Measured Space Heating Hot Water Distribution Losses in Large Commercial Buildings

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ABSTRACT

Designers and operators typically do not include distribution losses when analyzing the performance of heating hot water systems. Though these losses are very small compared to design-day loads, they are not zero. As the losses occur continuously whenever the systems operate, and these systems spend the vast majority of time operating at low part loads, the losses can still comprise a substantial fraction of annual heating energy consumption. When the entire building requires heating, these distribution losses have little negative effect. However, the losses unnecessarily waste heat whenever the air handlers operate above minimum outside air. In warmer weather, when temperatures are above air handler economizer lockout conditions, the losses are doubly detrimental as they both waste heat and increase cooling plant loads.

We reviewed the literature and could not find measurements of hot water distribution losses in real buildings. Here, we report results from 7 large commercial buildings at 5 different organizations, all located in California, climate zones 3B and 3C. For each building, we commanded the valves closed on heating hot water end-use components and shut down the air handlers. We operated the heating hot water system to maintain a constant flow and a constant hot water supply temperature setpoint typical for each building. We then measured the steady-state heating power required to maintain that setpoint. Building characteristics varied widely in terms of size (5,100-15,000 m^2 or 55,000-160,000 ft^2), type (e.g., city administrative office, college lab and classroom), HVAC design (VAV reheat or dual duct systems), and year of construction (1917-2000). Despite this, the results were reasonably consistent when normalized to building conditioned floor area. The median loss rate was 1.2 W/m^2 (0.37 BTU/hr.ft^2) with a min/max range of 0.8 - 2 W/m^2 (0.25 – 0.63 BTU/hr.ft^2) across all buildings at typical supply temperatures for each building. For comparison, this is roughly a third of average office plug loads, and though it is low on a conditioned floor area basis, it ranged from 6% to 60% of the annual HW energy consumption for the five buildings for which we had long term data. We discuss the methods, buildings, and results in more depth in this paper, as well as the opportunities for improving system design and operation.

INTRODUCTION

Designers and operators typically do not include distribution losses when analyzing the performance of heating hot water systems, though they are not zero. For example, 20 mm (¾") diameter pipe with 1.5" insulation according to ASHRAE 90.1-2019 pg 150, with no gaps in insulation loses 10 BTU/hr.ft of pipe at 180 °F water temperature and 75°F ambient air temperature, or 0.3BTU/hr.ft^2 assuming 0.03 linear feet of pipe per square foot of conditioned building area. See free tools such as 3E for calculations (3E Plus Software 2022). Losses increase by a factor of 7.5 for completely uninsulated piping in otherwise identical conditions. Valves and fittings are often uninsulated even in new construction,

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while in older buildings field inspection typically reveals substantial sections of missing insulation (Hart 2011). Though these losses are low compared to design-day heating loads, these systems typically spend most of the year operating at low part loads compared to design loads. The losses occur continuously whenever the system operates and continue for a substantial period of time after the system shuts down. These intermittent cool-down losses must be 'paid for' when the system starts up, when heating equipment warms everything up to setpoint from ambient temperatures. In summer or swing seasons when the actual heating load of the building is minimal, the loses can make up a substantial portion of the load on the heating equipment. Heating equipment typically operates at very low part load, at very low efficiency at those times of year. This is particularly notable in older boilers with limited turndown capability. See (Beliso et al. 2012) for boiler part load curves measured in laboratory settings. Given these compounding effects, the losses may be a substantial fraction of annual primary heating energy consumption.

Some argue that the losses can be ignored because they occur within the building envelope. This is at best only true during the heating season, and the heating hot water system typically operates all year round in most commercial buildings. Further, for many commercial buildings, heating hot water system piping is typically in the return air plenum. Thus, the building rejects this heat via relief or exhaust air whenever the air handlers are in economizing or cooling modes. The losses have an additional negative impact whenever the air handlers operate above economizer high lockout conditions (above 69-75 °F outdoor air depending on climate, ASHRAE Guideline 36-2021 pg 53) as they directly increase load on cooling equipment. The impact of the losses is mostly negated only when the air handling unit is in heating mode, at minimum outside air, as the whole building requires heat under those conditions.

