ENERGY CONSERVATION AND OUTDOOR-RESET CONTROL OF SPACE HEATING SYSTEMS

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ABSTRACT

This paper examines the causes of high energy consumption in centrally heated buildings which lack thermostatic controls. The energy savings potential of various retrofit strategies and the efficiency limitations that can be encountered in operating such systems are discussed. The results are based the analysis of an occupied two-pipe steam heated apartment complex in New Jersey.

Ways to represent energy use in buildings of the class considered are developed for the purpose of determining the sources of inefficiency in a given building, assessing energy conservation measures, and evaluating the performance of retrofits. A new, component-based model for outdoor-reset controlled two-pipe steam heating systems is presented, providing quantitative links of parameters representing the mechanical equipment and the building structure to measured fuel use and indoor temperatures. (For fuel use, this approach reduces to PRISM when component parameters are combined.) The new framework is applied to clarify the way space heating is regulated and to develop guidelines for the operation of such systems.

The methods developed were validated using data from the building studied and are applied here to determine an energy use diagnosis and recommended outdoor-reset control settings for the building. The analysis reveals that the most important reason for high energy use is in fact the central and open-loop nature of heating system control. It is predicted that significant heating fuel savings (up to 60% for the building studied, even without shell retrofits) can be achieved through improved heating system control. However, full realization of such savings is likely to require retrofit with some form of thermostatic control.

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INTRODUCTION

This paper addresses the energy conservation implications of a space heating control system, namely, outdoor-reset control, which is common in existing centrally heated multifamily buildings. Outdoor-reset control refers to heating control based solely on measured outdoor temperature, in contrast to measured indoor temperature, on which thermostatic control is based. The analysis reported here is a case study of a particular building which has outdoor-reset control of a two-pipe steam heating distribution system. The analysis may be generalized to any other heating system in which the primary means of regulating the space heating energy delivery is based on measured outdoor temperature. A fundamental characteristic of the space heating systems discussed here is that their control is open-loop, that is, they lack feedback of the controlled variable (indoor temperature) to the heating system. A system controlled only by outdoor-reset has no thermostats and it cannot automatically correct for conditions other than those for which the controller was designed.

The conventional literature on buildings with central steam heating systems is oriented to procedures for maintaining the equipment and operating the systems according to their design specifications. Notably missing, however, are discussions of how to represent the determinants of energy consumption in such a way that the effects of differing operating procedures can be quantified. In the case of outdoor-reset controlled systems, moreover, there is an lack of specific guidance on setting the operating parameters of the system.

Recently, information for improving the operation of single-pipe steam systems has become available, as given by Peterson (1986) by Katrakis et al. (1986). One purpose of the present study has been to provide a similar analysis for two-pipe steam buildings having outdoor-reset control. Some buildings of more recent vintage have central hydronic heat with thermostatic radiator valves in the apartments and so their control is intrinsically closed-loop; adding an outdoor-reset controller to lower the water temperature as outdoor temperature rises can be a cost-effective conservation measure. Such forms of supplementary outdoor-reset are not covered here; see Peterson (1986). For two-pipe steam systems, a major retrofit option that has generally been successful is conversion to hot water (hydronic) heat distribution; see Robinson, Nelson, and Nevitt (1986).

Background to the present study

The research reported here was conducted at Lumley Homes, a six-story, sixty-unit apartment complex located in Asbury Park, New Jersey. Lumley Homes is a public housing project for senior citizens. It has a floor area of 35,000 ft^2 and has central heat and hot water systems utilizing steam from a 2160 kBtu/h (633 kW) gas-fired boiler. Annual gas consumption at the building (for heat, hot water, and cooking) is typically 6800 MBtu/year (221 kW), corresponding to a heating factor of 31 Btu/ft^2DD65, which is about double that observed in a sample of single family homes in the area. The building was very overheated, with indoor temperatures averaging 27 C (81 F) over the heating season and many tenants opening windows throughout the winter.

Previous research at Lumley Homes included an analysis of gas consumption, an experimental reduction in the heating control settings, an analysis of the central water heating system, and an examination of the behavioral factors relating to energy use. (A full report is given by DeCicco 1988.) The control setting reduction experiment, which took place in early 1984, involved lowering the steam pressure from 8 to 3 psig, lowering the settings of the outdoor-reset controller, and increasing the number of hours of night setback from 4 to 6. These changes seemed to result in a 26% savings in gas use for the half-season of modified operation. This savings is apparent at Period C in Figure 1, which is a plot of weather-normalized annual gas consumption for the six-year period of the study. The savings were temporary, however: as researchers ceased intervening in the operation, the boiler operator reverted back to higher operating settings during the following (1984-85) heating season (Period D in Figure 1). It was, moreover, impossible to unravel specifically how the control changes effected the change in energy use. A clear understanding of the operation of such a system was lacking at the time, and so achieving a quantitative understanding of how a central, two-pipe steam system having outdoor-reset control operates became the goal of the work reported here.

