

Final Report

10-06-2019

Literature Review of Multifamily Central Domestic Hot Water Distribution Losses

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Executive Summary

Domestic hot water (DHW) systems represent one of the largest end uses of energy in residential buildings. A majority of new mid-rise and high-rise multifamily buildings have central domestic hot water (CDHW) systems with a temperature maintenance system so that the apartments distant from the water heater can receive hot water at any time of the day or night. In CDHW, water is often continuously circulated through a loop to maintain the hot water temperature close to the fixtures, but this constant recirculation of hot water can lose a great deal of thermal energy. This review compiles studies that either directly report recirculation loop losses or provide information to find an averaged value, for 46 multifamily buildings (Zhang, 2013; Dentz et al., 2015, Heller and Oram, 2015; Springer et al., 2015, Heller et al., 2017).

Notably, this project found that most literature on CDHW systems is about how to save energy using pump control strategies for the recirculation loop, many of these studies measure the delivery of hot water through tenant complaints and ignore measuring the loop thermal losses. While most studies saw savings several noted that implementing pump controls increased energy use (Zhang, 2009; 2013) or failed to deliver hot water in a timely manner (Dentz et al., 2017).

The range of loop losses presented range from 10 to 553 W/unit with an average of 143 W/unit and a median of 93 W/unit, with a median temperature drop between the supply and return of 4 °F. On average this is 30% of the total water heating energy used or heat produced.

Recirculation loops, predominately in unconditioned spaces, can show a large degree of seasonal variation in energy loss. In Heller et al. (2017) this was about 100 W/unit from winter to summer. Seasonality associated with the recirculation loop losses could be removed by moving the recirculation loop into a conditioned space. There is no standard placement among designers or recommendation in the code for placement of recirculation loops within conditioned spaces.

In general, there is no standard design practice for CDHW recirculation piping layout. In reviewing building plans and speaking with plumbers Zhang (2013) found there were no widely accepted guidelines, and different designers followed their own practices which may be unrelated to improving system efficiency. This is a need for developing standards for recirculation loop designs.

A comparison to theoretical loop losses showed that measured losses were increased 130% compared the theoretical losses in two buildings, perhaps due to uninsulated pipe hangers and fittings (Heller et. al. (2017). However, one building with insulated pipe hangers had measured losses with an increase of 5% of the theoretical. Plumbing codes do not require insulation around pipe fittings and the pipe insulation that is required is interpreted as a relatively low R-value.

Future research should shift focus from pump controls to collecting better information on the general recirculation system design including piping sizes, lengths, and insulation in new buildings to compare to loop losses. Ideally this research could lead to a calculation methodology which could be used to predict loop loses and identify energy efficiency

measures that could be used to reduce losses. Studies that can directly show energy savings between a classic recirculation system design and an optimized design are likely to make a high impact in the field.

1. Introduction

Domestic hot water (DHW) systems typically represent the second-largest end use of energy in residential buildings nationwide, about 20%, exceeded only by space conditioning (Sachs et al., 2011). In Seattle, for new multifamily buildings DHW is now the largest energy end use after major strides in HVAC energy reduction since Heller et al. (2009). A majority of mid-rise and high-rise multifamily buildings in the Washington, Oregon, Idaho, and Montana (NEEA**,** 2019**)** have central domestic hot water (CDHW) systems. However, in the past decade, of its own new construction projects, Ecotope has observed nearly all buildings using CDHW systems (Heller et al. 2017). In multifamily buildings, using CDHW has numerous advantages including reducing floor space required for water heating, reducing capital cost, ease of maintenance, and, in some cases, decreased energy use per unit compared to having in-unit DHW.

In a centralized system, water is often continuously circulated through a loop to maintain the hot water temperature close to the fixtures. Having water constantly circulated through a loop results in the water continuously losing thermal energy to its surroundings. One estimate of the losses associated with distribution suggests it is approximately 33% of the energy used or the heat produced for water heating. This could represent 5 – 10% of the energy use of an entire building, based on direct measurements and billing assessments of a small number of buildings (Zhang, 2013; Heller et al. 2009). Collected in this review are 46 buildings from publications in the literature and measurements made by Ecotope that largely agree with the results of Zhang (2013). Distribution losses were found to range from 10 to 553 W/unit, both from Zhang (2013), with a median of 93 W/unit.

This large portion of wasted energy has been targeted since the 1980s when one study estimated loop loses represented 46% of total DHW use for one New Jersey building (DeCicco, 1988). Researchers during this period, and after, sought to reduce the recirculation loop losses mostly by incorporating pump controllers and temperature modulation into the CDHW system.

The bulk of the literature on CDHW systems is about how to save energy using pump control strategies for the recirculation loop. This is likely for a variety of reasons but largely because most studies are retrofits where insulating piping behind finished walls, or relocating the piping, would be extremely costly and difficult, but putting controls on the recirculation pump is relatively easy and lower in cost.

Pump controls seek to save energy by reducing temperature in the recirculation loop thus reducing heat loss but also reducing the temperature of water at the fixtures. Studies on pump controls used tenant complaints to measure if hot water was delivered successfully often touting only one complaint during the testing periods. Studies largely failed to measure quantitative changes in the hot water usage when using pump controls, which was observed to increase for two large buildings where tenants had to wait longer for hot water (Dentz, 2017). Ecotope measurements of 92-unit and 118-unit buildings (Heller and Oram, 2015) and a study of three new 12-unit buildings by Ecotope (Heller et al., 2017) showed there were few periods when the recirculation pump could be turned off by the controller, even at 3 AM. There were some nights

where no water was used for several hours, but not every night, and knowing the non-use nights *a priori* is likely not possible.