Despite this, typical approaches to building modeling and standards and codes neglect these losses in analyses. For example, ASHRAE 90.1-2019 pg 208 requires modelers to ignore piping losses: "Piping losses shall not be modeled". There are very few references even to this as a potential issue of concern at design or operation. We reviewed the literature and did not find measurements of distribution losses in real buildings. Thus, this paper presents an exploratory study which measured these losses in 7 difference commercial buildings, across 5 different organizations, and discuss the implications.

METHOD

We used the following method to estimate the distribution losses from the heating hot water system. First, we aimed to operate the system with the hot water piping at reasonably typical temperature conditions, without any actual intentional heating at air handlers or terminal units. To do this, we shut off the air handling units to ensure no forced air flow through the system. Second, we commanded heating end-use valves closed, and then operated the heating hot water system at constant temperature using typical controls for that building. Last, we waited for the system to stabilize (typically under an hour), and measured the heat required to maintain that hot water temperature setpoint.

The method required modification to account for the diversity of HVAC systems in buildings. For systems that did not have any bypass flow (e.g., those that use only 2-way valves to serve all reheat coils), we opened a small percentage of valves to ensure some flow in the system and to ensure that most branch piping was operating at typical temperatures. In other buildings, we did not have the resources to command all reheat valves closed and instead relied on observing that few valves opened during the test period. In addition to the substantial variation in the selected buildings and HVAC systems themselves, the sampling rate, instrumentation, and length of test period varied. In some buildings it was only feasible to run the test once (e.g., overnight, yielding ~8 hours of data), while in other buildings we could continue the test each night for several weeks. Last, in two buildings we repeated the test at lower supply water temperatures.

Limitations

The age and quality of the metering equipment varies widely in each building from high-quality insertion magnetic flow meters and matched supply/return temperature sensors that were installed recently by the project team members, to existing instruments that are 10 years old. We used these existing instruments to cost-effectively increasing the number of buildings that we could obtain a loss estimate for while remaining within the allocated budget. For each building, we reviewed the historical data to ensure it was reasonable over the range of operation. However, the temperature difference between supply and return is typically quite small when measuring distribution losses, approximately 1-4 °C (2-7 °F), which is low when compared to typical temperature sensor error. For these reasons, we expect the accuracy of the individual building distribution loss estimates to be quite poor, perhaps as high as ± 50% for the buildings with older instrumentation. The method itself also incurs some error compared to typical operation, for example:

- the air handlers are off during the test so ceiling return plenum airflow rates are lower, which will reduce losses.
- hot water return temperatures are higher when there is no heating end use, which will increase losses.
- though supply water temperature was stable at setpoint for buildings with district systems, it oscillated widely around setpoint in buildings with boilers due to short cycling at low load conditions.

Overall, we expect these methodology-related effects to have little impact on the accuracy of the loss estimate compared to the effects related to the instrumentation and low temperature difference being measured.

BUILDINGS STUDIED

We selected the buildings for this study from a set of buildings that we collectively had access to based on a minimum set of criteria: a) a medium to large commercial building, b) has a heating hot water system with an existing water flow meter and supply/return temperature sensors showing reasonable trend data, and c) was operated by staff who were willing and available to perform the test. Table 1 summarizes the high-level characteristics of this reasonably diverse set of buildings. However, it is far from a representative sample of buildings; for example, all of the buildings are in California. A representative sample would require a much larger number of buildings as well as a randomized sampling method and neither was feasible given available resources.

Table 1. Building Characteristics

Org–Building	Building Type	Conditioned Floor Area 1000 m^2 (ft^2)	Year Constructed (Renovated)	Climate zone	HVAC system
A-1	Office	11 (120)	1999	3C	Single duct VAV with HW reheat
B-1	Academic	13 (140)	1917 (2019)	3C	Dual duct VAV and baseboard/fan coil
C-1	Academic	5.1 (55)	1978	3B	Single duct VAV with HW reheat
D-1	Lab/Office	6.2 (66)	2000	3B	Single duct VAV with HW reheat
D-2	Library	15 (160)	1987	3B	Single duct VAV with HW reheat
E-1	Office	11 (120)	2006	3C	Single duct VAV with HW reheat
E-2	Office	10 (110)	2007	3C	Single duct VAV with HW reheat

