

Energy and thermal comfort performance evaluation of thermostatic and electronic mixing valves used to provide domestic hot water of buildings

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ABSTRACT

Building codes require domestic hot water supplied to high-rise residential buildings to be stored at 60°C or above to avoid bacterial contamination (e.g., Legionella), while the supplied water delivered to residential units should not exceed 49°C to avoid scalding. Inefficient mixing of hot and cold water to lower the water temperature can cause temperature and pressure fluctuations of supplied water resulting in resident discomfort, higher energy consumption and risk to plumbing fixture. This work compares the efficiency of two mixing devices (a) an electronic mixing valve (EMV) and (b) a thermostatic mixing valve (TMV) experimentally and numerically. The energy savings, pressure drop, and temperature fluctuation caused by each device in the same building are presented. Each 24-hour period is divided into 4 time periods based on hot water demand. The results show that the EMV can provide steadier temperature during the transition between low demand period overnight and peak consumption in the early morning, and lower pressure drop in the hot water system. In addition, depending on the circulation flowrate in the building, the EMV can potentially reduce energy consumption by more than 40% particularly during low demand periods.

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1. Introduction

The residential building sector energy consumption accounts for 16–50% of total energy in most countries [1–4]. In Canada, buildings consume approximately 30% of all secondary energy (energy used by final consumer). More than half of this amount (54%) were used by residential buildings while the rest was consumed by commercial and institutional buildings. Of the residential building portion, 18% is used in apartment buildings [5].

To reduce this environmental impact, energy and water consumption of high-rise buildings should be optimized (the Official Plan (OP) of Canada defines a high-rise building as a building that is ten storeys or more in height [6]). Domestic Hot Water (DHW) demand accounts for a large portion of energy and water consumption of such buildings. To ensure health and safety for the high-rise buildings' residents, new regulations in many countries including Canada mandate the buildings: (a) to deliver hot water to resident units not hotter than 49°C (120°F) to avoid tap water scald burns [7], (b) to store hot water at 60°C (140°F) or higher to avoid bacterial contamination (e.g., Legionella) [8–10].

Consequently, stored hot water at 60°C needs to be mixed with cold water to deliver DHW to units at the required temperature. There are two types of mixing design being used in high-rise buildings:

1. Using a mixing valve before each fixture or faucet
2. A master mixing valve installed in the boiling room to mix hot and cold water before being fed to the building's risers (main pipe delivering DHW to all units)

In large buildings, using a master mixing valve reduces the cost significantly compared to installing a mixing valve for each faucet and is commonly used. However, master Thermostatic Mixing Valves (TMV) available in the market are usually designed for industrial applications with constant pressure and flowrate of hot and cold water streams not the variable demand of a residential building.

1.1. Challenges of DHW delivery

Some of the most common problems for delivering DHW in high-rise buildings are:

Hot water pressure/temperature fluctuations: Most TMVs in the market control the temperature of DHW by changing the flow

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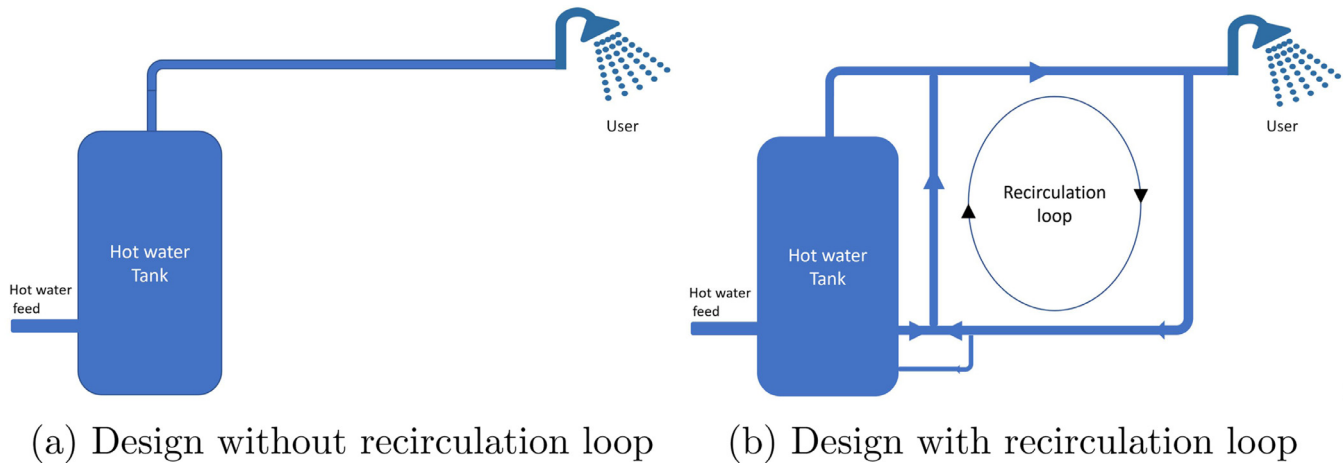


Fig. 1. Domestic hot water's design with/without return loop.

rates of the hot and cold water streams. This method is applied mechanically using thermal expansion of a temperature sensing material (wax, spring, etc.) to open or close hot/cold water streams. Pressure fluctuation of the hot water caused by this process can also lead to crossover between hot and cold flows in faucets or fixtures resulting in higher thermal fatigue for these components. Mechanical TMVs require costly maintenance (approximately twice a year according to most TMV manufacturers!) due to calcification that affects proper hot/cold water mixing.

