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Emerging Combi AHU Laboratory Evaluations

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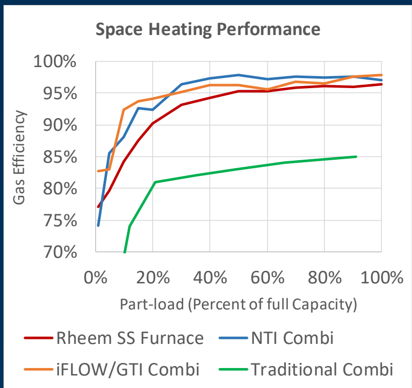

Performance based on natural gas HHV

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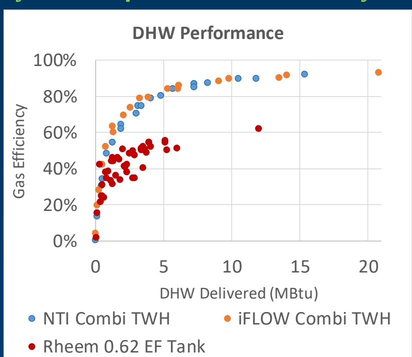

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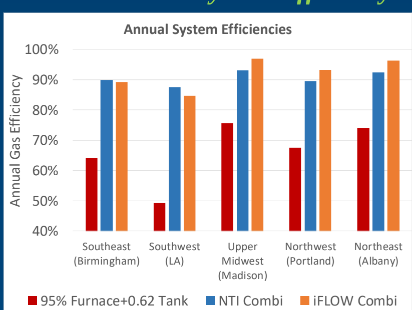

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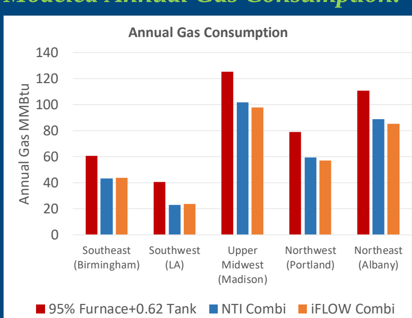


GTI Laboratory Test — Emerging Combis

Technology

Combis use one appliance to provide domestic hot water (DHW) and space heating for a building. The combination of a hydronic air handler unit (AHU), condensing water heater, and in some cases a heat pump can provide gas energy savings with hydronic heating in residential applications if the appliances are properly engineered and integrated; however, traditional combis generally are not.

GTI's research focused on two specific advanced combi systems including the NTI GF 200 Combi Furnace, which is the only completely integrated combi system and has a Navien tankless water heater engine built into the furnace. The second combi system was the iFLOW AHU in combination with a separate Navien tankless water heater. This is the only combi system that dynamically monitors air and water temperatures and modulates water and air flows to maximize efficiency and comfort. Both of these systems have reported high efficiency ratings as tested in accordance with the "P9" Canadian combi rating method. No combi rating standard exists in the US. GTI evaluated these units in the Virtual Test Home (VTH), which GTI uses to evaluate space heating equipment including furnaces and heat pumps in real world conditions as they would be installed in the field.

Laboratory Tests and General Observations

The objective of the project was to evaluate the advanced forced-air combi system technologies to validate manufacturer's performance claims and determine if the systems could overcome the technical barriers preventing traditional combis from consistently reaching condensing efficiencies. Using the VTH, GTI developed performance curves for the advanced combis, as was previously done with condensing furnaces and traditional combis. Those performance characterizations were built into building energy modeling software to predict potential annual energy savings in various climates for the various space heating systems.

Research results are summarized in the adjacent side bar. Results indicate these advanced combi systems performed much better than traditional combi systems. Moreover, the advanced combis performed significantly better than condensing furnaces, especially in part-load conditions where these low-load appliances operate the majority of time. However, these advanced combis still have some challenges. The NTI combi cost about \$5,800, weighs about 250 pounds, and is available in only one capacity – 80 MBH. The iFLOW/Navien system is still under development as GTI continues to work with the manufacturers to develop the control algorithms that achieve consistent performance at low part-loads.

The research findings for this project are significant as forced-air combis are particularly attractive for utility energy efficiency programs. They can improve the economics of upgrading to a condensing water heater for DHW use, as the combined DHW and space heating loads are accomplished with one program measure. Other ancillary benefits of combis include space savings and single combustion air and vent piping with one heating appliance.

Summary of Findings

Conclusions

The objective of this project was to evaluate the advanced forced-air combi systems in the lab against replicable space and water heating loads typical of low-load residential applications. By doing so, GTI validated manufacturer's claims that these emerging combi systems have in fact overcome significant technical barriers preventing traditional combis from consistently reaching condensing space heating efficiencies. GTI developed performance curves for the combis with VTH data sets, and predicted energy savings relative to traditional space heating and water heating appliances using calibrated building energy modeling software. The following conclusions were gathered from the research:

1. Prior research has shown forced-air combis utilizing condensing water heaters together with typical off-the-shelf hydronic AHUs operate at sub-condensing space heating efficiencies and generate little or no energy savings. That has changed with the emergence of two advanced combi systems including the NTI Combi Furnace and iFLOW/Navien combi system. Research under this project has shown these novel combi technologies can generate an estimated 20% to over 30% annual gas savings in low-capacity homes compared to a typical 95% AFUE condensing furnace and NAECA standard 0.62 EF tank water heater. However, these nascent combi technologies still have some barriers to overcome.
2. The iFLOW/Navien technology is the only combi system that dynamically monitors air and water temperatures and modulates water and air flows to maximize efficiency and comfort. It produced the best part-load space heating and water heating performance of any system evaluated by GTI in the VTH; but its performance was underpinned by novel control logic that GTI implemented in order for the system to maintain very high efficiencies at very low part-loads while delivering adequate space heating comfort. Fortunately, the iFLOW/Navien system has all the elements required to accomplish these principle goals.
3. The NTI Combi Furnace is the only completely integrated one-box combi system. It has a Navien tankless water heater engine built into the furnace. Its part-load space heating and water heating performance in the VTH was nearly as good as the iFLOW/Navien system, and superior to traditional readily available gas space heating and water heating equipment. However, offered at only one capacity – 80 MBH, the system is less likely than the iFLOW/Navien system to perform well at very low part-loads. As such, it is a good fit for homes with higher space heating loads than the iFLOW/Navien system might serve. Its cost of about $5,800 and weight at 250 pounds carries additional challenges.
4. One common technical concern with combis is if a single heating appliance serving DHW and space heating loads can deliver comfort even when the heating loads are contiguous or coincidental. For contiguous loading (space heating immediately before DHW or vice versa), the combi water heaters were effectively preheated, and performance and comfort were positively impacted, especially at low loads where it mattered most. For coincidental loading (DHW during space heating), the two combis operated differently. When DHW draws were applied to the iFLOW/Navien combi during a space heating cycle, the space heating cycle was always suspended until the DHW draw was complete. This is referred to by combi manufacturers as "DHW priority", and it resulted in a few degrees drop in room air temperature depending on heating load and DHW duration. When DHW draws were applied to the NTI combi during a space heating cycle, hot water and AHU leaving air temperatures decreased. Here again, a few degrees drop depending on the DHW draw durations.

