DOMESTIC HOT WATER SERVICE IN LUMLEY HOMES: A COMPARISON OF ENERGY AUDIT DIAGNOSIS WITH INSTRUMENTED ANALYSIS

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ABSTRACT

The domestic hot water (DHW) system in a multifamily building was analyzed using billing data, energy audit data, and detailed performance data obtained from intrumentation. The system configuration has central storage tanks heated by steam from a gas-fired boiler and has uninsulated distribution piping with recirculation. It serves sixty apartments in a six-story building. The DHW system recently underwent renovations, including replacement of the tank, heat exchanger, pump, and controls, while retaining the boiler and distribution system.

Thermal and volumetric DHW loads were estimated indirectly based on gas meter billing data, indicating possible system inefficiency in meeting end-use needs. Consumption was then broken down into estimates of the service load supplied plus various loss components using procedures such as those available to a walk-in energy auditor. Next, intensive microcomputer-recorded measurements of water flows and temperatures in the system were used to refine and validate the audit-based diagnoses.

The diagnostic techniques were succesfully applied in estimating the major heat loss components in the water heating system. The largest components were the boiler on- and off-cycle losses (especially for the large winter boiler), and heat losses from the distibution system. The DHW efficiencies estimated were relatively low--around 20% in the summer, rising to 30% or more in the winter when the boiler also provides space heat, if boiler losses are charged to the space heating system. Detailed monitoring also yields information on hot water consumption patterns in the building. The consumption averaged 22 gal/apt.-day with peaks in the morning and early evening.

The elimination of the steam leak as part of the recent renovation should halve the summertime gas use for water heating. Additional savings are possible through improved control of the hot water distribution pump, e.g. by reduced nighttime circulation. Spectacular savings are possible in new apartment buildings by specifying shorter runs and insulation for hot water piping.

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INTRODUCTION

Domestic water heating is the second largest component of energy use in houses [1] and is believed to be a major component in multifamily buildings as well. In this paper we present an analysis of energy used for water heating at Lumley Homes, a 60-unit public housing project for senior citizens located in Asbury Park, New Jersey. This building has been the subject of a continuing comprehensive energy conservation case study; previous work has focused on total gas consumption and the performance of the space heating system [2].

The primary motivation for our study is to develop diagnostic procedures that a walk-in energy auditor can use to identify energy conservation opportunities in other buildings. Although the auditor's tool kit will ultimately include only portable, non-intrusive measurement devices, we have installed extensive instrumentation at Lumley Homes for the purpose of validating our diagnostic procedures. Since little is known about energy use for water heating in multifamily buildings, our findings will also contribute to a better understanding of this end use of energy.

In this paper we analyze the performance of the water heating system at Lumley Homes using engineering calculations, non-intrusive measurements, and data acquired through specially installed instrumentation. A comparison of these approaches leads us to the development of a procedure for diagnosing energy conservation opportunities in central domestic hot water systems in multifamily buildings.

DESCRIPTION OF HOT WATER SYSTEMS

Lumley Homes has its domestic hot water supplied by a central system with storage tanks located in the boiler room and heated by steam from a gas-fired boiler. During the heating season, steam is generated by the same boiler used for space heating in the building. Beginning in 1982, a separate smaller boiler has been used to supply steam for water heating during the summertime when the central heating system is shut down.

Prior to September 1985, water was heated in an 865 gallon (3270 l) tank with an internal heat exchange coil. This configuration is shown in Figure A-1a (in appendix, not in this version). The valve regulating steam flow to the heat exchanger was originally controlled by an aquastat; this, however, had failed in 1984 and so the boiler operator left the steam valve at a fixed opening which he judged sufficient to keep the water hot. The boilers were controlled by a pressuretrol to maintain a fixed head of steam at all times. Continuous circulation of the heated water was maintained in the distribution loop throughout the building, with circulated water drawn back into the storage tank by a centrifugal pump. The pipes in the distribution loop are uninsulated.

In September 1985, as part of a building modernization program, the boiler room components of the DHW system were replaced by the configuration shown in Figure A-1b (in appendix, not included in this version). The new system has two 200-gallon storage tanks (total capacity 1510 l) which are heated by a single external heat exchanger. Insulation on the storage tanks, heat exchanger, and associated piping in the boiler room was not installed until mid-April 1986, after we took the measurements reported below. One pump for each tank circulates water to the heat exchanger; these pumps and the steam valve to the heat exchanger are controlled by an aquastat near the top of each storage tank. Each tank also has its own pump for returning water from the distribution loop. These pumps are controlled by an aquastat on the return piping just upstream of the pump; however the aquastats appear to be set so that the circulation is still maintained continuously.

