The Performance of Integrated Hydronic Heating Systems, published in the proceedings of the 5th Aachener Ölwärme-Kolloquium, Aachen Germany, Sept. 13-14, 2006.

Dr. T. Butcher, Y. Celebi, and G. Wei
Brookhaven National Laboratory, New York

The Performance of Integrated Hydronic Heating Systems

Dr. T. Butcher, Y. Celebi, and G. Wei
Brookhaven National Laboratory, New York

Abstract
A variety of system configurations are used in North America to meet the heating and domestic hot water needs of single-family homes. This includes: warm air furnaces with electric water heaters; boilers with integrated domestic hot water coils; boilers with "indirect" hot water storage tanks; and water heaters with space heating as a secondary function. Integrated hydronic systems which provide both heat and hot water are more popular only in the Northeast and mid-Atlantic regions. For those making decisions about configurations of these integrated hydronic systems, including control options, little information is available concerning the annual energy cost implications of these decisions. A project is currently underway to use a direct load emulation approach to measure the performance of hydronic systems and to provide decision tools to consumers. This is a laboratory measurement system involving direct energy input and output measurements under different load patterns. These results are then used to develop performance correlations for specific systems that can be used to predict annual energy use in specific applications. Both gas- and oil-fired systems are included in the project. Results to-date, as well as an overview of North American system equipment types are presented.

Introduction

Across the U.S. the dominant heating system in single family homes is a warm air furnace which integrates easily with central air conditioning. In the Northeast and some other colder regions, hydronic heating systems are more popular. For these systems there are a wide range of configurations used for producing domestic hot water including, for example, use of a domestic water coil inserted in the heating boiler (low cost, traditional system); use of an indirect domestic hot water tank heated from the heating boiler; and use of a separate, fuel or electric fired hot water heater. There are also an increasing range of control configuration options available including outdoor reset, cold start, thermal purge, and variable setpoint differential.

The main measure that is used for identifying the efficiency of heating systems in the U.S. is termed the Annual Fuel Utilization Efficiency (AFUE). A standard for this measure is maintained by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) [1]. and this is adapted for a federal labeling procedure by the U.S. Department of Energy. The AFUE measure is based upon a heat loss method and involves measurement of excess air and flue gas temperature over an operating cycle considered typical of national average conditions. This method considers heating load only, not domestic hot water. Annual efficiency is based on an assumption of a typical national oversize factor for the heating load of 1.7. In the case of a boiler the prescribed conditions are: supply temperature 60 ºC, return temperature 49 ºC, burner average on-time (9.68 minutes), burner average off-time (33.26 minutes). Energy loss during the off cycle is accounted for through the rate of cooling of flue gas following the burner shutdown and the mass flow of flue gas during the off cycle (estimated or measured). The ASHRAE procedure provides a method for measuring "jacket" energy losses for a boiler while firing in steady state and then calculating the annual cost of these losses based upon a location factor. The test involves measurement of the surface temperatures on the boiler jacket and then calculation of the convective and radiative heat loss. In lieu of a measurement, a 1% default value for steady state jacket loss can be assumed. In the formal labeling procedure it is assumed that all boilers are located within the conditioned space of the home and that jacket energy losses become useful heat, so in practice jacket loss is not commonly measured or used in the rating.

For appliances which have as their sole function heating domestic hot water there is a separate ASHRAE procedure [2] which has also been adopted as part of a national labeling procedure. Termed the Energy Factor the test method involves a direct input/output measure with the use of a standard domestic hot water draw pattern of 6 draws over 6 hours, followed by 18 hours of idle period. Another ASHRAE test standard [3] provides a method for combining the results of the AFUE and Energy Factor test into a combined measure for integrated systems. This standard is currently undergoing a regular revision and has not been adopted as part of a national labeling procedure. Some field data which is available for integrated space and water heating appliances indicates much lower efficiency levels than heating-only ratings indicate [4,5]

Presently there is under development an ASHRAE test standard for commercial boilers which provides an interesting alternative methodology. Termed the Application Seasonal Efficiency (ASE) this standard would apply to steam or hot water boilers with capacity ranging from 88 to 3600 kW for space heating applications only. For the test boiler a heat input / output curve is developed from test data. This curve, for many boilers, is linear providing the need to measure only steady state, full load efficiency and energy input at an idle condition. The procedure provides for optional tests at part load and steady state, full load at different supply water temperatures. Where the boiler control changes water temperature a series of different performance curves are produced, each for one temperature. These curves are then applied to specific buildings with an analysis procedure considering building type, location, design heat load, boiler size, number of boilers installed, and control strategy. The result is the ASE for this specific installation. The procedure to use the results for specific buildings is implemented in a user-friendly computer tool.

The approach of a linear input/output relation to modeling the performance of a boiler has been explored by others [6,7]. Based on all results to date a linear model may not be expected to be fully accurate, even for a fixed temperature (supply, boiler average, or return flow) for all systems. The approach being taken here does not rely on a fully linear relationship but may allow for a curve also. Several standards for evaluating the performance of boilers take a related approach in which the efficiency is measured at several defined points along the load curve.

The project discussed in this paper is focused on hydronic heating systems which also provide domestic hot water. It has been created to provide a method to estimate the actual energy savings that may be realized when replacing old equipment and the effects that different configuration decisions have on annual energy use. The basic approach taken relates to the ASE method discussed above. For integrated systems performance curves are developed based on direct energy input / output measurements under a range of load conditions. These performance curves can then be used in either a simple “bin” type analysis or in hourly simulation programs such as DOE-2.