Cooling during no-demand periods (water waste): There are two types of DHW design for a high rise building: 1- The distribution of DHW to the apartment units is one-way (Fig. 1a), 2- The DHW line returns back to the boiler room and being fed to the system again (usually through the hot water tank or the cold stream entering the TMV) (Fig. 1b) [11]. For a system with no return loop, during no-demand periods (e.g., usually overnight 12 a.m. to 6 a.m.), the water is stationary in the pipes and risers and it will cool. Therefore, the first user in the morning ends up wasting water until hot water is delivered (note, most recent buildings in Canada and around the world have been built with a recirculation loop due to new regulations for energy savings, health and safety; however, there are still many older buildings in Canada using a one-way systems).

Thermal fatigue of fixtures: Cooling and reheating the water in risers and pipes can cause thermal fatigue in fixtures and shorten their life-span [12,13].

Energy consumption: Aside from the water waste, for no return systems, more energy may be required to reheat the water in the morning compared to systems with return loop. Recirculating hot water at low flow rates overnight can save energy required for reheating the water and also ensure faster delivery of hot water to residents.

Several studies have proposed more efficient control systems for Domestic Hot Water (DHW) in residential buildings. Some researchers provided data-driven optimal heating schedules based on resident's behaviour and comfort or historical weather data [14,15], while others have tried to find a better configuration for a DHW system equipment including hot water tank, 3 or 2-way mixing valves, etc. [16]. All these studies used traditional mixing valves or TMVs.

Aside from optimizing a system, analysing each component such as storage tank or TMV can identify significant opportunities for total energy savings of a DHW system. While many researchers have studied DHW storage tank efficiency and control strategies [17–19], very few studies examined the mixing device used independently.

Since most TMVs were initially designed for industrial applications, most publications related to hot and cold fluid streams mixing are based on their use in industry rather than residential DHW systems. For instance, several computational and experimental studies have investigated thermal fatigue caused by mixing hot and cold water in power plants, petrochemical plants, electronic cooling devices, etc [12,20–27]. The flowrates of hot and cold streams were constant in all these studies, while the hot water demand fluctuation is one of the main issues for TMVs used in residential buildings as residents want delivery of hot water.

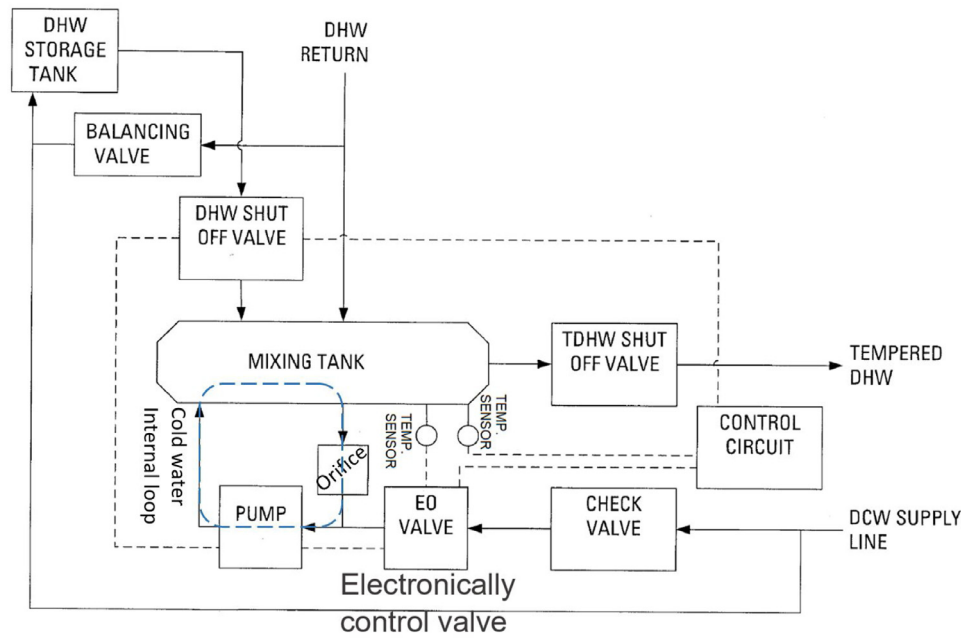
Attempts to provide advanced control system for a TMV have included 1D modeling of a thermostatic mixing valve to evaluate the response time of the system to sudden change in hot and cold water stream [28,29]; however, no experimental data was provided to support the modeling. There is a need for data on the performance of a residential TMV.

1.2. An alternative solution

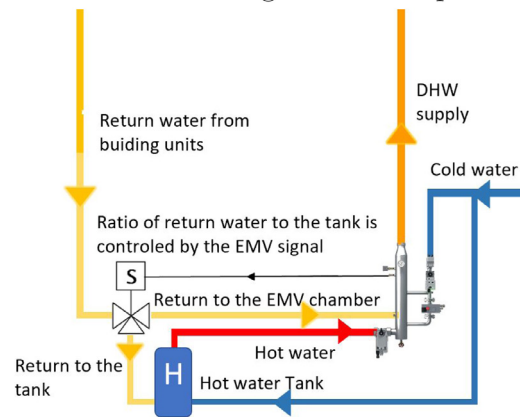
Electronic Mixing Valves (EMV) are also being used in the DHW distribution systems of high-rise buildings with a return loop. An EMV unit has three entrances, mixing the hot, cold and return water streams in a small chamber (0.1 m diameter and 1 m long) to provide 24-hr hot water supply to the buildings (Fig. 2). The EMV controls the flow rate of hot and cold water streams entering the tank based on the output water temperature.