We have seen this DHW system configuration--central storage tanks heated by an external heat exchanger--in a number of public housing complexes in New Jersey. As at Lumley Homes, many of these are fairly recent replacements of older systems. This type of system, which has a layout very similar to that illustrated in Figure 1 of the chapter on service water heating in the ASHRAE systems handbook [3], appears to be a popular configuration for public housing complexes in this area.

METHOD OF ANALYSIS

The parameters used to disaggregate the energy consumption in a steam-heated central DHW system are shown in Figure 1. Energy flows are given as rates (energy/time) and correspond to system performance averaged over some time interval. We model the components of energy use according to Equations 1 - 6, shown in the figure and discussed below.

Gas Consumption for Water Heating

Following the path from the top of Figure 1, we start with the energy content of gas consumed by the boiler for water heating, Q_B, which is determined as the product of the volumetric gas consumption and the heating value of the gas. During the summer, when central heating is turned off, Q_B may be obtained directly from billing data. Data from the past five summers are listed in Table I. During the heating season, it can be obtained by measuring gas use during times when the space heating distribution valves may be closed off from the boiler, such as periods of mild weather.

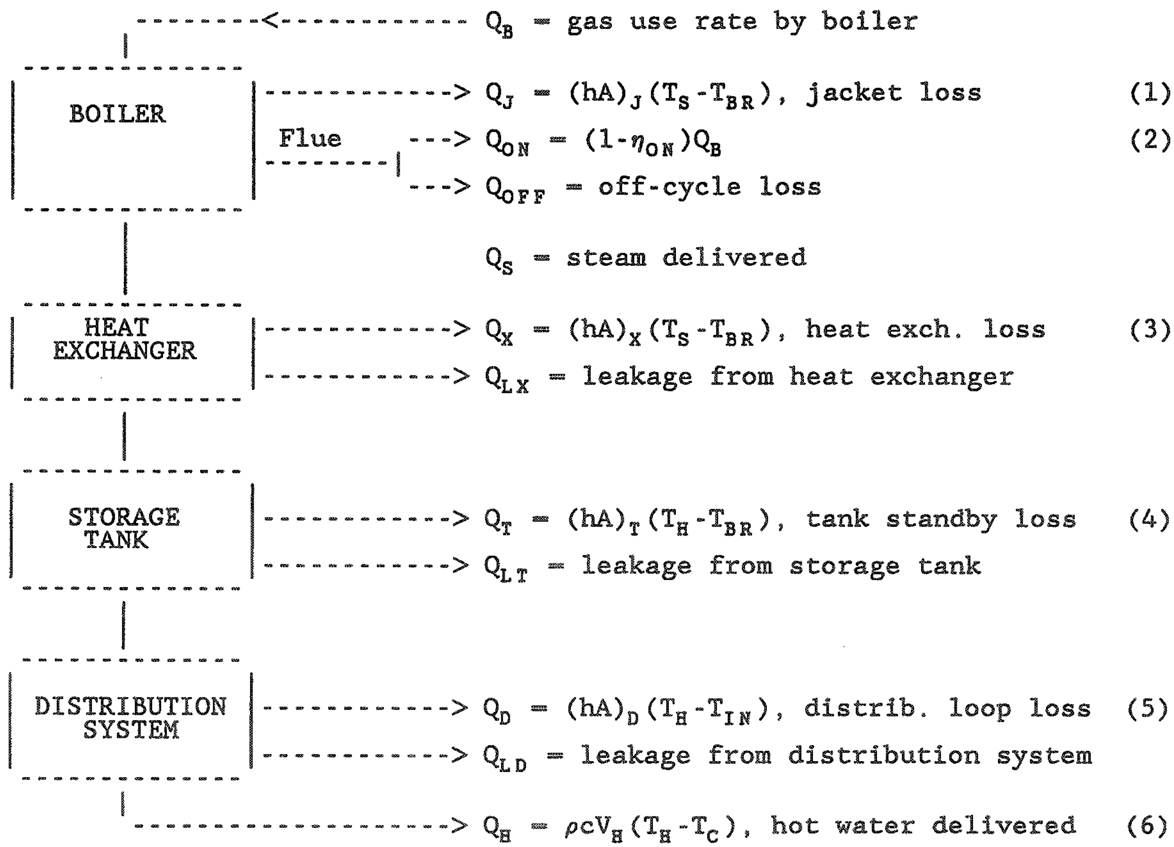

Figure 1. Energy flow paths in the Lumley Homes DHW system

Table I. Summertime main meter gas consumption at Lumley Homes

Period	Average consumption
15 June - 14 Sept 1981	74 kW
16 June - 14 Sept 1982	35 kW
16 June - 14 Sept 1983	33 kW
15 June - 13 Sept 1984	43 kW
17 June - 13 Sept 1985	84 kW