SYSTEMS ANALYSIS

A schematic diagram of an outdoor-reset controlled two-pipe steam heating system for an apartment building is shown in Figure 2. While some particulars of this diagram correspond to the system found in the case study building, Figure 2 illustrates the major features of any two-pipe steam system. To elucidate the system for control analysis, it is useful to recast the components in the form of a block diagram, shown in Figure 3, where the inputs, outputs, and intermediate variables which determine the levels of energy flow are made clear. Shown in each box is a graph of the relationship between the principal physical variables for that component.

The boiler burns a fuel to boil water, producing steam. The rate of energy input to the system, designated Fb, reflects the energy content of the fuel consumed by the boiler (for example, the heating value of natural gas). At the boiler, energy is lost by convection and radiation from the boiler jacket and in the hot exhaust vented up the flue. The rest of the input energy generates steam, which carries the thermal power output of the boiler, designated Eb. Boiler operation can be represented by a linear model,

$$Fb = B + Eb/e \tag{1}$$

where in there is a minimum standby fuel consumption, B, whenever the heating system is operating, and the fuel use, Fb, increases in proportion to the energy output (steam load), Eb, as specified by a marginal output, e.

Low-pressure boilers used for space heating deliver saturated steam vapor at a set pressure, designated here by P1. Their operating range is from atmospheric pressure (101 kPa absolute) up to the legal limit for low pressure boilers of 15 psig (205 kPa absolute). The energy delivered as useful heat per unit mass of steam is the difference in enthalpy between liquid at the condensate temperature, Tcond, and vapor at the saturation temperature, Tsat, corresponding to P1. The sum of the latent and sensible portions of the energy delivery per unit mass will be termed the combined enthalpy and designated here by h. For typical operating conditions (140 kPa, 109 C saturated steam and 65 C condensate), the combined enthalpy is 2400 kJ/kg (1150 Btu/lbm), about 92% of which is latent heat (heat released by condensation). Being a function only of the heating medium's thermodynamic state, which is constrained to a fairly narrow range, H is essentially constant. The rate of heat delivery by the system is therefore determined by the mass flow rate of the steam, Mheat, and is given by the product MheatH.

In some systems a portion of the steam is diverted for water heating. During the heating season, however, the main portion of the boiler's energy output is delivered to the space heating distribution system, a network of pipes connecting to radiators, where the steam condenses, releasing heat to the living space. Upon condensing, the water leaves each radiator through a steam trap, which is designed to pass condensate but hold back steam. Vacuum steam systems, as installed at Lumley Homes, employ a vacuum pump, which provides a negative pressure as low as 25 inHg (about 17 kPa absolute, designated here by P2) to suck condensate and air that leaks into the system into a tank, from which the air is vented and the water is returned to the boiler. Cold makeup water is added if the tank contains insufficient condensate to meet the needs of the boiler's level controller. The heating of makeup water should normally be a small effect, but it can be a significant energy loss when there are excessive leaks.

Control of the steam flow rate in the distribution system is accomplished by automatic valves, termed zone valves, (there is one valve for each zone, e.g., four in the case of Lumley Homes). For space heating applications, these valves are designed to have a linear characteristic, so that the flow rate is proportional to the valve position, V, and can be represented by

$$Mheat = K\ V \tag{2}$$

where K is a valve flow factor, having dimensions of mass flow rate per percentage valve opening. K in turn depends on the operating pressures, P1 and P2. The operating pressures are control inputs, selected by the boiler operator but not meant to be frequently adjusted. Ideally, P2 should be set low enough (i.e., the vacuum level should be high enough) relative to P1 so that critical (choked) flow is maintained through the valve. Flow rate then becomes independent of P2 and K varies linearly with P1.

Valve position, V, is itself determined by the zone controller, which is the device that implements the outdoor-reset control law. Outdoor temperature, To, is the primary input to the zone controller, as it is to the system as a whole. The zone controller increases the valve position as To drops below a fixed cutoff temperature, τc, and its operation can be represented by

$$V = (b1 + b2BAL)(\tau c - To)_+ + b3COM \qquad (3)$$

The variables BAL and COM represent the settings of controller knobs (labeled the "heat balance" and "compensator," respectively, on the model found in Lumley Homes) which may be adjusted by the boiler operator. The parameters b1, b2, b3, and τc are device characteristics of the particular controller installed. The "+" subscript in Equation (3) indicates that only positive values of $(\tau c - To)$ are considered, so that this term is zero whenever $To > \tau c$.