A-1: This building is primarily open plan office with double-pane windows and approximately 50% window to wall ratio (WWR). The HVAC system is served by a natural gas boiler and the building recently underwent a full controls retrofit that involved updating to ASHRAE Guideline 36 sequences, replacing heating hot water valves (2-way) and newly installed, high quality flow meter and supply and return temperature sensors. Reducing zone minimum airflow rates to the required ventilation minimum significantly reduced heating loads in this building, though overall heating system efficiency is poor due to distribution losses and continuous operation of the hot water system (Raftery et al. 2018).

B-1: This historic building contains a mix of classroom, office, and other academic space types. A district steam to hot water system serves the dual duct air handlers (3-way valves) and baseboard radiators or fan coils (2-way valves at each floor). The HVAC system recently underwent a major retrofit which involved new hot water piping, insulation, and control valves. Combined with relatively little hot water piping, we expected distribution losses to be low. The building's envelope is mostly unchanged from original construction including single pane windows.

C-1: This building is predominantly classroom and office space. The lower two above-grade levels contain classrooms, workshops, music rooms, offices, a gallery, and an auditorium. The third story houses faculty offices and additional classrooms. A single VAV air handler with fan walls on both the supply and return serves 97 VAV boxes. An airside economizer and chilled water coil fed by the campus chiller loop provide cooling. Heating is provided by zone hot water reheat coils served by the district hot water plant. Most have 2- way valves except for 3-way valves located at the end of each branch on each floor.

D-1: This building contains a mix of office, laboratory, and classroom space types. A district steam to hot water system heats the heating hot water. The air side HVAC systems are variable air volume with single duct air handlers (3-way valves) and terminal unit reheat coils (2-way valves). Approximately half of the heating hot water branches have pressure reducing valves that provide heating hot water bypass flow. In the experiment we shut off fans in three of the five air handlers that serve office and classroom spaces and commanded all heating coil valves closed but did not shut off the 100% outdoor air flow to laboratory spaces with fume hoods. We commanded the terminal unit heating coil valves serving the laboratory spaces shut for the test, but if any have passing valves the losses will be affected accordingly.

D-2: This 1987 library expansion added floor space including a 3-story central atrium as well as study areas, book stacks, and offices. A district steam to hot water system heats the heating hot water. A variable air volume HVAC system with single duct air handlers and terminal unit reheat coils serve the expansion. A prior retro commissioning project removed all 3-way valves from heating hot water branches so there are 2-way valves on the reheat coils throughout and no bypass flow. In the experiment, though all air handlers were off and there was no forced airflow, we intentionally opened a few end of branch heating hot water valves to allow water to circulate in the piping system.

E-1 and E-2: Both buildings are mix of private and open office space, constructed by the same design team for the same client shortly after the other. They have double glazed facades with approximately 50% WWR. Newly installed condensing gas boilers serve reheat coils throughout each building. Most have 2-way valves except for a 3-way valve located at the last coil on most branches of the hot water pipe risers. Under normal operation, the zone level controllers modulate the VAV box valves even if the air handling units are off, so in these buildings some valves opened during the distribution loss testing. However, the number of open valves is minimal as the valves respond to the zone night setback temperature of 18 °C (65 °F) and we performed the tests in April.



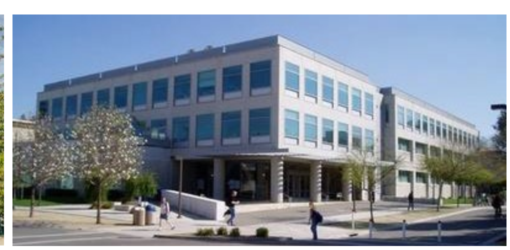

Figure 1: Photographs of three of the studied buildings (left: A-1, center: B-1, right: D-1)