Boiler and Heat Exchanger

Part of the energy entering the boiler in gas leaves in the steam delivered to the heat exchanger, Q_S. The rest is lost either up the flue or by heat transfer through the boiler jacket. Jacket loss, Q_J, can be estimated by taking measurements of the boiler dimensions and surface temperature along with the surrounding air and wall temperatures in the boiler room and then using values obtained from a handbook (e.g., [4]) for the heat transfer coefficient in Equation 1. The on-cycle flue loss, that is, the part that occurs while the burner is firing, may be obtained from Equation 2 using the steady-state efficiency, η_{ON}, as measured by a flue-gas analyzer. However, off-cycle flue loss is more difficult to measure. Since the total boiler loss depends on the cycling rate which depends in turn on the load, the value based on standby loss is a rough estimate of overall boiler loss. One approach is to isolate the boiler so that Q_S is zero and all the energy goes into making up the total boiler standby loss, i.e.,

$$Q_B = Q_{ON} + Q_{OFF} + Q_J \qquad (7)$$

Then Q_{OFF} may be obtained by subtraction. Other methods, which we plan to try in the future, are to use a burner-to-stack flow model [5] or to measure the off-cycle flue flow with a tracer gas technique [6].

Energy is also lost in the process of heat exchange from steam to water. For a heat exchange coil internal to the storage tank, this loss is negligible if there are no steam leaks and the piping from the steam main to the tank is well insulated. The loss from an exposed external heat exchanger, as in the new system at Lumley, can be modeled using Equation 3 with on-site temperature and dimension measurements and handbook values for the heat transfer coefficient. Energy loss through steam leakage is nearly impossible to measure directly--it must be left as a balance term. The old Lumley Homes system developed a steam leak due to failures in the condensate return system during 1985 before it was replaced; as discussed later in the paper, we indict it as a possible reason for the increased gas consumption seen in summer 1985, but we are unable to quantify the loss due to the leak since we do not have enough direct measurements of other losses during that time.

In Equations 1 and 3, we model the heat losses Q_J and Q_X using steam temperature, T_S, rather than surface temperature. Steam temperature is readily determined either by direct measurement or from steam tables given the boiler pressure, while surface temperatures are uneven and require many measurements to characterize. We measured surface temperatures on the boilers and heat exhanger once and carried out a fairly detailed surface heat transfer analysis, considering separately the radiation and natural convection components. (Under the conditions observed, radiation accounts for about two-thirds of the heat transfer.) We then used the result to determine a scaled effective linear heat transfer coefficient considering

T_S as the source temperature. The advantage of this approach is that we can easily extrapolate the results for Q_J and Q_X to different operating conditions and different steam temperatures without having to repeat the detailed calculations.

Storage and Distribution Components

At this point in Figure 1 we have heated some water, but the hot water storage and distribution components provide several more places where energy is dissipated without reaching the tap. Heat transfer losses from the tank and associated piping in the boiler room, Q_T, and those from the distribution system, Q_D, are modelled using Equations 4 and 5 respectively. In the case of Q_T we can also determine the loss by using measured surface temperatures and dimensions plus handbook values of the heat transfer coefficient. Because of the complexity and inaccessibility of the distribution system, such an approach will be weakest for the determination of Q_D. However, with measurement of the circulation flow, V_R, and return temperature, T_R, we can calculate the losses during circulation, Q_R, which will provide a close estimate of the loss from the distribution loop:

$$Q_D \approx Q_R = \rho c V_R (T_H - T_R) \qquad (8)$$

where ρ and c are the density and specific heat of water. The additional loss because hot water drawn at the taps is cooler than T_H is discussed in the following section. An experimental determination of the combined losses Q_T plus Q_D is possible in two ways. The first method is to monitor the energy input to maintain the system at a steady-state operating temperature over some period of time when there is no hot water use. A second approach, also requiring a period of no hot water use, is to isolate the storage and distribution system from the boiler, so there is no heat input, and monitor the temperature decay. We have obtained consistent results using both approaches as discussed later in this paper. Leakage from the distribution system is difficult to measure unless localized to a few isolated places. With direct monitoring of makeup flow, we can estimate the leakage from the flow late at night when little intentional usage is expected.