A time clock connected to the zone controller provides night setback, whereby the zone valves are closed for certain hours. The space heating energy delivered over the course of a day is therefore reduced by a fraction related to the portion of the day during which setback occurs. To incorporate night setback into the analysis, a night setback factor, f, is defined as the fractional adjustment to the daily average valve position needed to account for the valves being closed during night setback. For example, with a 4-hour setback period, f would be 20/24 = 0.83 if the average valve position would otherwise have been constant throughout the day. The night setback factor, f, is then applied as a multiplier of the daily average valve position, V, to obtain an average rate of steam supplied to the building. To determine the values of f for various night setback periods, it is necessary to account for the way valve position varies with outdoor temperature over a day. Using a sinusoidal approximation to an average 24-hour outdoor temperature profile, values of f for the New Jersey climate were found to be 0.80 for 4 hours setback and 0.71 for six hours setback.

The final component of the system is the heated indoor space, represented by the apartment box in Figure 3. For apartments, as for buildings in general, the rate of heat loss is proportional to the indoor-outdoor temperature difference, other things being equal. The energy delivered by the heating system should match the heat loss rate above that met by intrinsic heat. If the match is perfect, the result is a stable indoor temperature, which is the ideal flat response shown in the apartment box of Figure 3. The model for indoor temperature based on a steady-state energy balance in the indoor space

$$Tin = To + (MheatH + Qint)/L \qquad (4)$$

Here L is the lossiness, Qint is the intrinsic heat, and Mheat is the rate of energy delivery by the heating system. Equation (4) hides the wealth of complexity actually involved in attempting to represent the thermal conditions of indoor space (the apartments in this case). The parameters Qint and L may vary greatly through time and there can be even more variation among the apartments within a zone; they are affected by occupant behavior, the condition of the apartments, and secondary weather variables like solar radiation and wind.

Combining the component models

To construct an integrated model for the space heating process, Equations (1) to (4) are combined by substituting for the intermediate variables Mheat and V, working from bottom to top in Figure 3. The result gives fuel consumption and indoor temperature as functions of outdoor temperature and other system parameters:

$$Fb = B + Ehw/e + (fHK/e)[b3COM + (b1+b2BAL)(\tau c-To)+] \quad (5)$$

$$Tin = To + Qint/L + (fHK/L)[b3COM + (b1+b2BAL)(\tau c-To)+] \quad (6)$$

Equations (5) and (6) express the system outputs (Fb and Tin) in terms of the primary input (To), the control inputs (BAL, COM, P1, P2, and f), the equipment parameters (B, e, τc, Cv, b1, b2, b3, and h), the water heating load (Ehw), and the thermal characteristics (L and Qint) of the heated space. Note the parallel structure of Equations (5) and (6): both are segmented linear functions in which the zone controller settings (BAL, COM) and the pressure-dependent valve flow factor (K), and night setback (f) play similar roles.

The responses of fuel use rate and indoor temperature as functions of outdoor temperature are illustrated in Figures 4(a) and (b), which show plots of Equations (5) and (6) for Lumley Homes. The upper (solid) lines represent the Lumley Homes system under current operating conditions, based on parameter estimates obtained from monitoring data. The lower lines (dashed) represent the response predicted under improved control (to be discussed below). The similarity in the models for Fb and Tin is readily apparent in that both have an elbow-like, segmented linear response to outdoor temperature with a joint (change point) at the controller cutoff temperature, τc. Note that if L and Qint are both constant for To above τc and there is no air conditioning, then Tin would rise sharply (with unit slope) as To rises. In reality, increased ventilation (e.g., by window opening) in mild weather increases the heat loss to keep the intrinsic gains from heating the apartments to such high temperatures.

For fuel consumption, Equation (5) provides an interpretation of a variable-base heating degree-day model in terms of the components of the heating system. A standard model (PRISM, Fels 1986) for fuel use is

$$Fb = \alpha + \beta(\tau - To)+ \quad (7)$$

Identifying the base level consumption, α, and heating slope, β, with the corresponding terms in Equation (5), the relations among the parameters are given by

$$\alpha = B + (fHKb3COM+Ehw)/e \tag{8}$$

$$\beta = fHK(b1+b2BAL)/e \tag{9}$$

and τ is identified with τc, the cutoff temperature of the controller. For periods longer than a day, the term $(\tau c\text{-}To)+$ can be replaced by $H(\tau c)$, that is, heating degree days per day to base τc.