The reason pumps cannot be turned off is as follows: Plumbing design requires pipes to be sized for peak flow events – when many fixtures on the same distribution pipe are in simultaneous use. That leads to distribution (riser) pipe diameters from one to several inches depending on end uses present. Spread out from tens to hundreds of feet in a building, that creates a significant volume of water in the piping. If the circulation pump is turned off and the water allowed to cool, in excess of the entire pipe volume (nominally 1.5 times) must be cleared before it is possible to provide hot water at the farthest fixtures from the water heater. Even in the best case (where only tens of gallons are contained in the distribution pipe volume), it will still take several minutes for a typical 5 - 10 gallon per minute (gpm) pump to clear the cold water. In more typical cases, it takes even longer. It is not possible to increase the pump size to, say 20-100 gpm because then the pipe diameter would need to be increased to allow the higher flow rate which in turn requires a bigger pump and larger pipe diameter.

Further still is the minimum amount of measurements needed in these studies to show energy savings over a short period. These studies measure the energy use of the water heating equipment and the pump, without a focus on measuring temperatures and flows necessary to calculate recirculation loop losses. (Lobenstein et al, 1990; Goldner, 1999; Enovative Systems, 2008; 2009; 2010a; 2010b; 2011; Benningfield Group. 2009; Bender and Kosar, 2014). Research is done by retrofitting CDWH systems with a pump controller and alternating between continuous recirculation and controlled recirculation weekly or biweekly for up to a year, but often shorter, i.e., six months. All the studies listed above show energy reduction of 6 – 28% compared to continuous recirculation when using a pump controller. Other studies have seen an increase in the DHW energy usage when using pump controls (Zhang, 2009; 2013).

More important to this review are the few studies that directly measure, and report temperatures and flows related to, or directly report, recirculation loop losses (Zhang, 2013; Dentz et al., 2015, Heller and Oram, 2015; Springer et al., 2015, Heller et al., 2017). Of these studies only Springer et al. (2015) and Heller et al. (2017) was conceived and written with a focus on recirculation loop losses. This review will focus on the methods and results of these studies as well as numerous other monitoring projects done by Ecotope Inc.

2. Loop Loss Calculation

A graphical summary of the energy inputs and outputs to a CDHW system is given below, from Zhang (2013), illustrating how the water heating equipment provides hot water energy to the recirculation loop and branch. In Figure 1, the thermal energy in the recirculation loop is split into two components, firstly the recirculation flow and secondly the hot water draw. The supply from the water heating equipment to the recirculation loop is as labeled as $\dot{E}_{RecircFlow_Supply}$ and $\dot{E}_{Draw_Supply}$ for the two components respectively. The recirculation flow loses energy through pipes, labeled by $\dot{Q}_{RecircFlow_Loss}$. Hot water draw events also have pipe losses through the recirculation loop and the branches labeled, $\dot{Q}_{Draw_Recirc_Loss}$ and $\dot{Q}_{Draw_Branch_Loss}$ respectively. The

delivered energy, $\dot{E}_{Draw_Deliver}$, is equal to $\dot{E}_{Draw_Supply} - \dot{Q}_{Draw_Recirc_Loss} - \dot{Q}_{Draw_Branch_Loss}$, and the total recirculation pipe heat loss, $\dot{Q}_{Recirc_Loop_Loss}$, is the sum of heat losses associated with the recirculation flow and the hot water draw events in the loop, $\dot{Q}_{RecircFlow_Loss} + \dot{Q}_{Draw_Recirc_Loss}$.

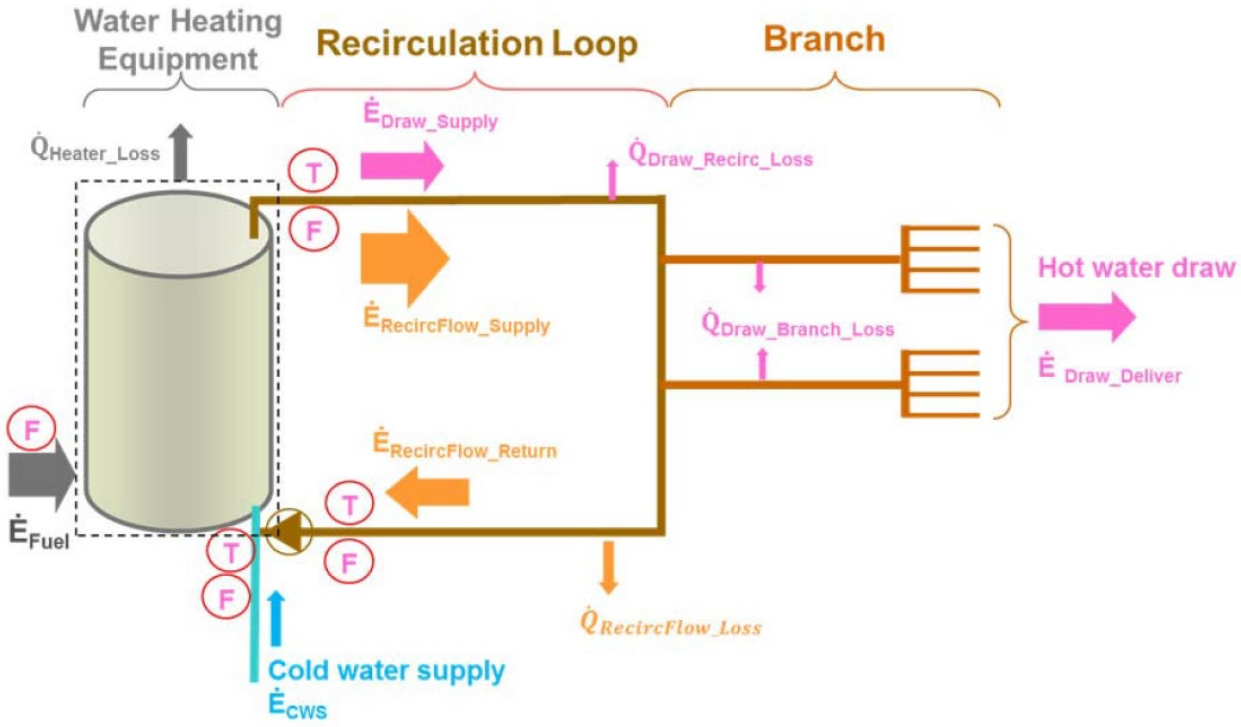


Figure 1. Illustration of energy sources and losses in CDHW from Zhang (2013).