Recommendations

1. The advanced combi technologies are well-aligned with trends toward low-load homes- including high performance homes, multifamily, and the low-income sector. However, they require builders and contractors to proactively embrace the single-appliance approach, even while typical gas appliances maintain a strong foothold in the market. As builders and contractors increasingly commit to home

performance warranties, such technological shifts may become necessity in order to realize energy savings. These emerging technologies are ready for field deployment in order to validate performance, costs and savings, educate trades on the benefits of combis, and collect homeowner's perspectives in terms of comfort, satisfaction, and cost savings.

2. Performance of the iFLOW/Navien system was predicated on control logic implemented by GTI. Therefore, in order to assure the system as a product can deliver very high part-load efficiencies with adequate space heating comfort, these control functions must be permanently programmed into the combi system. All of the elements GTI required to reach the combi performance are integral to the iFLOW/Navien system. Only program development is required by the manufacturers.
3. The advanced combis not only enable very highly efficient hydronic gas heating, they offer the opportunity to easily integrate heat pumps. Further research is required in the Virtual Test Home to optimize gas or electric heat pump integration that leverages the best performance from each system and assures comfort is delivered.
4. GTI has focused VTH research on gaining an understanding of exactly why space heating performance suffers in part-load conditions, and more importantly, what can be done to improve low-load performance. It is important to note all space heating, including gas and electric, staged and even modulating systems are challenged with the same low-load problems. GTI believes combis using condensing tankless water heaters offer a unique opportunity to improve space heating performance at very low loads by logically controlling water and air flows, and temperatures. GTI recommends further research in the VTH, to gain a better understanding of how other space heating systems such as electric heat pumps are impacted by part-load conditions.

Introduction

As building envelope performance for new homes continues to improve, needs are increasing for high-efficiency, low-capacity, gas-fired forced-air technologies. Combis can fill this need by serving the entire home with a single condensing appliance - - providing a single EE measure that can improve the net benefit of a utility's energy conservation program for customers. Moreover, the combi's single-vent solves the dual-condensing-vent problem that can occur when conventional individual equipment is used in some applications.

While the potential for highly efficient combis exists, lab and field research has proven forced-air combis utilizing condensing water heaters together with typical off-the-shelf hydronic air handler units (AHUs) tend to operate at sub-condensing efficiencies. As such, they generate insufficient energy savings to qualify for EE programs. Until recently, the combi system market has consisted of mix-and-match field-engineered systems with a myriad of water heaters and off-the-shelf hydronic AHUs provided by separate manufacturers. Rheem and Bosch offer pre-engineered combi systems utilizing condensing tankless water heater (TWH). However, they use traditional hydronic AHUs that generate sub-condensing efficiencies as demonstrated in previous GTI field work.

Two advanced combi systems have emerged out of Canada that incorporate strategies to overcome technical barriers preventing traditional combis from consistently reaching condensing efficiencies. The NTI GF 200 Combi Furnace shown in Figure 1, is the only completely integrated combi system. It incorporates a Navien NPE-240A tankless water heater engine built into the furnace. The second combi system is the iFLOW AHU in combination with a separate Navien NPE-240A tankless water heater shown in Figure 2. The AHU and TWH are designed to communicate with each other, and is the only combi system that dynamically monitors air and water temperatures and modulates water and air flows to maximize efficiency and comfort. Both of these combi systems have reported high efficiency ratings as tested in accordance with the "P9" Canadian combi rating method. No combi rating standard exists in the US, but for this project, GTI has evaluated them in the Virtual Test Home (VTH), which GTI developed to evaluate and compare space heating equipment in real world conditions as they would be installed in the field.

Figure 1 – NTI Combi Furnace with Navien Tankless

Figure 2 – iFLOW/Navien Combi

Objectives

The objective of this project was to evaluate emerging forced-air combi system technologies in the lab against replicable space and water heating loads typical of low-load residential applications. Tangible goals for the project were as follows:

1. Validate manufacturer's claims the emerging combi systems have overcome technical barriers preventing traditional combis from consistently reaching condensing efficiencies.
2. Compare the emerging combi systems to low-capacity condensing furnaces and traditional water heaters recently tested in the VTH.
3. Develop performance curves for combis, as was done with condensing furnaces to predict energy savings using building energy modeling software.

Background

Neither pre-engineered nor field engineered forced-air combis utilizing condensing water heaters are likely to cost-effectively provide significant gas energy efficiency (condensing efficiencies) in residential applications with traditional hydronic AHUs prevalent in the US market.

Condensing water heaters will only condense if enough thermal energy is removed to cool the flue gas down to at least 135°F. That is because moisture in combustion gas begins to condense out of the gas at the dew point temperature, which varies depending on combustion excess air (See **Figure 3**).

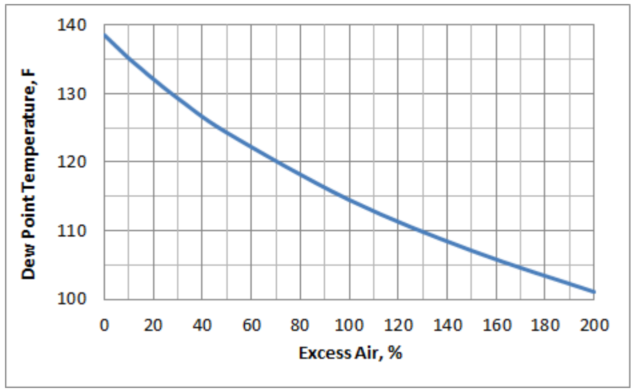


Figure 3 – Flue Gas Dew Point Temperatures

The primary heating section of a hydronic AHU is a hot water coil heat exchanger (Figure 4), which is generally a prefabricated component with predetermined heat transfer characteristics. With reasonably short and insulated piping runs, the entering water temperature (EWT) into the coil is roughly the same as the water heater outlet temperature; and the leaving water temperature (LWT) returning back to the water heater varies based on water flows (GPM) and air flows (CFM). The entering air temperature (EAT) into the coil is about the same as the return air from the conditioned space. Air flows across the coil and picks up heat to supply warm air to the space at the leaving air temperature (LAT).

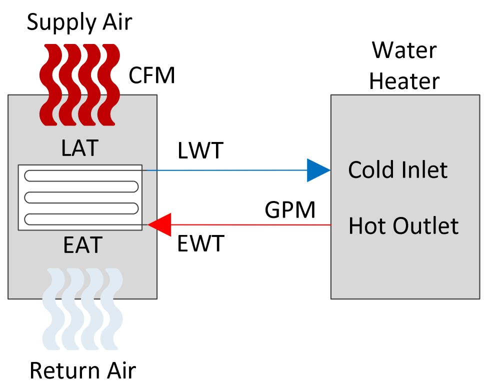


Figure 4 – Combi Air/Water Diagram

The greatest challenge with proper combi system AHU and water heater integration is inducing condensing operation in the water heater while delivering adequate space heating comfort from the AHU. This can be achieved, and combi efficiencies can be improved, by reducing LWTs, but doing so can compromise LATs and therefore comfort. Controls for the advanced combi systems evaluated in this project, were designed to minimize LWTs and maximize LATs by:

1. Minimizing the water heater set point (EWT), and maintaining comfortable LATs from the AHU based on outdoor ambient conditions and building heating loads,
2. Minimizing the water flow rate (GPM), and maintaining required heating capacities based on outdoor ambient conditions and building heating loads, and
3. Maximizing the air flow (CFM) and maintaining comfortable LATs.