A control law for outdoor-reset heating

Equation (6) enables one to calculate explicitly the values of the control inputs needed to achieve a stable indoor temperature for fixed values of the other inputs. The discussion that follows is given on the whole building level but it may also be applied to zone specific control, for which one would use Equation (6) with zone-specific variables. Given a desired indoor temperature, designated T', Equation (6) can be rearranged as

$$(fHKb3COM+Qint) + fHK(b1+b2BAL)(\tau c\text{-}To)+ = L(T'\text{-}To) \tag{10}$$

In mild weather ($To \geq \tau c$) the slope term vanishes and fHKb3COM should be chosen to satisfy the heating requirements at $To = \tau c$:

$$fHKb3COM = L(\tau'\text{-}\tau c) \tag{11}$$

where

$$\tau' = T' - Qint/L \tag{12}$$

is the "natural" balance point temperature of the building for the given values of Qint and L. Thus, the COM setting can be viewed as a way to correct for the zone controller's cutoff temperature not being tuned to the particular intrinsic heat and lossiness of the building in question. However, this is only meaningful if $\tau c \leq \tau'$, that is, if the cutoff temperature is no greater than the balance point temperature of the indoor space. If $\tau c > \tau'$ the building will overheat when the outdoor temperature is in the range $\tau' < To < \tau c$, that is, a negative solution (cooling) is implied as long as L and Qint remain fixed.

For cold weather ($To < \tau c$) and if $\tau c \leq \tau'$, the expression for the compensator term from Equation (11) is substituted into Equation (10) and rearranged to yield

$$fHK(b1+b2BAL) = L \tag{13}$$

that is to say, the heating slope factor, fHK(b1+b2BAL), should be chosen to match the lossiness of the building. This insures that the heating slope term in Equation (6) is equal to one, so that the heating system matches a falling outdoor temperature degree for degree, keeping the indoor temperature stable. On the other hand, if $\tau c > \tau'$ then the compensator term is still zero but the temperature differences do not cancel. In this case, the building will overheat when $\tau'<To<\tau c$ and there is no fixed control setting which will balance the heat loss for outdoor temperatures below τ'. Overheating in mild weather is therefore inevitable in buildings having a fixed controller cutoff temperature which is higher than the natural balance point temperature and there can be overheating in cooler weather unless the boiler operator adjusts the controls as a function of To.

The analysis here shows that there are inherent difficulties with outdoor-reset control of space heating. While based on the fundamentally sound principle that space heating should increase in proportion to decreasing outdoor temperature, the open-loop nature of a pure outdoor-reset scheme makes accurate control difficult, if not practically impossible. The control law depends on knowledge of lossiness and intrinsic gains, both of which are difficult to estimate. The control law remains valid only while L and Qint are constant. Even for constant L and Qint, controllers having a fixed cutoff temperature will have a fixed control solution only if the cutoff temperature is no greater than the balance point temperature of the building or zone being controlled. Lumley Homes provides an illustration of this problem in practice, since its controller cutoff temperature 15 C (60 F) is greater than the building's estimated balance point temperature of 8 C (47 F). A separate issue is the centralized nature of the control, which cannot automatically address differences among apartments.

APPLICATION TO IMPROVING BUILDING OPERATIONS

The systems analysis for outdoor-reset space heating has provided a useful clarification of how buildings with such systems operate. A problem with the "ideal" formulation just given, however, is that for a given building, it is quite difficult to determine the control settings analytically because the building parameters are unknown. Estimating the lossiness, even a target lossiness, for an occupied building is a challenging problem for researchers. Attempting to design an ideal open-loop control specification is not practical without allowing for a sizable margin of error, which becomes an efficiency penalty. Such an approach was presumably used by the engineers who installed the existing system. An analytic approach such as developed here is not known to have been used, but the "rules of thumb" (e.g., the 60 C nominal cutoff temperature) are based on similar concepts. In practice what happens, of course, is oversizing, since it is better to err on the side of too little rather than not enough (the engineer's analog of the way a boiler operator runs an outdoor-reset system).

Behavioral factors regarding to how the tenants and boiler operator interact with the heating system were also investigated at Lumley Homes. At first glance, one might blame wasteful behavior by tenants, such as window opening in cold weather, and find an explanation in the fact that tenants do not pay heating bills. DeCicco and Kempton (1987) found, however, that the tenants are really not the root cause of inefficiency. The only part of the heating system that tenants can control are radiator valves, which they perceive as difficult to use and tend not to use. Tenants perceive windows to be their best means of comfort control during the heating season and as a way to meet their desire for fresh air. Such views are reasonable given a central heating system without thermostats and apartments which can be underventilated when all the windows are closed. Tenants also occasionally complain to the boiler operator about lack of heat. The boiler operator, quite naturally, does not like to get complaints. His desire to avoid complaints, coupled with the poor automatic control capabilities of the heating system, a lack of energy cost feedback to him, and the range of his other, often more pressing, responsibilities, makes it reasonable for him to set the heating controls at high levels.

