JACKET AND STACK LOSSES FROM MULTIFAMILY BOILERS

Mark Modera
Lawrence Berkeley Laboratory

BACKGROUND

Over the past several years, a number of conservation groups have studied the inefficiencies in the hot-water and steam boilers used to heat low-rise multi-family buildings. In general, the goal of this work has been to improve upon the standard stack-loss steady-state efficiency measurements traditionally used to characterize boiler performance. The work has focused on evaluations of particular technologies to reduce boiler losses, the development of diagnostic techniques to evaluate a boiler's performance, and on measurements and modeling to characterize general boiler performance.

Quantification and reduction of off-cycle losses from boilers has been an important component of many of the recent boiler efficiency studies. These off-cycle losses fall into two categories, stack losses or jacket losses*, where stack losses refer to the heat lost by free convection of air through the boiler, and jacket losses refer to the radiative and convective heat transfer from the outer surface of the boiler. Relative to off-cycle stack losses, the Minneapolis Energy Office (MEO) has made the most extensive study to date (to the author's knowledge) of the effectiveness of using vent dampers to reduce these losses. The MEO study involved flip-flop experiments over the course of two heating seasons in six buildings with single-pipe steam and hot water boilers (Hewett 1988). This study showed a large variability in savings from building to building and from year to year, and discusses the likely mechanisms for the observed savings variability. However, the indirect method, PRISM (Fels, 1984), used to evaluate the savings is probably incapable resolving the observed differences in savings, and does not provide any physical reasons for the variations. Katrakis, at the Center for Neighborhood Technology (CNT), while studying several retrofits for improving boiler efficiency, developed a straightforward diagnostic technique for estimating off-cycle losses for single-pipe steam boilers (Katrakis, 1988). This technique, which measures the time required to make steam after an off-cycle period, can determine the off-cycle losses as a function of off-time, but does not separate the effects of different loss mechanisms. DeCicco, at Princeton University, performed extensive measurements on a two-pipe steam boiler (DeCicco, 1988). His work includes a quasi-steady-state model of boiler cycling efficiency (which does not take into account temporal variations in loss rates), and a diagnostic technique for determining off-cycle losses. The diagnostic involves isolating the boiler from the building steam distribution loop, and measuring average energy consumption required to maintain the boiler water temperature. To separate stack from jacket losses, DeCicco estimated jacket losses from surface temperature measurements, and tested his results using tracer-gas measurements of stack and flue flow rates. Robinson, working with the Energy Resource Center (ERC), has studied retrofits of hot-water boilers with high-efficiency front-end boilers, and has examined a diagnostic technique for separately determining stack and jacket off-cycle losses (Robinson, 1988). The diagnostic involves isolating the boiler from the hot water

* Hot-water circulation-loop losses also occur during the off-cycle, but are more aptly classified as distribution losses.

circulation loop, measuring the heat capacity of the boiler from heat input and temperature rise, and then determining off-cycle losses from the decay of the boiler water temperature. Stack losses are separated from jacket losses by measuring the decay with and without the flue sealed.

Researchers at Lawrence Berkeley Laboratory (LBL), in collaboration with the staff at CNT and MEO, have examined off-cycle losses from boilers in multifamily buildings in Chicago and Minneapolis (Modera, 1985). This summary paper describes the results of jacket loss measurements on several different types of boilers, briefly describes a model developed to predict flows through multiple combustion appliances vented by a single chimney, and compares the relative magnitudes of jacket and stack losses.

JACKET LOSSES

As the ages of the boilers in multifamily buildings span a large range, from oversized brick-set boilers that were constructed around the turn of the century, to modern boilers which are claimed to have negligible jacket losses, the operating efficiency differences between these boilers has been blamed somewhat upon jacket losses. To characterize these losses for different types of boilers, researchers at LBL made field measurements of jacket-loss rates using heat-flux transducers and surface-temperature sensors on three types of boilers, a brick-set fire-tube boiler (turn-of-the-century), an insulated steel-case fire-tube boiler, and a cast-iron sectional boiler with an insulated sheet-metal jacket. The results of these measurements are summarized in Table I.

Table I: Jacket losses from single-pipe steam boilers.