EMV control system: An EMV unit is controlled electronically with a central processing unit (Control Circuit). By measuring the output water temperature (Temp. Sensor), the control unit activates the balancing valve to direct a portion of the return water to a hot water tank so that an equivalent amount of hot water can enter the mixing tank. The remaining return water is mixed with the hot and cold water in the mixing chamber (Fig. 2). The control unit also determines the cold water flowrate required for mixing based on the output temperature (E0 valve). The cold water branch has an internal loop with a pump (Fig. 2a). As the pump operates continuously to control DHW pressure, the cold-water requires a return to protect the pump from net positive suction head (NPSH) for periods where there is no need for the cold water and E0 valve is closed by the Control unit [31]. Also, the cold-water return requires a significant pressure drop (Orifice), otherwise its pressure dominates the system.

During no-demand periods (e.g., overnight), a small portion of return water (the trim line) will be replaced by hot water to maintain temperature. The cold water branch is closed during these periods. In addition, the EMV allows a temperature drop for the



(a) A standard flow diagram for tempered water



(b) Installation diagram of an EMV

Fig. 2. Electronic mixing valve (EMV) diagram [30].

supplied water overnight (e.g. 46°C rather than 49°C) to save energy. During high and mid-demand periods, the trim line is closed and all return water is directed to the mixing chamber where it is mixed with hot and cold streams while the control unit sets the cold water flow rate based on the supplied water temperature.

TMV control system: A TMV controls the temperature mechanically through expansion and contraction of a temperature sensing material. The TMV used in this study was a spring type. The unit was calibrated based on the thermal expansion of the spring (the temperature sensor); so that if the output temperature exceeds a set value, the spring expands and consequently partially closes the hot water stream to adjust the output temperature. The reverse happens when the output temperature is lower than the set value. Reviewing the literature has shown limited independent reviews of TMVs and EMVs and their effect on the performance of a residential building DHW system.

The objective of this work is to provide a comprehensive analysis of these systems and compare the performance of a TMV and an EMV installed in buildings with unsteady demands with respect to energy consumption and resident comfort. Experimental

and numerical comparisons are presented of the performance of a TMV and an EMV unit installed in a 14-story residential building. After collecting data and analysing the performance of the DHW system of the building with a TMV, the TMV was replaced by an EMV unit. The same measurement and analysis were performed for the DHW system with an EMV. Flowrate and temperature fluctuations were measured for both TMV and EMV systems. In addition, a general energy analysis is presented to allow determination of the benefits of both approaches. General 3D numerical simulations of both systems are provided to elucidate details of the mixing and pressure drop in both systems.

2. Methodology

2.1. Experimental procedure

A 14-story building with one zone of DHW (i.e. one loop provides DHW to all floors) was selected for this study. To compare the performance of EMV and TMV units, the building's DHW system was operating for a week (a) with a TMV while data was

