Best Practices for Hot Water Distribution Systems in Multifamily Buildings: A Comparative Evaluation of Balancing Methods

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ABSTRACT

Hot water distribution systems in multifamily buildings are crucial for both occupant comfort and energy efficiency. Ensuring these systems are well-balanced is paramount to maintaining consistent hot water delivery while minimizing energy consumption and waste. This research conducted laboratory testing to address the design and best practices of balancing methods for central recirculation distribution systems.

For this research, PG&E's Applied Technology Services research laboratory developed a full-scale recirculation system for serving a 3-story multifamily building with 36 dwelling units. This system provides process measurement data that unavailable from field studies and allows for an in-depth investigation of the balancing methods. The study evaluated three types of balancing valves (i.e., manual, thermostatic, and automatic constant flow types) to assess their performances. Through a comprehensive comparative analysis, this research reveals the impact of interactions among balancing valves, hot water draws, and recirculation pump speed controls on system performance. Considering the manual balancing method with 0.5 gallons per minute (GPM) per riser recirculation flow as the base line, the best performing balancing valve has the potential to reduce up to 12% of the thermal losses in the HWD system by providing the opportunity of using lower recirculation flow without compromising the user's comfort. It was found that automatic balancing valves did not always achieve the expected performance target because their flow control capabilities were limited and were greatly affected by recirculation pump speed controls.

Introduction

In domestic hot water systems, recirculation heat losses contribute to roughly one-third of hot water system energy use both in existing single family (Backman & Hoeschele, 2013) and multifamily (Zhang, 2013) buildings. Given the prevalence of central domestic hot water systems in buildings, minimizing these recirculation energy losses presents a significant opportunity for enhancing overall hot water system performance.

The awareness of significant heat losses from Hot Water Distribution (HWD) systems is not new. However, stricter energy regulations have led to reduced available energy for designing new buildings, resulting in renewed interest in HWD energy waste reduction. Also, the recent integration trends of central heat pump water heaters into both new and existing buildings underscored the critical importance of reducing HWD system energy losses for heat pump's optimal operation. (Bøhm, 2013) conducted filed monitoring from 13 apartment buildings and two offices to record the consumption of hot water, heat loss from HWD system and evaluate the overall efficiency of the HWD system. One of the findings of this study is that, between 23-70% of the supplied heat for each apartment has been lost in the recirculation and distribution system. In a similar study, (Zhang, 2013) studied domestic hot water system operations in 28 multifamily

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buildings. These multifamily buildings had between 11 and 250 dwelling units each and ranged from two to five stories tall. This study concluded that "the average DHW system efficiency of all the monitored buildings was 35 percent. The average recirculation system heat loss fraction of all monitored buildings was 33 percent. The remaining 32 percent of total DHW system natural gas consumption was mostly accounted by heat loss by water heating systems." (Zhang, 2013). (Thrasher & DeWerth, 1993) performed monitoring and analysis of hot water consumption monitoring at five commercial buildings in four different building uses. They analyzed hot water demand patterns for two dormitories, a nursing home, a full-service restaurant and a hotel. (Ayala & Zobrist, 2012) analyzed the conditions of common central domestic hot water systems, best practices for improving efficiencies, the potential impact on a national level, and how utilities and governments can help drive the penetration of these practices. Their findings showed that, despite water heaters becoming more efficient, and fixtures becoming low flow, the method for distributing hot water to the point of use has lagged in terms of performance improvement. Furthermore, (Klein, Lutz, Zhang, & Koeller, 2021) conducted a detailed literature review outlining the design issues within hot water distribution systems and approaches taken to combat them. (Carl C. Hiller, 2009) conducted an extensive laboratory research to quantify water and energy waste of a variety of hot water distribution system pipe materials and sizes in different environments and installation configurations mostly focused on residential building applications. One common outcome in these studies has been the large portion of heat losses observed through the HWD systems.

Although the literature on central hot water systems from field measurements and computer simulation studies is abundant, details on heat losses from large-scale HWD system of pipes is rarely available. Field-measured recirculation heat loss could be much higher than design and modeling predictions. The reason for this discrepancy can be due to imperfect pipe insulation and/or recirculation system being un-balanced and/or cross flows across the cold and hot flows. Providing detailed information on large scale HWD system energy performance is necessary to improve the ability of designers and building operators to enhance conventional practices effectively.

In many multifamily Hot Water Distribution (HWD) systems, the supply pipe is split into parallel paths to reach different parts of the building before being connected to the return pipe. One popular design, especially in mid-rise and high-rise multiple buildings, is to use vertical risers as parallel paths to reach all dwelling units on different floors. Water will travel through the least resistance path whenever there are parallel paths in a piping system. In these systems, it is important to ensure balanced recirculation flows among all parallel paths so all dwelling units can receive hot water quickly. In an unbalanced system, the path with highest resistance (usually the farthest riser) will not receive enough hot water flow. This means excessive flows in some part of the piping with the potential of large energy losses, erosion in the piping and pump failure, as well as long wait for the hot water at remote fixtures.

The goal of the current work is to present best practices for design and operation of a multifamily HWD system, focused on various balancing methods and their effect on system energy efficiency. A real-life size hot water generation and distribution system has been developed in a controlled laboratory environment for a 3-story residential building with 36 dwelling units. Three common methods to balance the system (including manual, automatic flow control and thermostatic flow balancing), were implemented and performance of the system has been evaluated for each method. It is more likely that the production and distribution of hot water in buildings will constitute a dominant share of both the present, and the future energy design requirements of buildings. The results of this project could influence not only future buildings, but also existing buildings when energy retrofit projects are taken place.

Testing Method and Materials

The HWD tests were conducted at the ATS Advanced Technology located at 3400 Crow Canyon Road, San Ramon CA. The testing apparatus consists of an insulated test chamber with its ambient conditions (i.e., dry bulb air temperature) controlled tightly according to the test requirements.

Test Chamber

The test chamber is constructed with dimensions of 30 ft in length, 12 ft in width, and 20 ft in height. Chamber walls and ceilings are insulated with overall resistance value (R-value) of 19 hr-ft^2-°F/Btu. The floor is concrete and not insulated. Figure 1 shows a simplified single line diagram of fabricated domestic hot water recirculation system. More detailed design of the piping as well as equipment placements inside and outside the chamber are depicted in Figure 2. Type L copper tubing has been used in the piping system. And straight pipe runs have been insulated according to California's Title 24 requirements. Total length of various pipe diameters inside the chamber can be found in Table 1. The ambient condition inside the chamber is controlled using electric heat pumps. Two outdoor units which feed two air-handlers each, have been employed to keep the dry bulb air temperature inside the chamber at test conditions continuously.