Research Description

Systems Tested / Compared

Table 1 – Space Heating System Specifications

NTI GF 200 Combi Furnace (with Navien condensing TWH built in)	
Water Heating Capacity	19.9 MBH to 199.0 MBH
Space Heating Capacity	19.9 MBH to 80.0 MBH
Space Heating AFUE	97.1%
Water heating EF	0.97
CSA P.9-11 rating	96% TPF
Blower motor	ECM
Air flow	500 cfm to 1,200 cfm
iFLOW iFLH-180000 + Navien NPE-180A condensing TWH combi System	
Water Heating Capacity	15 MBH to 150 MBH
Space Heating Capacity	15 MBH to 60 MBH
Space Heating AFUE	95%
Water heating EF	0.97
CSA P.9-11 rating	98% TPF
Blower motor	ECM
Air flow	1000 cfm to 1,450 cfm
Dettson C45MV combi (for comparison)	
Water Heating Capacity	19.9 MBH to 199 MBH
Space Heating Capacity	20 MBH to 45 MBH
Space Heating AFUE	92%
Water heating EF	0.92
CSA P.9-11 rating	NA
Blower motor	ECM
Air flow	500 cfm to 1,200 cfm
Rheem R95T Single-stage condensing furnace (for comparison)	
Space Heating Capacity	41 MBH
Space Heating AFUE	95%
Blower motor	ECM
Air flow	982 cfm
Rheem XG40 0.62EF tank water heater (for comparison)	
Volume	40 gallons
Water Heating UEF	0.62
Recovery	40.4 GPH
First-hour	71 gallons

Test Methods

The advanced combi systems were evaluated in three space heating/water heating modes, including space heating only, water heating only, and coincidental space heating and water heating. Figure 5 shows all of the measurement points along with the combi system test boundary, which included the AHU and tankless water heater. Instruments used for the entire test rig are listed in Appendix A and methods for calculating energy balances and performance within the test boundary are described in Appendix B.

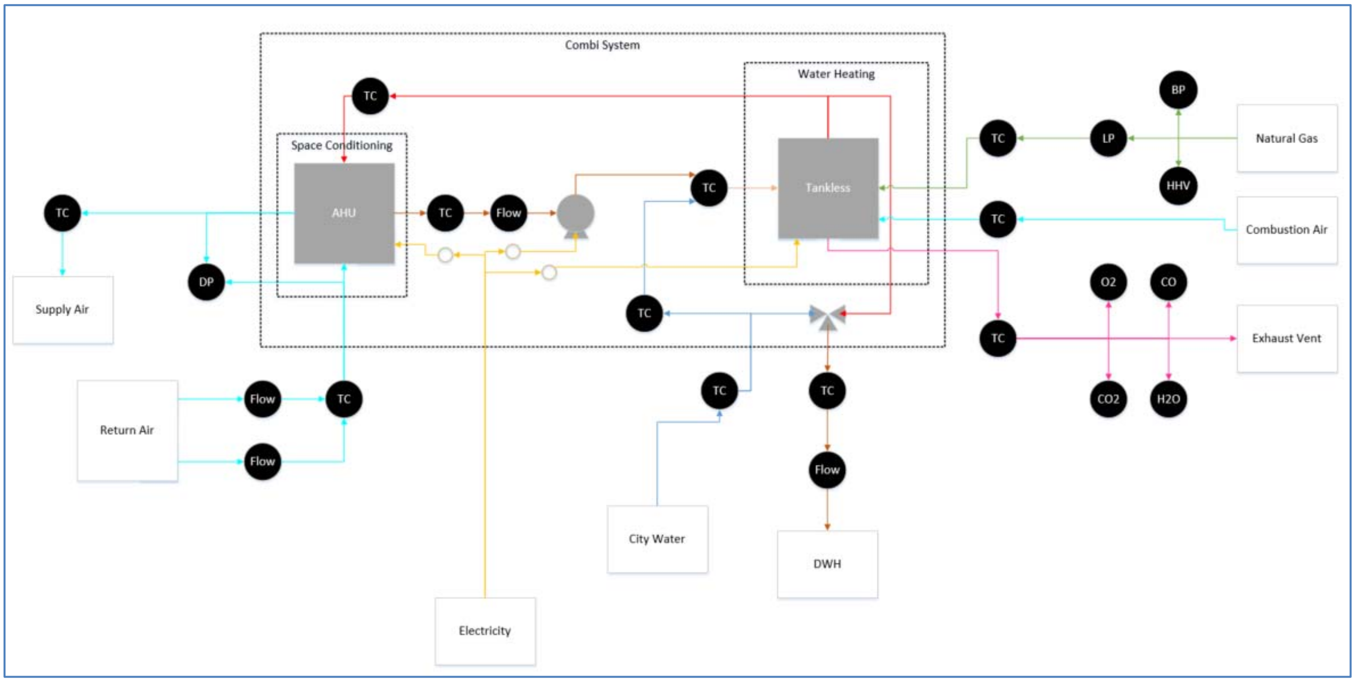


Figure 5 – Combi Systems Test Boundary

Space Heating Tests

The experimental methods employed for this project used the VTH and are, collectively, alternatives to standardized test methods such as AFUE 103 for estimating seasonal heating performance. Both of the advanced combi systems were configured in the VTH laboratory test setup to draw preconditioned air from the lab into the hydronic air handler, and dump the heated supply air out of the lab. Algorithms developed specifically for the VTH evaluations were used to control the on/off thermostat calls. A series of 13 space heating tests were conducted for each of the combis in order to develop part-load efficiency profiles. Data sets of direct energy input and output measurements were collected for each of the combis operating under incremental part-loads, including 1%, 5%, 10%, 15%, 20%, 30%, and continuing at 10% intervals to 100%. For example a 50MBH furnace operating at 10% part-load, would have to deliver 5,000 BTU/hr for that test.

Thermostat simulations

The VTH setup was designed such that energy in warm air delivered by the combis could be determined using accurate airflow measurements along with supply- and return-air temperature measurements. However, that energy was not delivered to a conditioned space, like it would be in a home. Rather, the test setup was designed to expel the warm air from the lab space. As such, the combis did not operate on actual calls from their thermostats. Instead, for each incremental part-load test, algorithms in a computer-generated, or virtual home were used to calculate room air temperatures and simulate thermostat cycle times (on/off calls). During the on cycles, the amount of energy delivered in warm air by the combis was calculated every five seconds using measurements from the test setup. Knowing the energy delivered at 5-second intervals, and the required heating demand for the particular part-load test, room air temperatures in the virtual home were calculated every five seconds as well. It is important to note, conditioned space volume is also needed to determine how the room air temperatures change. Since part-loads were based on the Building America B10 Benchmark reference house, building volume and construction were arbitrarily defined by that reference model. The model used to define the volume can be arbitrary as only the resulting cycle times are important in order to map the part-load combi performance for any given combi design. Once the part-load performance is mapped, it can be used in building energy modeling software to predict energy consumption from the system in various types of buildings in various climates.

Thermostats operate based on room air temperature set points and deadbands, which are adjustable. The thermostat deadband is important because space heating equipment efficiencies are negatively affected by smaller deadbands. The smaller the deadband, the shorter the system cycle time, and the lower the efficiency. The deadband allows the heating equipment to cycle on and off between allowable minimum and maximum room air temperatures. The cycling algorithms developed for this project used a 2°F deadband, allowing the room air temperature in the virtual home to be between 65°F and 67°F. Therefore, the combis came on at 65°F and shut off at 67°F. The thermal efficiency for each combi system incremental part-load test was based on an average of four full on/off cycles.