Experimental

The basic test arrangement is shown in Figure 1. The “system” in this figure may include a boiler and water storage tank, a boiler with an internal coil for hot water production, a tank type water heater used also for domestic hot water, or any other integrated system. Fuel input is measured using a Coriolis flow meter calibrated against a precision balance. The fuel heating value and density are measured using ASTM standard procedures.

For the heating load, boiler water is circulated through a plate heat exchanger. The mass flow rate of cooling water through the heat exchanger is directly measured with a platform weigh scale which communicates with the lab computer. Average flow rate during a heat load period is determined using a linear regression of the scale readings. The mass flow rate is combined with inlet and outlet temperature readings on the cooling water to determine heating energy output. High accuracy for water mass flow, temperature rise, and fuel heating value are required.

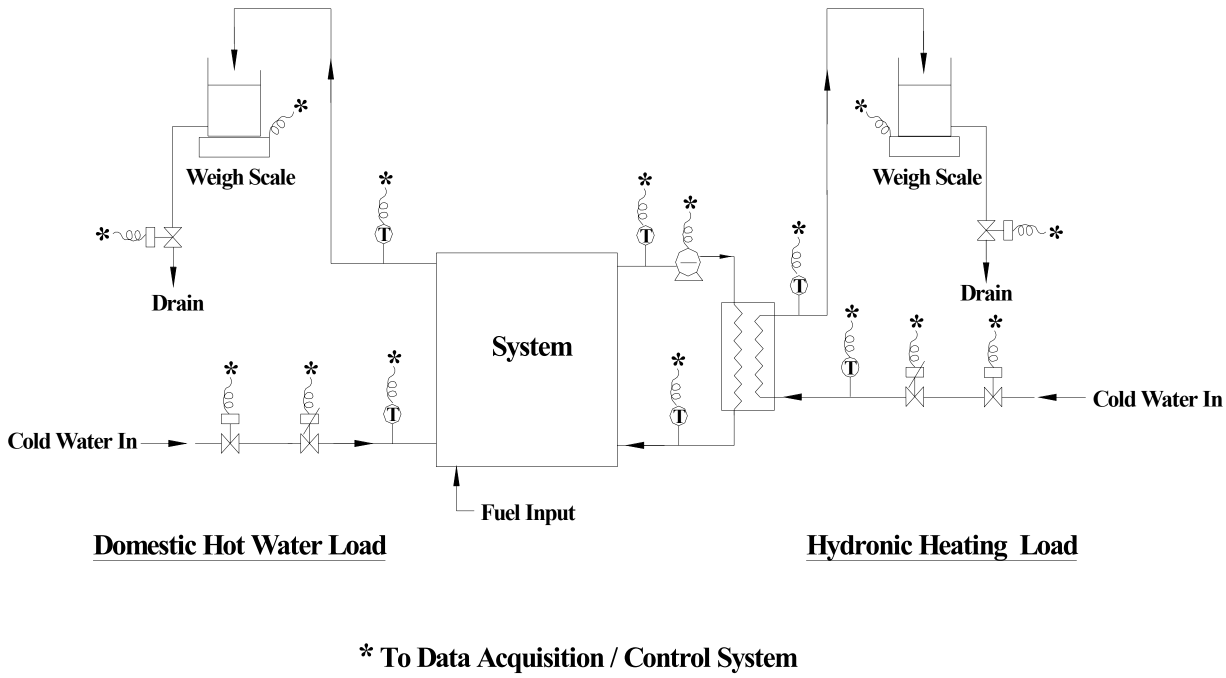

Figure 1: Illustration Of The Measurement Arrangement For System Performance Testing

For the domestic hot water load the approach is similar. Mass flow of hot water is measured with a platform weigh scale in the same way and temperature rise of the water, integrated over a draw period, is used to determine domestic hot water output.

Steady state efficiency is determined for hydronic heating only and the effect of supply water temperature on efficiency is determined by adjusting the cooling water flow rate. The boiler supply / return differential temperature is essentially set by the internal flow rate. Each steady state test is about 2 hours in duration.

In the idle state the average fuel consumption required to maintain the system under a no-load condition is measured over an extended time period. This can vary widely among systems and is very dependent upon control decisions such as cold-start or maintain temperature and the degree of system insulation. These tests normally take several days. Where systems have indirect storage tanks the temperature profile in the tanks is measured and a correction is made for differences in the amount of stored energy between the start and end of a test.

For part load tests periodic loads are imposed on the system and these may include heating only, domestic hot water only, or a load pattern that combines both load types. Test periods typically last from 12 to 72 hours. The load patterns can be very complex if desired. Figure 2, for example illustrates one domestic hot water load pattern tested which has been adopted from the literature [8] as a typical daily hot water draw pattern.

All load patterns are defined in an input file to the computer which controls the flow on/off valves, controls the weigh tank fill and draining, adjusts the modulating flow control valves, and records system temperatures and water flows.

Table 1 provides a list of the types of units planned for evaluation under this project. The work is not intended to compare specific products at all but rather to enable conclusions to be drawn about configuration and control features that provide the most energy savings as well as the magnitude of savings that may be expected when older systems are replaced. To date the first four units included in Table 1 have been evaluated.