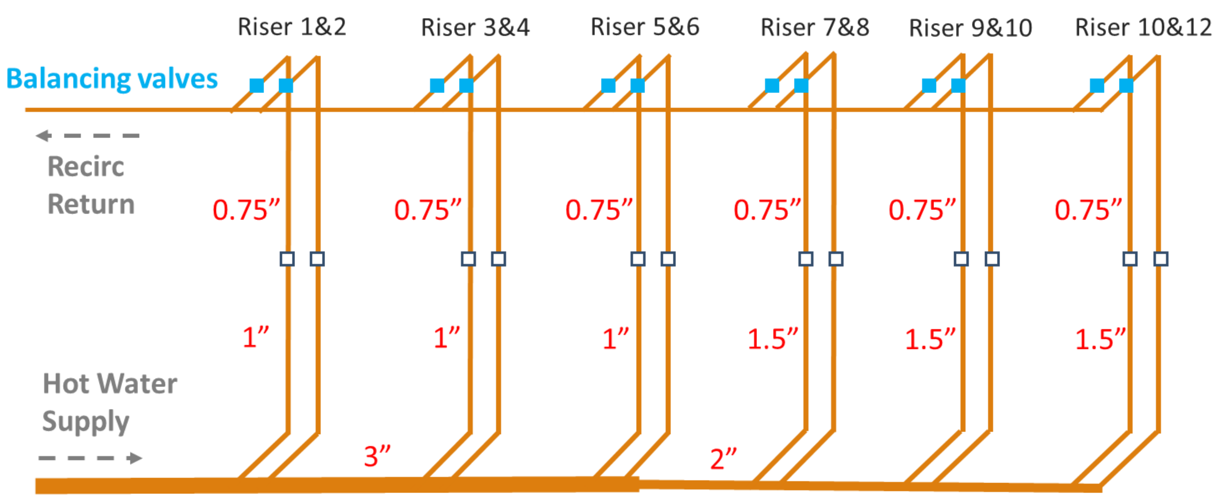

Figure 1. Simplified single line diagram of the domestic hot water recirculation piping.

Table 1. Total length of various pipes sizes installed.

Pipe size	3 in	2 in	1.5 in	1 in	¾ in
Total length	40 ft	102 ft	107 ft	130 ft	724 ft
Insulation thickness	2 in	2 in	2 in	1.5 in	1 in

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Instrumentation

The hot water distribution system is instrumented thoroughly to provide precise control and data collection capabilities during each test. These instruments include: 18 water flow meters, 54 temperature sensors, 37 pressure sensors, and one power meter to record various metrics of the HWD system during each test.

Table 2 summarizes the information regarding sensors installed in the setup. Instruments are connected to several National Instruments Compact-RIO chassis, which are dedicated for test chamber control and data collection and recording. The Compact-RIO chasses communicate over an Ethernet network to a central host computer, which ran a custom data acquisition and control program developed with National Instruments LabVIEW™ graphical programming language. The program acquires readings from the chasses twice per second, applies calibration scaling, maintains a running average for each measurement, and logs the averages to a file every 5 seconds.

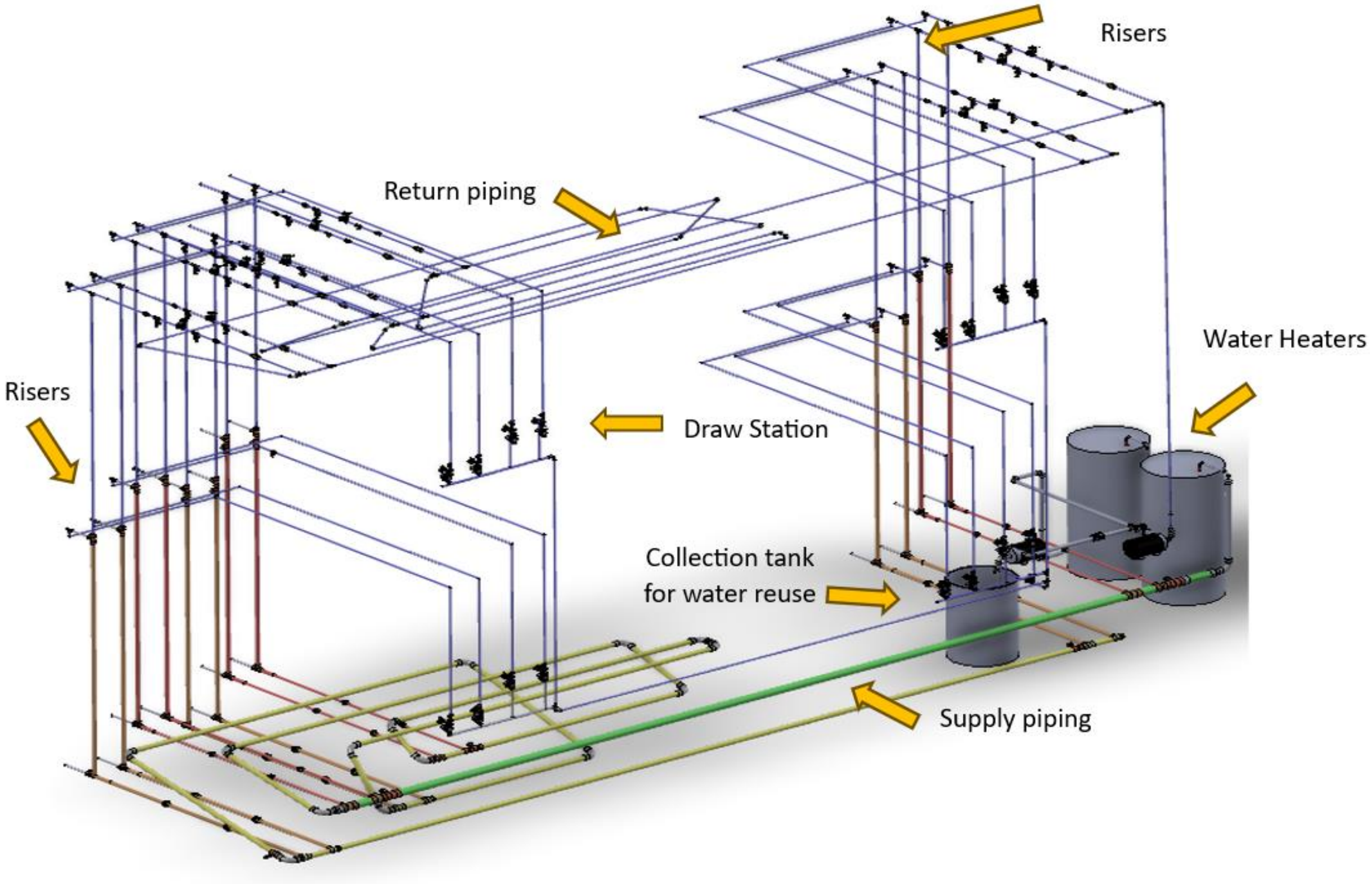

Figure 2. piping design and equipment placement (3D view).