Water Heating Tests

As with space heating, the experimental methods employed for evaluating combi water heating capabilities also used the VTH. Here again, the methods are collectively an alternative to standardized test methods such as ASHRAE 118.2 for rating water heaters. The VTH was used to conduct simulated-use tests under controlled conditions with water draw events at various conditions. Efficiencies were calculated using an input-output method rather than a uniform energy factor (UEF) as applied in ASHRAE 118.2.

A series of 20 water heating tests were conducted for each of the combis in order to develop efficiency profiles for various DHW draws. Similar DHW draws were used for coincidental space heating and water heating experiments described in the next section. Data sets of direct energy input and output measurements were collected for each of the combis operating at 1, 2, 3, and 4 gpm draws each for 1, 3, 5, 7 and 10 minutes. Between each scenario, the water heater was cooled down to about 65°F.

Coincidental Space Heating and Water Heating Tests

Three scenarios were considered for space heating and water heating operation including hot water draws immediately before and after space heating cycles, and during space heating cycles. Each of these scenarios were predicted to have positive impacts on efficiencies as the combi water heaters were effectively preheated prior to space heating or water heating service. However, the coincidental loads were predicted to have negative impacts on delivered water and supply air temperatures. The following tests were conducted to determine the extent of efficiency and temperature impacts due to coincidental space and water heating loads.

1. <u>DHW draw before a space heating cycle:</u> A series of 40 tests including 1, 3, 5, 7 and 10-minute hot water draws at 1, 2, 3, and 4 gpm before a 6 and 10-minute space heating cycle.
2. <u>Space heating cycle before a DHW draw:</u> A series of 40 tests including 1, 3, 5, 7 and 10-minute hot water draws at 1, 2, 3, and 4 gpm after a 6 and 10-minute space heating cycle
3. <u>Hot water draw during a space heating cycle:</u> A series of 30 tests including 1, 3, and 5-minute hot water draws at 1, 2, 3, and 4 gpm during a 6-minute space heating cycle; and 5 and 10-minute hot water draws at 1, 2, 3, and 4 gpm during a 10-minute space heating cycle

Building Energy Modeling

The data sets collected from the testing were used to calculate part-load efficiencies based on energy input and output (thermal efficiencies) and to develop part-load space heating and water heating performance maps for each of the combis. Annual heating therms were then calculated using building energy modeling software applying the performance maps together with weather data and hourly load calculations for specific climates and buildings. Building energy modeling was based on a 1,600 sq-ft residential model using the 2010 Building America Reference Home, which incorporates 2009 IECC building code measures.

Research Findings and Detailed Discussion

Combi Space Heating Performance

Previous gas space heating systems research conducted in the VTH found traditional combis performed poorly when utilizing condensing tankless water heaters and off-the-shelf hydronic AHUs. On the other hand, GTI found some traditional condensing single-stage furnaces, such as Rheem performed very well. GTI used those systems as comparative baselines for the advanced combi systems research for this project. Figure 6 shows the space heating performance at part-loads for the NTI and iFLOW/Navien combi systems relative to the Rheem condensing furnace and the traditional combi system. The traditional combi system used for comparison was the Dettson C45MV combi system, which has since been discontinued. It was a typical mix-and-match combi that used a Quietside condensing tankless water heater and Dettson AHU sold as a packaged system by Dettson.

Figure 7 is presented in tandem with Figure 6 and shows the frequencies at which the iFLOW/Navien combi would operate at various part-loads in the 1,600 sq-ft Building America Reference Home model. Figure 7 helps illustrate how important it is for these space heating systems to be able to operate efficiently at part-loads less than 50% of full capacity, because that is where they would operate the majority of time, even in cold climates. Additionally, the graph in Figure 6 is highlighted in yellow showing where high part-load efficiencies are most important in order to achieve consistently high efficiencies across heating seasons.

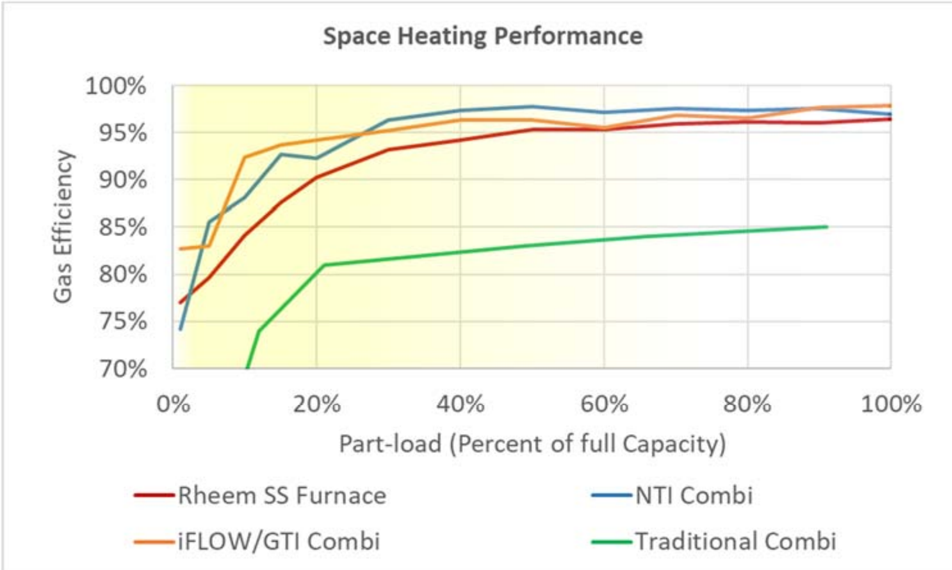
GTI has focused VTH research on gaining an understanding of exactly why space heating performance suffers in part-load conditions, and more importantly, what can be done to improve low-load performance. It is important to note all space heating, including gas and electric, staged and even modulating systems are challenged with the same low-load problems. GTI believes combis using condensing tankless water heaters offer a unique opportunity to improve space heating performance at very low loads by logically controlling water and air flows, and temperatures.

Figure 8 shows the iFLOW combi before (Unmodified iFLOW Combi) and after (iFLOW/GTI Combi) iFLOW and GTI implemented novel algorithms to control the combi system and achieve 90%+ efficiencies down to 10% part-load (about 6MBH in this case). The Navien tankless water heater had a turndown of 10:1 or down to about 15 MBH. As such, a significant drop in efficiency occurred at part-load less than about 10% as can be seen in Figure 8. If the tankless water heater turndown can be increased beyond 10:1, efficiencies could likely be improved at very low part-loads.

