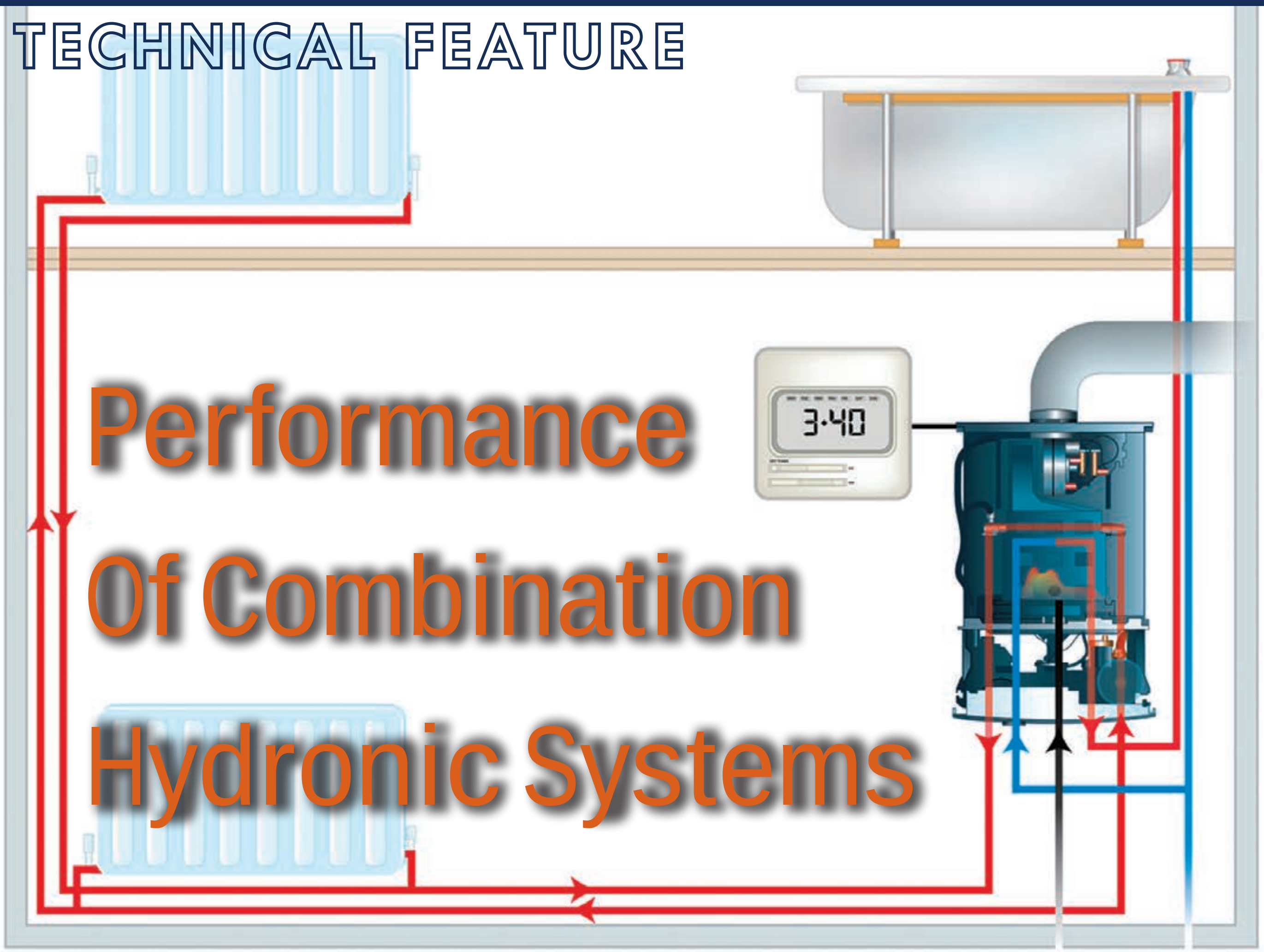
Performance Of Combination Hydronic Systems



By Thomas Butcher, Ph.D., Member ASHRAE

Combination hydronic systems meet space heating and domestic hot water (DHW) loads in residential buildings. However, the current practice of labeling these appliances for just one function (typically space heating) fails to indicate their actual annual performance and to identify the energy saving potential possible with a system upgrade.