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Table 2. Test Instrumentation types and accuracy ranges

Measurement	Instrument	Make	Accuracy
Barometric Pressure	Multi-function weather station on roof of building	Vaisala WTX520	±0.007 PSIA (±50 Pa)
Chamber's DBT and water temperatures in the setup	Fast-response resistance temperature detectors (RTDs)	Burns Engineering	±0.2°F
Temperature trees installed inside tanks	Type T thermocouple sensor	OMEGA	±0.2°F
Water pressure	General Purpose Pressure Transmitter ATM.ECO	PMC Engineering	≤0.2% FS
Water flow	Recordall Disc Meters (Model 70 – 1 in)	Badger	±0.04 GPM
Water flow	Recordall Disc Meters (Model 25 – 5/8 in)	Badger	±0.04 GPM
Supply Power, Voltage and Current	3-element true-RMS power meter with outputs for total power, voltage and current	Yokogawa WT330	±(0.1% of reading +0.1% of range)

Performance Evaluation of Various HWD Balancing Methods

Properly balancing the HWD system makes sure enough water flow through each parallel path. Unbalanced recirculation can trigger end-user complaints, which may lead the building operator to increase the HWD system temperature setpoint or increase the recirculation flow (if possible). Consequently, higher hot water supply temperature and/or recirculation flow rate will result in higher heat losses through the HWD system. To solve this issue, balancing valves are often installed to obtain the desired flow balance. In a domestic HWD system, the objectives of balancing are:

- Provide a minimum hot water temperature to the farthest fixtures in all branches of the system.
- Prevent stagnant water within any part of the system that has little or no demand for hot water.

To reach these goals, balancing valves are often installed to obtain the desired flow in each parallel path. There are three common valve types used to achieve balancing in a HWD system (see Table 3 for more details):

- **Manual balancing valves** are sized assuming a minimum flow in each parallel path (as a rule of thumb, a minimum of 0.5 GPM to 1.0 GPM is selected. any lower values will make balancing the system too difficult). These types of valves require pressure measurement taken on both sides of the valve's orifice. By extracting the flow coefficient of the valve (i.e., C_V factor) from the manufacturer's spec sheet, it is possible to estimate the flow rate across the valve.

- **Automatic flow valves** contain a flow limiting cartridge, which is factory pre-set. They are selected based on the pipe size and flow. These valves will result in a tighter flow tolerance compared to manual balancing valves.
- **Thermostatic balancing valves** are self-adjusting devices that change the valve opening with respect to water temperature passing through. The hotter the water, the less flow it allows to pass. These valves are sized based on the pipe size and temperature range of the water. When the system is cold the valves in parallel paths are mostly open, as the hot water reaches each valve, they start to close resulting in more hot water directed to the cold parts of the system. These valves never close completely, always letting some water across it.

Table 3. High level characteristics of each balancing method

Balancing method	Advantage	Disadvantage
Manual	- Low initial cost. - No need for detailed flow and thermal evaluations during design phase. - Easy to perform thermal disinfection of the HWD system during operation phase.	- Labor intensive during commissioning phase. - Need to repeat the whole balancing process in case of changes during operation phase. - Usually results in the use of larger return pipe, recirculation flow rate, and pump size.
Automatic Flow	- Moderate initial cost. - Easy to install and commission. - Tighter flow control through each parallel path. - Usually results in smaller return pipe, recirculation flow rate, and pump size. - Easy to perform thermal disinfection of the HWD system during operation phase.	- Need for detailed flow and thermal evaluations during design phase. - Limited flexibility in case there are any changes to the HWD system after installation.
Thermostatic	- Easy to install and commission. - Lower precision for flow and thermal evaluations during design phase will do the job. - Usually results in smallest return pipe, recirculation flow rate, and pump size. - Adjustable models are available to do fine tuning after installation.	- High initial cost. - Usually gets pricier if thermal disinfection of HWD system is considered, since the valves are designed to limit the flow through each path during normal operation.

In total, 7 different balancing valves were selected for evaluation. One manual balancing valve (i.e. Caleffi 142 series) with the target to set 0.5 GPM flow through each riser. Two automatic flow valves (i.e. Caleffi 127 series FlowCal) with flow cartridges 0.5 GPM and 0.35 GPM respectively. And four thermostatic balancing valves from different manufacturers (i.e. CircuitSolver manufactured by ThermOmegaTech, ThermoSetter-116 Series by Caleffi, Multi-Therm thermostatic balancing valve by Kemper, and Temp Setter from Xylem). The main goal of the study is to assess the performance of each balancing method.

Two sets of tests were performed with each balancing method. A series of tests were performed without any draws from the HWD system to evaluate the performance of each balancing method during stand-by conditions. During closed loop tests the recirculation pump controller was used to target specific total recirculation flow rates. The pump was set to aim and facilitate flow rates between 1.0 to 6.0 GPM. The test chamber ambient temperature kept at 70±2 ℉ and hot water temperature outlet from the mixing valve kept at 125 ℉ to provide tests boundary conditions consistent when comparing different balancing methods.

When there is a draw in a HWD system, the temperature of the water in the supply piping usually goes up. The second set of tests were performed with uniform draw profiles to evaluate the effect of hot water draws on operation of balancing valves and temperature distribution in the system. All four draw stations were utilized to observe the effects of neighboring draws on the operation of balancing valves, recirculation pump and hot water delivery temperatures.

Results and Analysis

In this section the characteristics and observations of the multifamily HWD system with different balancing methods are presented. Figure 3 and Figure 4 present the flow and temperature distributions of all 12 risers using the manual balancing method at 6 different recirculation flow levels. Figure 3 shows the flow rate across each riser (on the left) as well as total recirculation flow rate (on the right) for each recirculation level. It is worth mentioning that flowmeters could not capture flow rates below 0.1 GPM. Hence, level 1 and level 2 flow rates across risers may have been shown zero despite risers having a very low flow rate during these tests. Additionally, Figure 4 depicts the temperatures recorded at the top of each riser when the system reached steady state condition at each recirculation level.