Hot Water Delivery

The bottom line in Figure 1 is useful hot water delivery, the average energy content of which is Q_H. Without flow measurement, the useful hot water delivery can only be inferred from the system energy balance, using estimates of the other terms as discussed above. Estimates obtained in this fashion can be compared to hot water supply design guidelines (as found, for example, in [3]) as a check on whether their magnitude is reasonable, but such estimates are not useful for the specific diagnosis of a DHW system. With flow and temperature monitoring, the thermal energy delivery in hot water may be calculated directly using Equation 6.

Finally, we can compute the efficiency of the domestic hot water system according to

$$\eta_H = Q_H / Q_B \; . \tag{9}$$

Flow measurements include leakage, so the above result would need to be corrected by subtracting the leakage rate, estimated as discussed above, to obtain the useful hot water energy delivery. Since the hot water gets cooled down by various degrees before arriving at the point of use, the actual energy delivered is less than Q_H. An average cool down can be estimated as $(T_H - T_R)/2$. The correction is small and was not made in our analysis. One can also consider penalizing the Q_H estimate if the supply temperature is too hot by subtracting the energy use due to the elevation of T_H above a desired useful temperature; we have not done so in this analysis. Overheated water increases storage and distribution losses since the hot water temperature is the driving potential for heat transfer from these components (see Equations 4 and 5).

ENERGY USE DIAGNOSIS

Inefficiency in DHW production at Lumley Homes was first suspected during our analysis of gas bills. When the central heating system is off for the summer, all of the gas use recorded by the main meter is for water heating. Referring to Table I, we see that the average summertime gas consumption was 74 kW (1981 data) when the main boiler was in use year-round; it fell to an average of 34 kW (1982-83 data) when the separate summer boiler was used. Average consumption increased to 43 kW in summer 1984 and climbed to 84 kW during summer 1985 before major components were replaced. We had no reason to believe that the demand for hot water would change so precipitously as to explain the drop from 1981 to 1982 and the subsequent jump in 1984-85. These numbers suggest an inefficiency for the times when the main boiler is used to supply steam for water heating in the summertime. They also point to a dramatic degradation in performance in 1984-85 before the system was refurbished.

To investigate the DHW system, we simultaneously took two approaches. The first was a set of diagnostic procedures, such as those that would be available during a walk-in instrumented energy audit:

1. Timing and observation of boiler operation while visually reading the calibrated disk in the gas meter; referring also to past gas bills.
2. Boiler combustion efficiency measurements using a flue-gas analyzer.
3. Spot temperature measurements using thermometers in the tanks and portable digital thermometers for air and surface temperature measurements.
4. Measuring the dimensions of accessible components (boilers, tanks, plumbing in the boiler room, etc.) and inspection of blueprints to find sizes and lengths of pipes in the distribution loop.
5. Consulting handbooks for heat transfer coefficients and water properties as well as information on standard practice and guidelines for hot water service systems.

Table A-1 (in appendix, not attaced in this version) lists dimensions, surface areas, etc. for components of the DHW systems. Secondly, we monitored the system in detail using a computerized data acquistion system [7] to record data from the following instruments:

1. Pulse counter on main gas meter
2. Piston-type flow meter on condensate return line
3. Disc-type flow meter on cold water makeup line
4. Paddle wheel flow sensor on circulation return line
5. RTD temperature sensor on hot water supply line
6. RTD temperature sensor on circulation return line
7. RTD temperature sensor on cold water makeup line
8. RTD temperature sensor on condensate return line

The purpose of the detailed monitoring was to thoroughly understand the performance of this one system as well as validate and refine the audit techniques. In Table II we summarize the performance of the water heating system at Lumley Homes. We discuss how we obtained these results below.