The iFLOW combi system has unique capabilities to monitor air and water temperatures and modulate water and air flows. Such capabilities, provide an opportunity to automatically control the combi system and strike balance between efficiency and comfort. The primary strategies iFLOW and GTI implemented to better control the iFLOW combi system were as follows:

1. "Flush" heat out of the hydronic heating loop after thermostat calls end. This was easily achieved with the AHU by simply programming the pump and blower to remain on for a few minutes after the thermostat call ends. However, the TWH is designed to fire whenever there is water flow. Therefore, the TWH had to be programmed to suspend firing during the heat flush period.
2. Modulate water flows and air flows to maintain 80°F to 90°F water returning to the TWH while maintaining AHU supply air greater than about 92°F.
3. Control the TWH firing rate during the thermostat calls to maintain 80°F to 90°F water returning to the TWH

Figure 6 – Advanced Combi Relative Space Heating Performance



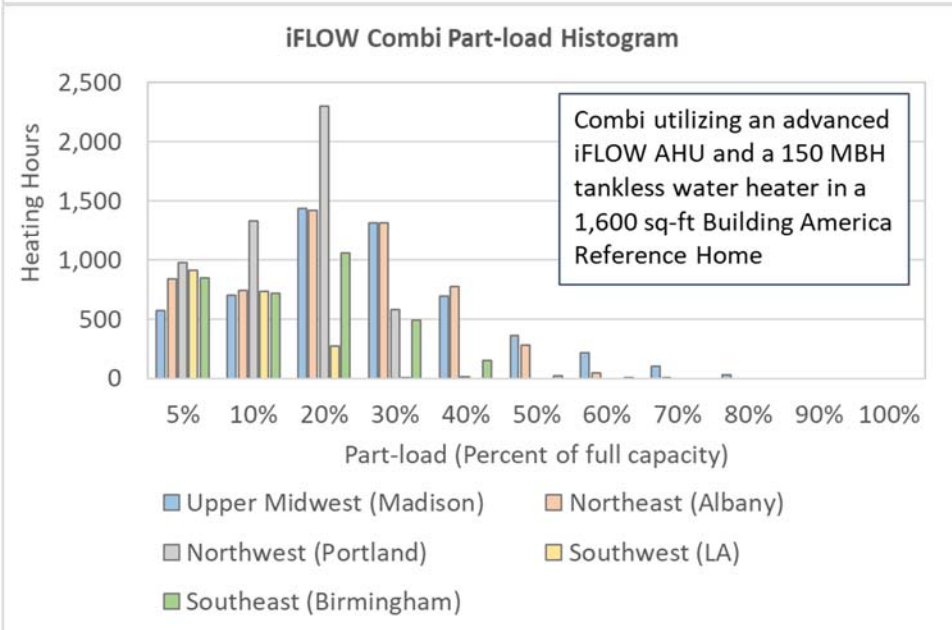


Figure 7 – Combi System Part-load Operating Frequency

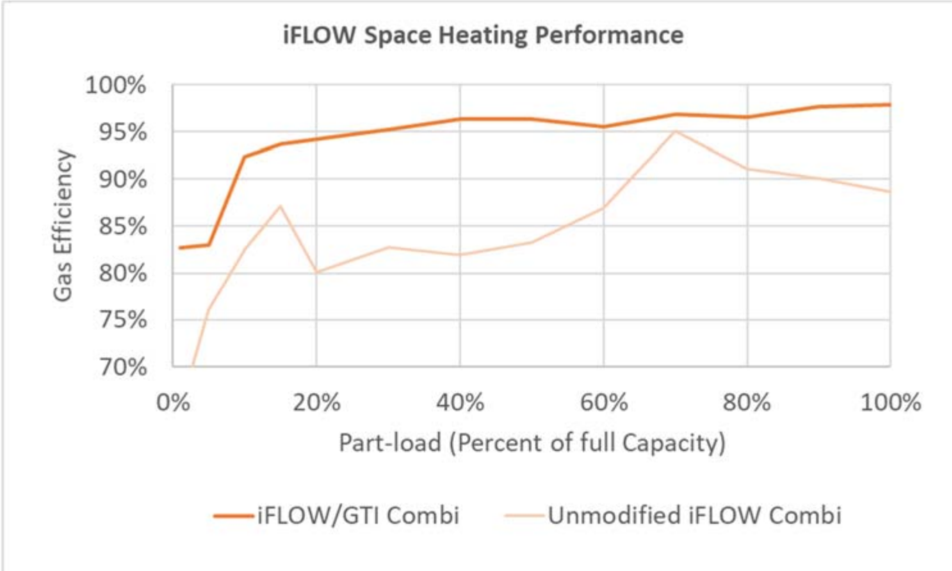


Figure 8 – iFLOW Space Heating Performance with Innovative Controls

Combi Water Heating Performance

Previous research in the VTH was conducted with a Rheem 0.62 EF 40-gallon water heater that met the minimum requirements of the National Appliance Energy Conservation Act (NAECA). GTI used the 0.62 EF Rheem water heater as a comparative baseline for the advanced combi systems research for this project. Figure 9 shows the DHW performance at part-loads for the NTI and iFLOW/Navien combi systems relative to the Rheem water heater. A typical 2 gpm 10-minute shower draw is shown for reference. Like short-cycling space heating calls, short low-volume hot water draws negatively impact water heating performance. Clearly, the 0.97 EF rated tankless water heaters used in the combis dramatically outperform the NAECA minimum water heater, but achieving greater than 90% efficiencies only occurs with long high-volume DHW draws.

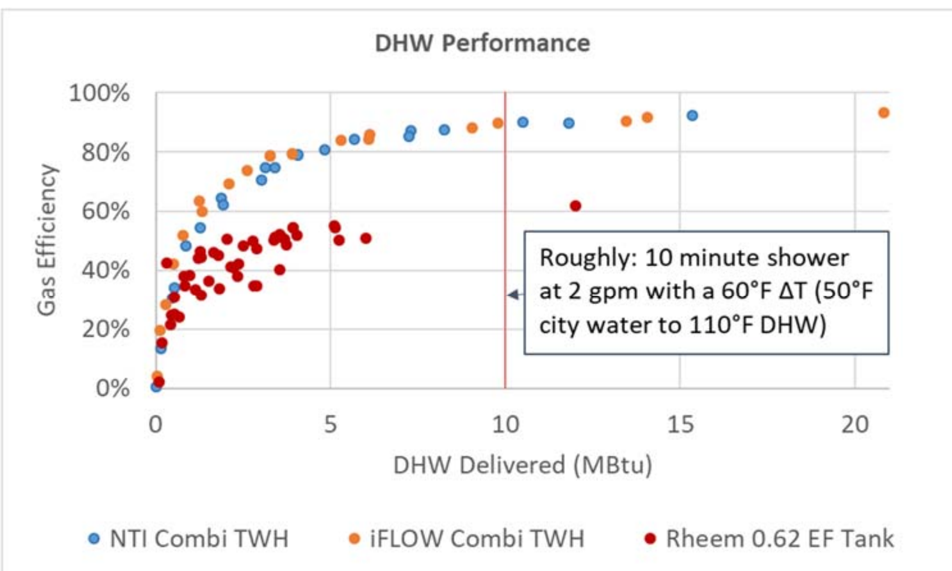


Figure 9 – Advanced Combi Relative Water Heating Performance

Combi Contiguous and Coincidental Space Heating and Water Heating Performance

Any time the combi water heaters were preheated prior to a thermostat call or DHW draw, it had positive impacts on efficiencies and supply air and DHW temperatures. For example, a DHW draw immediately before, but not during a space heating cycle or a space heating cycle immediately before, but not during a DHW draw improved subsequent space heating or DHW performance respectively. The impacts depended on the extent of preheating, but were quite significant, especially at low loads. Figure 10 and Figure 11 show the positive impacts on efficiencies at low part-loads. Efficiencies for the space heating cycles are over 100% because the tankless water heaters were preheated due to the prior DHW draws. The cumulative efficiency for each DHW and space heating cycle would of course be less than 100%, but the diagrams clearly show the dramatic improvement in low-load performance as a result of these contiguous loading scenarios. Figure 12 and Figure 13 show the slight increases in AHU leaving air temperatures due to preheating. Similar impacts on preheated water heating performance due to prior space heating cycles are shown in Figures 14 through 17.