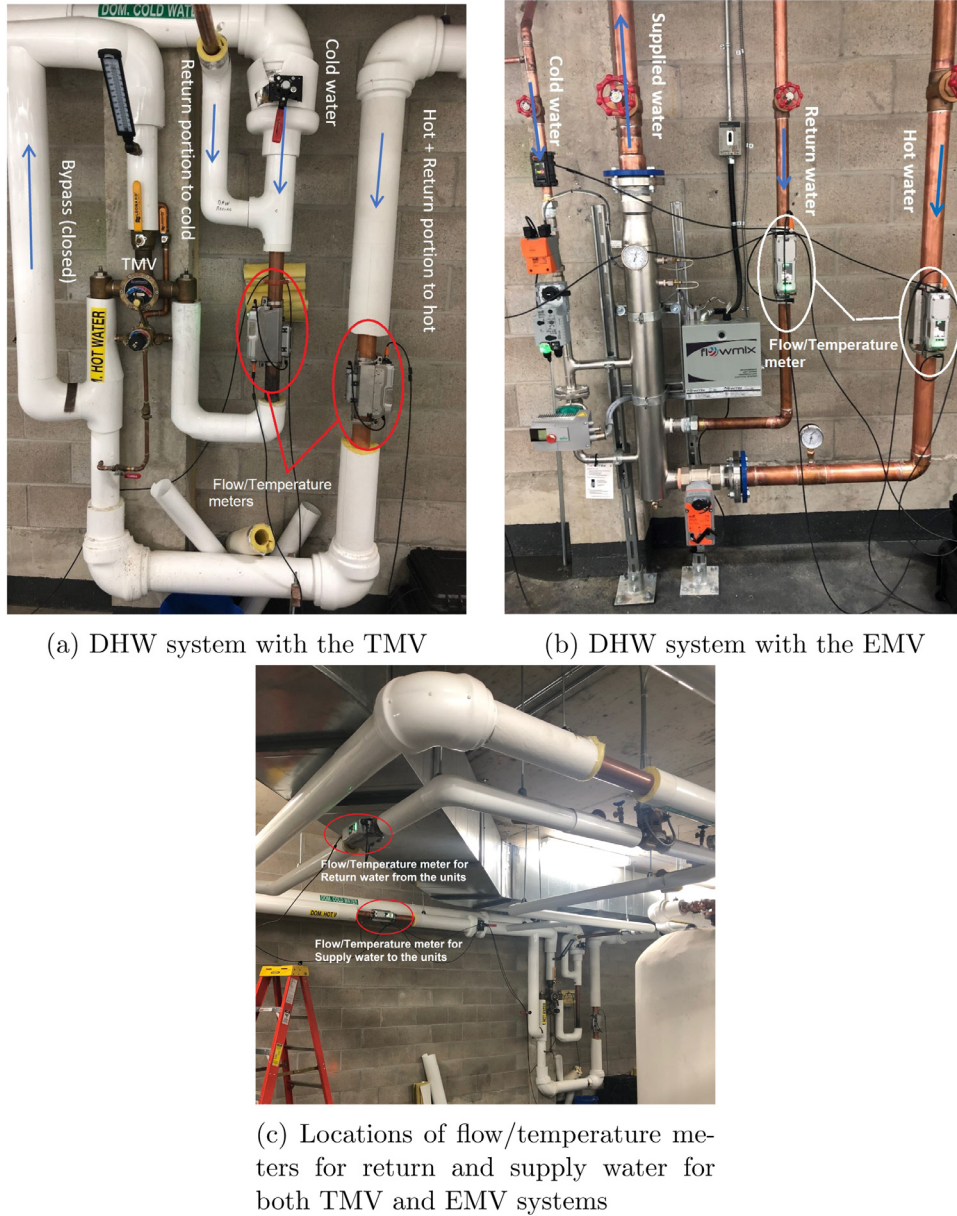


Fig. 3. DHW systems tested in a 14-story building for the present study.

recorded, and then (b) it was replaced by an EMV unit where data was recorded over an additional week. No other component of the DHW distribution system was changed. The piping system arrangement for the TMV/EMV section is shown in Fig. 3 (a schematic of the system is presented in appendix A).

The TMV DHW system: A DHW boiler heats and stores water in a hot water tank. The return water is partially mixed with the pressurized cold water at 370 kPa while the remaining return water returns to the hot water tank. The mixed cold-return water enters the TMV and is mixed with the hot water coming from the hot water tank at 370 kPa. The flowrates of cold-return and hot water streams are controlled by a spring thermostat inside the TMV by partially opening/closing of these streams.

The EMV DHW system: After replacing the TMV with the EMV, the entire or part of return water enters the mixing tank in the EMV (part of return water may go to the hot water tank depending on the output temperature) (Fig. 3b). Cold and hot water streams also enter the mixing tank of EMV. The flowrate of each stream

is controlled by monitoring the output temperature of the mixing tank.

Flowrate and temperature of each stream entering the TMV/EMV was measured for 7 days using an ultrasonic clamp-on flow/temperature meter (KEYENCE flowmeter FD-R80) and these locations are shown in (Fig. 3c).

The flowmeter stored the maximum and minimum flowrate/temperature over 5 minute intervals. Assuming a normal distribution for data in each 5-minute span, uncertainty of the flowrate and temperature measurements are:

$$u_{flowrate} = \pm \sqrt{u_{cal_f}^2 + u_{a_f}^2 + \sigma_{m_f}^2 + Res_f^2} = \pm 1.8 (L/min) \quad (1)$$

$$u_{Temp.} = \pm \sqrt{u_{cal_T}^2 + u_{a_T}^2 + \sigma_{m_T}^2 + Res_T^2} = \pm 1.6^\circ C \quad (2)$$

where u_{cal} is the calibration uncertainty, u_a is the accuracy, σ_m is the standard deviation of the mean and resolution of the DAQ, Res (subscripts f and T are for flow and temperature respectively) [32].