TABLE II. Energy use diagnosis for DHW system at Lumley Homes

System/year: Season:	old/85 winter	old/85 summer	new/86 winter
Hot water temperature, T_H (C)	62	72	63
Boiler jacket loss, Q_J [1]	4.0	1.8	4.0
On- and off-cycle flue loss[2]	28.0	11.1	28.0
Total boiler losses, Q_{BS}	32.0	12.9	32.0
Heat exchanger loss, Q_X	0.0	0.0	0.4
Tank and boiler room pipe loss, Q_T	1.8	2.4	2.9
Distribution and circulation loss, Q_D [2]	17.0	24.9	17.0
Total HX, tank, and dist. losses, Q_{XTD}	18.8	27.3	20.3
Energy of delivered hot water, Q_H	12.3	12.3	12.3
Sum = $Q_{BS} + Q_{XTD} + Q_H$	63.1	52.5	64.6
Measured gas consumption, Q_B	--	84.4	--
Difference[2] (sum - Q_B), due to leakage or other unmeasured losses	--	31.9	--
Efficiency of DHW service, η_H:			
with no space heating load	19%	15%	19%
with space heating load	30%	--	29%

[1]values of energy terms are given in kilowatts (kW)
[2]estimated by subtraction

Boiler Performance

The total boiler standby loss, Q_{BS}, was determined through reading the gas meter for a few hours while we isolated the boiler by closing the valves that supply steam to the DHW and space heating systems (winter) or the DHW system alone (summer). Boiler jacket loss, Q_J, was estimated using spot measurements of the surfaces and surroundings in the boiler room with handbook values of heat transfer coefficients. Combined on- and off-cycle flue loss was inferred by subtracting Q_J from Q_{BS}. During the summer 1985 visit, steam was being continuously blown from the vacuum pump, probably due to a malfunctioning steam trap or an incorrectly set valve; this is probably the main reason for the increased gas consumption seen in this summer's data compared to that of the previous two summers. An uncertainty in Q_{BS} remains for all periods due to our lack of direct measurement of boiler output under actual load conditions.

Performance of Heat Exchanger, Storage and Distribution Components

The loss terms Q_X, Q_T, and Q_D were first calculated using heat transfer relations, component dimensions, and spot temperature measurements. The estimated heat transfer coefficient is 10.7 W/m^2K, breaking down as 7.1 and 3.6 for radiation and natural convection respectively. Since the uninsulated supply and circulation return pipes are located in partition wall cavities within the building, we halved the temperature difference between the hot water supply and the average interior air temperature of 26 C to estimate the effective temperature difference driving heat loss from the pipes inside the partitions. For the new system, this gives an average effective heat sink temperature, T_A, of 44 C, which replaces T_{IN} in Equation 5, and results in an estimate of 18.3 kW for Q_D. Calculations using Equations 3 and 4 yield estimates of 0.4 kW for Q_X and 3.1 kW for Q_T repectively.

Losses from the distribution loop, storage tanks, and heat exchanger were also determined experimentally using data from the monitoring system. For the old system, with internal heat exchanger connected to the winter boiler, both steady-state and decay experiments were done by Linteris [8] in March 1985. He estimated a combined storage tank (Q_T) plus distribution (Q_D) loss rate of 30 kW at an average hot water temperature of 62 C. With our monitoring equipment in place, we performed a decay experiment on the new system in April 1986. We closed the steam supply valve to the hot water system and the cold water makeup valve while the circulation and heat exchanger pumps were allowed to remain running. From the resulting temperature decay we identified an overall heat loss conductance for the the heat exchanger, storage tanks, and distribution system:

$$(hA)_{XTD} = (hA)_X + (hA)_T + (hA)_D = 1.05 \text{ kW/K} . \qquad (10)$$

Dividing by the surface area yields an estimate for the average heat transfer coefficient of $h = 9.5\ W/m^2K$ (∓17%). We also determined an effective heat sink temperature, T_A, of 42.7 (∓0.8) C as the asymptote of the temperature decay. These experimentally determined values of h and T_A match fairly well the values (10.7 W/m^2K and 44 C) used in the previous estimates of these losses, thereby validating that approach for energy conservation audits of similar DHW systems.

Using the above parameter estimates we can calculate the heat loss rate from the heat exchanger, tanks, and distribution loop as

$$Q_{XTD} = (hA)_{XTD}(T_1 - T_A) = 20.3 \text{ kW } (\mp 10\%) . \qquad (11)$$

In order to apportion this among the three components, we use fractions based on the previous theoretical calculation. The resulting breakdown is 17.0 kW (84%) for Q_D, 2.9 kW (14%) for Q_T, and 0.4 kW (2%) for Q_X. A further check on the estimate for Q_D can be obtained from Equation 8 using measurements of the circulation flow rate, V_R, and the difference between supply and return temperatures. A spot measurement of V_R was 0.94 l/s (15 gpm). The average difference between supply and return temperatures over the week following the experiment was 4.8 C. Using these values in Equation 8 yields a value for distribution and circulation loop loss of 18.6 kW, which matches fairly well the value estimated from the decay experiment and Equation 11.