In North America, the most common example of a combination hydronic system has historically been a heating boiler with an internal "tankless" heat exchanger coil to meet the DHW load. During the winter, the boiler is generally hot to meet the heating load and the system also can efficiently provide the smaller DHW load.

In the summer, a significant disadvantage is that the boiler must be maintained hot to be ready to meet DHW demand at any time. The key advantage of this approach is low first cost because a single appliance meets both loads. This factor may be increasingly important as more expensive condensing appliances are available in the market and heating loads decrease relative to DHW loads.

A second common arrangement involves using an indirect DHW tank that is heated as with other heating zones from the boiler. A key advantage of this approach is that the boiler no longer needs to stay hot in the summer. This design is the standard approach for most of Europe.

Warm air furnaces are uncommon in Europe, which is associated with a low market penetration of residential air conditioning, particularly in Northern Europe. While residential combination hydronic systems typically do not provide cooling capability, they offer the advantage of much lower distribution system losses relative to conventional, ducted forced-air systems.

Many other system configurations are available on the market including combination tank or tankless (ultra-low mass, instantaneous) type water heaters, and units designed as combination appliances with low-to-moderate volumes of separate storage for both space and water heating. *Figure 1* illustrates options for arrangement of common combination systems.

The test standards for equipment in this category are simple to execute, strongly constrained in operating conditions, and intended to provide comparative indica-

---

About the Author

Thomas Butcher, Ph.D., is head of the Energy Conversion Group at Brookhaven National Laboratory in Upton, N.Y.

tion of average annual performance. This includes ASHRAE Standard 103[1] for furnaces and boilers in a heating mode, ASHRAE Standard 118.2[2] for residential water heaters, and ASHRAE Standard 124[3] for combination appliances.

Standard 103 is based on a stack loss method and considers effects of cyclic operation under standard temperature and cycling conditions. Standard 118.2 is an input-output test method with a 24-hour simulated use pattern involving six equal draws, one hour apart, followed by an 18-hour standby period. The federal appliance labeling procedures for heating furnaces and boilers and for residential water heaters are adapted from these ASHRAE standards. Standard 124 combines the results of Standards 103 and 118.2. Currently, no federal labeling procedure has been adopted for combination appliances. Standards 118.2 and 124 are undergoing revisions.