As shown, manual balancing method effectively restricted the flow through closest risers and increased the hot water passing through farthest risers to generate a well-balanced temperature distribution in the HWD system. It is evident that by reducing the recirculation flow rate up to 50% (i.e. from level 6 to level 3), the water temperature at the top of all risers remains above 120 ℉. This observation Indicates the energy saving potential of a well-balanced system. The other observation from Figure 3 is that if a HWD system is balanced using the manual balancing method, there is no need to balance the system at specifically low flow rates, which is harder to achieve. The HWD system can be balanced at the highest possible recirculation flow rate during commissioning. Afterwards, and during operation phase, recirculation flow can be reduced to bring down the thermal losses in the system.

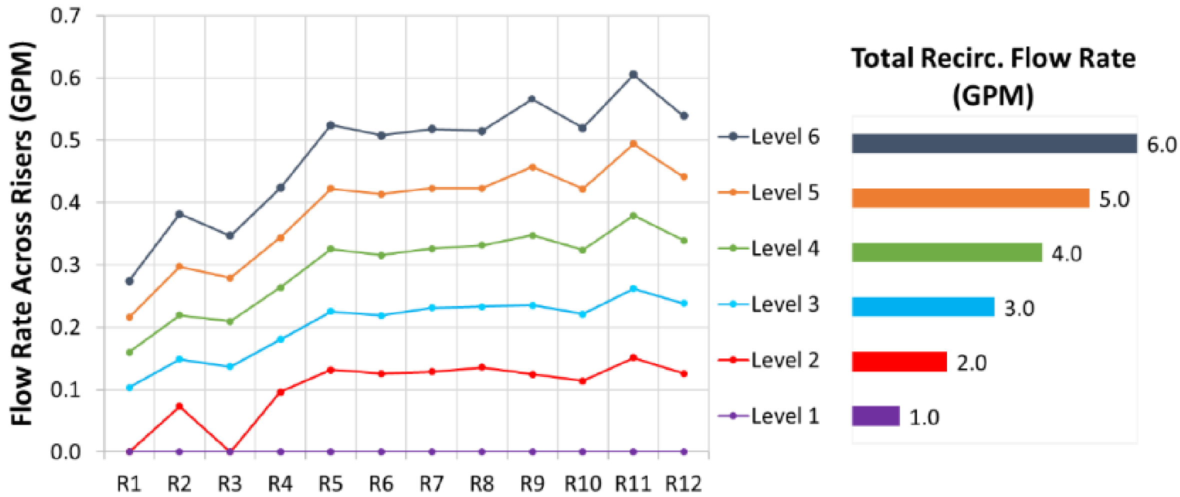

Figure 3. Flow distribution through 12 risers(left) and total recirculation flow rate (right) using manual balancing method.

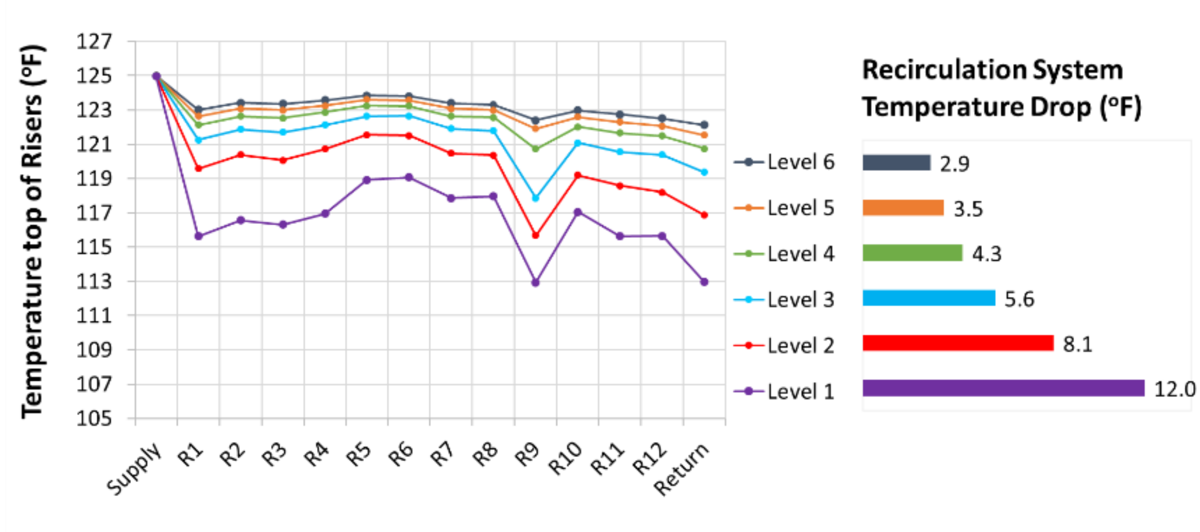

Figure 4. Temperature distribution through 12 risers and return temperature using manual balancing method (Note: there was a faulty temperature sensor installation on riser 9 which is visible).

Figure 5 through Figure 10 show the performance of different balancing methods for recirculation at target levels 6 through 1. At higher recirculation flow targets (i.e. level 6 and 5) almost all balancing methods reach well distributed temperatures between 2 ̊F to 5 ̊F across all risers. However, at lower recirculation flows (i.e. level 4 and 3), the temperature difference between the farthest and the closest risers starts to widen for automatic flow control valves and some of the thermostatic balancing valves. The reason for this drift can be described according to design characteristics of these devices. Automatic flow valves are designed to keep the flow constant across a specific pressure range. However, when there is not enough pressure applied through the valve at lower total recirculation flow levels, flow rate of farther risers starts to drop compared to the closest risers to the pump. Lower flows through farthest riser will result in the

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HWD system becoming thermally unbalanced. Similarly, thermostatic balancing valves usually allow a minimum flow through the valve to ensure that the recirculating pump is not "dead headed." At lower recirculation flow rates only one of the thermostatic balancing valves (i.e. BV-4) had low enough minimum flow to effectively balance the temperature distribution across the HWD system. BV-4 is the only thermostatic balancing valve tested that reduces the flow in each riser at pumping levels 6 through 3 low enough that the installed recirculation pump cannot ramp the total recirculation flow to the target pumping level.

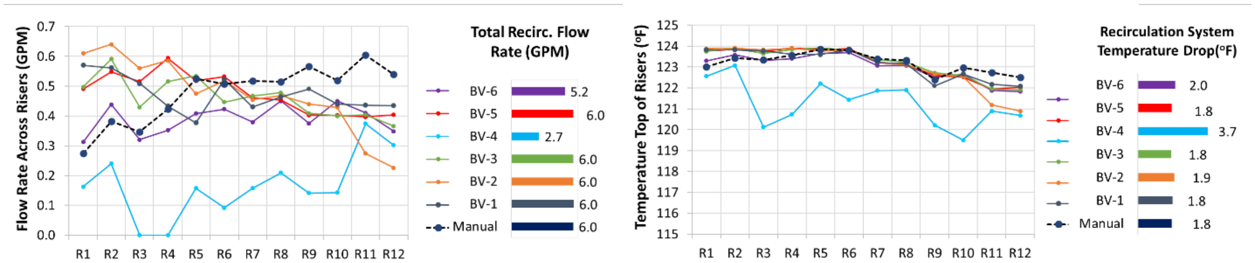

Figure 5. Temperature and flow distribution for recirc pumping level 6.