Hot Water Consumption

Direct measurements of hot water consumption were obtained using the monitoring system for a nine day interval, 4-12 April 1986. A plot of the average usage profile throughout a day is shown in Figure 2. The average value of the delivered hot water energy, Q_H, is 12.3 kW. The average temperature rise was 51 C and the average volumetric consumption rate was 0.0568 l/s. Converting to normalized hot water delivery per day yields a value of 82 l/day/apt (22 gal/day/apt), or 75 l/day/person. This is comparable to the average value of 72 (∓29) l/day/person based on a study of single family houses [12]. It is lower than the 144 l/day/apt. given by ASHRAE [3] for apartment complexes of this size, but this is not surprising since Lumley Homes is a senior citizens project with typically only one resident per apartment. The minimum flow at night of 0.011 l/s (4.1 gal/day/apt) is the leakage rate in the hot water system. The maximum hour (9:00 to 10:00 AM) showed a flow rate of 0.14 l/s (2.2 gal/hour/apt). By measuring the flow from wide-open taps in one apartment, we found an instantaneous peak hot water draw rate of 0.63 l/s/apt (10 gal/min/apt).

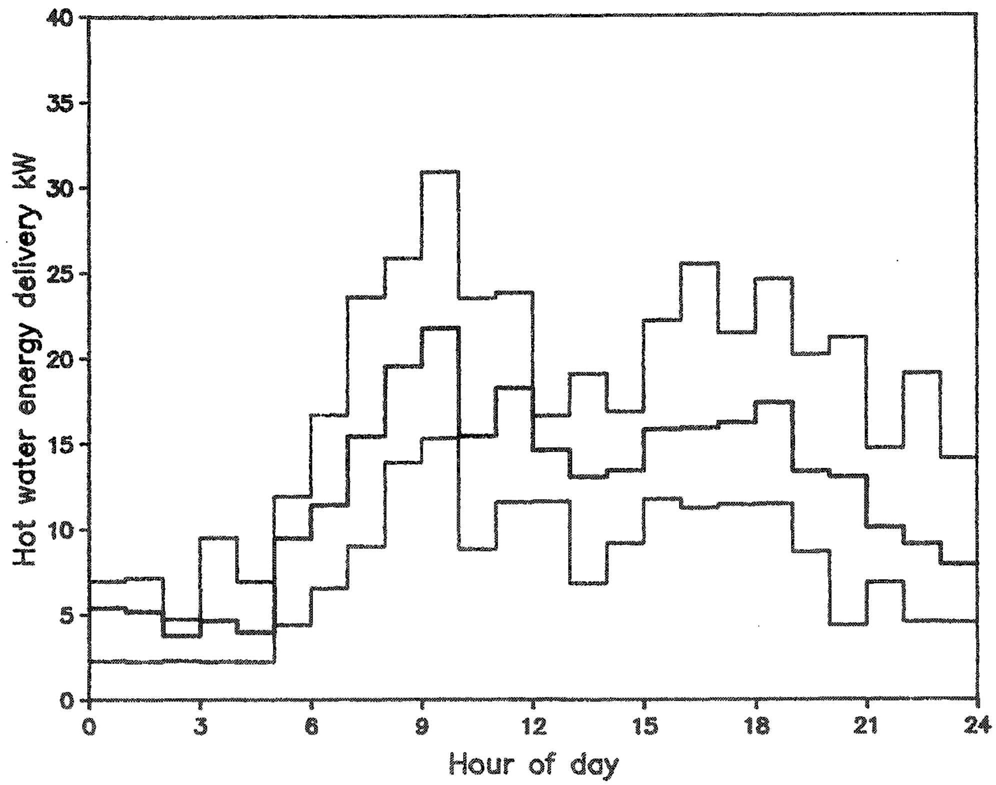

Figure 2. Minimum, average, and maximum hourly hot water energy delivery at Lumley Homes

Water Heating Efficiency

Using Equation 9, we computed the efficiency values shown in Table II. We only have recent direct measurements of hot water consumption, when the monitoring system was operational, but assuming that the measured value of 82 l/day/apt has not changed significantly since 1981, we can estimate past efficiencies from the gas consumption data in Table I. We have some information, based on conversations with tenants and a spot measurement recorded in early 1983, that the hot water supply temperature was lower than in recent months. We estimate a typical value of 50 C for 1981-83, yielding an average hot water energy delivery rate of 9.2 kW.