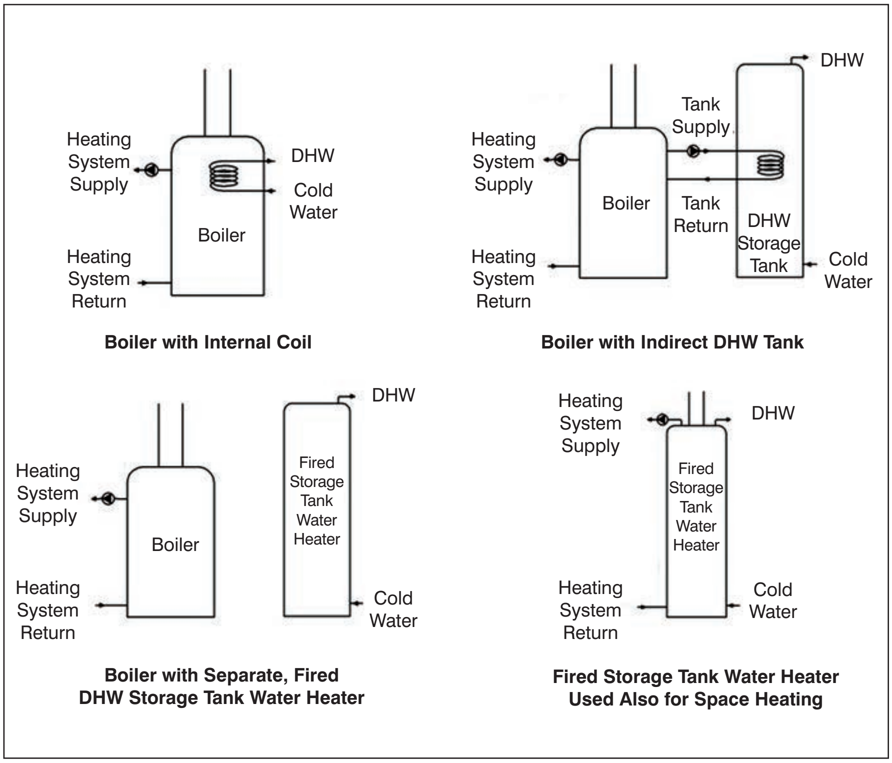


Figure 1: Types of combination systems.

Performance Evaluation

In our research, the performance of a range of combination hydronic heating systems has been evaluated to help identify design features and practices that can promote reduced fuel use. The approach that has been taken is different than used in the standard performance test procedures discussed previously. This approach allows the use of the results to estimate system performance under a range of load scenarios (heating climates, high and low DHW load). Also, the approach allows evaluation of the impact of system oversize.

This approach is more closely related to that being considered by ASHRAE Standards Project Committee 155, Method of Test for Commercial Boilers.[4] The approach is a set of direct energy input/output measurements under full load, partial load, and idle. This leads to a performance line (or curve) for a particular unit. Given this line for a specific system temperature annual performance can be determined for a specific load situation using a bin method or results of an hourly annual load calculation for a specific building.

In developing the performance curves for specific system types, measurements of energy input and output have been made over a wide range of load patterns. This includes full load, steady input and output. It also includes a direct idle loss measurement. Here the combination system is allowed to operate with the normal controls fully functional and the fuel energy input required to keep the system at its design idle condition is measured. This idle loss is expressed as a percentage of the steady-state full-load input or as a loss rate, Btu/h (kW). Other measurements include part-load tests during which the call for heat or the DHW flow is cycled on and off according to a determined pattern. These part-load tests are programmed as a group in the lab operating computer/data acquisition system and run unattended for extended periods. Part-load tests include heating only, DHW only, or a combination of these.[5]

Figure 2 illustrates the results of measurements made on one system: a heating boiler with an internal tankless coil. As this figure shows, the input/output relationship is nearly linear, and this has also been the result in investigations done as part of the SPC 155 work on larger commercial boilers under heating-only load conditions.

For the range of load evaluated, we have found this linear relationship to fit the measured input/output relationship for a wide range of systems for a specific system temperature. This leads to the need for only two parameters to characterize the performance of a combination system: steady state thermal efficiency (input and output at full load) and the system idle loss. Based on testing over many load patterns, we have determined these parameters for a wide range of system types. A non-linear input/output relationship could occur, but the analysis procedure would be similar.

The combination appliances in this study included several high-efficiency, well-insulated boilers with internal, tankless coils. Others in this class were old (removed from the field after 22 years of service) and poorly insulated. Some of the units tested included DHW storage tanks and this includes modulating, condensing gas-fired units, condensing oil-fired