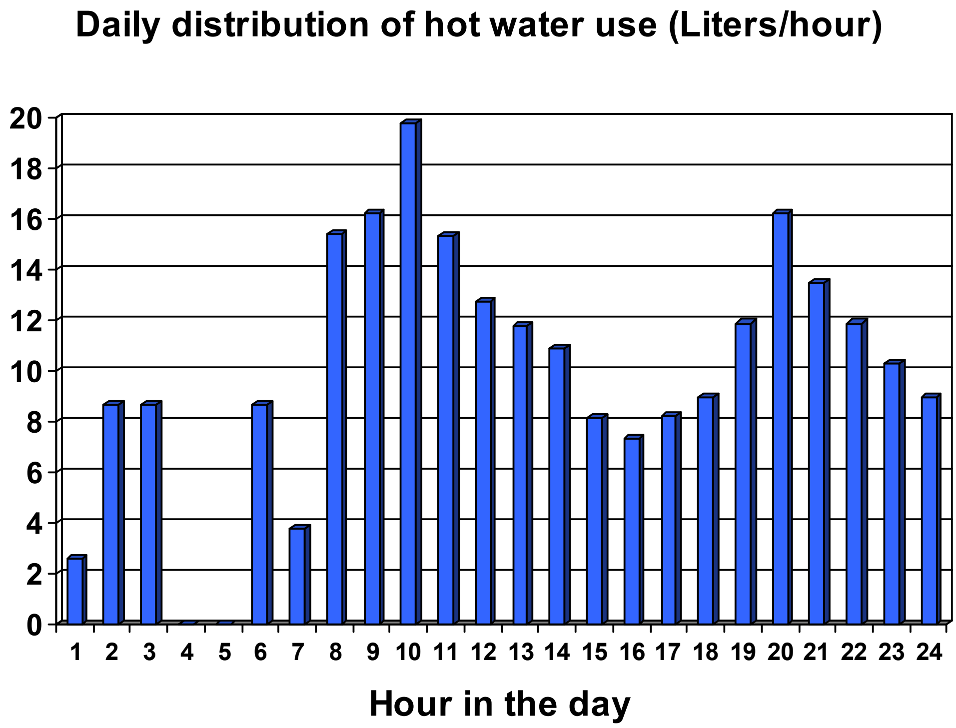

Figure 2: Example Of A Typical Hourly Distribution Of Domestic Hot Water Load Which Can Be Used During System Performance Testing [8]

Another parameter of interest in this project is the boiler "jacket" loss or energy lost to the surroundings through the boiler outer insulation. In a steady state test this could be evaluated through the difference between the combustion efficiency (based on flue gas measurements) and the thermal efficiency (based on input/output measurements) but the nominal accuracy of the fuel heating value measurement leads to the potential for large errors in this determination, particularly at low jacket loss values.

Table 1: List of Heating Systems Planned for Evaluation

1	Cast iron boiler, oil-fired, high capacity, fixed temperature, internal tankless coil for domestic hot water
2	Cast iron boiler, oil-fired, fixed temperature, indirect tank for domestic hot water
3	Steel boiler, oil-fired, with thermal purge control, indirect tank for domestic hot water
4	Condensing boiler, oil-fired, with various control options, indirect tank for domestic hot water
5	Cast-iron boiler, oil-fired, very well insulated, various control options, indirect tank for domestic hot water
6	Storage tank water heater, oil-fired, used for both heating and domestic hot water
7	Combi-system, oil-fired
8	Condensing boiler, gas-fired, with indirect tank for domestic hot water
9	Cast iron boiler, gas-fired, with atmospheric burner, heating only mode, outdoor reset control
10	Cast iron boiler, gas-fired, with atmospheric burner and separate, gas-fired water heater

As an alternative, a jacket loss estimation procedure, based on surface temperature measurements and defined in the ASHRAE Standard for heating boilers [1] has been adapted. This is useful in evaluating the impact of location of the system on heating costs.

Experimental Results

In establishing the test conditions, a considerable amount of time, with the first units, was spent on exploring the sensitivity of results to test conditions. For example, for chimney vented boilers a decision concerning the imposed draft is necessary. To evaluate draft impacts a chimney was arranged with a variable eductor arrangement to allow fixed control of this parameter. Figure 3 shows the impact of variable draft on the idle loss rate for System 1 from Table 1. The magnitude of draft, over the range explored is modest. For all subsequent tests a draft level on the order of 2.5 Pa has been used.