The recirculation loop heat loss is a much larger inefficiency in the CDHW systems than the losses in the branches associated with draws[1]. As mentioned above this heat loss is given by:

[1] In Zhang (2013), the heat loss associated with hot water flowing through the branches during draws can be written as:

$$\dot{Q}_{Draw_Branch_Loss} = \rho\, C_p\, f_{Draw}\left(T_{HW_Branch} - T_{HW_Fixture}\right)$$

Where ρ is the density of water, C_p is the heat capacity of water, T_{HW_Branch} is the hot water temperature at the entrance of the branch, $T_{HW_Fixture}$ is the how water temperature at the fixture, and f_{Draw} is the hot water draw flow rate. The heat loss due to draws moving through the branches was estimated to range from 0.1% to 3.6% (with a median of 0.4%) of the aggregate energy consumption for 28 multifamily buildings, which is a negligible part of the total energy use.

$$\dot{Q}_{Recirc_Loop_Loss} = \dot{Q}_{RecircFlow_Loss} + \dot{Q}_{Draw_Recirc_Loss}$$

Using an energy flow analysis method, the two components can be found from easily measured variables of temperature and flow:

$$\dot{Q}_{RecircFlow_Loss} = \rho\, C_p\, f_{Recirc}(T_{HWS} - T_{HWR})$$

$$\dot{Q}_{Draw_Recirc_Loss} = \rho\, C_p\, f_{Draw}(T_{HWS} - T_{HW_Branch})$$

Where $\boldsymbol{\rho}$ is the density of water, $\boldsymbol{C_p}$ is the heat capacity of water,$\boldsymbol{T_{HWS}}$ is the hot water supply temperature from the water heating equipment, $\boldsymbol{T_{HWR}}$ is the hot water return temperature, $\boldsymbol{T_{HW_Branch}}$ is the hot water temperature at the entrance of the branch. $\boldsymbol{f_{Recirc}}$ is the recirculation flow rate, and $\boldsymbol{f_{Draw}}$ is the hot water draw flow rate. Using the energy flow method accounts for all the hot water flows entering and leaving the recirculation loop, and all energy inputs into and out of the loop.

In Zhang (2013) $\dot{Q}_{Draw_Recirc_Loss}$ and $\dot{Q}_{Draw_Branch_Loss}$ are calculated with temperatures which are parameterized based on loop supply temperatures and distance to branches and fixtures for the, eight, full on-site field study buildings. The parameters derived for eight buildings are extrapolated to the other 20 buildings. Whether the average loop configuration of the 8 buildings is representative of the entire sample of buildings is unknown.

Measurements of the flow variables are commonly drawn from flow meters in the recirculation loop for f_{Recirc}, and the cold water supply for measuring f_{Draw} as new water entering the system is used to replace the water exiting the system during hot water draw events. T_{HWS} and T_{HWR} also are simple to measure temperatures at the inlet and outlet of the recirculation loop.

We will ignore the draw (re)circulation losses in the analysis since we are most concerned with the temperature maintenance load, or the difference in the heat supplied to the loop and returned from the loop, because this is the load that the water heating system must bring back up to the supply temperature. The draw (re)circulation losses only lead to lower supply water temperatures at the tap. Further, the draw recirculation losses were found to be, on average, 2% of the total hot water energy used in Zhang (2013) a much smaller portion than the recirculation loop losses, 33%.

3. Studies

We will review the purpose and methods of studies which monitored recirculation loops in multifamily buildings and published recirculation losses or information to calculate the losses.

3.1. Zhang (2013)

By far, the most comprehensive single study on multifamily CDHW distribution is the Public Interest Energy Research (PIER) report (Zhang, 2013), which built on years of prior study (Zhang, 2009; Zhang et al., 2012).

The PIER report was written to guide recommendations for the energy code in California along with the CASE report, which was part of the prior research, (California Utilities Statewide Codes and Standards Team, 2011) to develop an understanding of the recirculation system performance and assess potential energy savings. The study monitored 28 multifamily buildings ranging in size from two to five stories to identify potential energy savings. The site details of these buildings are available in Table 1. In-depth monitoring of eight specific buildings went for over one year. These detailed measurements provided constants that could be used in extrapolation for the other 20 buildings. For example, the water heater equipment loss due to inefficiencies with gas and loss of thermal energy was, on average, 33% of the total energy use for the eight buildings studied in-depth and was assumed to be a constant 30% for the 20 buildings with a partial study.

All the monitored buildings were outfitted to find the recirculation loop losses directly. Temperatures were measured using pipe surface-mounted thermocouples and thermistors. Water flow was measured using inline magnetic flowmeters and surface-mounted ultrasonic designed for low flow measurements.

Zhang (2013) also sought to characterize recirculation system piping layouts by interviewing the designers to understand common practices, visually inspecting piping, and collecting building plumbing plans. This research revealed the fact that there are no widely accepted guidelines or methods used by designers. Recirculation piping varied in location and length, sometimes reaching every unit in the building and other times using long branches to reach units. Further still, the number of recirculation loops varied and did not follow any pattern. The study published only four buildings with detailed recirculation loop designs.

After aggregating 28 buildings and simulating four buildings in detail, Zhang (2013) concluded that the best solution for reducing recirculation losses was moving the mechanical room and the recirculation loop to the middle of the building to minimize pipe length and thus improve overall system efficiency by reducing the loop losses.

Table 1. Buildings in California from Zhang (2013).