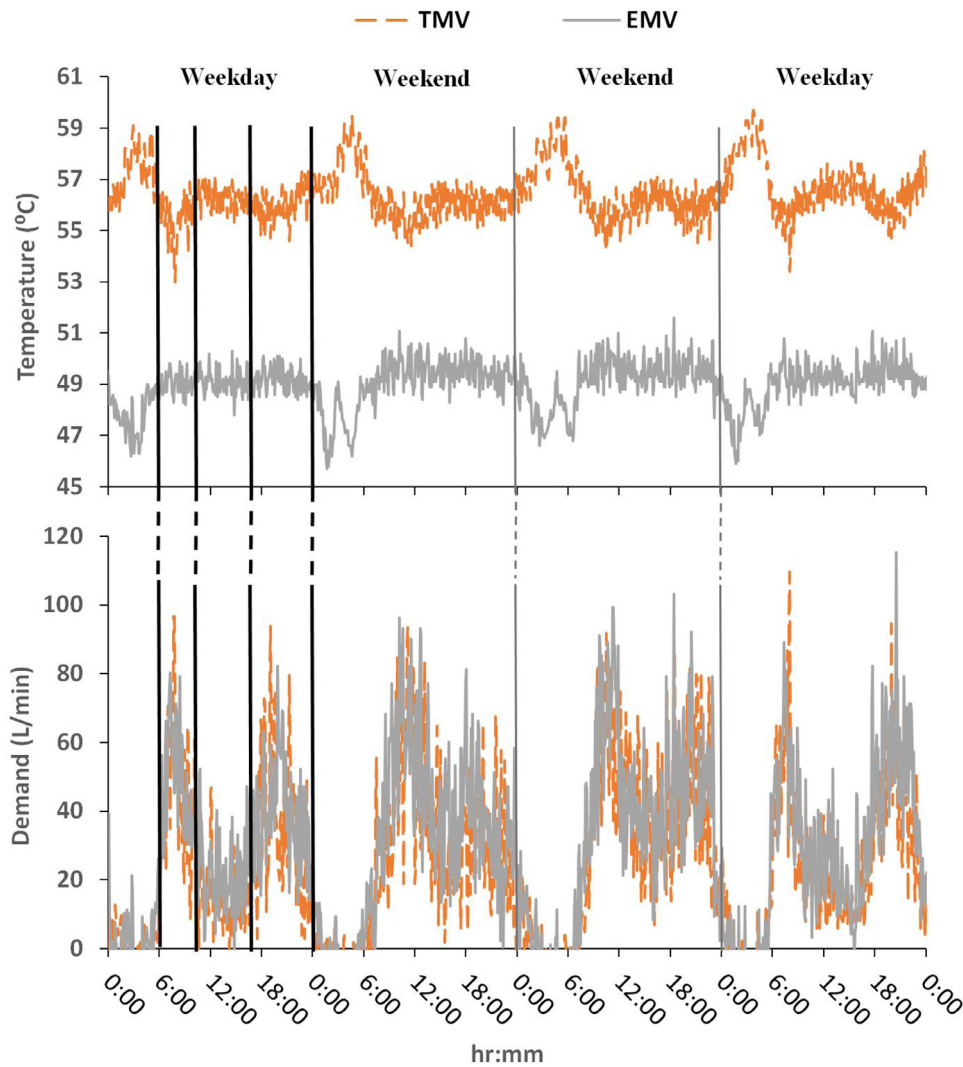


Fig. 4. DHW supply temperature and the calculated demand for the building during 4 days (2 weekend and 2 week days).

2.2. Numerical method

To supplement the field measurements, 3D numerical modeling of the TMV and EMV were provided to estimate pressure loss in the TMV and EMV. OpenFOAM [33] was used to solve the Reynolds Averaged Navier-Stokes (RANS) equations along with the energy equation. The turbulent flow was modeled by using the RNG k-model [34]. A steady-state solver for incompressible fluids, SIMPLE (Semi-Implicit Method for Pressure Linked Equations), was used to obtain the solution. The Boussinesq approximation was used to predict buoyancy forces while the other water properties were constant [34].

3. Results and discussion

3.1. Experimental results

Fig. 4 shows the building's demand and supplied water temperature for 4 days between Friday and Monday (two weekend days and two weekdays) for both the TMV and EMV systems. The recirculation pump was set to a constant power/flowrate over 24-hr (i.e. constant return water flowrate during the day). The return water temperature was between 1 and 3 °C lower than the supplied water temperature - a higher supply temperature leads to higher

temperature drop in the return line. The recorded data for other days also showed similar trends (note, temperature set point of the TMV was slightly higher than that of the EMV to compensate for potential supplied water temperature fluctuations). The demand is calculated by subtracting the averaged DHW flowrate during no demand period (overnight 12 a.m. to 6 a.m.) from the measured DHW flowrate during each day. Averaged DHW flowrate overnight is similar to the circulation flowrate shown in Fig. 5.

Each day was divided into 4 different periods based on demand:

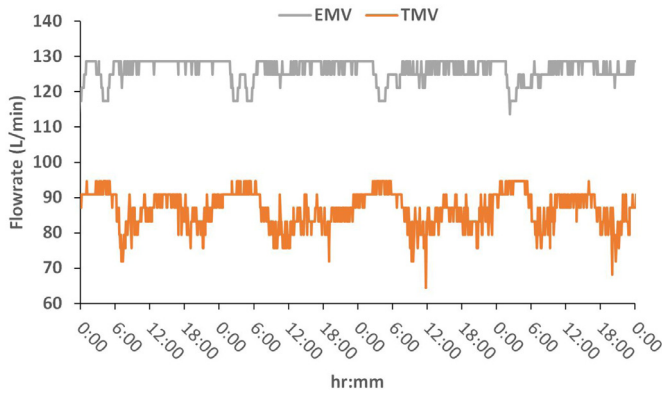
1. Overnight 12 a.m. to 6 a.m.
2. Morning high demand period 6 a.m. to 10 a.m.
3. Morning mid-demand period 10 a.m. to 5 p.m.
4. Evening/night high demand period 5 p.m. to 12 a.m.

Overnight 12 a.m. to 6 a.m. Overnight (Fig. 4), there is almost zero demand, and water is circulating through the building (Fig. 5). As a potential energy saving strategy, lowering the temperature during minimum demand period can reduce the energy consumption of the building [35]. However, for the TMV unit, overnight with the minimum demand and consequently lower pressure drop, the hot water pressure from the tank (at 60°C) was slightly higher than the cold water pressure entering the TMV which resulted in overheating the supplied water up to 59°C (inefficient mixing).

Table 1

Averaged temperature and demand for a weekday and a weekend day during four different periods.

	Overnight		Early morning		Mid-Day		Evening/Night	
	12:00 PM-6 AM		6-10:00 AM		10 AM-5 PM		5-12:00 PM	
	Demand (L/min)	Temp. (°C)	Demand (L/min)	Temp. (°C)	Demand (L/min)	Temp. (°C)	Demand (L/min)	Temp. (°C)
TMV (weekday)	0	57.3	43.6	55.4	13.5	56.2	44.1	55.5
TMV (weekend)	0	57.5	23.7	56.2	44	55.8	29	56.2
EMV (weekday)	1.2	47.8	48.4	49.1	22.1	49.1	39	49.2
EMV (weekend)	0	47.6	31.8	49.2	48.6	49.6	36.2	49.5

**Fig. 5.** Comparing recirculation flowrate for the systems with TMV and EMV during 4 days.

On the other hand, the EMV allowed the temperature to drop overnight (up to 46°C for this study as compared to 49°C during the rest of the day) to save energy. The same trend happened over weekdays and weekends (Fig. 4).