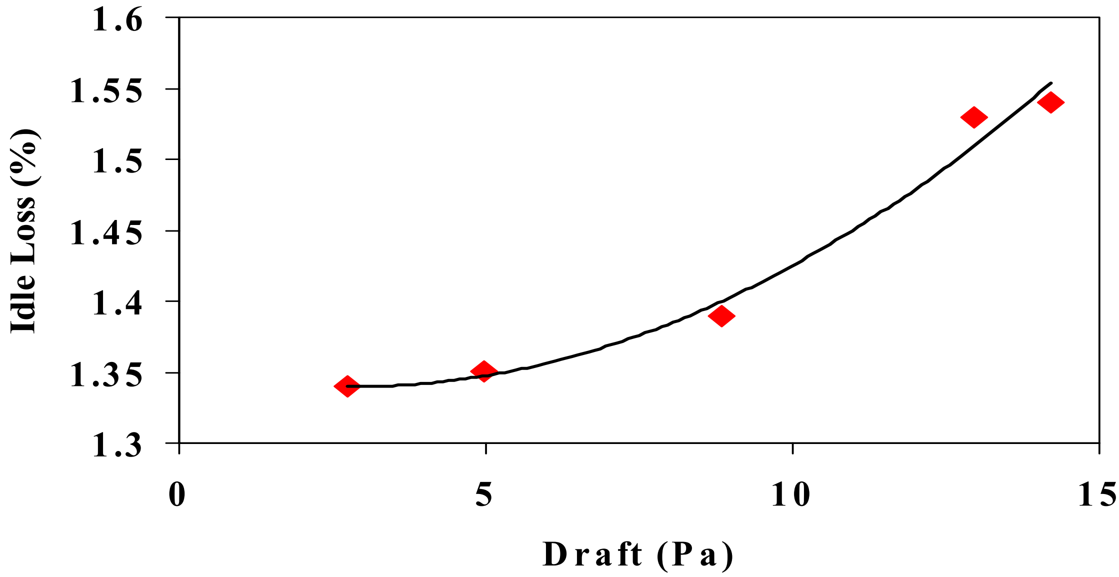

Figure 3: Impact Of Draft Adjustment On Idle Loss. Example Of One Of The Studies Done To Establish Test Conditions

<u>System 1</u> includes an internal coil for domestic hot water production in the boiler ("tankless coil" arrangement). The burner in these tests was operated with a steady state firing rate of 1.46 gal/hr. With a system of this type the boiler control will function to maintain a minimum temperature of 65 °C when a heat call is not present. When a heat call is present the boiler temperature will increase to 80 °C and operate with a differential of 8 °C. Figure 4 shows the results of all measurements with this unit. In this figure, and in similar presentations for the other systems, red points represent heating only load, blue is domestic hot water only load, and green points represent test periods that included both (not done for all systems).

<u>System 2</u> includes a cast iron boiler and an external, indirect hot water tank. The burner steady state firing rate is .73 gal/hr. During a call for space heating or a demand from the domestic hot water tank the control maintains the supply temperature in the range 70 to 80 °C. When there is no demand for heat the control can be arranged to either maintain the boiler at a lower temperature (65 °C) or to not maintain boiler temperature ("Cold Start Mode"). Tests were done in both cases. Figure 5 shows the results of all measurements with this unit in the input / output format.