<u>Contiguous loading: DHW draw before a space heating cycle (preheating space heating cycle)</u>

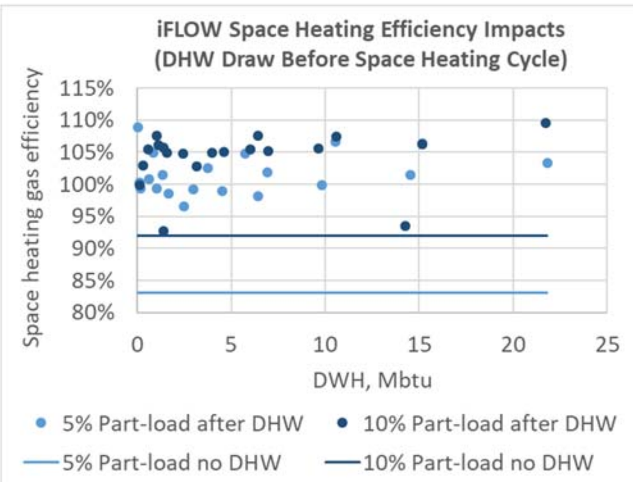


Figure 10 – iFLOW Preheated Space Heating Efficiency Impacts

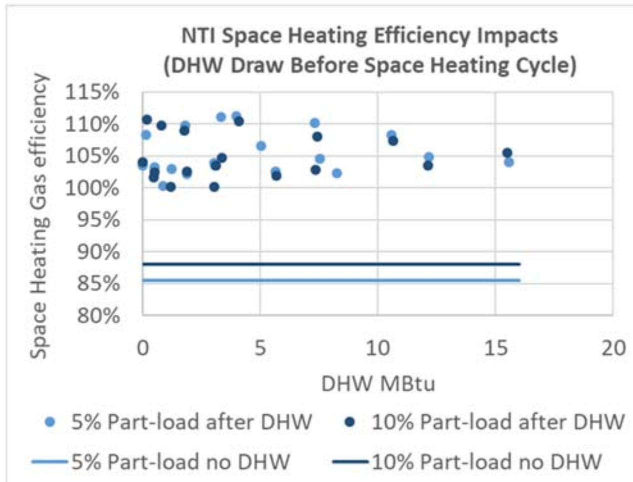


Figure 11 – NTI Preheated Space Heating Efficiency Impacts

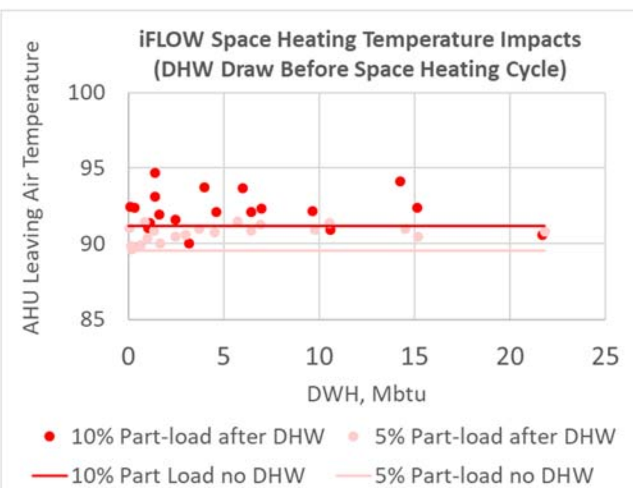


Figure 12 – iFLOW Preheated Space Heating AHU Temperature Impacts

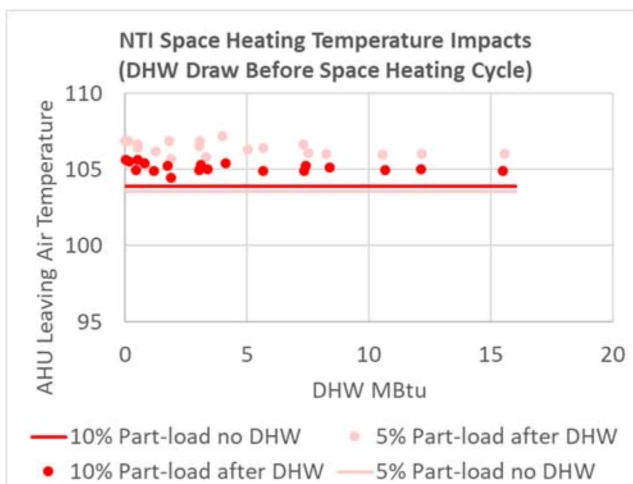


Figure 13 – NTI Preheated Space Heating AHU Temperature Impacts

Contiguous loading: Space heating cycle before a DHW draw (preheating DHW)