The summertime savings following the installation of the small boiler results from the elimination of the greater standby losses that occur when the large boiler is used year-round. We estimate that the pre-1982 summertime DHW efficiency was 12% with the large boiler in use whereas a 27% efficiency was obtained for the best performance with the small boiler during summers 1982 and 1983. The low summertime efficiency of 15% shown in Table II for 1985 was due to the steam leaks and overheated water mentioned previously. The summertime performance of the renovated system should be similar to that of the old system before it degraded; we plan to verify this shortly using the installed instrumentation.

During the heating season, with the large boiler in use, the DHW efficiency cannot be determined without apportioning the standby losses between space heating and water heating. Moreover, virtually all of the distribution loop losses contribute to space heat (albeit in an uncontrolled way). A lower bound of heating season DHW performance occurs when there is no space heating load and the large boiler is kept on just to heat water. Then the efficiency falls to 19% (winter 1985 and 1986) because all boiler losses are charged to water heating. An upper bound for η_H is obtained by considering that, since the space heating demand requires the boiler to be on in any case, no boiler standby losses should be charged against the DHW system. Specifically, this eliminates boiler jacket losses and off-cycle flue losses; the on-cycle flue loss corresponding to the steam delivered to the DHW heat exchanger remains, as do the heat exchange, storage and distribution losses. In this case, for example, η_H would be 30% for winter 1985. Counting the space heating delivered from the distribution loop as useful output gives a combined efficiency for space and water heating via the DHW heat exchanger of about 50%.

CONCLUSIONS

We can refer back to Table II to summarize our estimates of the various components of energy use by the water heating system at Lumley Homes. While major losses were identified with non-intrusive techniques, obtaining closure on the DHW system energy balance remains elusive with currently available audit techniques. We closed the energy balance only when a flow meter and additional temperature sensors were installed to directly measure hot water consumption. Future work in this area should be directed at exploring the use of portable, non-intrusive flow meters that can be clamped onto pipes without cutting them. While temperature sensors with inexpensive portable recording devices may be found, the non-intrusive flow meters currently available are unreliable or very expensive.

Nevertheless, an important result of this study is that we could accurately quantify major losses in a DHW system using non-intrusive methods that would be available to an energy auditor. An example is the large loss in the distribution and circulation loop: pipe sizes, spot temperature measurements, and heat transfer calculations yielded an estimate of this loss within 8% of the value we determined experimentally. Radiation and convection losses from the boiler jacket, heat exchanger, and storage tanks were also estimated in this fashion.

We were able to estimate the total boiler standby loss by reading the gas meter when the boiler was isolated from its load. Estimates of the on-cycle flue losses were obtained with a combustion gas analyzer. We plan further experimental work, such as tracer gas measurement of flue flows and analysis of condensate flows, as well as the testing of boiler models that might be useful for such performance diagnoses, in order to better determine boiler performance under load.

Potential for Improving Efficiency

Downstream of the boiler, losses in the distribution and circulation loop account for most of the energy waste. Losses from the storage tanks and heat exchanger were relatively small, and with the insulation recently installed should become minor. A comparable retrofit of the distribution piping is impractical because most of the pipe runs are in enclosed wall cavities (exposed pipes in the basement are already insulated). Large DHW distribution and circulation losses have also been reported in other buildings [10,11]. Current recommendations include keeping the supply temperature as low as possible and cycling the circulating pumps, or even turning them off entirely, at night. One commercially available device controls the storage temperature based on the pattern of hot water demand. We will be evaluating these procedures both analytically and experimentally. It is noteworthly that a different layout during construction could have reduced the length of hot water piping runs by 80%, saving plumbing costs as well as energy. If the pipes were also insulated, we estimate that distribution and circulation loss in a building like Lumley Homes could have been reduced to about 1 kW even with continuous circulation, decreasing energy loss by 16 kW and saving about $3000 per year in gas bills. Apartment building designers can therefore greatly improve the energy efficiency by specifying shorter runs and insulation for hot water piping.

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