Morning high demand period 6 a.m. to 10 a.m. As people wake up starting at roughly 6:00 a.m., an abrupt jump appeared in the building's DHW demand. During morning peak demand, the water temperature remained at $49 \pm 1^\circ\text{C}$ for the system with the EMV, while temperature varied between 53°C and 57°C for the system with the TMV. The EMV measures exit temperatures every 5 (s), while the TMV response time can be on the order of a couple of minutes (based on the sensitivity of temperature sensing material).

The high temperature differences between high and low demand periods for the TMV (between 59°C overnight to 53°C during high demand (Fig. 4)) required setting a higher set temperature for the TMV than recommended (49°C) to ensure resident comfort and efficient hot water delivery. While, the temperature fluctuation of EMV system was less than 3°C . The results show that the electronic controlled system provided steadier flow temperature particularly during high demand.

Morning mid-demand period 10 a.m. to 5 p.m. After 10 a.m., demand decreased until 5 p.m. when the residents returned. As demand dropped, water temperature rose again for the TMV while the water temperature remained relatively constant at 49°C for the EMV. It is worth noting that this building had a young demographic (i.e. most residents left for work during weekday working hours). The main difference between a weekday and a weekend day is during this period. The morning mid-demand was higher during the weekend compared to a weekday.

Evening/night high demand period 5 p.m. to 12 a.m.: The trend during this period is similar to the trend for the early morning high demand period. The only difference is that the water consumption spanned a longer period of time, 7 h, as compared to 4 h during the morning. As a result, for the TMV, the maximum peak

demand was lower, and the minimum temperature was higher in the evenings than the early mornings. For the EMV, the hot water was maintained at a steadier temperature during both early morning and evening periods. Table 1 compares the averaged demand and temperature during each of these periods for a weekday as well as a weekend day.

Fig. 5 compares the recirculation flowrate (flow returning from the units) for both systems. The minimum peaks for the EMV occurred during low demand period (overnight) which could reduce the energy consumption during this period; while the minimum flowrate of the TMV was during early morning with high demand. The flowrate variations (i.e. difference between minimum and maximum peaks) was approximately 12 and 23 (L/min) for the EMV and TMV respectively. In addition, the flow from the TMV is approximately 40% lower than the EMV system. This indicates a TMV can cause a significant pressure drop and consequently flow fluctuations in the DHW loop.

This effect directly influences the hot water pressure delivered to each unit. Pressure difference between hot and cold water at the taps and faucets may result in water crossover. Beside causing water temperature fluctuation and discomfort for residents, water crossover between hot and cold streams can lead to higher thermal fatigue in the piping system. From the recirculation pump curve, the pump provided a 97 kPa pressure boost for the TMV as compared to 62.7 kPa for the EMV system at the average flowrates which indicates a significant blockage effect of the TMV in the system.

3.1.1. Energy savings overnight

To save energy during the minimum demand period, two factors can be considered: (a) supplied water temperature and (b) flowrate. Reducing either temperature or flowrate of the recirculation flow can save energy when there is lower demand overnight. Assuming no demand, Eq. (3) can be used to estimate the energy loss, $q_{\text{loss,ref}}$, and $(hA)_{\text{ref}}$ (convective heat transfer coefficient $\times$ piping system effective area).

$$q_{\text{loss,ref}} = (hA)_{\text{ref}} \times \left(\frac{T_{\text{S,ref}} + T_{\text{R,ref}}}{2} - T_{\text{amb}} \right) = \dot{m}_{\text{ref}} \times C_p \times (T_{\text{S,ref}} - T_{\text{R,ref}}) \quad (3)$$

$T_{\text{amb}} = 15^\circ$ is the ambient temperature (assumed to be constant inside the building), $T_{\text{S,ref}} = 58.3^\circ\text{C}$ is the reference supplied water temperature, $T_{\text{R,ref}} = 55^\circ\text{C}$ is the reference return water temperature to the boiler room and $\dot{V}_{\text{ref}} = 94$ (L/min) is the reference recirculation flowrate (reference values are based on the measured corresponding values for the building in this study). As mentioned, the reference heat loss can be reduced by controlling temperature and flowrate of the return water.

Temperature: Lowering the supply temperature can reduce heat loss (while the flowrate ($\dot{m}$) is assumed to be constant). As $(hA)_{\text{ref}}$ will not be affected significantly by changing the temperature less than 10°C , Eq. (3) can be used to calculate T_{R} and system heat loss, q_{loss} , for a new T_{S} ($< T_{\text{S,ref}}$). Eq. (4) then estimates en-