Boiler	Q_{boiler} [kW]	Surface Area [m^2]	$\frac{Q_{jacket-on}}{Q_{boiler}}$ [%]	$\frac{Q_{jacket-off}}{Q_{boiler}}$ [%]	$\left(\frac{Q_{jacket}}{Q_{avg}}\right)_{13\%}$ [%]
Brick-set	380	42	1.8	1.5	11.8
Insulated Steel-case	760	19	1.0	0.4	3.7
Insulated Cast-iron	300	8	0.6	0.2	1.9

In Table I, Q_{boiler} is the firing rate of the boiler, $Q_{jacket-on}$ is the heat loss rate from the jacket measured when the boiler was firing, $Q_{jacket-off}$ is the average heat loss rate from the jacket when the boiler was off, and Q_{avg} is the average rate of fuel consumption by the boiler during the heating season. Thus, the last column in the table represents the fraction of the heating bill that is lost through the jacket assuming that the boiler is firing an average of 13% of the time, the measured seasonal average on-time for the Minneapolis boiler. Using the same fractional on-time for the other two boilers allows the three boilers to be compared at the same degree of oversizing. Also, due to the smaller relative magnitudes of their off-cycle jacket losses, the overall jacket losses of the latter two boilers does not decrease rapidly with increased fractional on-time (e.g., doubling the fractional on-time only changes their overall losses from 3.7% and 1.9% to 2.1% and 1.2%).

Several observations can be made based upon Table I. First, it appears that the jacket losses from the brick-set boiler are a significantly higher fraction of the input compared to the other two boilers, and that the major factors driving this difference are the large off-cycle losses and the relatively large jacket surface area of the brick-set boiler. The importance of off-cycle losses is illustrated by taking the ratio of on-cycle to off-cycle jacket losses for the three boilers. For the cast-iron boiler this ratio is 3, decreasing to 2.5 for the steel-case boiler, and down to 1.2 for the brick-set boiler, indicating that the jacket loss rate for the brick-set boiler is as high during the off-cycle as during the on-cycle. This is a result of the large thermal mass and subsequently long time constant of the bricks. It is also clear that for all three boilers the jacket losses are a rather small fraction of the boiler firing rate, and that it is oversizing and off-cycle cooling of the thermal mass that has the potential for making jacket losses significant. Finally, even with only 13% average on-time during the heating season (i.e., significant oversizing), the overall jacket losses from the relatively modern cast-iron boiler remain small. The importance of jacket losses in this type of boiler becomes even less significant if a more typical average on-time of 25% is used.

As a point of reference, the losses presented in Table I can be compared with measurements made by DeCicco and Robinson. DeCicco's diagnostic measurements on a 25-year-old two-pipe steam boiler indicate $\frac{Q_{jacket}}{Q_{boiler}}$ to be 0.7%, whereas similar measurements that he made on a 5-year-old steam boiler used to heat domestic hot water indicate $\frac{Q_{jacket}}{Q_{boiler}}$ to be 0.5%. These results are comparable to the LBL values, excluding the old brick-set boiler. On the other hand, Robinson's results for a hot water boiler, based upon the decay of the hot-water temperature, imply significantly larger jacket losses ($\frac{Q_{jacket}}{Q_{boiler}}$=1.6%), comparable to those of the brick-set boiler. However, there are several reasons why Robinson's jacket losses are high. First, he tested a large-surface-area derated coal-conversion boiler, which is expected to have relatively high jacket losses. Also, the boiler had not been operated for several days before the decay test, implying that some of the presumed jacket losses may have been heating the large thermal mass of the boiler and the ground below it. Finally, the boiler-water was being circulated through a short loop during the decay, which would also tend to increase the quoted jacket losses.

STACK LOSSES

This section briefly discusses a model that can estimate stack losses based upon its predictions of air flows and temperatures in a chimney system venting two combustion appliances (Dumortier, 1987). This model was developed to be able to simulate the performance of stack-loss reduction strategies for multifamily boiler rooms (e.g. vent dampers or flow restricters). In the model, mass conservation, energy conservation and pressure loss equations are used in conjunction with a thermal model of a chimney to define the system. The resulting system of 18 equations and 18 unknowns is reduced to a single equation, which is then solved by a numerical method. The model requires as input: the leakage areas of each of the components of the venting system (obtained either by on-site diagnostics or from ASHRAE (American Society of Heating Refrigerating and Air Conditioning Engineers) pressure-loss factors for ductwork), the steady-state efficiencies and firing rates of the boiler and water heater, the system geometry and chimney construction, estimates of the boiler and DHW time constants, and ambient temperature conditions.

A preliminary examination of the model was performed by comparing air flow and temperature predictions with measured values for a multifamily boiler-DHW system in Chicago. The predictions of vent system flows based upon leakage areas derived from ASHRAE pressure-loss factors and time constants derived from measured temperature decays are compared with some overnight flow measurements made in the field (see Table II).

Table II: Measured and predicted flow rates in Chicago apartment building.