Sites	Stories	Units	Age	Monitor Period (months)	Recirculation Loop Location	Insulation
A-SAM	3	87	1999	>12	Top floor	1 inch
B-SFD	4	98	2005	>12	Garage	1 inch
C-SFH	3	44	2008	>12	Garage	1 inch
D-SFF	5	82	1993	>12	Garage	1 inch
E-DAE	3	250	<1980	2	First Floor	Unk
F-SAA	5	49	1993	2	Top floor	Unk
G-LAB	2	20	1965	2	Garage	Unk
H-LAR	2	20	1960	2	First floor	Unk
1-SFB	4	40	2006	2	Ground floor	Unk
2-BKS	4	27	1999	2	Ground floor	Unk
3-BKU	3	35	2005	2	First floor	Unk
4-SAP	2	11	1950	2	Garage	Unk
5-SAC	2	16	1950	2	Garage	Unk
6-DAK	4	88	2005	2	Ground floor	Unk
7-DAL	4	88	2005	2	Ground floor in neighboring building	Unk
8-OAL	2	22	2008	2	Next to building	Unk
9-OAL	3	28	2008	2	Garage	Unk
10-SFF	5	>60	> 1990	2	Garage	Unk
11-HOB	2	20	1965	2	Garage	Unk
12-HOB	2	12	1965	2	First floor	Unk
13-HOL	3	25	1960	2	Basement	Unk
14-HOC	2	16	1935	2	First	Unk
15-HOL	3	35	2003	2	Garage	Unk
16-DAR	2.5	>60	1965	2	In a stand-alone building serving multiple buildings	Unk
17-SAP	2	16	1960	2	First floor	Unk
18-SFP	5	>60	>1990	2	On the roof	Unk
19-OAO	2	<30	<1990	2	First Floor	Unk
20-LAE	2	<30	< 1990	2	First Floor	Unk

3.2. Springer et al. (2015)

The focus of Springer et al. (2015) was to test making up recirculation losses with solar water heaters in the San Francisco Bay Area of California. The use of solar thermal water heating to cover recirculation heat loss had not been studied; in part this is likely due to the cost of retrofitting existing buildings to modify the piping.

Due to this focus, they do directly measure and report the recirculation losses for two new buildings built in 2013 and 2014, 3 stories tall, with 50 and 46 units, see Table 2. Both use 1-inch thick fiberglass insulation on the recirculation loop piping, as is required in California's 2008 Title 24 building energy code in accordance with ASHRAE Standard 90.1-2007. However, branches are uninsulated. A standard continuous recirculation mode was monitored for five weeks between July and October 2014, alternating between the baseline and a solar water heater.

The study measured temperatures on hot water supply and return of the recirculation loop using surface-mounted thermocouples, and recirculation flow using nonintrusive sonic flowmeters.

The study saw energy savings of 25% and 41%, for the Lafayette and Dublin sites respectively, by diverting recirculated hot water to solar storage tanks during July and August. Numerical modeling showed savings could be increased in climates with higher solar insolation.

Authors noted the payback of less than one year for some climates easily justifies the implementation of a solar water heater recirculation system in new buildings. The cost of retrofitting a building to include such a system does not justify a retrofit measure. Although a building with higher recirculation loop losses due to a lack of pipe insulation and a relatively large solar collector area could benefit.

Table 2. Buildings from Springer et al. (2015).

Location	Sites	Stories	Units	Age	Monitor Period (months)	Recirculation Loop Location	Insulation
Lafayette, CA	Site 1	3	50	2013	1	Inside the conditioned space	1 inch
Dublin, CA	Site 2	3	46	2014	1	Inside the conditioned space	1 inch

3.3. Dentz et al. (2015)

The focus of Dentz et al. (2015) is on CDHW control strategies and how they are cost-effective in retrofits in New York, where temperatures can drop to -25 °F in the winter. The authors looked at four buildings, details of which are available in Table 3. Buildings C and D were sister properties in Brooklyn, NY, with similar architecture and mechanical systems; both buildings were only three stories tall.

The baseline situation run in Dentz et al. (2015) was a continuous recirculation pump with a constant supply water set point. The authors switched between the baseline and multiple control strategies every 1 – 3 weeks for 12 months for buildings A and B, and eight months for buildings C and D, covering all the seasons.

The study measured numerous water and room temperatures in the CDHW and runtimes for the boilers and recirculation pumps in the interest of monitoring temperature modulation controls and calculation energy savings. Relevant temperature measurements to this study were made with Watlow thermocouples at the supply and return of the recirculation loop. The recirculation loop flow was measured once for each building using a Portaflow ultrasonic flow meter. For the analysis in this review, this one-time measurement is assumed to be average for the baseline condition during the monitoring period.

Building C has a higher supply temperature due to a broken controller, which was not fixed during the monitoring period.

Table 3. Buildings from Dentz et al. (2015).

Location	Sites	Stories	Units	Age	Monitor Period (months)	Recirculation Loop Location	Insulation
Flushing, Queens	A	7	54	Unk	12	Unk	1/2 inch
Coney Island, Brooklyn	B	15	122	Unk	12	Unk	1/2 inch
Brooklyn, NY	C	3	54	Unk	8	1st floor ceiling	1/2 inch
Brooklyn, NY	D	3	48	Unk	8	Unk	1/2 inch

3.4. Ecotope Inc.

Ecotope has a continuing interest in recirculation loop losses in multifamily buildings to reduce inefficiencies in CDHW systems. We have collected a set of four buildings where continuous monitoring occurred over varying periods, as well as seven more buildings where various spot measurements were made with surface mounted thermistors and an ultrasonic flow meter. Data include two reports (Heller and Oram, 2015; Heller et al., 2017), and multiple measurements shared in public presentations. The profiles of measured buildings are available in Table 4.

During its monitoring period, the Elizabeth James and Yesler 2E site recirculation and return pipes data was incomplete due to thermistor malfunctions, therefore, for Yesler 2E we report only a single spot in this review, and for Elizabeth James, we report an average of three spot measurements made over a few months. The period is unimportant for Elizabeth James as the recirculation loop is in a conditioned space.