The implication of highly uncertain building parameters is that indoor temperature measurement is needed to calibrate the system. Such an approach was implicit in the control experiment at Lumley Homes in 1984--temperatures in the sample of apartments were monitored as the control settings were reduced, so as to avoid reducing them too far. No low temperature problems were encountered and there were no complaints from tenants. There was a 3 C reduction over the experiment period, from a median of 28 C down to 25 C. Lacking a quantitative understanding of how the system worked, however, no specific guidelines were determined other than the common sense statement that "lower settings are better."

Savings predictions for Lumley Homes

Use of the model enables specification of the operating guidelines needed to improve the situation in the building studied. A first estimate was made assuming that the existing heating system is kept but operated with control parameters that better match the heating load. The most important change needed is a reduction of the steam pressure, from a current setting of 6 psig down to 0 psig (atmospheric operation) with the vacuum pump set at 12 inHg. This is with the average BAL knob set to the middle of its range (5), the COM knob set to zero, and four hours of night setback. The expected savings in annual energy use would be 44%, or $15,000 in gas costs. Under this scenario, the existing open-loop system remains and the tenants would have to adjust to the new conditions by opening their windows less and using their radiator more. This would be facilitated by insulating steam risers, keeping radiator valves and traps in good repair, and perhaps adding T-bars or extensions to make the valves easier to operate. Implementing such an improved operation would require technical expertise in calibrating the system initially as well as different ongoing procedures on the part of the boiler operator: he would have to respond to tenant complaints by going to apartments to fix local problems, maintain the distribution system, and avoid turning up the controls. Direction and incentive from higher management, along with feedback about success in containing energy costs, will be needed if such improved control is to be sustained.

A more ambitious reduction in energy use is possible with changes in the heating plant. To estimate the savings if the heating system delivered exactly the heat needed and if various standby losses were reduced, it was assumed that the rate of heat delivery, characterized by

TABLE 1. Energy savings predictions for Lumley Homes	NAC kW	Predicted Savings
Observed gas use (from billing data)	221 (± 7)	-
(1) Lower steam pressure and control settings	123 (±10)	44 %
(2) Use of thermostatic controls as well as base level reduction measures	81 (± 8)	63 %

the reference temperature and heating slope, matches the local needs of each zone, so that imbalances and overheating are eliminated and heat is supplied only as needed to keep Tin at a design value, i.e., 22 C (72 F). This would require closing the temperature control loop, for example, by installing thermostats to control to zone valves or adding thermostatic radiator valves. It was also assumed that a smaller boiler, already installed in the building for summertime water heating, is used year-round instead of the main boiler and that the hot water supply temperature is reduced to 52 C (126 F). Under such a scenario, it was estimated that the normalized annual consumption would be 81 kW, a 63% decrease from the current 221 kW, saving $22,000 in gas bills. This operating scenario is represented by the dashed lines in Figure 4. The predicted improved control operation also implies a 5 C (9 F) drop in the average heating season indoor temperature, down from the current value of 27 C (81 F).

Table 1 summarizes the savings predictions as compared to the currently observed energy use in Lumley Homes. By far the largest savings is due to improving the heating control by eliminating the wasteful overheating--all of the 98 kW reduction for case (1) and 19 kW of the additional 42 kW reduction predicted for case (2); the remaining savings in case (2) are due to base level reductions from lowered standby loss with the smaller boiler (16 kW) and a lowered hot water supply temperature (7 kW). Note that neither of these scenarios involves shell retrofits; an important lesson of this analysis is that, for buildings like Lumley Homes, bringing the heating system under control is far more important than shell tightening.

If control reductions were to be attempted in a given building, more specific guidelines could be developed using the theory presented here. Developing such an experimental audit-and-adjustment procedure is left as a suggestion for future work. It should be done in conjunction with a more conventional audit that makes envelope lossiness assessments, which could be used to set a preliminary target. The procedure would entail visits for temperature measurement and adjustment over a range of outdoor temperatures. It would also entail attention to problems in individual apartments, which might require localized measures (some of these will be suggested below). Speaking with the staff of the building and the residents would provide information about problem areas and where to check temperatures. Temperature measurement might be done with strip chart recorders or having residents contact the retrofitter who would then visit problem areas with hand-held monitors. A more sophisticated solution might involve temporary use of remote monitoring methods, such as power-line-carrier equipment, although further development work is needed on such systems before they could have widespread use in this application.