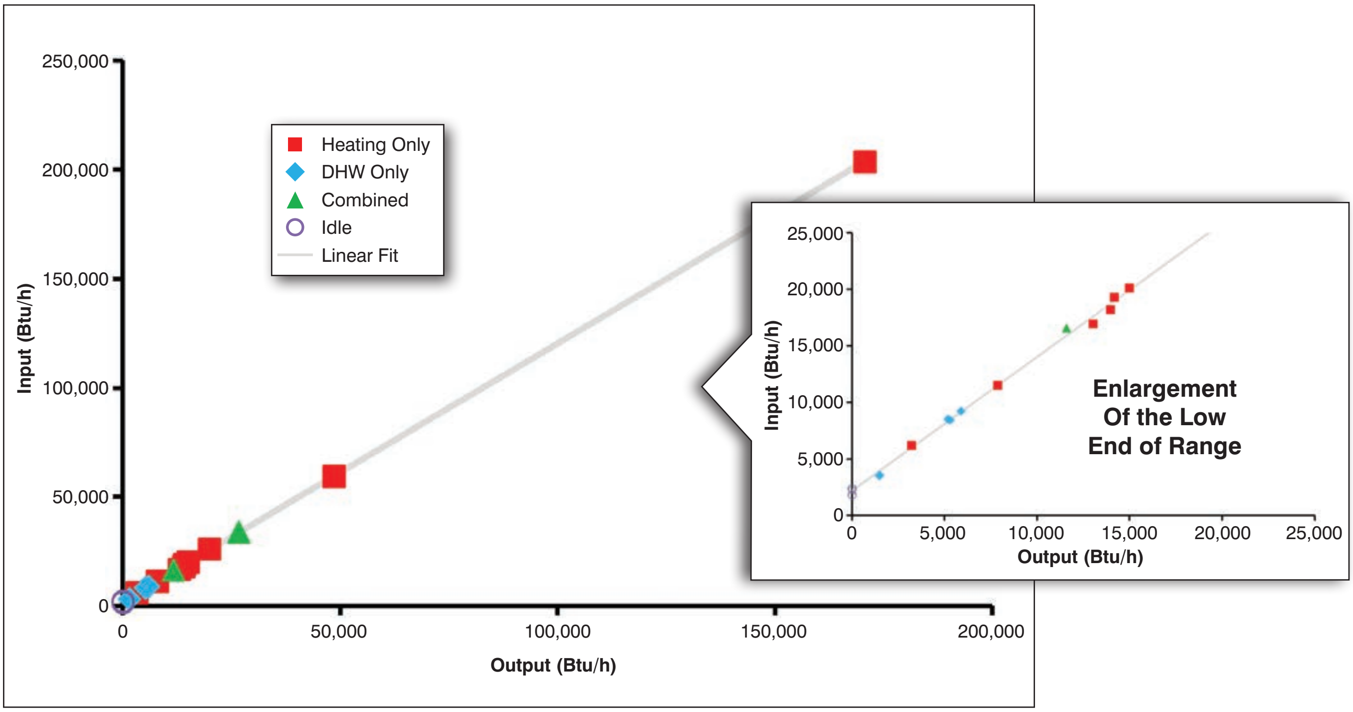


Figure 2: Example results with a tankless coil boiler. (Input/output relationship for three different load types.)

systems, and high-efficiency non-condensing boilers with storage tanks.

One system tested was an oil-fired storage tank water heater operated at higher temperatures to provide space heating loads in addition to DHW loads. Also tested was the combination of a gas-fired, space-heating-only boiler and a tank-type, gas-fired water heater. Both units had atmospheric burners. These units were tested separately but results combined to allow direct comparison with other combination systems.

For a fixed set of system temperatures (supply and return water temperature), the steady-state thermal efficiency is dependent on the heat exchanger surface area and design relative to the input rate. For the set of 12 units included in our studies, this was found to range from 73% to 93%. The highest efficiency level is associated with a condensing boiler.

The measured idle loss varied from 0.15% to 4.9% and this was found to be a strong function of system controls as well as insulation level. The highest idle loss was found in a poorly insulated boiler with an internal tankless coil arrangement and an operating control which maintained a boiler temperature of 160°F (71.1°C) all summer. When this same boiler was tested in an indirect mode and allowed to fall to 130°F (54.4°C) between tank calls the idle loss dropped to 1.2%.

For the units tested, the DHW-only efficiency was found to vary from a low of 25% (tankless coil boiler with a high idle loss) to a high of 75% (indirect DHW, well insulated, thermal purge control). This result can be compared with prior studies. Caron and Wilson,[6] in a field study of 24 units found the DHW efficiency of typical units to be in the 49% to 54% range. Subherwal,[7] in a field study involving six units, found the DHW-only efficiency of the tested combination units to range from 47% to 58%. In support of the development of the ASHRAE Standard 124, Liu, et al.,[8] conducted laboratory evaluations of the performance of heating boilers combined with indirect tanks for DHW. The energy factor (EF) was found to range 0.45 to 0.50 and a linear relationship was found between the output capacity of the boiler and the EF with decreasing EF with increasing size. Relative to these studies, the current work included both very modern systems with newer controls (available roughly in the 2005 and later time frame) and much older systems removed from the field.