RESULTS

Figure 2 shows the results from the testing; the median loss rate was 1.2 W/m² (0.37 BTU/hr.ft²) with a min/max range of 0.8 - 2 W/m² (0.25 – 0.63 BTU/hr.ft²) at each building's typical operating hot water supply temperature setpoint. For context, this is about a third of the average office plug loads of 3 W/m² (1 BTU/hr.ft²) measured by the GSA in 2013 (US General Services Administration 2014). As expected, increasing water temperature does not clearly correlate with increased losses between buildings because other characteristics of these buildings have a far larger influence on the losses than water temperature alone. However, physics dictates that distribution losses within a given building will increase in an approximately linear relationship based on the temperature difference between the ambient air around the piping and the water it contains. Figure 2 also shows that this was the case for the two buildings in which we repeated the test at a lower water temperature. Thus we also normalized the results using the temperature difference between the supply water temperature and an assumed ambient temperature of 21 ° C (70 ° F) approximating the low end of room and return plenum temperatures where most piping is located; the median was 0.024 W/°C.m² (0.0041 BTU/hr.°F.ft²).

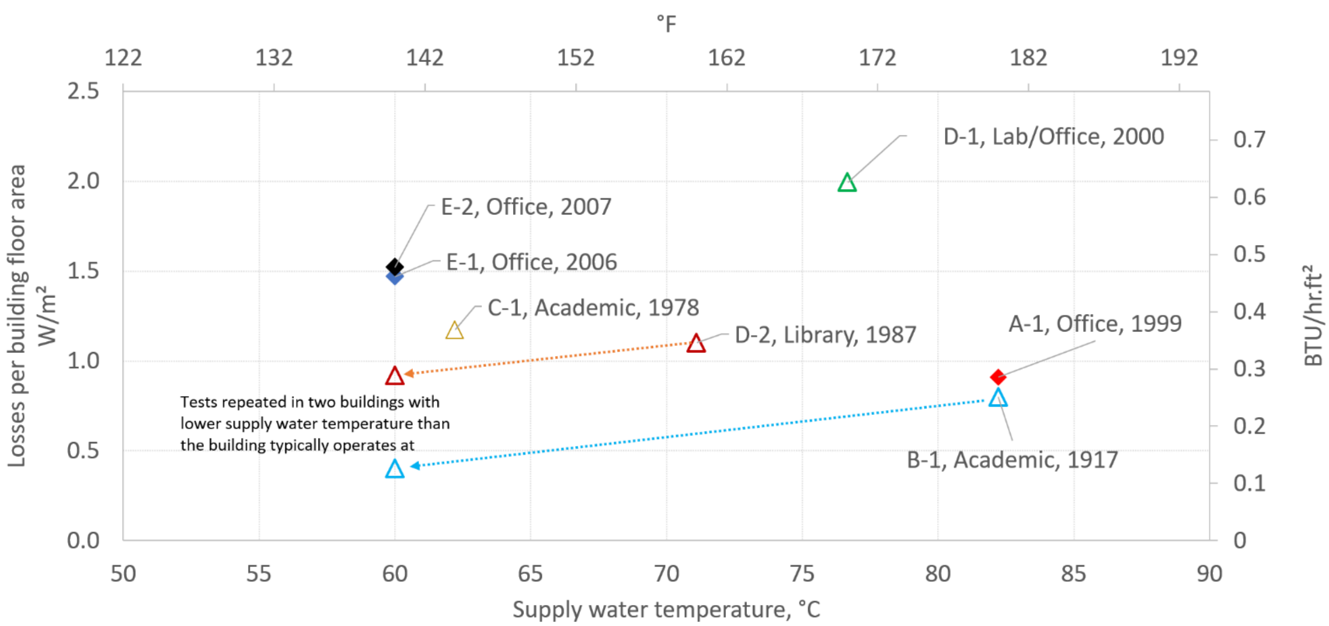

Figure 2: Measured hot water distribution losses in 7 buildings (indicated by color). Filled, diamond shapes indicate relatively new, high-quality instrumentation; unfilled triangular shapes indicate existing instrumentation.