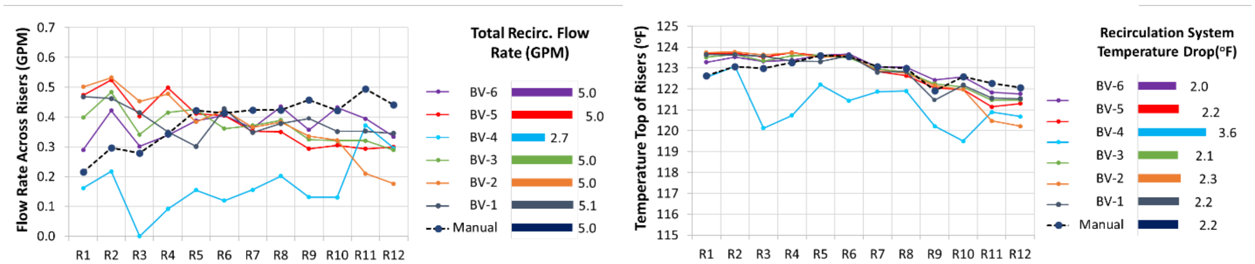

Figure 6. Temperature and flow distribution for recirc pumping level 5.

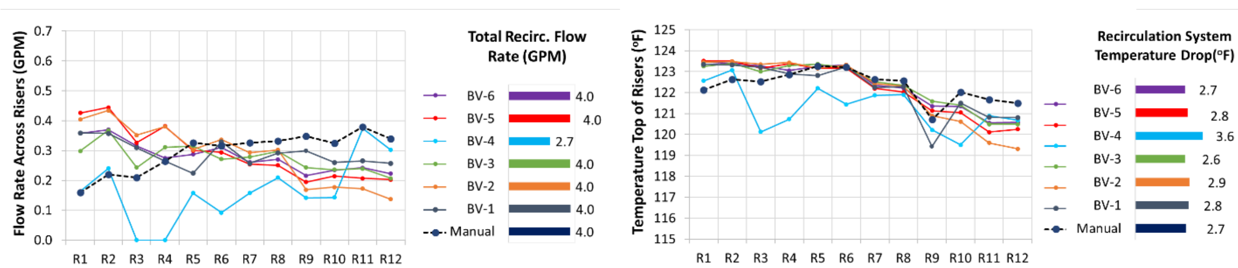

Figure 7. Temperature and flow distribution for recirc pumping level 4.

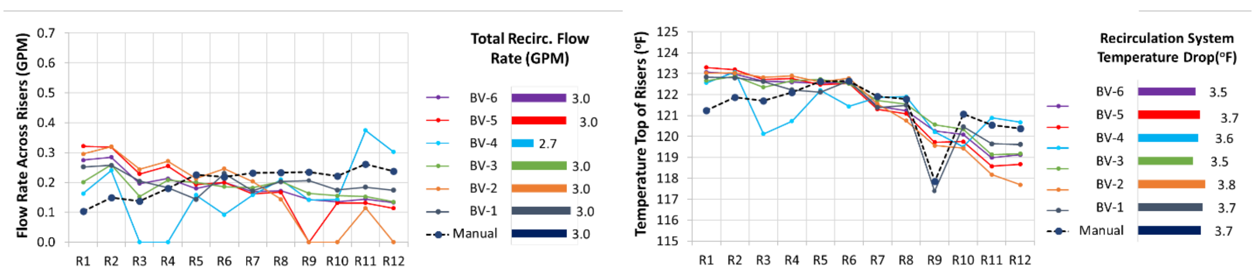

Figure 8. Temperature and flow distribution for recirc pumping level 3.

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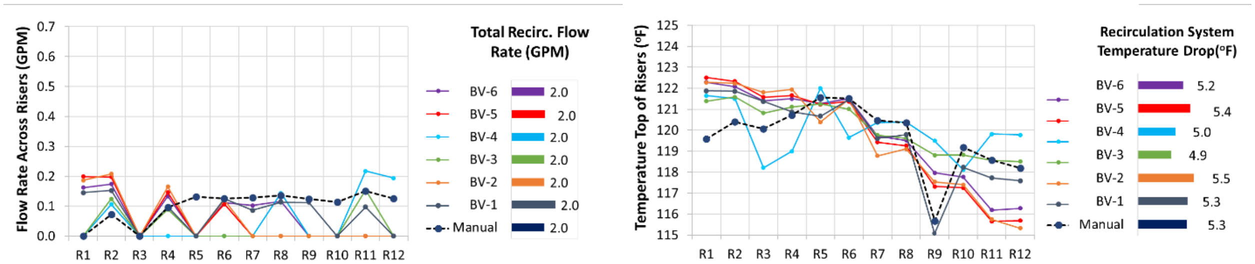

Figure 9. Temperature and flow distribution for recirc pumping level 2.

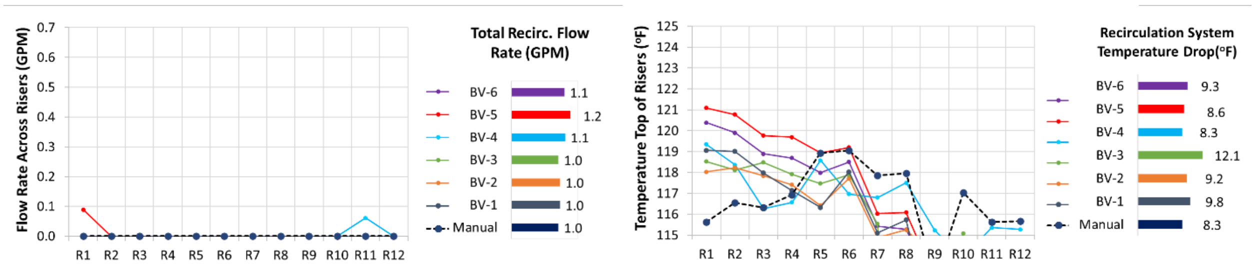

Figure 10. Temperature and flow distribution for recirc pumping level 1.