“Cold-start” boilers, in indirect combination systems (which are allowed to decrease their temperature to ambient during extended periods in which there is no heat demand), have low idle losses. In this case the idle loss is largely determined by the rate of heat loss from the storage tank.

In one case a condensing boiler in an indirect tank combination system was found to have a relatively high idle loss (1.5%) and this was because the manufacturer’s controls keep the boiler at a minimum of 150°F (65.6°C) at all times to avoid corrosion in the heat exchanger. For comparison, a modulating, condensing gas boiler with a control configured for cold start was found to have an idle loss of 0.6%. The lowest level of idle loss (0.15%) was found to occur in systems with well-insulated indirect tanks that use a purge control strategy to remove heat from the boiler following an indirect tank call and move this heat into the storage tank.

The tankless coil boiler is often criticized as having low efficiency for DHW production. The current results confirmed this for boilers in this class that operate at high temperatures in the non-heating season and are poorly insulated. However, some of the boilers in this class tested had moderate idle losses, in the 1.2% range. These better-performing tankless coil boilers are simply better insulated. The performance of these boilers could also be improved through more effective internal heat exchangers which would allow them to meet the hot water demand without the need for high summer time setpoint temperatures. Add-on external heat exchangers can also be used to allow operation of these boilers at lower temperatures during non-heating periods.

For all combination hydronic systems, idle losses can be lowered by reducing water temperature. Outdoor reset or other control concepts which lower the boiler temperature clearly improve performance and this is most important during low load periods when the systems idle for long time periods. Reducing water temperature, particularly return water temperature can also improve steady state thermal efficiency and this is most important in condensing boilers.

Extremely low mass, condensing heating boilers that were currently available on the market, were not included in this study. With suitable control strategies, the smaller energy content in the heat exchangers of these boilers offers the potential to also achieve very low heat loss rates.

Use of Measurement Results To Analyze Annual Performance

For the units tested, the developed input/output relationships can be used to estimate energy requirements for heating, domestic hot water or both. For the combination hydronic systems the basic inputs used are the full load output rate, the full load thermal efficiency and the idle loss.

To illustrate the way that the results of integrated system input/output tests can be used to determine annual performance we assume here that the input/output relationship is linear. As discussed above, this is not a necessary assumption but we have found it to closely represent results with all units we have evaluated. Based on test results the parameters a and b in the following linear relationship can be determined:

$$q_{in} = a \times q_{out} + b \qquad (1)$$

Thermal Efficiency (%)	Idle Loss (%)	Calculated Annual Efficiency (%)	Estimated DHW Production Efficiency (%)
72	4	54	20
83	2	71	36
88	1	81	53
88	0.5	85	67
88	0.15	87	80

Table 1: Example analysis of the performance of combination hydronic systems. (Location is Albany, N.Y.; design day maximum space heat load is 40,000 Btu/h, hydronic system rated maximum output is 110,000 Btu/h.)

Thermal Efficiency (%)	Idle Loss (%)	Calculated Annual Efficiency (%)	Estimated DHW Production Efficiency (%)
72	4	62	30
83	2	77	49
88	1	85	65
88	0.5	86	75
88	0.15	87	84

Table 2: Example analysis of the performance of combination hydronic systems. (Location is Albany, N.Y.; design day maximum space heat load is 40,000 Btu/h, hydronic system rated maximum output is 60,000 Btu/h.)

Thermal Efficiency (%)	Idle Loss (%)	Calculated Annual Efficiency (%)	Estimated DHW Production Efficiency (%)
72	4	55	30
83	2	72	49
88	1	82	65
88	0.5	85	75
88	0.15	87	84

Table 3: Example analysis of the performance of combination hydronic systems. (Location is Hampton, Va.; design day maximum space heat load is 25,000 Btu/h, hydronic system rated maximum output is 60,000 Btu/h.)

