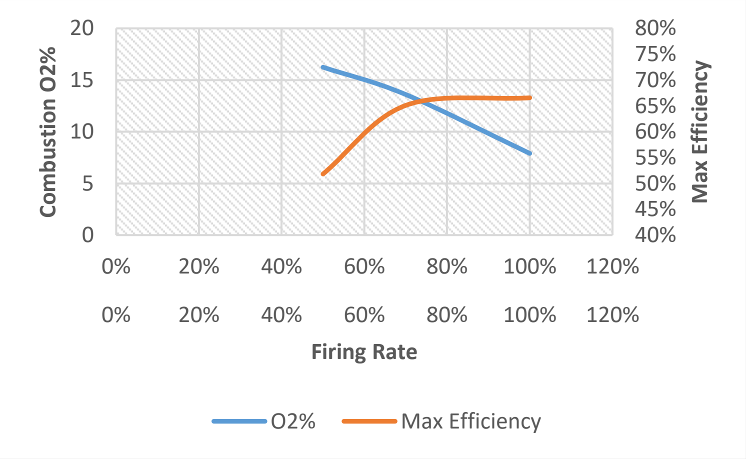

Figure 7 – Gas Efficiency and Combustion Gas Oxygen Level at 5% Part Load

Based on the part-load tests and research literature, the Modulating Gas Valve lacks solutions for gas savings in single-stage furnaces. It also disrupts the designed combustion chemistry in a furnace with unknown negative effects in the primary furnace coil. Therefore, GTI does not recommend further evaluation of this technology.

Appendix A – Instrumentation

Instrumentation is listed in Table 3.

Table 3 – Instrumentation

ID	Parameter	Instrument	Range	Accuracy
T01	Laboratory Air Entering the Return Air Conditioning Coil	Open-Ended Direct Exposure RTD Omega P-L-A-1/8-6-0-T-3	–100 to 250°F	± 0.65°F at 130°F
T021-T029	Furnace/AHU Entering Air Temp	T-Type Insulated Thermocouples KK-T-20-36	–100 to 250°F	at >32 to 662°F ±1.8°F or 0.75%
T031-T039	Furnace/AHU Leaving Air Temp	T-Type Insulated Thermocouples KK-T-20-36	–100 to 250°F	at >32 to 662°F ±1.8°F or 0.75%
T04	Furnace/AHU Exhaust Temp	Open-Ended Direct Exposure RTD Omega P-L-A-1/8-6-0-T-3	–100 to 250°F	± 0.65°F at 130°F
F01	Furnace/AHU Conditioned Air Flow Low	Duct-Mounted Air Flow Measurement Station Dwyer FLST-C8	100 to 10,000 FPM	± 2%
F02	Furnace/AHU Conditioned Air Flow High	Duct-Mounted Air Flow Measurement Station Dwyer FLST-C10	100 to 10,000 FPM	± 2%
DP01	Furnace/AHU Conditioned Air Flow Differential Pres Low	Low Differential Pressure Transmitter Dwyer 607-2	0” to 0.5” wc	±0.5%
DP02	Furnace/AHU Conditioned Air Flow Differential Pres Hi	Low Differential Pressure Transmitter Dwyer 607-2	0” to 0.5” wc	±0.5%
DP03	Furnace/AHU Total Static Pressure	Low Differential Pressure Transmitter Dwyer 610-01A-DDV	0” to 1” wc	±0.25%
J01	Furnace/AHU Power	WattNode Pulse WNB-3Y-208P	48 to 62Hz at -20% to +15% Voltage	± 0.5%
F03	Furnace/AHU Gas Flow	Gas Flow Diaphragm Meter Elster American Meter AC-250	0 to 656 SCFH (5 psig)	± 0.5%
W01	Furnace Condensate Weight	Texas Electronics Inc. Model: TR-5251	4.726 mL (0.0104 lbm water @ 70degF)	+/-1% of reading per tipping (a tip is equal to 4.726mL)
U01	Flue Gas Composition – O2	Rosemount Analytical Model: X26P –pO2	2-25%	-
	Flue Gas Composition – CO/CO2	Make: Rosemount Analytical Model: X26P – IR IR	CO: 100-3000 ppm CO2: 2 – 25%	-
	Flue Gas Composition – Hydrocarbons	Rosemount Analytical Model: 400A	0 – 4ppm/ 0 -1%	-
	Flue Gas Composition – NO/NOX/NO2	Eco Physics Model: CLD700EL	0 – 1000ppm/ +/- 1 FS	-