System Operation	Location	Measured Flow [m^3/h, 24 °C]	Predicted Flow [m^3/h, 24 °C]
Boiler off, DHW off	Chimney	1100	1100
	Boiler Flue	350-500	430
	DHW Stack	200	220
Boiler off, DHW on	Chimney	1150	1200
	Boiler Flue	350-500	410
	DHW Stack	220	250

Table II shows that the predicted flows are close to the measured values, indicating that the model can provide reasonable estimates of flows through two-appliance venting systems. However, although the comparison in Table II is encouraging, a more comprehensive validation of the model is needed. Such a validation should address several limitations of the program which do not appear in the presented comparison. Namely, the leakage areas of certain components can be difficult to determine from the ASHRAE pressure-loss factors, the model presently does not take into account heat transfer or stack effect in the ductwork between the appliance and the chimney (i.e., the stacks), and the program does not take into account for the fact that the leakage areas of certain components depend upon the flow direction (potentially important for predicting the magnitude of spillage from draft diverters). A diagnostic procedure based upon a stack-gas analyzer and a pressure gauge can potentially eliminate the most significant uncertainties of the ASHRAE pressure-loss calculations.

An example of the results of the simulations performed is presented in Figure 1, in which the boiler (i.e., boiler-flue), boiler-draft-diverter and boiler-stack flows are plotted as a function of time. It shows that the boiler-draft-diverter flow, the boiler flow, and thus the boiler-stack flow increase by about 25% when the boiler turns on. Also in Figure 1, the cycling of the DHW heater can be seen in the variations of the boiler-draft-diverter flow. On the other hand, the flow through the boiler flue is basicly unaffected by the cycling of the DHW heater.

COMPARISON OF JACKET AND STACK LOSSES

Based upon the collected measurements of jacket losses and stack losses for five boilers, a comparison of the relative importance of these two loss mechanisms can be made. Table III presents such a comparison for the brick-set and insulated sheet-metal boilers tested by LBL, the steam boilers tested by DeCicco, and the hot water boiler tested by Robinson.

Table III: Comparison of off-cycle jacket losses and stack losses from boilers.

Boiler	Q_{boiler} [kW]	$\frac{Q_{jacket}}{Q_{stack}}$ [-]
Brick-set 1-pipe steam (LBL)	380	0.61
Insulated Sheet Metal 1-pipe steam (LBL)	300	0.12
Steel-case 2-pipe steam (DeCicco)	590	0.18
Steam-DHW (DeCicco)	280	0.17
Coal-converted hot water (Robinson)	100	2.1

Based upon the results in Table III, the boilers can be grouped into three categories. The first category consists of the middle three boilers, for which the jacket losses represent only a small fraction of the total off-cycle losses. For this group of boilers, all of which are relatively modern, it seems that efforts to improve efficiency are better directed towards the stack. The second category consists of the brick-set boiler, for which the jacket losses are a little more than half the magnitude of the stack losses. Thus, even for a boiler with a massive uninsulated jacket, the jacket losses still do not exceed the stack losses. The third category, the hot-water boiler for which jacket losses are twice as large as stack losses, appears to be somewhat anomalous. As discussed above, the jacket losses can elevated for several reasons. Also, as the boiler had not been fired for several days before the diagnostic test, the chimney was probably cold. This fact, combined with the fact that the outdoor temperatures were mild during the diagnostic, imply that the stack losses were probably somewhat underestimated. Combining this result with the potentially overestimated jacket losses may account for the apparently anomalous behavior of this boiler.

CONCLUSIONS

Some tentative conclusions can be drawn from the work presented in this report. First, these results indicate that jacket losses are normally small compared to stack losses for relatively modern boilers, and that they do not exceed stack losses even in an old oversized brick-set boiler. This implies that efforts to improve the performance of multifamily boilers should more often be directed towards the stack. On the other hand, based upon the measurements made by MEO, it seems that the effectiveness of stack-loss reduction methods such as vent dampers is not easy to pin down by utility bill analysis. The stack-loss model presented in this report, along with a more critical evaluation of the utility of boiler-room heating, will hopefully provide the needed understanding for evaluating vent-damper (and other stack-loss reduction methods) performance.

REFERENCES

J.M. DeCicco, "Modeling, diagnosis, and implications for improving the energy efficiency of centrally heated apartment buildings", Center for Energy and Environmental Studies, Princeton University, PU/CEES Report No. 225, April 1988.

D. Dumortier, M.P. Modera, "A Model for Predicting Air Flow Through Venting Systems for Multiple Combustion Appliances" to be published by Royal Institute of Technology, Stockholm, Sweden, October 1987, Lawrence Berkeley Laboratory Report, LBL-23151.

M.F. Fels, "The Princeton Scorekeeping Method: An Introduction", Princeton University, Center for Energy and Environmental Studies, PU/CEES-163, March 1984.