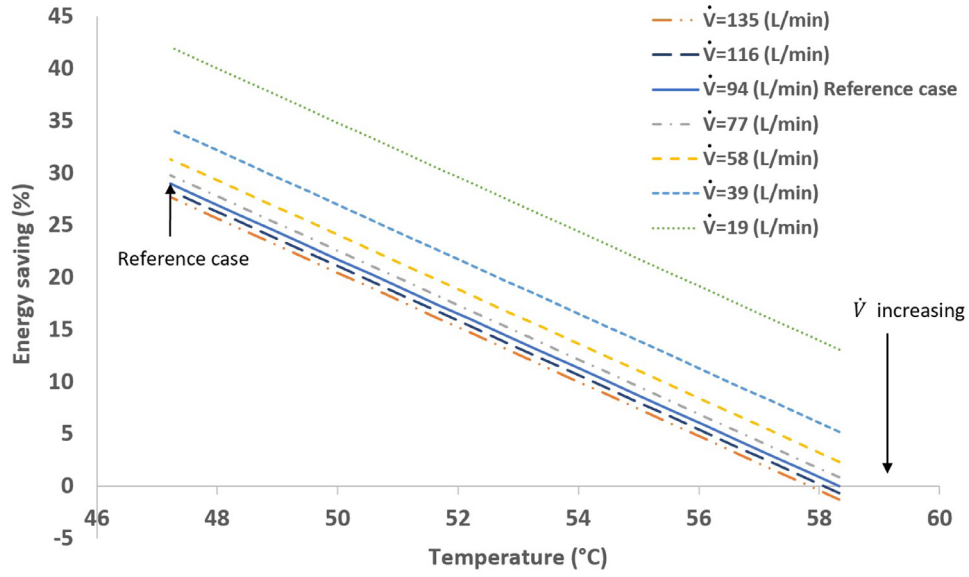


Fig. 6. Percentage of energy savings by changing flowrate and temperature of supplied DHW overnight compared to a reference case ($T_{s,ref} = 58.3$ °C, $T_{R,ref} = 55$ °C, $\dot{V}_{ref} = 94$ (L/min))

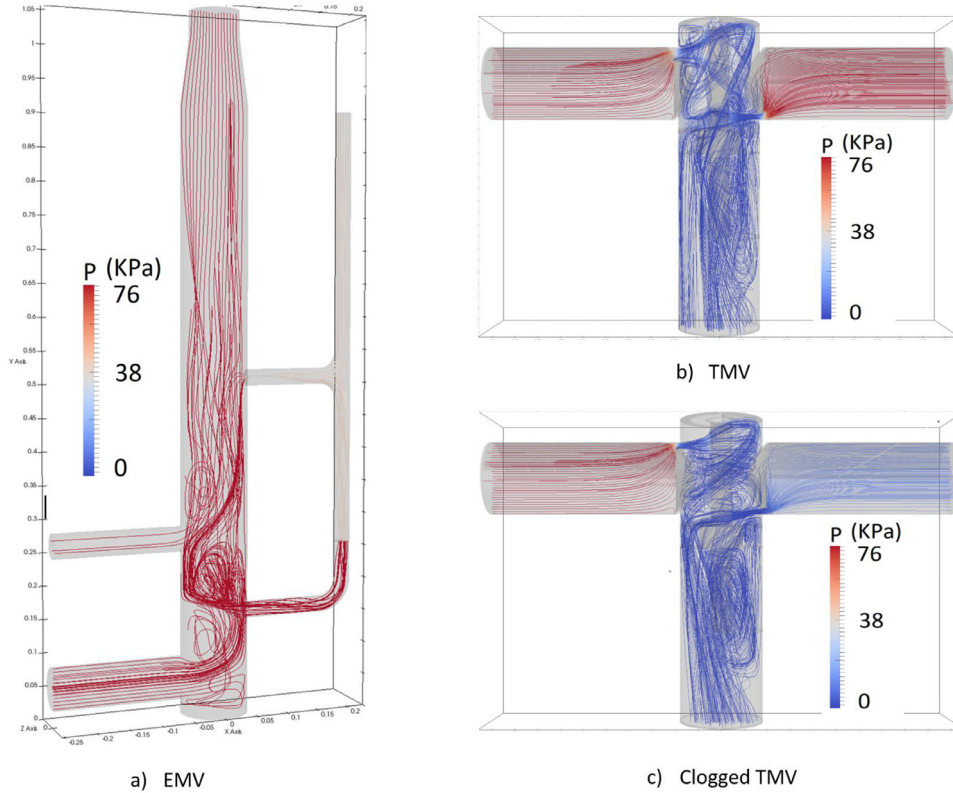


Fig. 7. Flow streamlines inside a EMV, a TMV and a clogged TMV colored by pressure.

ergy savings overnight for a specific DHW system with the new supplied water temperature, T_s , as compared to the reference situation.

$$\text{Energy savings(\%)} = \frac{q_{\text{loss,ref}} - q_{\text{loss}}}{q_{\text{loss,ref}}} \times 100 \quad (4)$$

Flowrate: Decreasing the recirculation flowrate can also save energy during low demand periods (e.g., overnight). However,

changing the flowrate may change $(hA)_{\text{ref}}$. To estimate a new (hA) associated with a lowered flowrate, $\dot{m}$, an equation [36,37] for the Nusselt number in a pipe ($Nu = aRe^{0.8}Pr^n$ - for fully developed turbulent flow for fluids with Prandtl number in the approximate range of 0.7–100, $Re > 10,000$ and tubes with $L/D > 60$) was used to relate the new (hA) to $(hA)_{\text{ref}}$. This equation showed $(hA) = (hA)_{\text{ref}} \left(\frac{\dot{m}}{\dot{m}_{\text{ref}}} \right)^{0.8}$ if the system flowrate was changed from $\dot{m}_{\text{ref}}$ to $\dot{m}$. With the new (hA) , Eq. (4) can be used to calculate en-

Table 2
Boundary condition for hot, cold and return water streams in the numerical model.