When the recirculation target level drops to very low values (i.e. level 2 and 1) none of the balancing methods can keep the system thermally balanced. Hence, it is not advised to reduce the recirculation flow to such a low value due to bacterial growth potentials during operation phase (ASHRAE standard 188, 2000).

When a HWD system is thermally balanced, usually total heat loss of the HWD system drops by decreasing the recirculation flow rate. However, if the pump is not working in the optimum operating conditions, the excessive heat dumped by the pump into the return flow will mask some of the energy savings. Hence it is important to use the right size pump in its optimum operation point with automatic and thermostatic balancing valves.

Figure 11 shows the improvement of energy performance of a balanced system by reducing recirculation flow rate when the farthest riser temperature (R12) remains above 120 ̊F. The heat loss of the HWD system is presented per apartment (i.e. 36 dwellings in the building) to make it easier compare results. Considering the manual balancing method with 6 GPM recirculation flow as the baseline, the best performing balancing valve reduces up to 12% of the thermal losses in the HWD system by providing the opportunity of reducing recirculation flow without letting the farthest riser temperature drop below 120 ̊F. However, if changing the balancing valves in the building is not an option, by reducing the recirculation flow it is possible to reduce up to 7% of HWD thermal losses for the same balancing valve type. It is worth mentioning the savings would be widely different for each building depending on insulation levels and other characteristics of the HWD system.

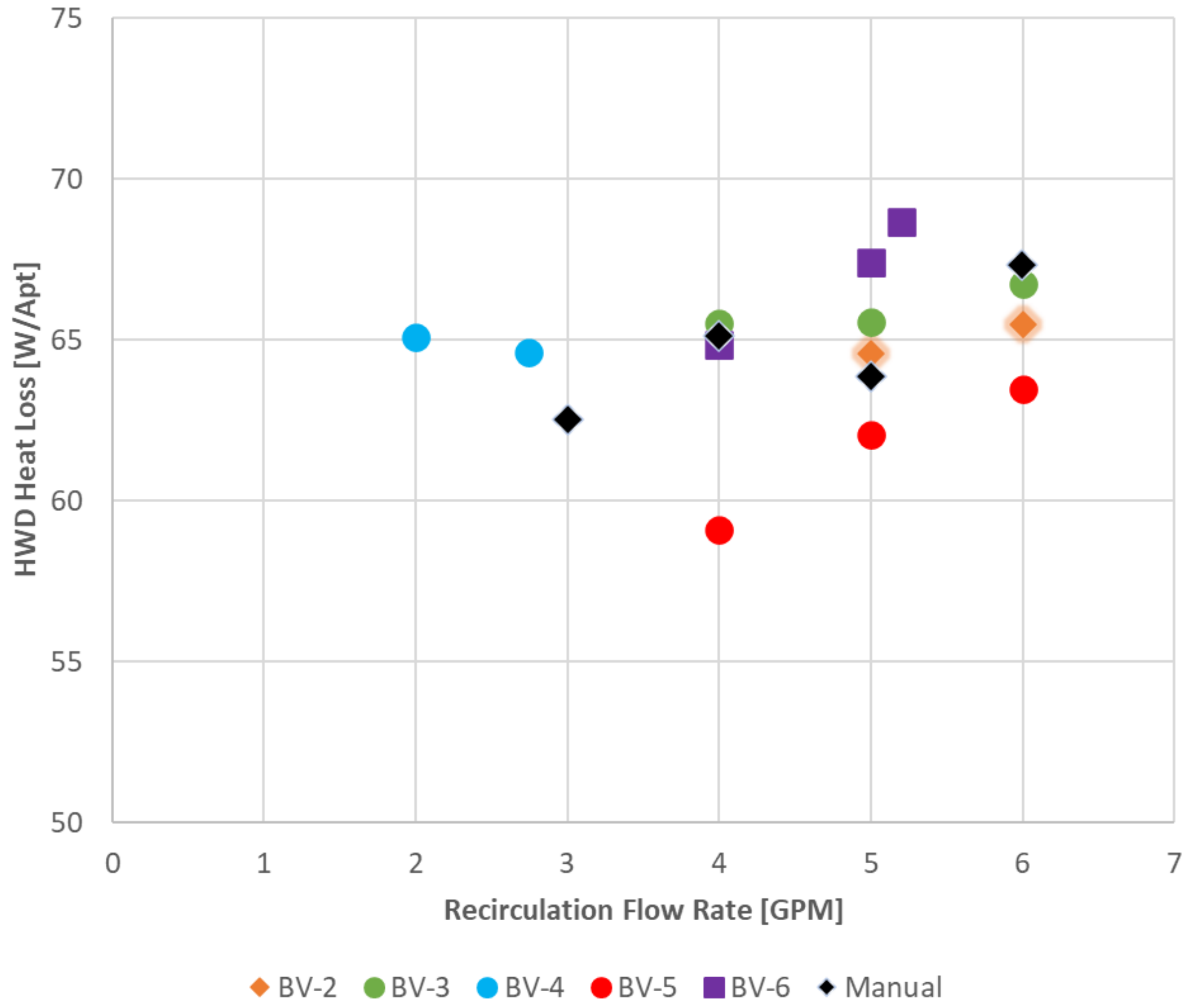

Figure 11. Heat loss through HWD system (presented as Watts per Apartment) vs. recirculation flow rate for the balanced system.

It has been suggested by manufacturers to use thermostatic balancing valves paired with a variable speed circulator, controlled by constant pressure rise across the pump. To evaluate the pump controller effect on the HWD system performance, a series of tests with similar draw profiles through draw stations were performed. During each test a fixed amount of hot water (between 1 to 8 GPM) was drawn from draw stations across risers. As it is shown in Figure 12 and Figure 13, no considerable performance difference has been observed comparing constant flow pump operation vs. constant pressure pump operation. At lower recirculation flow rates (i.e. Figure 13Figure 12) the return flow drops to zero. However, this should not generate any comfort issues for the user since hot water is being supplied constantly through the system and all risers would have access to hot supply water in a short time.