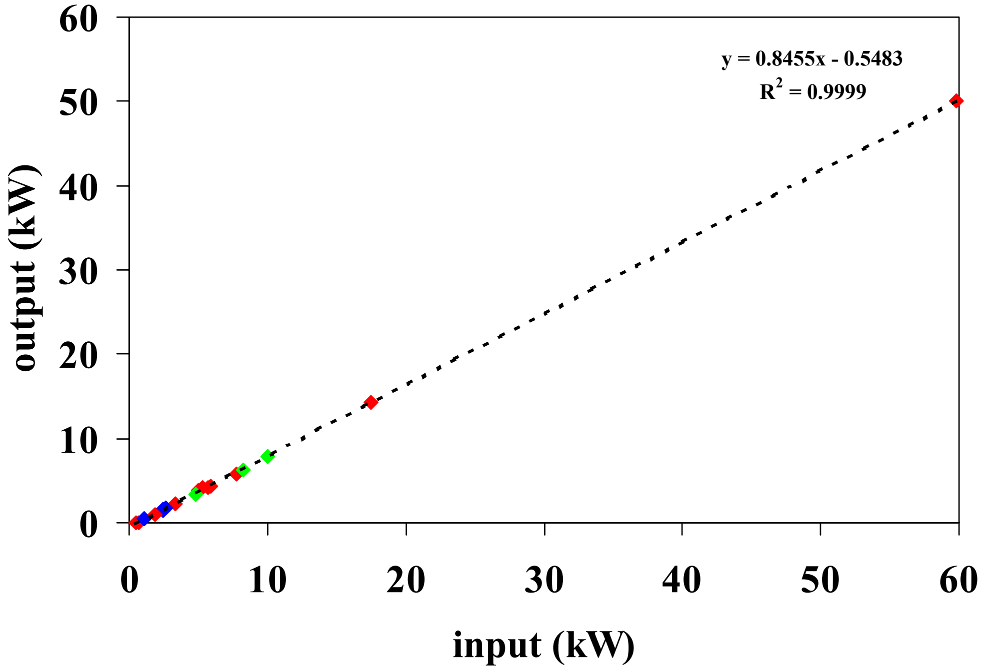

Figure 4: Results Of Input / Output Tests With System 1

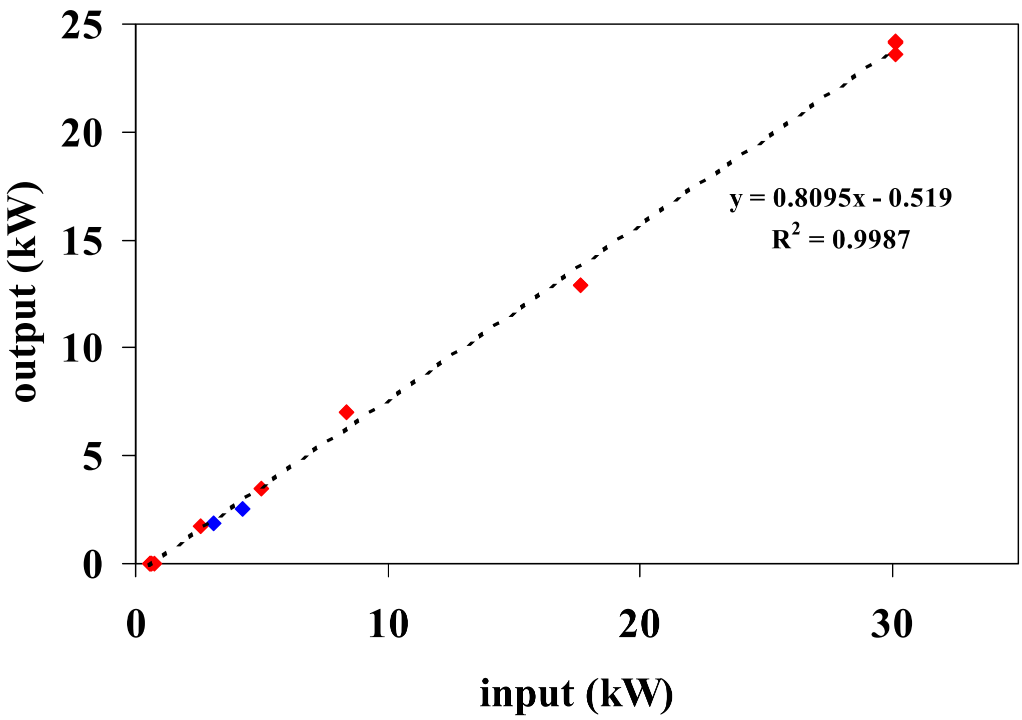

Figure 5: Results Of Input / Output Measurements With System 2

System 3 is a steel boiler also with an indirect storage tank for domestic hot water. The boiler has a control system that purges residual energy from the boiler following a demand for heat. If the demand was for space heating the residual energy is purged into the heating zone, leaving the possibility of a very small amount of overheating of the space (typically negligible). If the demand was for reheating of the domestic hot water tank the residual energy in the boiler is purged into the domestic hot water tank. The purge strategy reduces the boiler temperature to about 40 °C at the end of each cycle. During periods when there is no demand for heat the boiler temperature is not maintained. The result of this strategy, in combination with a very well insulated domestic hot water storage tank, is a very low idle loss for this system. Figure 6 shows the results of all measurements with this unit in the input output format.

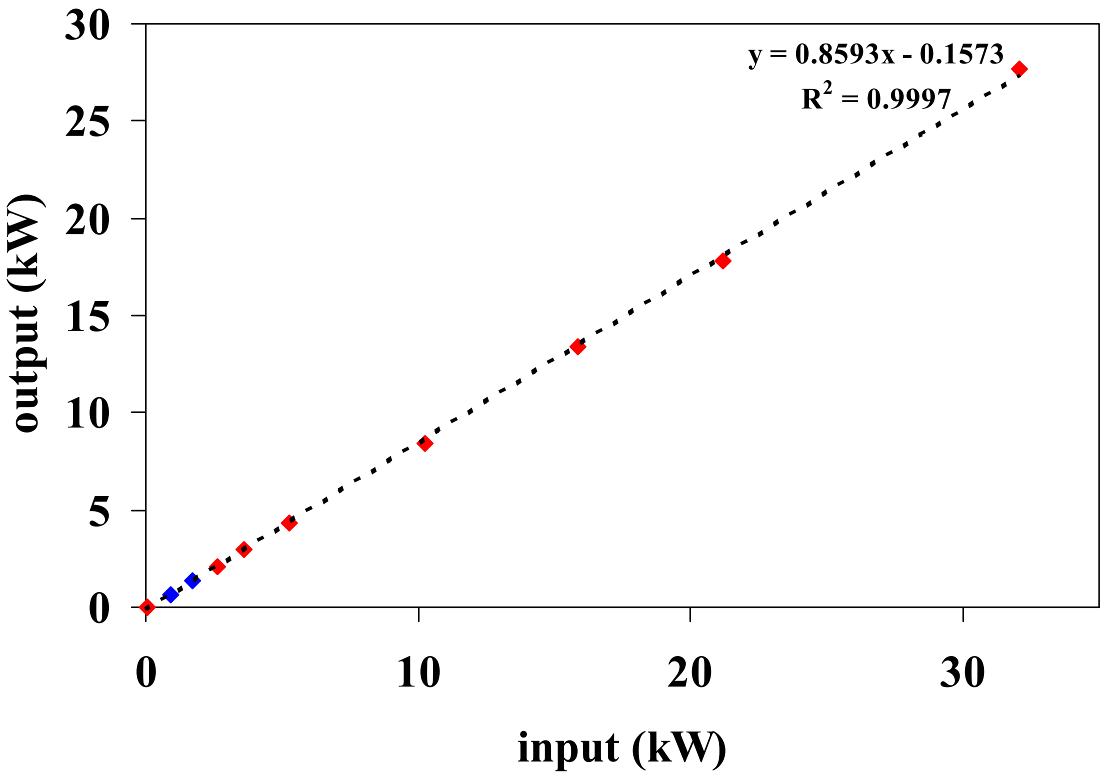

Figure 6 Results Of Input/Output Measurement For System 3

System 4 is an oil-fired condensing boiler with an indirect storage tank. The boiler includes a primary (non-condensing) section and a separate secondary (condensing) section. The control on this boiler maintains the boiler temperature during periods when there is no heat demand. The boiler incorporates a circulating pump and mixing valve for the space heating zones which allows for the delivery of a low temperature supply to the distribution system. When the domestic hot water tank calls for heat the supply is provided at the maximum boiler temperature. Figure 7 shows the results of all measurements with this unit in the input/output format.