Heller et al. (2017) performed an analysis on two new nearly identical buildings, Grow Bainbridge Building A and Building D, to minimize variation in independent variables while changing the recirculation loop designs. Building A uses a classic recirculation loop as a reference case and Building D uses a pipe in pipe plumbing system.

The pipe-in-pipe system recirculates water within concentric pipes, the hot water supply flows on the outside of the pipe and the return water flows back through the interior pipe. This reduces the heat loss by combining the supply and return recirculation pipes into one pipe thereby reducing the surface area of piping, however as the radius of the pipe-in-pipe piping must be larger than classic recirculation the surface area is not cut in half.

Table 4. Buildings from monitored by Ecotope Inc.

Location	Sites	Stories	Units	Age	Monitor Period (months)	Recirculation Loop Location	Insulation
Seattle, WA	Denning	5	46	2014	4	Rooftop solarium	Unk
Bainbridge Island, WA	Building A - Classic	3	12	2016	22	Garage	Risers in wall insulation, R-11
	Building D – Pipe-in-pipe	3	13	2016	19	Garage	
Seattle, WA	Stream Uptown	6	118	2013	Spot	Garage	1 inch
	Sunset Electric	6	92	2014	Spot	Garage	1 inch
	Sitka	6	384	2018	Spot	Garage	1.5 inch
	Elizabeth James	4	60	1968	Spot	First Floor Ceiling	Unk
	Yesler 2E	7	195	2018	Spot	Garage	2 inch
	Yesler 3	7	237	2018	Spot	Garage	2 inch
Issaquah, WA	Vale Apartments	5	110	2019	Spot	Interior	1.5 and 2 inch
Pasadena, Ca	Pasadena HP	3	70	2016	Spot	Interior and Exterior	1.5 Inch

4. Results

4.1. Measured Values

Table 5 summarizes loop losses for 46 buildings measured by the above studies and Ecotope's project monitoring.

Table 5. Summary of recirculation loop losses across studies.

Study	Sites	Stories	Units	Recirc Flow (GPM)	Average Loop Temp Drop (°F)	Loop Losses (W/unit)	Annual Loop Losses (kWh/unit)	Loop Losses % of Total DHW
Zhang (2013)	A-SAM	3	87	2.2	12.2	45	395	37%
	B-SFD	4	98	12.1	8.3	150	1311	32%
	C-SFH	3	44	5.1	4.2	71	623	15%
	D-SFF	5	82	7.7	2.1	29	252	6%
	E-DAE	3	250	16.2	4	38	332	29%
	F-SAA	5	49	4.7	11.5	161	1411	38%
	G-LAB	2	20	6.1	2.9	129	1132	32%
	H-LAR	2	20	3.3	4.5	108	950	25%
	1-SFB	4	40	9.1	3.7	123	1077	36%
	2-BKS	4	27	5.4	2.8	82	717	31%
	3-BKU	3	35	11.4	0.2	10	83	3%
	4-SAP	2	11	3.8	6.2	313	2741	40%

	5-SAC	2	16	5.5	2.9	146	1276	38%
	6-DAK	4	88	3.6	11.4	68	597	9%
	7-DAL	4	88	4.1	10.6	72	632	9%
	8-OAL	2	22	14.6	5.7	553	4840	58%
	9-OAL	3	28	9.8	2.6	133	1164	30%
	10-SFF	5	>60[2]	14.7	8.5	281	2460	39%
	11-HOB	2	20	5.7	1.5	62	547	15%
	12-HOB	2	12	4.4	3.7	198	1736	42%
	13-HOL	3	25	10.3	2.3	138	1213	61%
	14-HOC	2	16	4.6	2	84	736	36%
	15-HOL	3	35	3.6	17.8	267	2343	19%
	16-DAR	2.5	>60[2]	23.1	5.1	265	2319	51%
	17-SAP	2	16	7.1	7.1	460	4031	47%
	18-SFP	5	>602 above	15.4	8	277	2425	29%
	19-OAO	2	<30[2]	3.9	10	228	1996	42%
	20-LAE	2	<30[2]	10.2	1.3	77	679	19%
Springer et al. (2015)	Site 1	3	50	7.93	4	93	812	47%
	Site 2	3	46	6.18	1.41	28	242	20%
Dentz et al. (2015)	A	7	54	9.54	3	77	678	11%
	B	15	122	19.1	3	69	601	9%
	C	3	54	11	6	179	1564	19%
	D	3	48	6.73	3	61	538	11%
Ecotope (Long Term)	Denning	5	46	21.7	4.1	278	2438	
	Building A - Classic	3	12	3.822	4	172	435	44%
	Building D – Pipe-in-pipe	3	13	3.141	2.5	100	1507	39%
	Elizabeth James	4	60	6.036	3.5	45	875	
RCC (2015)	Stream Uptown	6	118			49	377	33%
	Sunset Electric	6	92			53	429	45%
Ecotope (Spot)	Sitka	6	384			64	463	
	Vale Apartments	5	110			35	561	
	Yesler 2E	7	195			86	307	
	Yesler 3	7	237			80	700.8	
	Pasadena HP	3	70			435	3810.6	

[2] [2] Buildings with units greater than 60 and less than 30 where assumed to have 65 and 35 units respectively for calculation of the total loop losses in W/unit.

Loop losses, from spot measurements to yearly averages, presented ranges from 10 to 553 W/unit with an average of 143 W/unit and a median of 93 W/unit, seen in the histogram in Figure 2. Annually, the median is 812 kWh/unit or 27.7 therms/unit, which equates to driving 2706 miles, for each unit, in a Nissan Leaf at 0.3 kWh/mile. On average, this is 30% of the total water heating energy used or heat produced, based on Zhang (2013), Heller and Oram (2015), Springer et al. (2015), Heller et al. (2017) and other data collected by Ecotope Inc or approximately 10% of the total building energy use. Likewise, the temperature drop between the recirculation loop supply and return ranged from 0.2 to 17.8 °F, with a median of 4 °F. All of the bounding values given here are from Zhang (2013).