The above losses are quite low compared to design peak heating loads, which even in these relatively mild climate zones is still commonly above 30 W/m² (10 BTU/hr.ft²) in new construction. However, the losses occur continuously whenever the heating system operates and our observations to date have been that these systems operate far more frequently than necessary[1] or than many designers assume. Further, heating systems operate at very low part loads most of the year, so the losses can comprise a significant fraction of the annual heating load. In five of the seven buildings

[1] For example, due to poor sequences of operation, poorly implemented or commissioned controls, manual operator overrides, a small number of zones or end-uses which require heat frequently/constantly, or a combination of these issues. In some buildings operators run the HHW system continuously to avoid leaks which occur as the water cools off and the piping system contracts.

we have long term measured data and can compare the distribution losses to annual heating energy consumption (see Figure 3). The distribution losses range from 6% to 60% of annual heating energy consumption. On the low end, B-1 has high heating loads due to its historic construction and associated poor envelope performance, while distribution losses are minimal due to the newly replaced hot water system. The HVAC system type also has far less piping compared to a more common VAV reheat design. On the high end, A-1 has a much better envelope and recently completed a retrofit to minimize reheat energy so heating loads are low, but it has existing hot water piping and the hot water system in this building runs 24/7 to avoid leaks even though the air handlers switch off at night. This means that the boilers *solely* serve distribution losses for over half of the operating hours of the year, contributing to the high distribution loss fraction of annual load.

In building C-1 we also tracked the number of valves that opened during the night when the air handler was not operating (see Figure 4). This figure shows that the heat loss caused by valves opening even when the air handlers are off is not trivial and may impact the results in the buildings where we were unable to command all valves closed throughout the test (C-1, E-1, E-2). It is difficult to assess the impact of this as some of the increased heat transfer is due to the losses from the branch of piping serving the 2-way valve on the coil, as well as the heat lost into the duct from the coil itself. Note however, that removing these buildings has a minor impact on the overall median distribution loss estimate, decreasing it to 1 W/m^2 (0.3 $BTU/hr.ft^2$).

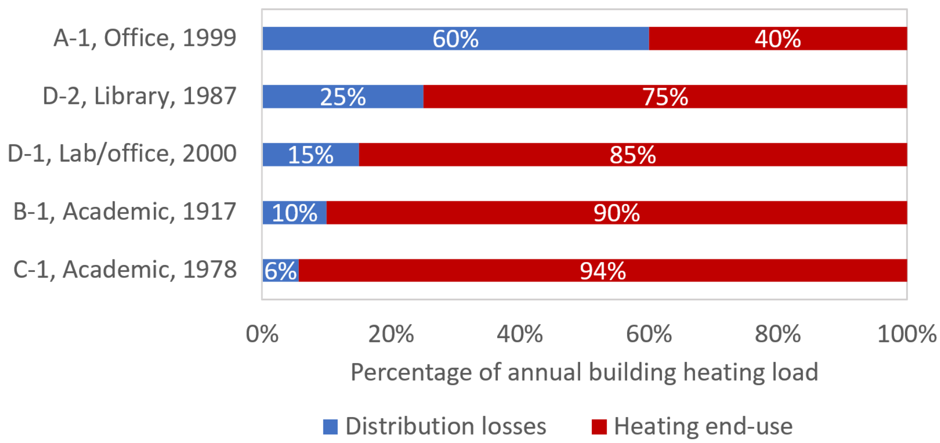

Figure 3: Distribution losses as a percentage of annual building heating load in 4 buildings.

Figure 4. Building C-1: One month of heating loss data (averaged hourly) vs number of valves (of 98 total) open during the night when air handling units are off but the HHW system still operates

Discussion

We believe this work highlights potential opportunities to improve design, installation and operation of heating hot water systems. First, as the distribution losses were not a trivial percentage of overall heating energy consumption in any of the studied buildings, designers should consider including these losses in analyses of these systems instead of the current practice assuming they are zero. That applies to comparisons for codes and standards (e.g. for ASHRAE Standard 90.1 or California Title 24) or within energy simulation tools used to evaluate annual energy consumption. Where feasible designers can reduce the losses by minimizing the amount of hot water piping using multiple riser designs instead of single riser designs, which use more pipe as they distribute piping across each floor plate. However, we recognize that the impact of the losses, and the attention they warrant is more significant in cooling dominated climates than in very cold climates[2].. Further work could measure losses on a larger number of buildings to inform an appropriate range of values to assume in these types of analyses. Operators should also consider these losses in building operations, by measuring them in their own buildings and reducing them as much as possible with cost-effective solutions described below.