CONCLUSIONS

The motivating question of how to model energy use in a way that facilitates diagnosis and cure of energy waste by outdoor-reset controlled space heating systems was answered by developing a component-based model that clarified energy use at a disaggregated level. A building and its heating equipment are conceptualized as a system having indoor temperatures and fuel use as the outputs and outdoor temperature as the primary input. The major pieces of mechanical equipment and the indoor space are then viewed as the constituent subsystems, each represented by a component model. The resulting framework integrates the mechanical and structural determinants of energy use into a set of equations which express the system outputs (fuel use and indoor temperature) as functions of the outdoor temperature and the control inputs of the mechanical equipment, with identifiable parameters that represent the operating characteristics of the heating system and the building envelope, as shown in Figure 3. For the building studied, this framework was applied to relate component performance to building performance, revealing that the major cause of inefficiency is the mismatch of the outdoor-reset control scheme to the building load. The model then enabled predictions of the effects of changes in control parameters on fuel use and indoor temperature, resulting in an estimated savings of 63% of annual gas consumption, primarily from improved heating control.

Another lesson of the research is that the energy-saving potential of improved heating system control can not be achieved by simply telling the boiler operator that there are better control settings that he should use. Since an important part of the problem has to do with equipment limitations, retrofits that would improve control capability by adding indoor temperature feedback must be examined. The findings here suggest, however, that such equipment retrofits will not be a panacea. For example, if the only change made were installation of thermostatic radiator valves, there is nothing to keep tenants from turning them all the way up, still occasionally complaining about the heat, and for the boiler operator to continue using high steam pressure and controller settings. On the other hand, if a retrofit with thermostatic controls were supplemented by guidance for the tenants on how to use controls that might be located in their apartments and by instructions to the boiler operator on operating the system according to the guidelines given here, the need for better maintenance, and making him sensitive to fuel costs, the savings can be as large as the 63% estimated above.

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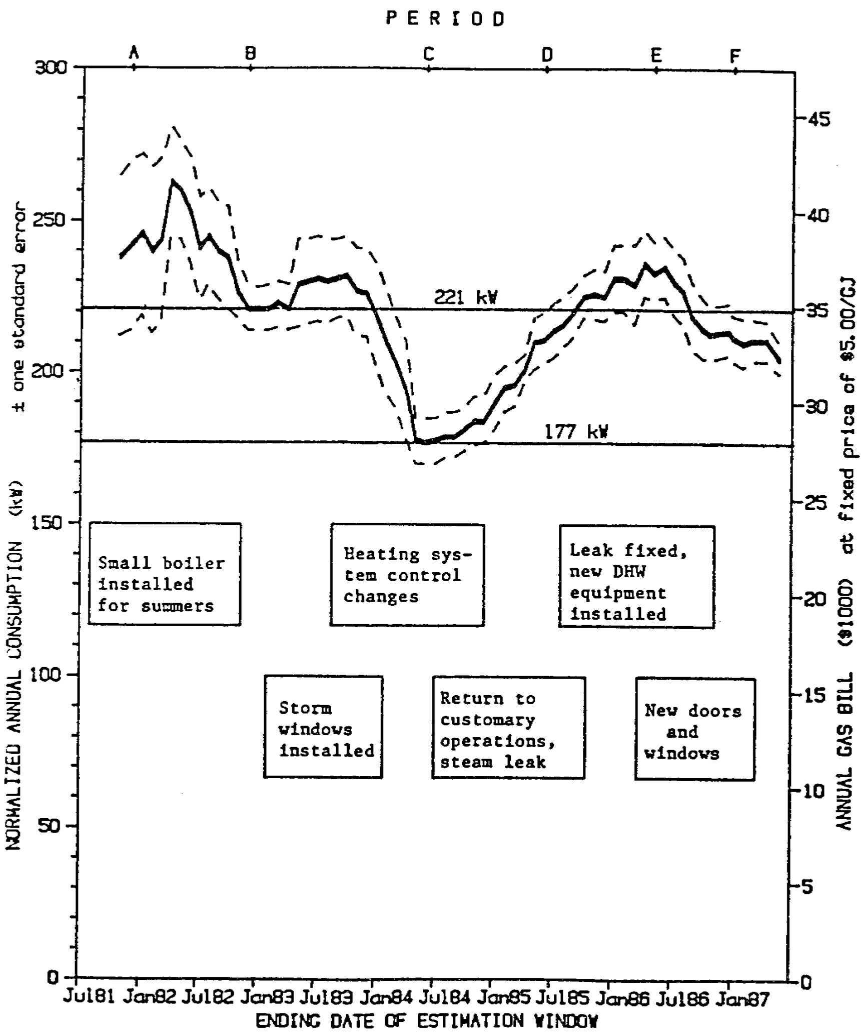