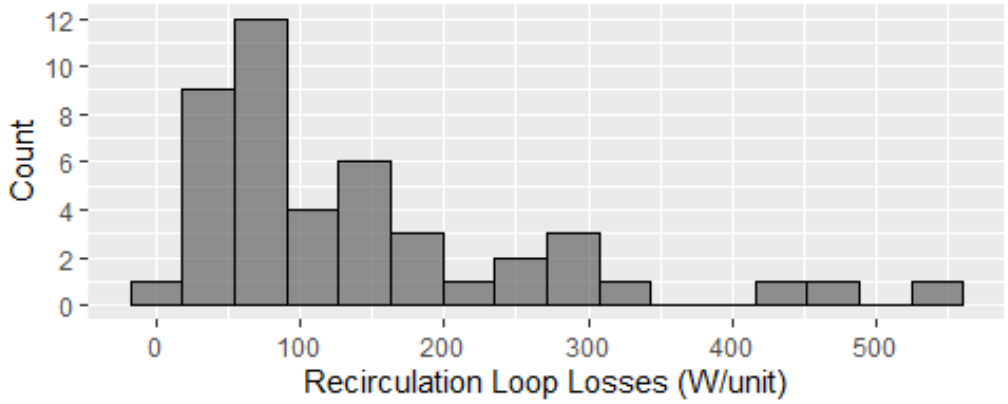


Figure 2. Histogram of Recirculation Loop Losses found in this review.

Most results reported in Table 5 are an average over the monitoring period, but Ecotope's long term monitoring demonstrates how the recirculation loop losses evolve. We can see in Figure 3, the evolution of the recirculation loop losses over the year.

Figure 3 shows an increase in loop losses in the winter months compared to the summer months. In the case of Bainbridge Building A, 84% of the total piping length of recirculation loop is in the unconditioned garage space, whose ambient air temperatures are highly correlated to the outdoor air temperature. The seasonal change in air temperatures cause the recirculation losses to approximately double between the summer and winter months. (Heller et al., 2017).

Based on descriptions given of recirculation loop locations, approximately 40% of the data collected here was made with a monitoring period of fewer than eight months with a loop at least partially in an unconditioned space, predominately from Zhang (2013) and spot measurements made by Ecotope. The measurements made in Dentz et al. (2015) include at least eight months of temperature data, but only one spot measurement of the recirculation loop flow. Based on continuous measurements from recirculation loops, the flow is somewhat constant over a year. These measurements that do not cover every season could be biased to be greater or less than the yearly average based on what time of year the measurements were made, which only serves to add more noise to our data.

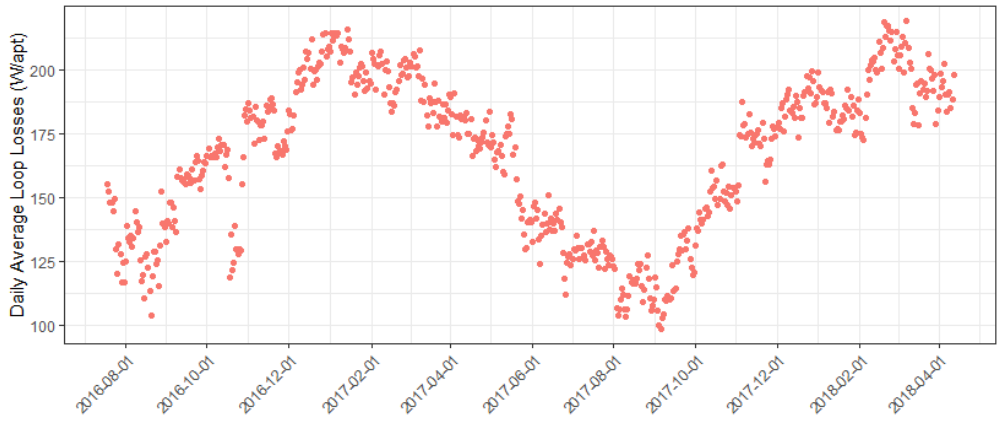


Figure 3. Recirculation Loop Losses in the Grow Bainbridge Building A.

4.2. Comparison to Theoretical

For Grow Bainbridge (Heller et al., 2017) and Yesler 2E, Ecotope had previously counted and totaled pipe lengths and diameters to attain a theoretical heat loss from the recirculation loops. To calculate the theoretical heat losses, we used the following temperature assumptions: garage 50 °F; the indoor air temperature 70 °F; and DHW a constant 122 °F in supply pipes and 118 °F in return pipes. The calculations, which exclude thermal bridging from pipe fittings and supports, are thus a low-end estimation.

The difference between the theoretically calculated and the measured values are shown in Figure 4. The Grow Buildings are both measured at 130% of the theoretical value. Remarkably the difference shown for Yesler 2E is only 5% of the theoretical value, possibly due to insulated pipe hangers which were explicitly required and inspected during installation. Figure 5 depicts an example of insulated pipe hangers that eliminate thermal bridging and maintain full pipe insulation depth through the pipe supports.