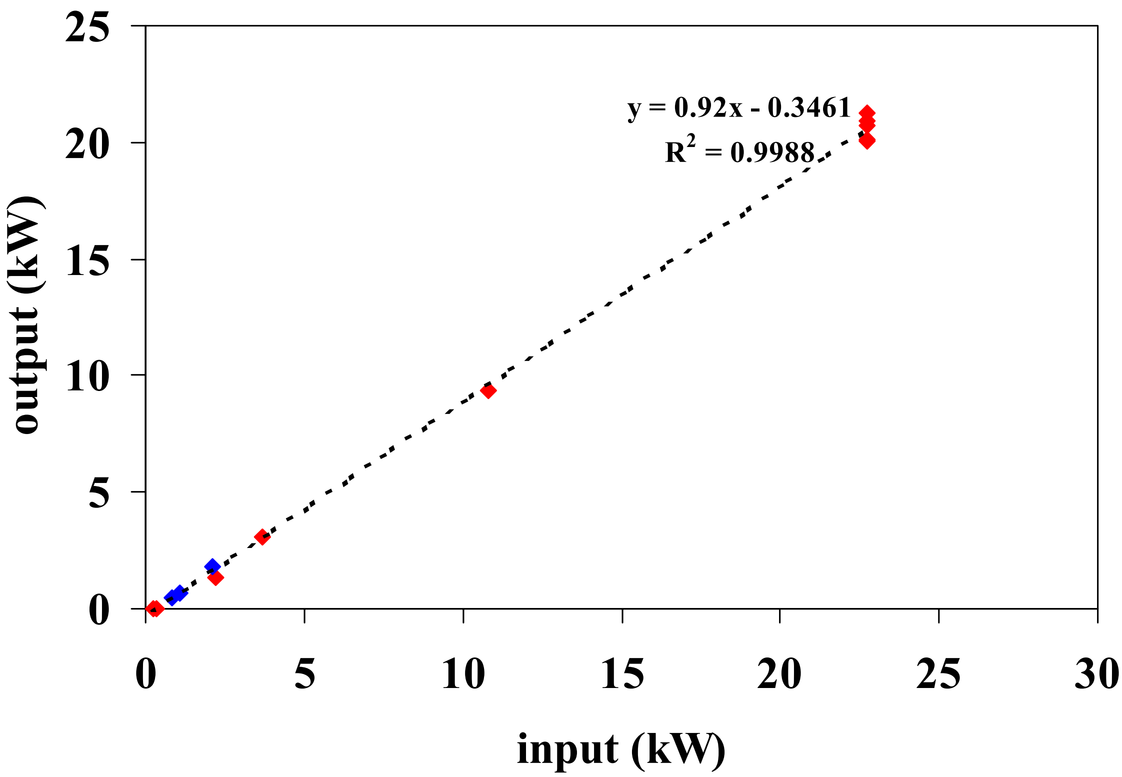

Figure 7: Results Of Input / Output Measurements For System 4

For each of the four units the input / output regression lines have been converted into efficiency/output curves in Figure 8. Table 2 provides a summary of the key performance parameters for each of the units.

Table 2: Performance Parameters for Four Units Tested To-Date

Unit	Firing Rate (gal/hr)	Steady State Efficiency (%)	Idle Loss (%)
1	1.46	83.7	1.2
2	.73	78.4	2.1
3	.78	86.5	.15
4	.55	92.0	1.5

It should be noted that in all cases efficiency is based upon fuel higher heating value, the customary U.S. approach.

Analysis

As discussed above, the input/output performance curves for each system tested can be used to estimate annual fuel consumption in specific applications. To illustrate this, a relatively simple analysis procedure has been developed based on a bin method. The heating season is divided into 10 degree (F) bins and the number of hours in each of these bins is determined from statistical weather data for specific regions. The heating load in each bin is assumed to be proportional to the temperature difference between the balance point for the building, taken as 18 °C and the outdoor temperature.