M.J. Hewett, T.S. Dunsworth, H.L. Emslander, M.J. Koehler, "Measured Energy Savings from Vent Dampers in Low Rise Apartment Buildings", Minneapolis Energy Office Report MEO/TR88-2-MF, May 1988.

J.T. Katrakis, "Space Heating Improvements in Multifamily Buildings", Center for Neighborhood Technology, To be published in Proceedings of ACEEE 1988 Summer Study (this volume), 1988.

M.P. Modera, J.T. Brunsell, R.C. Diamond, "Improving Diagnostics and Energy Analysis for Multi-Family Buildings: A Case Study," Proceedings of ASHRAE/DOE Conference, *Thermal Performance of the Exterior Envelopes of Buildings III*, Clearwater, FL, December 1985, Lawrence Berkeley Laboratory Report LBL-20247.

D.A. Robinson, G.D. Nelson, R.M. Nevitt, "Evaluation of Front-End Boiler Retrofits in Two Multifamily Buildings", To be published in Proceedings of ACEEE 1988 Summer Study (this volume), 1988.

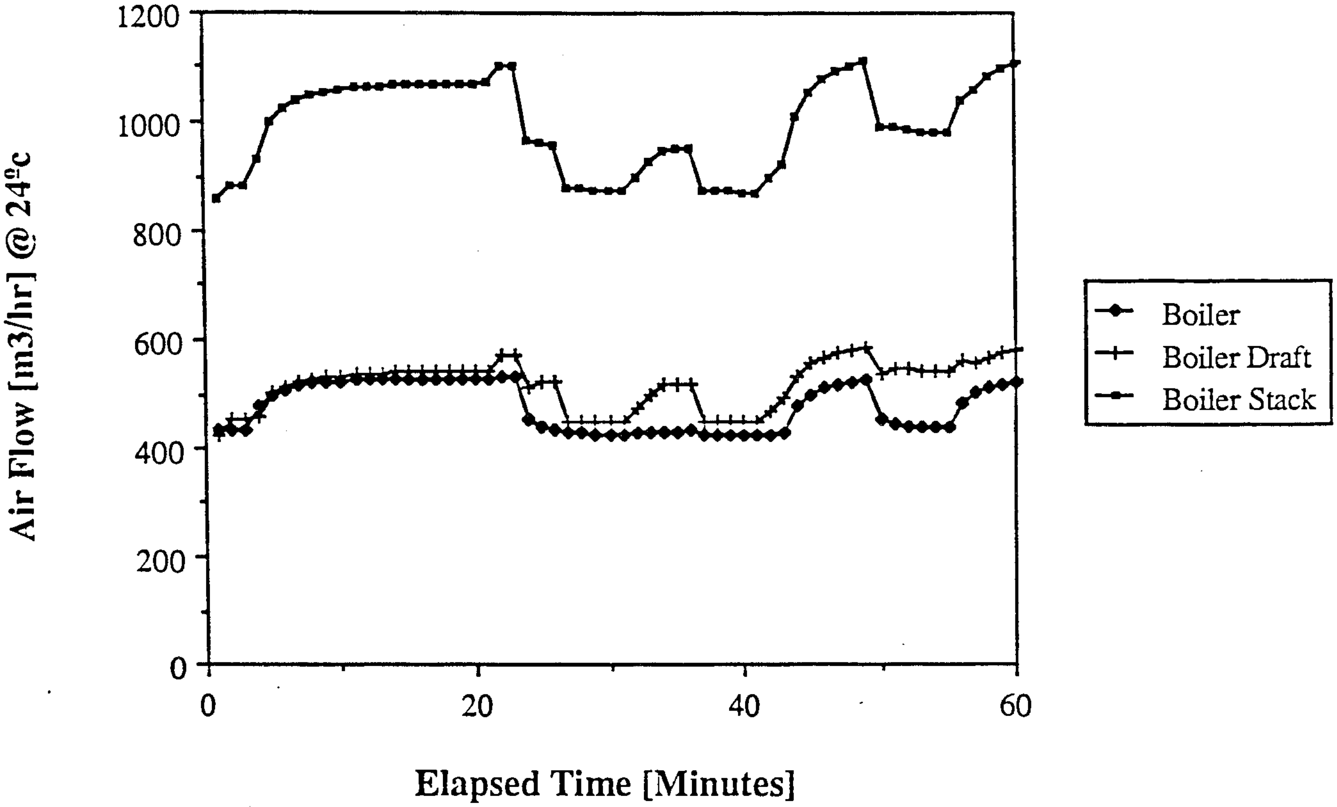

Figure 1. Simulated air flows through boiler venting system with both boiler and DHW cycling. All flows are at room temperature density.