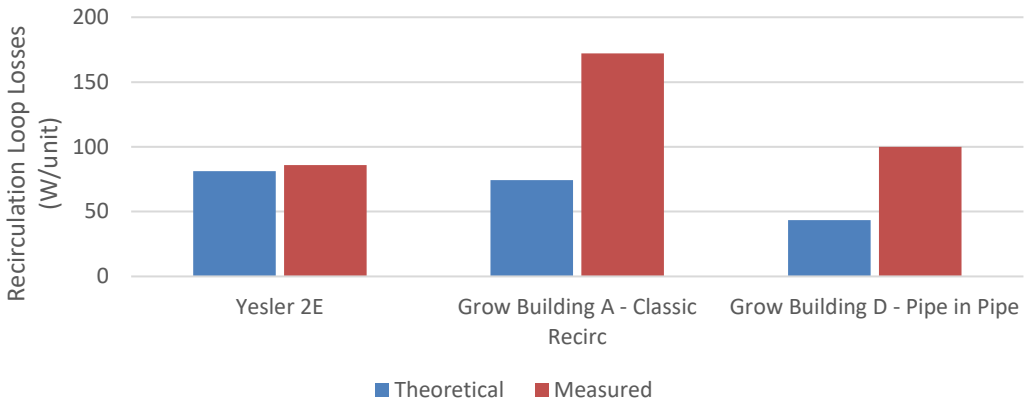


Figure 4. Difference in Theoretical and Measured Recirculation Loop Losses.

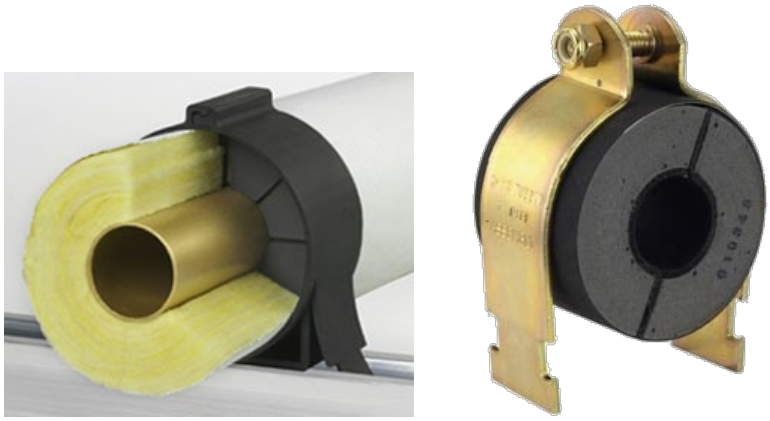


Figure 1: Insulated pipe hangers

Bainbridge Building D uses pipe in pipe technology, which effectively reduces the exposed surface area of the recirculation loop by putting the supply pipe inside the return pipe. The theoretical prediction is for a 42% reduction in the heat lost from Building A to Building D, which corresponds to what is measured. If the theoretical calculation accurately predicts heat loss from the idealized pipes, the difference in the theoretical and the actual measurements may be predominately attributed to heat loss from uninsulated pipe fittings and conductive thermal bridges from pipe clamps. This points to an obvious place to increase insulation.

5. Recirculation Loop Codes

Table 6 gives an overview of the codes and standards used in California, Oregon, and Washington in the regulation of recirculation loops.

To summarize Table 6, California is farthest along in reducing recirculation loop thermal losses through the highest insulation requirements and the prescriptive measure of incorporating a dual-loop design. This design measure comes at the recommendation of the conclusions of Zhang (2013) that to minimize heat loss the best action was to improve the recirculation loop design. The California Utilities Statewide Codes and Standards Team (2011) estimated that the surface area for the recirculation loops could be reduced in two prototype buildings, a high-rise, and a low-rise, by placing the mechanical room in the middle of the building and increasing the number of recirculation loops by two thus reducing the pipe diameter of each. The total surface area of the recirculation loop between the prototype buildings and the optimized buildings was reduced by 29% and 51% for the low-rise and high-rise respectively, see Appendix A. It should be noted, however, that the original and optimized recirculation loops did not recirculate the risers to the apartments.

California, Oregon, and Washington all require piping insulation on recirculating hot water piping of roughly R-3, with exceptions provided for fittings and obstructions such as going through walls. This low insulation requirement is arguably lagging stricter insulation requirements, such as the requirements for building envelope at about R-20. Ecotope Inc. current standard practice is to double the required amount of insultation in

new buildings and emphasize reducing thermal bridging by insulating pipe clamps and hangers.

All the states require recirculation pumps that can be controlled and turned off. This requirement is flexible in that no specific control system is required; the control system could use timers, aquastats, or some on-demand activation system. The prevalence of pump controls in the codes across these three states is likely linked to the long history of positive research and case studies on saving energy with pump controllers dating back to the 1980s. The results have often been published as the best solution to solving recirculation losses in multifamily buildings (Goldner, 1999; Ayala and Zobrist, 2012; Kerr and Sweeney, 2014), but these have focused mainly on retrofits where redoing the entire recirculation plumbing would be near impossible. Whereas, only recently have studies began to numerically model and place more significant importance on recirculation system design (Backman and Hoeschele, 2013; Zhang, 2013; Weitzel and Hoeschele, 2014).

Table 6. Summary of codes in California, Oregon, and Washington relating to circulation loops.

	Pump	Hot Water Piping		Loop Design
State	**Pump Control**	**Insulation**	**Size**	**Compact Design**
California (2019)	Capable of automatically turning off the system when hot water is not required. Such controls include automatic time switches, interlocks with HVAC time switches, occupancy sensors, and others that accomplish the intended purpose.	• Insulation is not required on the branches or twig serving the point of use. • All hot water to the kitchen must be insulated. • Recirc pipe insulation between 105 - 140 F needs conductivity 0.22 - 0.28 with 1 inch of insulation for pipes <1" and 1.5 inch of insulation for pipes >= 1" pipe	Maximum Volume of hot water with recirculation contained in the branches between the loop and the fixture fitting not exceed 16 oz.	A dual-loop design is each loop serves half of the dwelling units. Pipe diameters can be downsized compared to a loop serving all units and total surface area is effectively reduced.
Oregon (2020)	Must have a recirc pump. That can be set to include on-demand activation or timers combined with temperature sensing. (ASHREA 90.1-2016)	Recirc pipe insulation between 105 - 140 F needs conductivity 0.22 - 0.28 with 1 inch of insulation for pipes <1.5" and 1.5 inch of insulation for pipes >= 1.5" (ASHREA 90.1-2016)	Maximum Volume of hot water with recirculation contained in the branches between the loop and the fixture fitting not exceed 16 oz.	
Washington (2015)	Heated water circulation systems shall be provided with a circulation pump. Controls for circulating hot water system pumps shall start the pump based on the identification of a demand for hot water within the occupancy.	Recirc pipe insulation between 105 - 140 F needs conductivity 0.21 - 0.28 with 1 inch of insulation for pipes <1.5" and 1.5 inch of insulation for pipes >= 1.5" (ASHREA 90.1-2016)	Limitation on the maximum pipe length or volume given from the circulating loop to the fixture by Table C404.3.1, approximately 64 oz.	