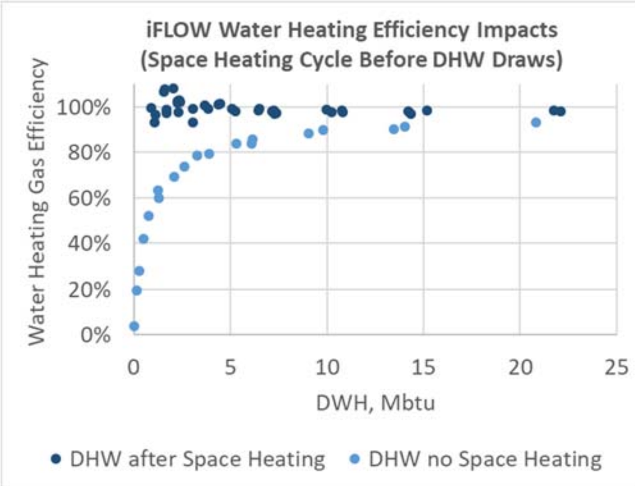


Figure 14 – iFLOW Preheated DHW Efficiency Impacts

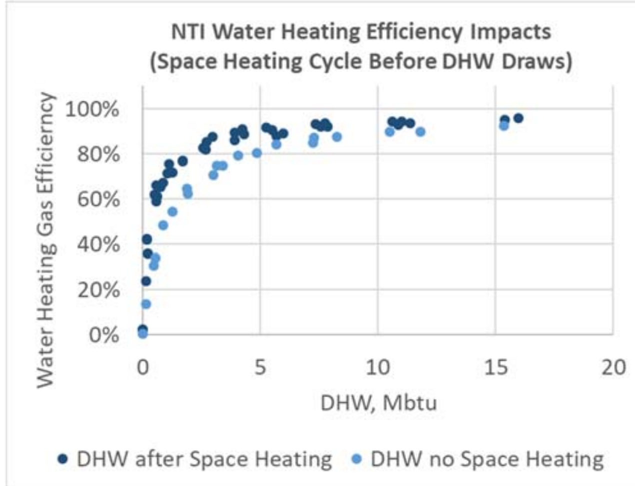


Figure 15 – NTI Preheated DHW Efficiency Impacts

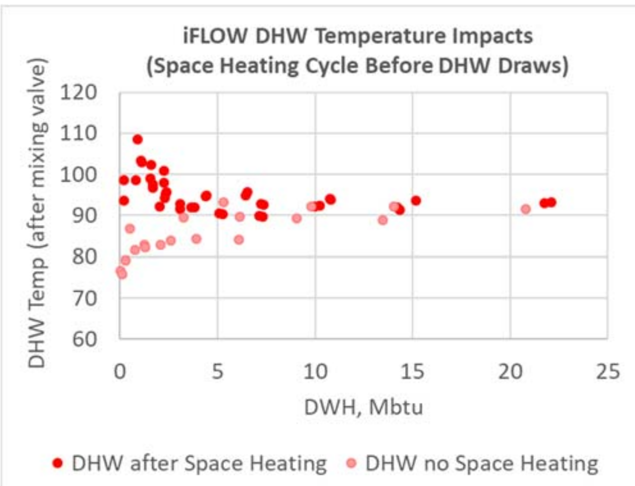


Figure 16 – iFLOW Preheated DHW AHU Temperature Impacts

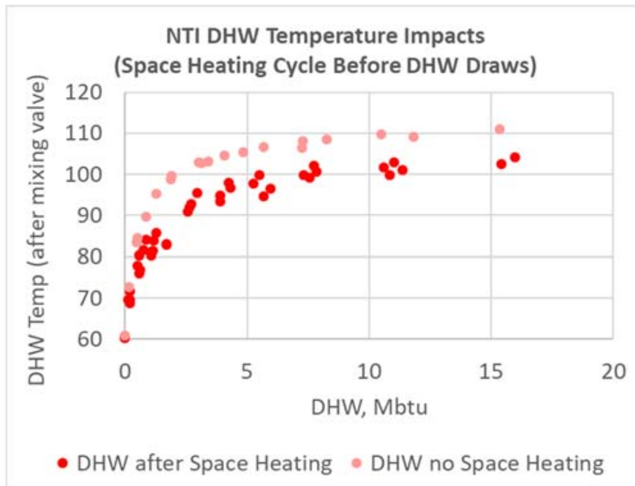


Figure 17 – NTI Preheated DHW AHU Temperature Impacts

Coincidental loading: Hot water draw during a space heating cycle

When DHW draws were applied to the NTI combi during a space heating cycle, hot water and AHU leaving air temperatures decreased. The impacts on temperatures depended on the DHW draw durations and are shown in Figure 18 and Figure 19. However, when DHW draws were applied to the iFLOW combi during a space heating cycle, the space heating cycle was always suspended until the DHW draw was complete. This is referred to by combi manufacturers as “DHW priority”. A flow switch in the AHU hot water loop senses a drop in water flow, and suspends the thermostat heating call. While it does serve to prioritize DHW, its primary purpose is to protect the AHU circulation pump from low flow cavitation. This is especially important with the iFLOW system as it operates at very low AHU water flow rates. Based on the 1,600 sq-ft 2010 Building America Reference Home residential model, suspending a thermostat call for 15 minutes on a 30°F day, results in a few degree drop in room air temperature.

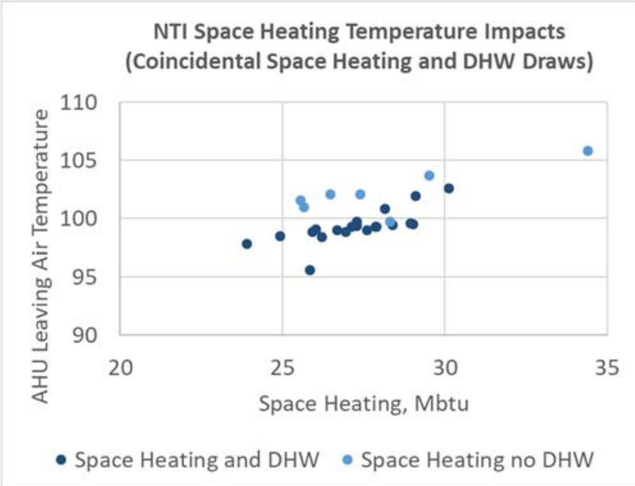


Figure 18 – NTI Coincidental Space Heating AHU Temperature Impacts

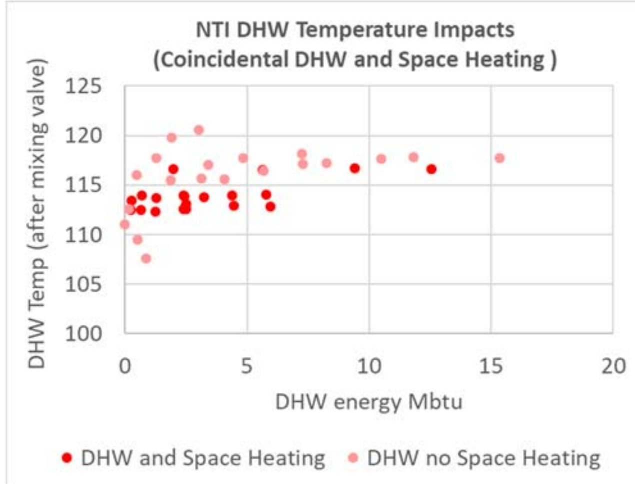


Figure 19 – NTI Coincidental DHW Temperature Impacts

Combi System Performance and Energy Modeling Predictions

Energy Plus building energy modeling software was modified with performance maps developed from the VTH testing. It was then used together with weather data and hourly load calculations to quantify annual energy performance and savings for the 1,600 sq-ft 2010 Building America Reference Home in various climates.

Figure 20 shows the cumulative annual efficiencies for the advanced combis relative to the baseline 95% condensing furnace and 0.62 EF tank water heater combination. Figure 21 shows annual efficiencies for only space heating. These annual efficiencies reflect what might be seen in real world conditions as the systems would be installed in the field. The NTI and iFLOW/Navien systems each performed on an annual basis substantially better than the baseline condensing furnace and NAECA standard tank water heater, even when only space heating was considered. Figure 22 shows relative annual gas consumption predictions. About 20% to over 30% annual gas savings are predicted with the advanced combi systems. Figure 23 shows relative annual gas cost predictions based on 2016 and 2017 EIA monthly gas rates by state. In many cases, very significant gas and cost savings are predicted with the advanced combis compared to the traditionally separate condensing furnace and tank water heater appliances.

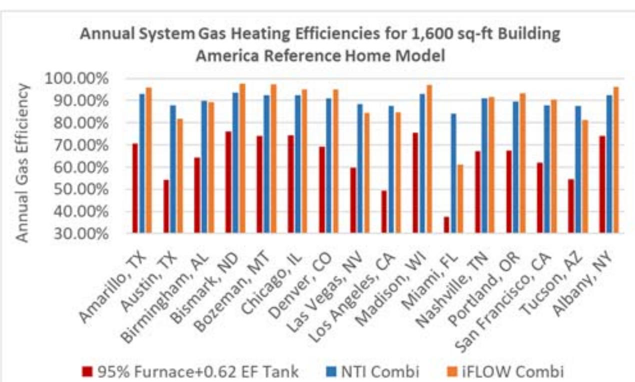


Figure 20 –Advanced Combi Relative Annual Space Heating+DHW Efficiency Predictions