Figure 1. Sliding PRISM estimates of NAC for Lumley Homes (using 12-month estimation intervals)

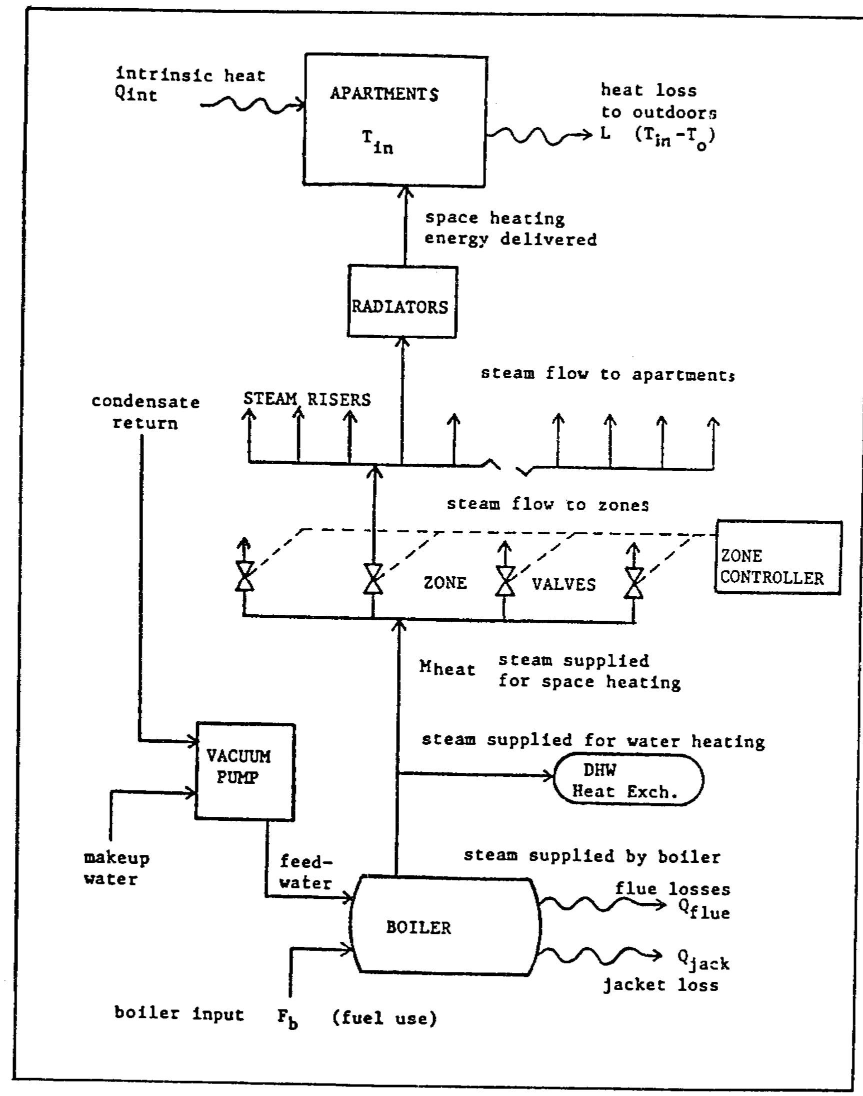

Figure 2. Energy flow paths in two-pipe steam heating