6. Conclusions

DHW use and delivery is a significant portion of energy consumption in residential buildings. In multifamily buildings the CDHW systems often use recirculation loops to deliver hot water to tenants in a timely fashion. To understand and develop a standard for multifamily CDHW recirculation loop losses this review gathered data on 46 buildings in California, New York, and Washington. On average, for buildings measured, the loop losses accounted for 30% of the energy used or heat supplied by the water heater in the CDHW.

The measured recirculation loop losses ranged from 10 to 553 W/unit, both reported in Zhang (2013). The median building is a three-story building with loop losses at 93 W/unit from Springer et al. (2015). Long-term monitoring in Heller et al. (2017) showed a seasonal variation of about 100 W/unit, which doubled the energy lost from the summer months to the winter months.

The seasonality associated with the recirculation loop losses can be removed by moving the recirculation loop into a conditioned space. There is no standard placement among designers, or recommendations in the code for placement of recirculation loops within conditioned spaces. In conditioned spaces, the heat lost by the loops will interact with the building heating and cooling loads; this is an understudied area touched on in Heller and Oram (2015) and Dentz et al. (2016). During winter months, recirculation loop losses will offset space heating energy in buildings, conversely, during the summer months, the loop losses will increase space cooling energy. Whether or not it is overall efficient in multifamily buildings to place recirculation loops in conditioned spaces is a question for a more extensive study, likely looking across multiple climate zones where heating and cooling loads vary.

A still understudied part of the picture is how much uninsulated pipe fittings and thermal bridges from mounts will de-rate the pipe insulation. As suggested in the Bainbridge buildings, this could be a significant portion of the heat loss. However, the direct impact on energy loss in larger buildings must be quantified.

In general, there is no standard design practice for CDHW recirculation piping layout. In reviewing building plans and speaking with plumbers Zhang (2013) concluded there were no widely accepted guidelines, and different designers followed their own practices, which may be unrelated to improving system efficiency. Another study that inspected 50 sites found that 80% of the systems had uninsulated piping, and at least 10% of sites had failed hot water recirculation pumps (KEMA, 2008). Meaning not only is code needed for recirculation loop design, but code enforcement is as well.

Future research should shift focus from pump controls to collecting better information on the general recirculation system design, including piping sizes, lengths, and insulation in new buildings to compare to loop losses. Ideally this research could lead to a calculation methodology which could be used to predict loop loses and identify energy efficiency measures that could be used to reduce losses such as reducing the length of distribution piping by sharing common risers between apartment, increasing insulation and eliminating thermal bridging, reducing the size of pipes by using optimized sizing

methods, and moving all piping into the insulated envelope of the building. Studies that can directly show energy savings between a classic recirculation system design and an optimized design are likely to make a high impact in the field.

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8. Appendix A

Tables A1 and A2 are adapted from California Utilities Statewide Codes and Standards Team (2011) to illustrate the reduction in surface area when incorporating two recirculation loops into the design. In both prototype buildings they took a mechanical room that was on the edge of a building and moved it to the middle of the building and split the circulation loop into two separate loops. Since each loop serves fewer units they also reduced pipe diameters. Decreasing the diameter greatly reduces the surface area. Neither of the loop designs circulated the risers however, which is a common practice in loop design. The optimized design with two recirculation loops has 29% and 51% less surface area for the low-rise and high-rise respectively. As recirculation loop heat losses could be expressed as a linear function of the surface area of the pipes, this could correlate directly to a 29% and 51% reduction in the loop heat loss.

Table A1. Low-Rise Recirculation Loop Surface Area adapted from California Utilities Statewide Codes and Standards Team (2011).

Low-Rise	Section Type	Supply 1	Supply 2	Supply 3	Return 1	Return 2	Return 3	Total (Two Loops in Optimized)
Default Design	Section Length (ft)	113	103	133	133	103	113	698
	Average section pipe diameter (inch)	2.67	2.43	1.75	1	1	1	
	Surface Area	2416.7	1824.6	1221.9	399.0	309.0	339.0	6510.2
Optimized Design	Section Length (ft)	57	59	59	59	59	57	700
	Average section pipe diameter (inch)	2.35	2	1.44	0.75	0.75	0.75	
	Surface Area (inch^2)	944.3	708.0	367.0	99.6	99.6	96.2	4629.4

Table A2. High-Rise Recirculation Loop Layout adapted from California Utilities Statewide Codes and Standards Team (2011).

High-Rise	Section Type	Supply 1	Supply 2	Supply 3	Return 1	Return 2	Return 3	Total (Two Loops in Optimized)

Default Design	Section Length (ft)	204	103	133	133	103	204.3	880.3
	Average section pipe diameter (inch)	3.5	2.93	2.14	1	1	1	
	Surface Area	7497.0	2652.7	1827.3	399.0	309.0	612.9	13297.9
Optimized Design	Section Length (ft)	56.6	59	59	59	59	56.6	698.4
	Average section pipe diameter (inch)	2.85	2.38	1.81	0.75	0.75	0.75	
	Surface Area (inch^2)	1379.2	1002.6	579.9	99.6	99.6	95.5	6512.6