Thermal Efficiency (%)	Idle Loss (%)	Calculated Annual Efficiency (%)	Estimated DHW Production Efficiency (%)
72	4	52	13
83	2	69	25
88	1	80	40
88	0.5	84	55
88	0.15	87	75

Table 4: Example Analysis of the Performance of Combination Hydronic Systems. (Location is Portland, Maine; design day maximum space heat load is 60,000 Btu/h, hydronic system rated maximum output is 200,000 Btu/h.)

where

q_{in} = input rate, Btu/h (kW)
q_{out} = output rate, Btu/h (kW)
a = slope of the input/output line
b = idle loss rate or intercept of the input/output line, Btu/h (kW)

This input/output relationship can be used to evaluate annual fuel requirements and efficiency in different ways. Either a bin-type analysis or an hourly heat load analysis using, for example, a building load simulation program can be used. Here a simple bin analysis has been used. For the building and location the design day outdoor temperature and heat load are set. For the selected location, the distribution of heating season hours in 5°F (2.8°C) bins are obtained from published weather data.[10] For any bin the average hourly heat load is calculated as:

$$q_{out\ i} = \frac{(65 - T_i)}{(65 - T_{dd})} \times q_{out\ dd} \qquad (2)$$

where

$q_{out\ i}$ = heat output rate required for heating in bin i, Btu/h (kW)
T_i = average outdoor temperature in bin i, °F
T_{dd} = design day outdoor temperature, °F
$q_{out\ dd}$ = design day building heat load, Btu/h (kW)

Assuming the system also meets a domestic hot water load, an average value of q_{out} for this would also be added to $q_{out\ i}$. For each bin the integrated system input rate required, $q_{in\ i}$ can then be determined from the linear relationship above. For the entire year, the total energy input and output is determined by adding all $q_{in\ i}$ and $q_{out\ i}$ values. Annual efficiency is simply determined from the ratio:

$$\textit{Annual Efficiency} = \frac{100 \times \sum_i q_{out\ i}}{\sum_i q_{in\ i}} \qquad (3)$$

To illustrate the application of this approach, energy use with a range of example systems has been calculated and results presented in *Tables 1* to *4*, Page 39. For all of these cases, daily domestic hot water use has been assumed to be 64.3 gallons (243 L). One of the points illustrated by these tables is that the annual efficiency can be much lower than the steady state thermal efficiency. This is consistent with discussion in the recent article by Durkin.[9]

Note that, in going from a poorly performing system to a better system with lower idle loss, the improvement in annual efficiency is considerably greater than that which would be predicted by thermal efficiency alone.

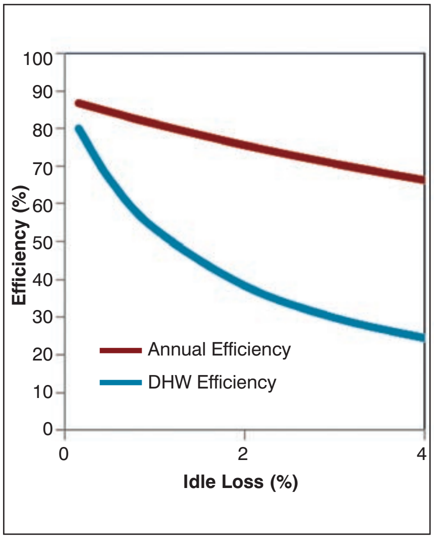


Figure 3: Example results of the impact of idle loss. (Assumed thermal efficiency is 88%; location is Albany, N.Y.; design day heat load is 40,000 Btu/h [11.7 kW], system maximum output is 110,000 Btu/h [32.2 kW], domestic hot water load is 64.3 gallons/day [243 L].)