Appendix B – Calculation

Measured data from all the instruments listed in Table 3 were continuously collected and recorded at 5-second intervals. All calculations were post-processed using the raw data from the data acquisition system as follows:

Energy Input

The following basic equation was used to calculate energy input to the systems in natural gas:

$$Q_{\mathrm{NG}} = HHV \cdot V_{NG}$$

Where:

Q_{NG} = Energy input from natural gas (Btu/day or Btu/hr)

HHV = Higher heating value (HHV) of natural gas (Btu/ft^3)

V_{NG} = Volumetric flow rate of natural gas (ft^3/day or ft^3/hr)

Fuel gas was sampled daily for major component analyses, and higher and lower heating value calculations. The gas meter used to measure volumetric flow was temperature compensated. Gas pressure was recorded before each test, and the flow rate was corrected for the actual pressure.

Furnace Energy Output

Heat supplied by the furnace was determined by measuring the air flow rate and supply and return air temperatures at the furnace inlet/outlet as follows:

$$Q_{\mathrm{sup}} = \sum_{time} C \cdot V_l \cdot \rho \cdot c_p \cdot |\Delta T| \cdot \Delta time$$

Where:

Q_{sup} = Summation of supplied heat by the furnace for each time step (Btu/hr or Btu/day)

V_l = Volumetric flow rate of air (ft^3/min) calculated by:

$$V_l = 3.1415926 \cdot \left(\frac{D}{12}\right)^2 \cdot \frac{1}{4} \cdot \left(1096.7 \cdot \frac{P}{0.07368}\right)^{1/2}$$

Where:

P = Velocity Pressure at each recorded interval

D = Duct diameter for the flow measurement station (8").

$|\Delta T|$ = the difference between weighted supply and return temperatures at each recorded interval (^{o}F). Note, ΔTs less than 15 ^{o}F were assumed to be zero.

c_p = Specific heat of air at the average temperature between the supply and return air, (Btu/lb-^{o}F)

ρ = Density of air based on air temperature at the flow meter for each recorded interval, (lb/ft^3)

C = *U*nit conversion factor

$\Delta time$ = time interval used in the data collection program (i.e., 5 seconds)

Furnace Thermal Efficiency

Furnace thermal efficiency (η_f) was calculated as the ratio of the heat supplied by air to the energy carried by the natural gas at the same time interval (i.e., hourly efficiency), as shown in the following:

$$\eta_{sh} = \left(\frac{Q_{\text{sup}}}{Q_{NG}}\right)\cdot 100$$

Where:

η_f = Furnace efficiency (%)

Q_{sup} = Total energy supplied by the furnace (Btu/day or Btu/hr)

Q_{NG} = Total natural gas energy input (Btu/hr or Btu/day)

Q_e = Total electrical energy input (Btu/hr or Btu/day)

Note: Q_e is added to the denominator when accounting for electrical energy. Results for this project are reported without electrical energy used during the tests.

Furnace Combustion Efficiency

Furnace combustion efficiency (E) was calculated based on the methods described in ASHRAE Standard 103:

$$E = 100 - [L_A + L_s - L_g + L_c]$$

Where:

L_A = 9.55 (constantly used for natural gas testing)
L_S is the sensible heat loss calculated per ASHRAE Standard 103
L_g is the latent heat gain due to condensation calculated per ASHRAE Standard 103
L_c is the heat loss due to hot condensate going down the drain calculated per ASHRAE Standard 103

Appendix C – Energy Modeling

The performance curves for gas efficiency and electric rate used in the energy modelling software are shown in Figures 8 and 9. The gas and electric rates used in the energy modelling software are shown in Table 4.