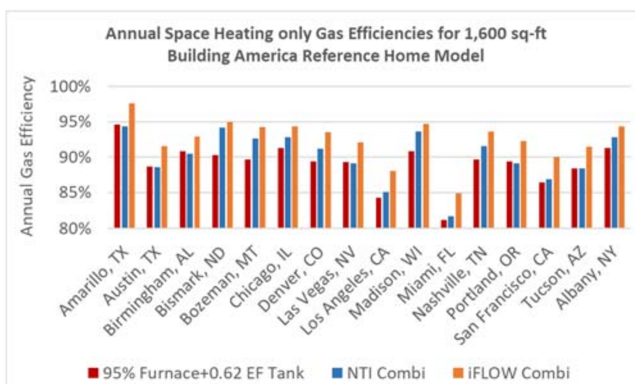


Figure 21 – Advanced Combi Relative Annual Space Heating only Efficiency Predictions

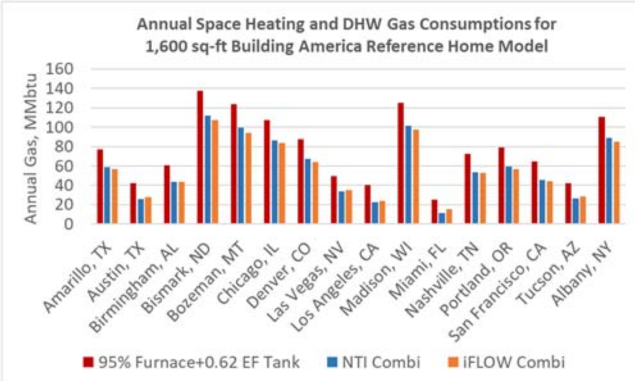


Figure 22 –Advanced Combi Gas Annual Consumption Predictions

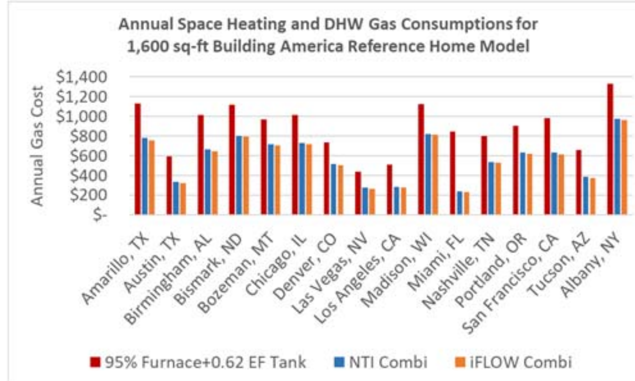


Figure 23 –Advanced Combi Annual Gas Cost Predictions

Appendix A – Instrumentation Lists

Parameter	Instrument	Range	Accuracy
Tankless Combustion 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%
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%
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%
Tankless Exhaust Temp	T-Type Insulated Thermocouples KK-T-20-36	–100 to 250°F	at >32 to 662°F ±1.8°F or 0.75%
AHU Conditioned Air Flow Low	Duct-Mounted Air Flow Measurement Station Dwyer FLST-C8	100 to 10,000 FPM	± 2%
AHU Conditioned Air Flow High	Duct-Mounted Air Flow Measurement Station Dwyer FLST-C10	100 to 10,000 FPM	± 2%
AHU Conditioned Air Flow Differential Pres Low	Differential Pressure Transmitter Dwyer 607-2	0” to 0.25” wc	±0.5%
AHU Conditioned Air Flow Differential Pres Hi	Differential Pressure Transmitter Dwyer 607-2	0” to 0.25” wc	±0.5%
AHU Total Static Pressure	Differential Pressure Transmitter Dwyer 610-01A-DDV	0” to 1” wc	±0.25%
AHU + Pump + Tankless Power	WattNode Pulse WNB-3Y-208P	48 to 62Hz at -20% to +15% Voltage	± 0.5%
Tankless Gas Flow	Gas Flow Diaphragm Meter Elster American Meter AC-250	0 to 656 SCFH (5 psig)	± 0.5%
Tankless 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)
Flue Gas Composition – O2	Rosemount Analytical Model: X26P –pO2	2-25%	-
Flue Gas Composition –CO/CO2	Make: Rosemount Analytical Model: X26P – 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	-
AHU Entering and Leaving Water Temp	T-Type Insulated Thermocouples KK-T-20-36	–100 to 250°F	at >32 to 662°F ±1.8°F or 0.75%
City Water and Domestic Hot Water Temp	T-Type Insulated Thermocouples KK-T-20-36	–100 to 250°F	at >32 to 662°F ±1.8°F or 0.75%
AHU Leaving Water and Domestic Hot Water Flow	Seametrics Turbine Flow Meter	0.2 to18 gpm	± 1% of full scale

Appendix B – Calculation Methodology

Measured data from all of the instruments listed in Figure 5 were continuously collected and recorded at 5-sec 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:

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

Where:

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

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

V_{NG} = Volumetric flow rate of natural gas (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.

Combi Energy Output

Heat supplied by the combi was determined by measuring the air side and water side energy delivered. The air side energy delivered was determined by measuring the air flow rate and supply and return air temperatures at the air handler unit inlet/outlet as follows:

$$Q_{air} = \sum V_l \cdot \rho_s \cdot C_p \cdot (\Delta T\,) \cdot \Delta t$$

Where:

Q_{air}= Summation of supplied heat to the air by the combi for each time step (Btu)

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

$$V_l = \sum 4005 \left(\pi \cdot \frac{D_i^2}{4} \cdot \frac{\rho_s}{\rho_i} \cdot \sqrt{P_i}\right)$$

Where:

P_i = Velocity Pressure at each recorded interval in each airflow station

D_i = Duct diameter for the airflow measurement stations (8in and 10in).

$|\Delta T|$ = the difference between weighted supply and return temperatures at each recorded interval (°F). Note, ΔTs less than 20 °F were assumed to be zero.

ρ_i = Density of air based on air temperature at the airflow meter for each recorded interval, (lbm/ft^3)

C_p = Specific heat of air at the average temperature between the supply and return air, (Btu/lbm-°F)

Δt = time interval used in the data collection program (minutes)

ρ_s = Standard density of air based on air temperature of 65°F at 14.646 psia, (lbm/ft^3)

The water side energy delivered was determined by measuring water flow rate and city water and domestic hot water temperatures at tankless city water supply/mixing valve outlet as follows:

$$Q_{water} = \sum V_l \cdot \rho_s \cdot C_p \cdot (\Delta T\ ) \cdot \Delta t$$

Where:

Q_{water} = Summation of supplied heat to the water by the combi for each time step (Btu)

V_l = Volumetric flow rate of water (gallons/minute)

C_p = Specific heat of air at the average temperature between the supply and return air, (Btu/lbm-°F)

Δt = time interval used in the data collection program (minutes)

ρ_s = Standard density of water based on air temperature of 50°F at 14.646 psia, (lbm/gallons)

Combi Thermal Efficiency

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

$$n_f = \left(\frac{Q_{water}+Q_{air}}{Q_{NG}}\right) \times 100\%$$

Where:

n_f = Combi thermal efficiency (%)

Combi Net Efficiency

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

$$n_N = \left(\frac{Q_{water}+Q_{air}}{Q_{NG}+E}\right) \times 100\%$$

Where:

n_N = Combi net efficiency (%)

E = Electric consumption (Btu)

Furnace Combustion Efficiency

Furnace combustion efficiency n_{ss} was calculated based on the methods described in ASHRAE Standard 103:

$$n_{ss} = 100 - [L_A + L_s - L_g + L_c]$$

Where:

L_A = 9.55 (constant 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

P9 Evaluation

The combination systems were tested per CSA P.9-11 – Test method for determining the performance of combined space and water heating systems.