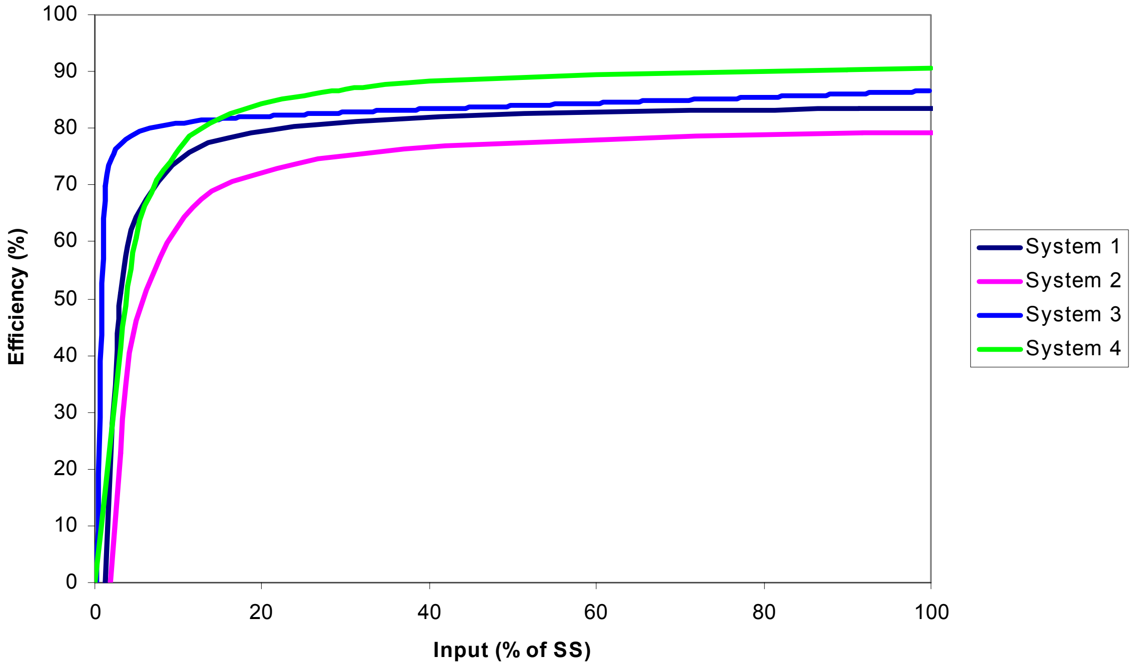

Figure 8: Efficiency Vs. Input Curves For All 4 Systems

The domestic hot water load is added to the heating load and the non-heating season (domestic hot water load only) is created as a separate bin. In each bin, based on the average load the heating system fuel input required and efficiency can be determined from the performance curves. In the example procedure for this the amount of fuel energy which is not useful ("wasted fuel") is explicitly calculated. To illustrate the use of this procedure the following assumptions are taken:

Building location: Harrisburgh, Pennsylvania
Design day temperature: - 14 °C
Design day heat load – 10.3 kW
Average daily domestic hot water consumption – 243 liters / day

Based upon the linear input / output curves developed for each of the systems the key performance parameters are the steady state thermal efficiency, the "idle loss", and the oversize factor which is the output capacity of the system divided by the required output capacity on the design day. Figure 9 shows example results for the case of a steady state efficiency of 82%, idle loss of 3%, and oversize factor of 2.0.

Using this procedure many different cases can be quickly compared. Table 3 shows the results of analysis done for specific cases based upon the range of performance parameters measured in the testing done to-date. Case 1 in this table represents what might be considered as the baseline – typical of older systems installed in the field. Case 2 represents a newer, high efficiency, non-condensing system in which the idle loss is 3%, the same as for the baseline case. The reduction in annual fuel use from the baseline is 6.8% and this is consistent with the increase in steady state efficiency. Case 3 represents a high efficiency, condensing unit in which the idle losses are low. The combination of the high steady state efficiency and the lower idle losses contribute to a very significant reduction in fuel use from the baseline – 20.5%. Case 4 is a non-condensing boiler and the assumed value of .15% here for idle loss represents the best level measured in the lab tests to-date. Here the reduction in annual fuel use is actually greater than with the condensing system and demonstrates the important impact that the idle losses have. Case 4 in this table represents the achievable savings through a combination on of condensing and very low idle losses.

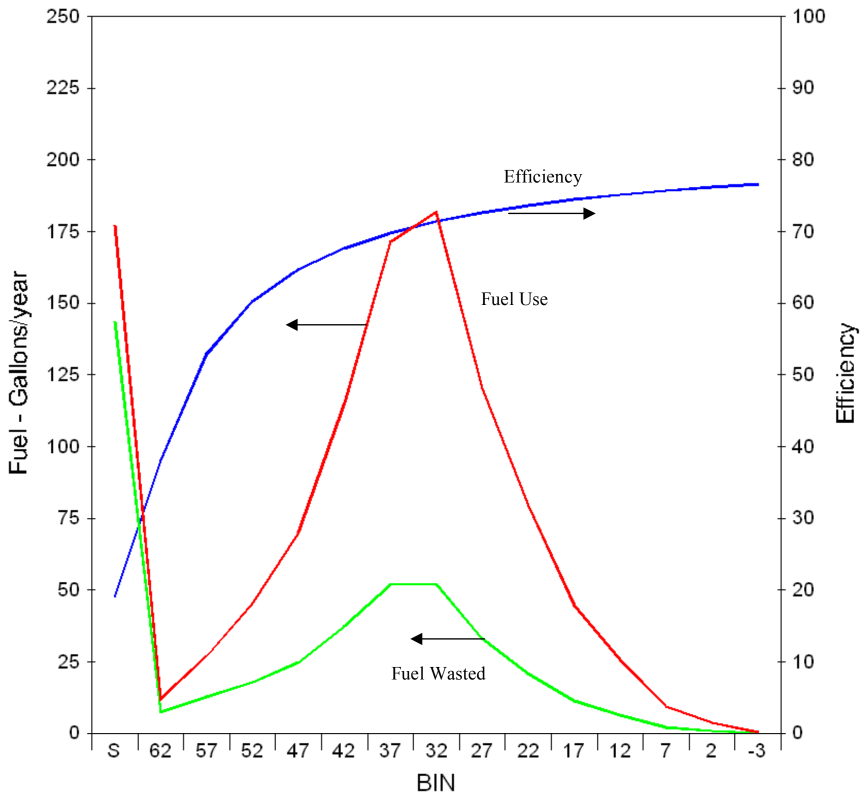

Figure 9: Example Results Of Analysis Of Annual Fuel Use For A Specific System And Application