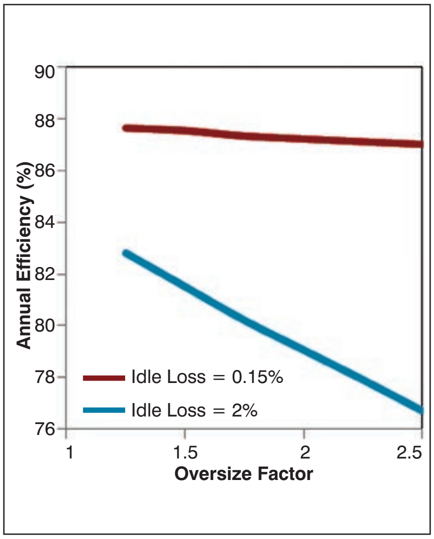


Figure 4: Example results. Effect of system oversize on annual efficiency at two different idle loss levels. (Assumed thermal efficiency is 86%; location is Albany, N.Y.; design day heat load is 40,000 Btu/h [11.7 kW]; domestic hot water load is 64.3 galllons/day [243 L].)

In a similar way, just a flue loss "combustion efficiency" does not fully predict the savings associated with replacing an older system with a high performance system.

The first row in *Table 4* is notable because of the very low efficiency for both heating and DHW. This is a result of the use of a large, oversized combination system with a high idle loss. During the non-heating season, with DHW load only, this unit is operating at the extreme low end of its range.

Figure 3 highlights the impact of idle loss through an analysis of one specific case. This is a home located in Albany, N.Y. with a design day heat load of 40,000 Btu/h (11.7 kW). The combination system is assumed to have a rated maximum output of 110,000 Btu/h (32.2 kW) with a full load thermal efficiency of 88%. Idle loss is varied in this analysis from 0.15% (lowest measured in this work) to 4%. The DHW efficiency is the efficiency with which this system would meet the domestic hot water load during the non-heating season. This result clearly demonstrates the importance of minimizing idle losses.

Figure 4 illustrates another interesting result of the analysis. Again a specific example is assumed: Albany, 88% thermal efficiency. Two levels of system idle loss, 0.15% and 2% are assumed and annual efficiency is shown as a function of system oversize. Oversize here is based only on heating load and is the rated output of the system divided by the design day heat load. This analysis shows that the annual performance of a system with high idle losses is much more dependent on the oversize factor than a system with low idle losses.

Summary

The results of this work show that a linear input/output relationship can be used as a simple model of the performance of a combination hydronic heating system over heating only, DHW only, and combined loads. This simple model can be used to study the impact of system parameters on the annual performance. In addition to steady state, full load thermal efficiency the idle loss is an extremely important parameter which impacts the performance of the system during low load periods, including DHW only, as well as the annual efficiency. These idle losses can be controlled through a combination of better insulation of boilers and indirect tanks (where used) and control strategies.

References

1. ANSI/ASHRAE Standard 103-2007, *Method of Test for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers.*

2. ANSI/ASHRAE Standard 118.2-2006, *Method of Test for Rating Residential Water Heaters.*

3. ANSI/ASHRAE Standard 124-2007, *Method of Test for Rating Combination Space-Heating and Water-Heating Appliances.*

4. Hewitt, M. 2005. “Inside ASHRAE Standard 155: A new measure of commercial boiler system performance.” *Boiler Systems Engineering*.

5. Butcher, T. 2007. “Performance of Integrated Hydronic Systems.” BNL Report BNL-79814-IR. www.osti.gov.

6. Caron, R.M., and R.P. Wilson Jr. 1983. “Water heating efficiency of integrated systems designed for space and water heating.” *ASHRAE Transactions* (89):18–29.

7. Subherwal, B.R. 1986. “Combination water-heating/space-heating appliance performance.” *ASHRAE Transactions* (92):415–432.

8. Liu, S., G.E. Kelly, C.P. Terlizzi. 1995 “Performance Testing of a Family of Type I Combination Appliances.” Report NISTIR 5256.

9. Durkin, T.H. 2006. “Boiler system efficiency.” *ASHRAE Journal* (48):51–57.

10. National Oceanic and Atmospheric Administration. Engineering Weather Data CD-ROM.

Acknowledgments

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