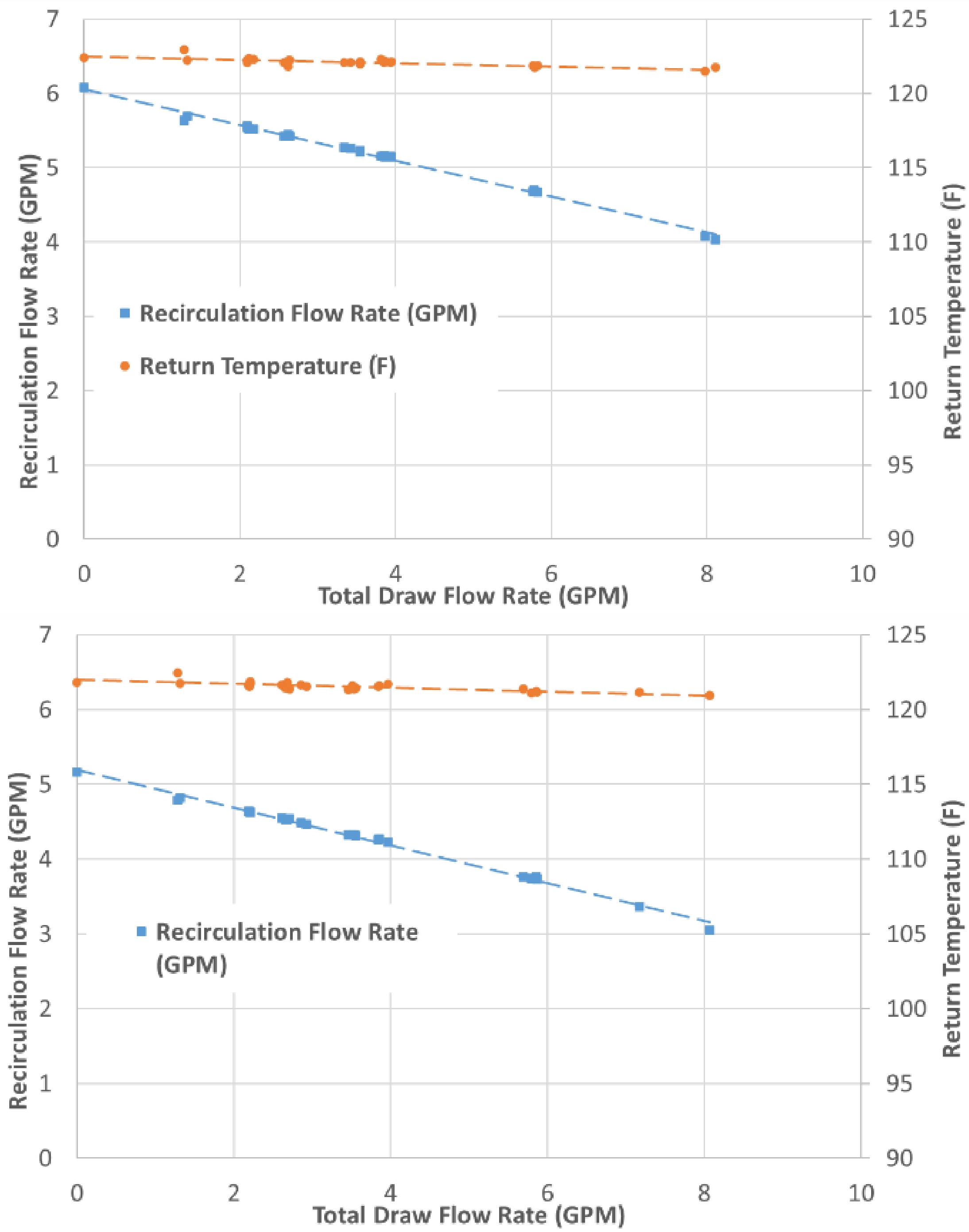

Figure 12. Illustrating hot water return temperature during various draw incidents. Constant pump speed at 100% (top) vs constant pressure rise across pump (bottom)

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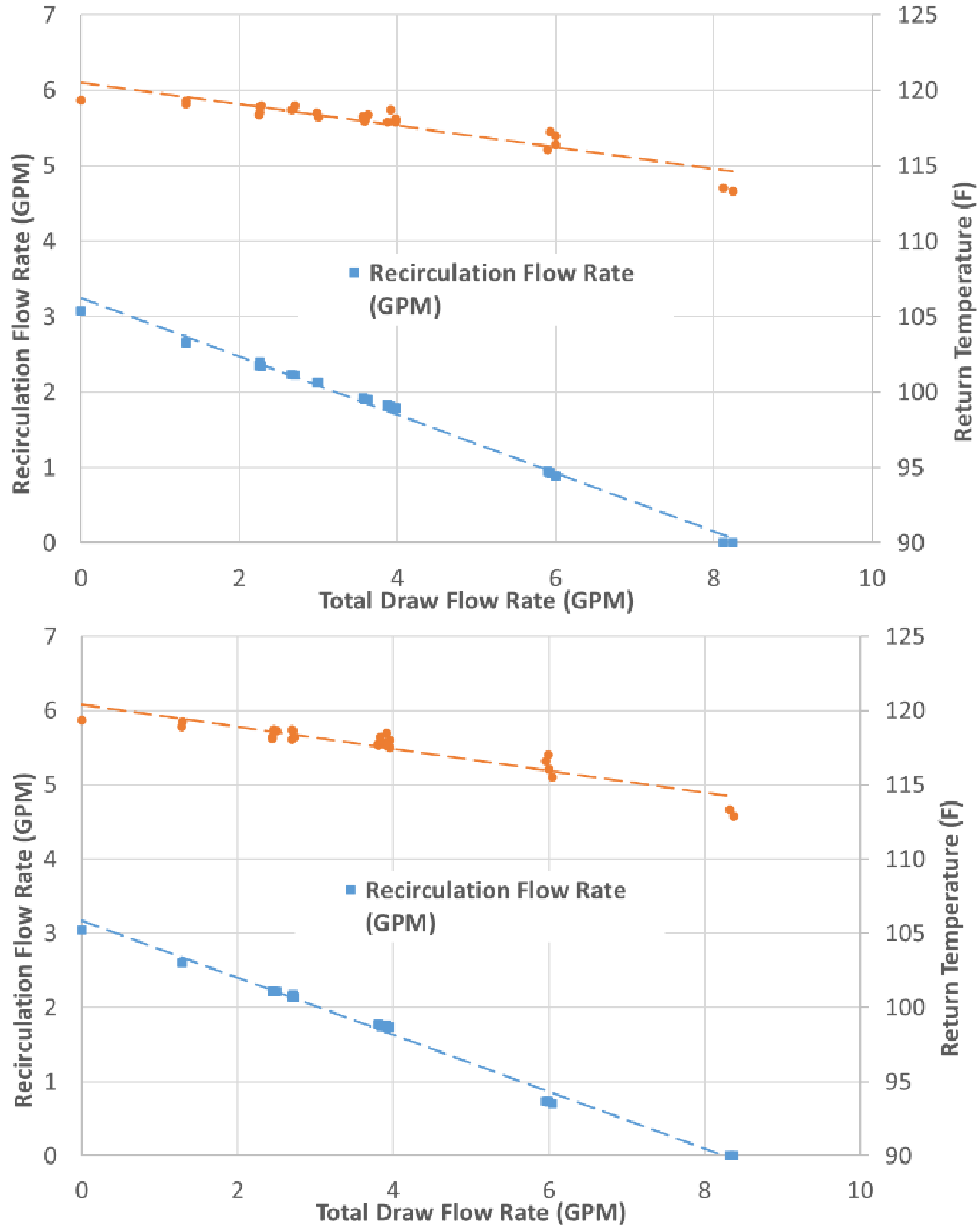