For new construction or gut retrofits, designing terminal units using lower than typical supply water temperatures – for example, no higher than 54 ° C (130 ° F) (Durkin 2006) or even lower in mild or cooling dominated climates – will

[2] Though we expect the losses to be similar in absolute terms in all climates (i.e. similar BTU/ft2 values), the losses will be a smaller percentage of total building heating loads in cold climates. Further, much of the negative impact of these losses is negligible in cold conditions when the air handling unit heating coil is operating as the building overall requires heat. These conditions occur far more hours of the year in colder climates.

reduce distribution losses, improve heating equipment efficiency, and save energy overall. This also will allow for a wider range of equipment selection options, such as air source heat pumps or chiller condenser water reheat systems. Similarly, consider designs using 2-pipe terminal units that either shut down or change over seasonally, such as radiant slabs, perimeter fan coils, or baseboard radiators/convectors, and/or using warmer supply air temperatures to remove the need for interior zone reheat coils. These systems should operate in heating mode only when the building perimeter actually requires heat, under which conditions distribution losses have little negative impact. Last, ensure that installers actually insulate hot water systems as required by most codes – this includes insulating the valve trains serving terminal units which is often not done in the field.

For existing buildings, the key is to reduce heating hot water supply temperatures, which decreases both annual heating and cooling energy consumption. Operators can easily implement this using seasonally scheduled setpoint changes if there are limited automation resources on site, or they can automate it using an outside air temperature-based reset. If the building already has a demand-based supply temperature reset, operators should review how it is performing and consider either adjusting parameters so it operates more effectively, or varying the limits within which it operates based on the outside air temperature. Few buildings require design temperature hot water in summer months, but engineering experience shows that many still operate at these high temperatures for a variety of reasons. In some buildings, a small number of zones (e.g. 5% of zones in the building) will consistently have insufficient heating capacity at lower water temperatures. In these cases, operators can consider adding thermostatically-controlled electrical resistance heating locally, as these zones would otherwise limit the hot water temperature for the whole building. There are several wall-mounted, thermostatically-controlled, schedulable electric resistance heaters which plug in to the existing electrical circuit outlets in the ~$100 range. To prioritize the primary heating system, the setpoint used for the electric heater should be below the setpoint used for the zone thermostat. The electricity consumption of these few electric resistance devices will be minimal compared to overall building energy savings from reducing heating hot water temperatures. This solution allows operators to reduce water temperatures and to do cost-effectively from the perspective of first costs and ongoing energy costs. We have also seen buildings where leakage occurs when the piping system contracts at low water temperatures. Here, the solution is to isolate and fix the leaks instead of continuously operating the system at high water temperatures. Aside from the clearly unnecessary operating costs, this latter approach invites disaster because an unexpected equipment shutdown will inevitably occur at some point in the future, and then the operator will have to address leaks throughout the building while also resolving the original cause of the shutdown.

CONCLUSIONS

We measured heating hot water distribution losses in seven large commercial buildings at a median value of 1.2 W/m^2 (0.37 BTU/hr.ft^2). Though low on a conditioned floor area basis when compared to peak heating design loads, the losses are approximately a third of measured plug loads in office buildings and ranged between 6 and 60% of annual heating energy consumption in the five buildings where that data was available. Though a larger sample is required before generalizing outside these seven buildings, the measured losses suggest that both designers and operators should consider losses in their analyses of these systems. Last, there are cooling and heating energy savings opportunities from simply reducing water temperatures in these systems, both in new construction and in existing building systems.

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CREDIT STATEMENT

Paul Raftery: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing - original draft, Writing - review & editing. **David Vernon**: Data curation, Investigation, Methodology, Resources, Writing - review & editing. **Rupam Singla**: Data curation, Investigation, Methodology, Resources, Writing - review & editing. **Mia Nakajima**: Data curation, Investigation, Methodology, Visualization, Writing - review & editing.

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