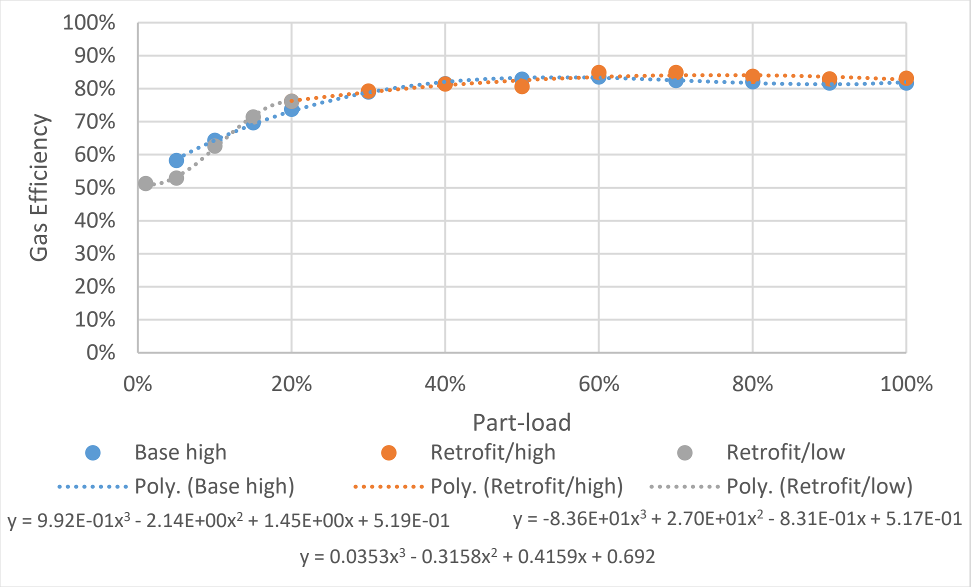

Figure 8 – Gas Efficiency Performance Curve for Baseline and Modulating Valve Retrofit Part-load Tests

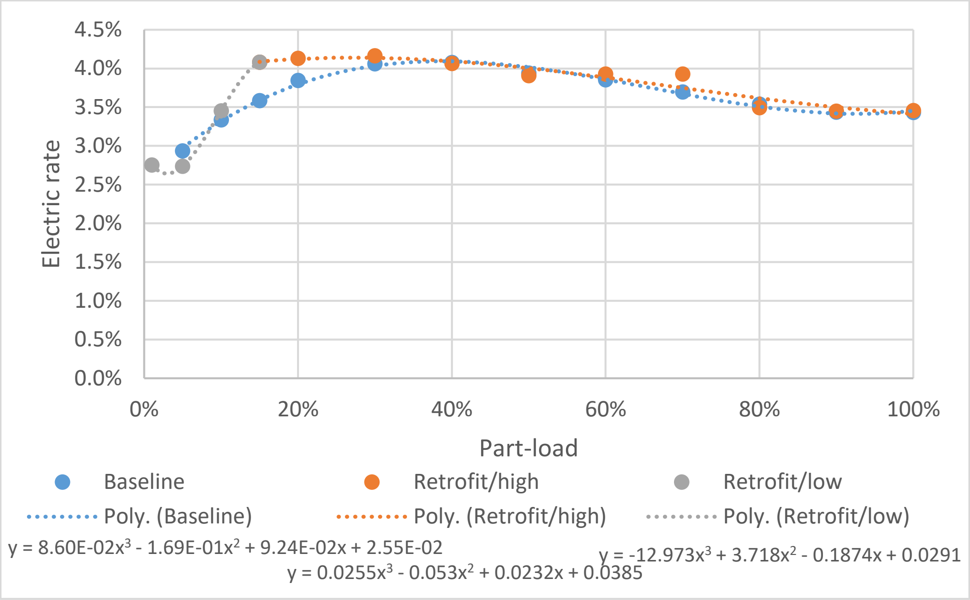

Figure 9 – Electric Performance Curve for Baseline and Modulating Gas Valve Part-load Tests

Table 4 – Gas and Electric Operation Cost

Month	$/1000 cF	$/100 kW-h
January	7.49	11.27
February	8.30	12.21
March	7.86	13.76
April	10.10	13.20
May	10.98	13.71
June	15.15	12.95
July	16.45	12.06
August	17.28	11.94
September	16.68	12.20
October	12.13	12.70
November	8.68	12.86
December	6.73	11.69