Figure 13. Illustrating hot water return temperature during various draw incidents. Constant pump speed at 50% (top) vs constant pressure rise across pump (bottom)

Conclusion

Laboratory testing of a full-scale central recirculation system provided extensive data revealing the performance of different balancing methods in regulating flow to achieve their respective balancing objectives. Key findings on the overall performance of BVs include:

- All BV products tested by the study were able to effectively balance the HWD system by enabling all risers to have a satisfactory recirculation temperature. The manual BV product required a time-consuming initial setup to achieve proper system balancing.
- The most uniform temperature distribution among risers was achieved at the highest recirculation flow rate (approximately 0.5 GPM per riser). As the recirculation flow was reduced, temperature differences between risers increased. When the recirculation flow was more than 0.25 GPM per riser, all BV products provided satisfactory temperature distribution among risers. With the recirculation flow less than this level, large temperature discrepancies were observed for some BV products, indicating degradation in balancing performance. None of the tested BV products could achieve satisfactory system balancing when the recirculation flow dropped to lower than 0.1 GPM per riser.
- Recirculation pump speed controls had little impact on system balancing and recirculation heating loss. Variable speed pumps may be used to achieve a proper recirculation flow rate.

Key findings on the performance of the three types of BVs include:

Manual BV:

- The manual BV product provided reliable system balancing after being set up to achieve equal recirculation flows through risers.
- The manual BV product provided more uniform recirculation temperature distribution among risers when the initial setup was performed using cold recirculation flows instead of hot recirculation flows. In fact, this BV setup achieved the most uniform temperature distribution among all BV products tested by the study.

Thermostatic BV:

- While all four thermostatic BV products provided satisfactory system balancing, only one product (BV#4) achieved the temperature setpoint by regulating recirculation flows. The other three thermostatic BV products had little impact on recirculation temperatures and heat loss, compared to the manual BV product.
- Thermostatic BVs need to be capable of significantly reducing recirculation flow rate to achieve temperature setpoint.
- To ensure all risers achieve the same temperature setpoint, recirculation flows through risers with a long flow path need to be higher than those with a short flow path. Only one thermostatic BV product (BV#4) was able to provide such a recirculation flow distribution.

Automatic flow BV:

- The two automatic flow BV products provided balanced recirculation operation even when the recirculation flow rate was below the BV flow rating.
- Test results show that automatic flow BV products were able to adequately reduce recirculation flow when the recirculation flow provided by the pump was moderately higher than the BV's flow rating. Due to limitations of the recirculation pump, the test study was not able to assess the capability of these BVs in regulating recirculation flow significantly higher than the BV's flow rating.

Acknowledgement

The presented work is a part of an ongoing research project being conducted at PG&E Applied

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Technology Services / Pacific Gas & Electric co. This project is supported by PG&E's Code Readiness Program, with the intention of providing data for the development of Codes and Standards Enhancements (CASE) proposals for consideration by the California Energy Commission to advance the California Energy Code (Title 24, Part 6). CASE proposals are developed and supported by the Statewide IOU Building Advocacy Program and in partnership with SMUD and LADWP.

References

ASHRAE standard 188. (2000). *Minimizing the Risk of Legionellosis Associated with Building Water Systems.*

Ayala, G. D., & Zobrist, D. (2012). Best Practices for Efficient Hot Water Distribution in Multifamily Buildings. *ACEEE Summer Study on Energy Efficiency in Buildings*, (pp. 14 - 22).

Backman, C., & Hoeschele, M. (2013). *Validation of a Hot Water Distribution Model Using Laboratory and Field Data.* U.S. Department of Energy's Building America Program Office of Energy Efficiency and Renewable Energy.

Bøhm, B. (2013). Production and distribution of domestic hot water in selected Danish apartment buildings and institutions. Analysis of consumption, energy efficiency and the significance for energy design requirements of buildings . *Energy Conversion and Management*, 152-159.

Carl C. Hiller. (2009). *Hot water distribution system laboratory testing phase III interim report.* Applied Energy Technology.

Eatherton, M. (2018, Dec). Challenges in DHW Distribution. *Contarctor Magazine*.

Feng, J., Delagah, A., Garcia, J., & Haile, J. (2023). *2025 Title 24, Part 6 Final CASE Report – Multifamily Domestic Hot Water.* California Statewide Codes and Standards Enhancement (CASE) Program.

Klein, G., & Sherman, T. (2016). Getting Into Hot Water – The New Energy Efficiency Frontier. *Summer Study on Energy Efficiency in Buildings 1* (pp. 1\1 - 1\10). ACEEE .

Klein, G., Lutz, J., Zhang, Y., & Koeller, J. (2021). *Code Changes and Implications of Residential Low-Flow Hot Water Fixtures.* California Energy Commission.

Knauth, E. (2019). *Pipe up! a leading edge prespective on best in cladd domestic hot water system design.* Armstron Hot Water.

Lutz, J. D., Klein, G., Springer, D., & Howard, B. D. (2002). Residential Hot Water Distribution Systems: Roundtable Session. *ACEEE*.

Moss, R., & Critoph, R. (2022). Optimisation of a recirculating domestic hot water system to minimise wait time and heat loss. *Energy & Buildings 260 (2022) 111850* .

Thrasher, W., & DeWerth, D. (1993). *COMPARISON OF COLLECTED AND COMPILED EXISTING DATA ON SERVICE HOT WATER USE PATTERNS IN RESIDENTIAL AND COMMERCIAL ESTABLISHMENTS.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Weitzel, E., & Hoeschele, M. (2014). *Evaluating domestic hot water distribution system options with validated analysis models.* Golden (CO): US Department of Energy - Contract No.: DE-AC36-08GO28308. NREL Subcontract No.: KDNJ-0-40340-04.

Wendt, R., Baskin, E., & Durfee, D. (20043). *Evaluation of Residential Hot Water Distribution Systems by Numeric Simulation.* Buildings Technology Center - Oak Ridge National Laboratory.

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Zhang, Y. (2013). *MULTIFAMILY CENTRAL DOMESTIC HOT WATER DISTRIBUTION SYSTEMS.* Heschong Mahone Group. California Energy Commission. Publication Number: CEC-500-2013-011.