Table 3: Results of Annual Oil Use Analysis for Selected Cases

	Steady State Efficiency	Idle Loss	Oversize Factor	Annual Efficiency	Annual Fuel Use	Reduction from Baseline Case
	(%)	(%)	-	(%)	(gallons)	(%)
1-Baseline	82	3	2	68.7	855	0
2	88	3	2	73.7	797	6.8
3	92	1	2	86.4	680	20.5
4	88	.15	2	87.2	674	21.1
5	92	.15	2	91.1	645	24.6

Figure 10 shows results of the analysis method in a different way. Here the annual fuel use is plotted against oversize factor with different levels of idle loss as a parameter. This figure shows that the impact that oversizing has on the annual fuel use decreases as the idle loss decreases. For systems with very low idle loss, oversizing does not significantly impact annual fuel use.

It should be noted that the linear input/output relations for the systems as presented in this paper are based on a single boiler temperature. Where temperature varies separate linear relations are developed for each temperature and the analysis of the annual fuel use must consider the control strategy and oversize factor. This is the approach taken in the developing ASE procedure for commercial boilers.

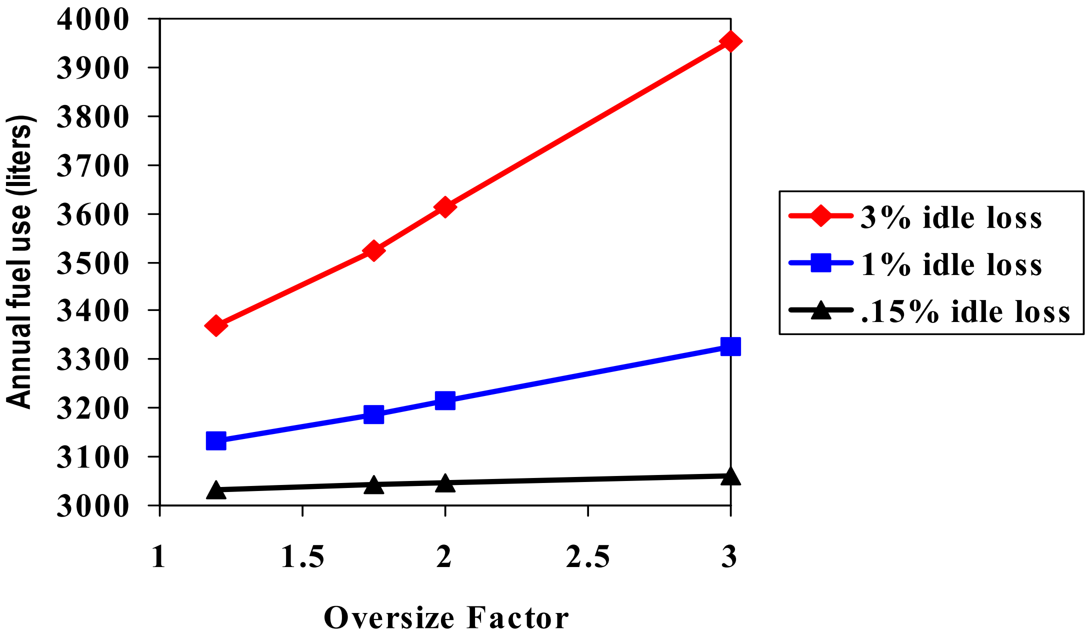

Figure 10: Comparison Of A Range Of Cases. Impact Of Oversize And Idle Loss On Annual Fuel Use

Conclusions

The work reported here has shown that a simple input/output measurement approach can be applied to integrated systems and be used to develop projections for impact of system design and configurations on annual fuel use. Results to-date show the strong importance of the energy losses at low loads, as indicated by idle loss, on the annual performance. The analysis of the results provides support for annual reductions in fuel use with system upgrade on the order of 25%.

Future Plans

Following the completion of all system tests and analysis it is planned to conduct a separate effort to develop education and planning tools using these results. The format for these tools is still under discussion but they may include simple tables of key results, software that can be used in the field under computer or “PDA” platforms, or web-based applications in which users can input prepared generic system configurations or specific parameters such as steady state efficiency and idle loss and calculated annual fuel use.

References

[1] Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers, American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), Standard 103-1993, 1993.

[2] Methods of Testing for Rating Residential Water Heaters. American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), Standard 118.2-2006, 2006.

[3] Methods of Testing for Rating Combination Space-Heating and Water-Heating Appliances. American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), Standard 124-1991, 1991.

[4] Subherwal, B.R., Combination water-heating/space-heating appliance performance. ASHRAE Transactions, Vol. 92, pp 415-432, 1986.

[5] Caron, R. and Wilson, R. Water-Heating Efficiency of Integrated Systems Designed for Space and Water Heating, ASHRAE Transactions Vol 89, pp18-29, 1983.

[6] DeCicco, J.M., Applying a linear model to diagnose boiler fuel consumption. ASHRAE Transactions, Vol 96, pp 296-304, 1990.

[7] Rosa, L. and Tosato, R. Experimental Evaluation of Seasonal Efficiency of Condensing Boilers. Energy and Buildings, 14, pp 237-241, 1990.

[8] HVAC Applications. American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), 2003.

Acknowledgements

This work has been sponsored by the National Oilheat Research Alliance and the New York State Energy Research and Development Authority.