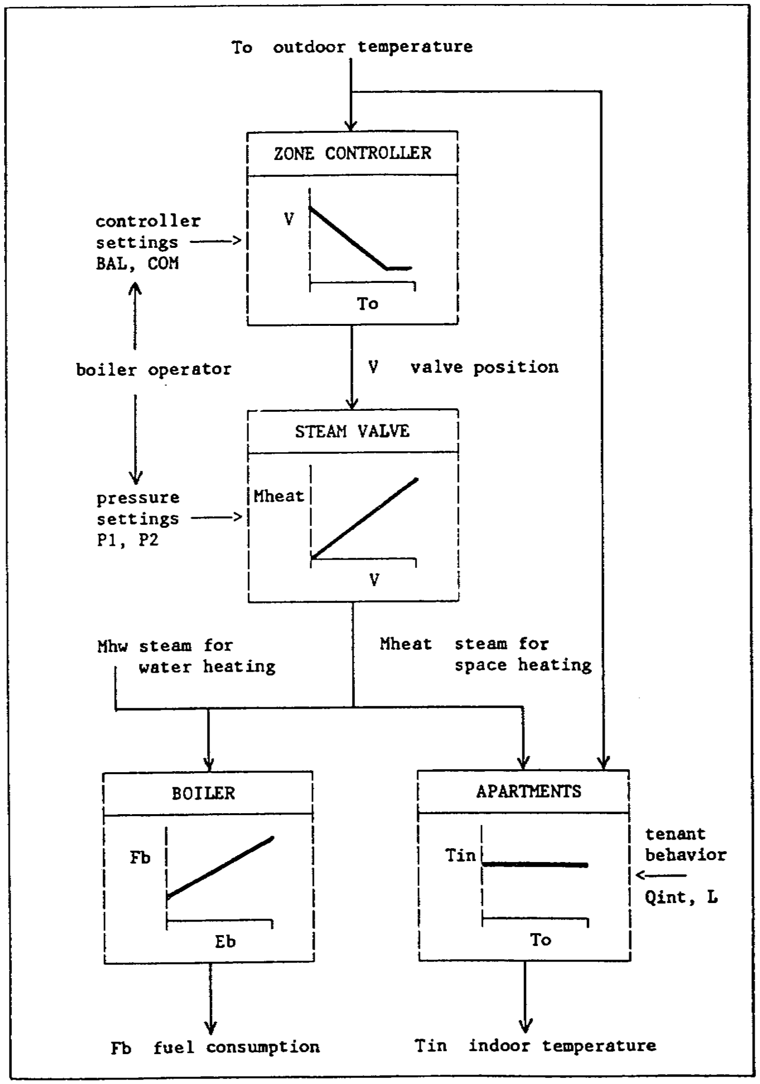

Figure 3. Block diagram of an outdoor-reset steam heating system

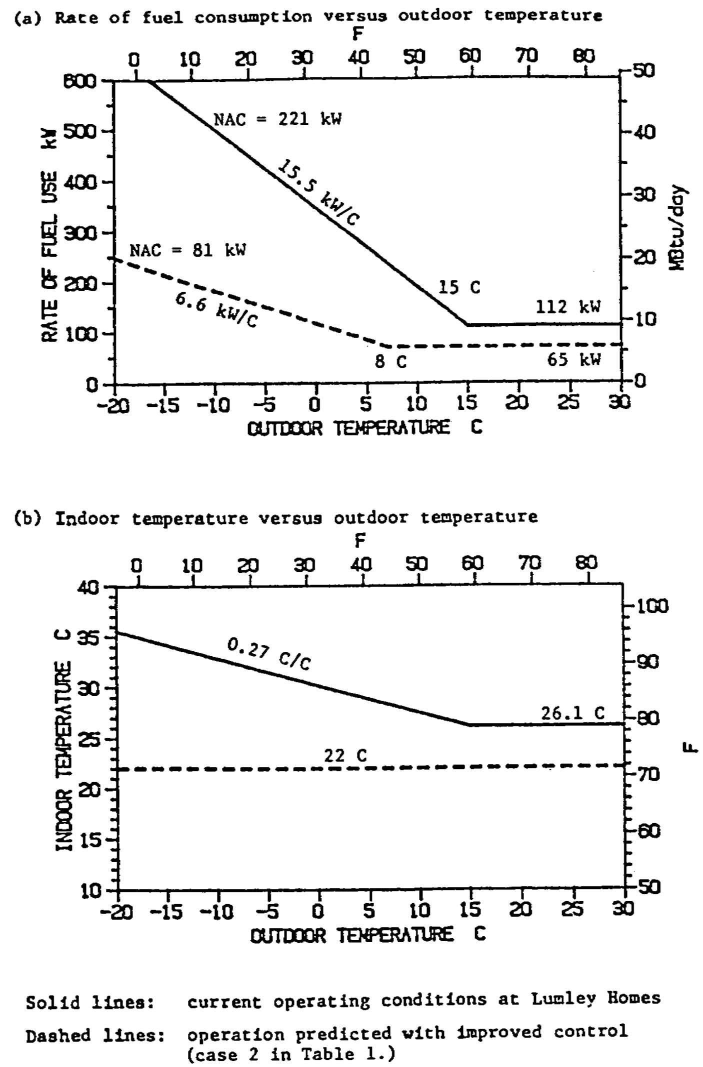

Figure 4. Open-loop fuel use and indoor temperature