	TMV		EMV	
	Temp. (°C)	Flowrate (L/min)	Temp. (°C)	Flowrate (L/min)
Cold stream	22	20.8	22	13.2
Hot stream	60	58.7	60	43.5
Return stream	N/A	N/A	46.7	22.7

ergy savings overnight by changing the flowrate (it is worth noting that the energy consumption of the cold water pump is between 0.04 and 0.1 kW depending on the flowrate).

Fig. 6 shows the energy savings overnight for a system by changing the flowrate and supplied water temperature. The effect of reducing the flowrate is slightly more than lowering the temperature as the system heat loss is directly proportional to the flowrate. The EMV has the potential to control the temperature directly and the flowrate of the supplied water indirectly (using a variable speed recirculation pump during the night - the building in this study did not use the flowrate energy saving mode).

3.2. Numerical results

Steady state mixing inside a typical TMV and an EMV was modeled for the flow and temperature of cold, hot and return water streams at values obtained from the averaged experimental data during the early morning high demand period. As a potential problem for a TMV is to be blocked due to calcification or dirt, a clogged TMV was also simulated to compare its pressure drop with a new TMV as well as an EMV. For the clogged TMV, the hot water opening was reduced to half of its original size. The boundary conditions for each system are presented in Table 2.

Fig. 7 shows streamlines inside the EMV, TMV and the clogged TMV colored by pressure. The pressure drop between the hot inlet stream and the outlet supplied water are 0 (EMV), 77 (TMV), 605 kPa (clogged TMV) respectively. The pressure drop in the new TMV and EMV are in the expected range. However, if the TMV is clogged, the pressure drop in the DHW line is significant and to minimize this loss, the TMV requires frequent maintenance.

Even for a properly operating TMV, the pressure drop is much greater than the EMV. This issue arises from the mechanism that a TMV using to control the temperature. When the TMV has to minimize either hot or cold streams, the TMV inlet for that stream will act like an orifice resulting in a high pressure drop in the system. This problem is avoided in an EMV by keeping the hot branch always open and controlling the output flow and temperature by adjusting the return stream. In addition, the small pump located on the cold line can compensate for possible pressure drops in the DHW line as well.

4. Conclusion

Two mixing devices being used in a building's DHW system were compared experimentally and numerically. The results showed

1. There was a high rate of fluctuation for the building's demand during a day (from 0 to more than 100 LPM). The abrupt changes in the demand resulted in fluctuation of the water

temperature depending on the response time of the mixing device. The EMV could reduce the water temperature fluctuation from 6 °C in the TMV to 3 °C between low and high demand periods.

2. Overnight, when there was minimum demand, the DHW temperature increased in the system with the TMV, while the EMV not only controlled the temperature but also could reduce the temperature below 49°C to further save energy.
3. The building's recirculation flowrate was 40% higher for the system with the EMV as compared to the system with the TMV. It shows that an EMV causes less pressure drop in the DHW loop. The numerical simulations of the systems also predicted lower pressure drop for an EMV. Keeping the hot water (from the hot water tank) open all the time and controlling the temperature by changing the return water flowrate provided less obstruction and consequently less pressure drop in the system and offers direction for energy and water use improvements.

Declaration of Competing Interest

None.

CRediT authorship contribution statement

Ali Rahmatmand: Writing - review & editing, Writing - original draft, Conceptualization, Software, Formal analysis, Investigation, Validation. **Marin Vratonjic:** Writing - review & editing, Formal analysis, Investigation, Conceptualization. **Pierre E. Sullivan:** Writing - review & editing, Supervision, Project administration, Methodology, Investigation.

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Appendix A

The engineering drawings for both EMV and TMV systems are shown in Figure A1, A2 and A3.

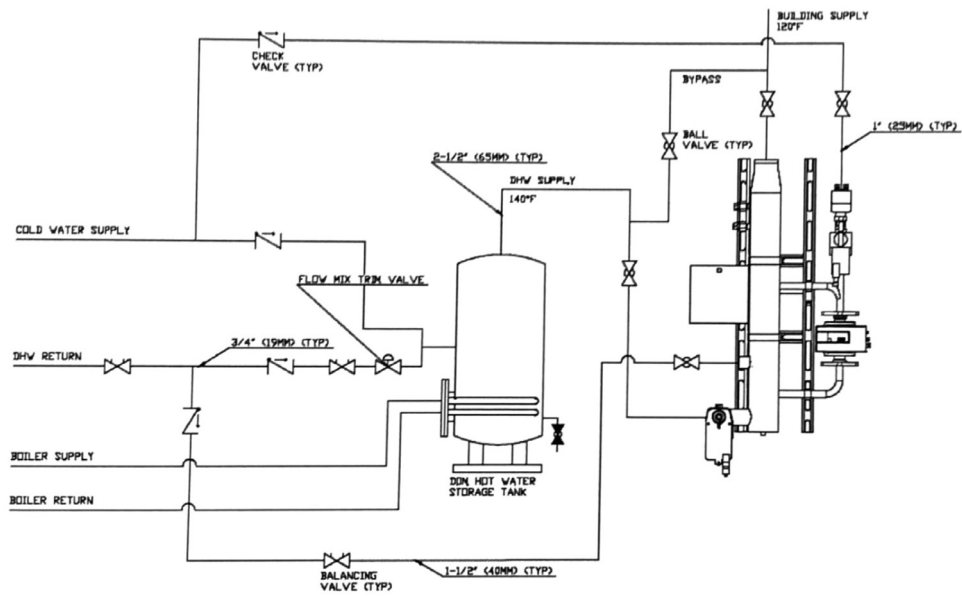


Fig. A1. Engineering drawing for the EMV system.

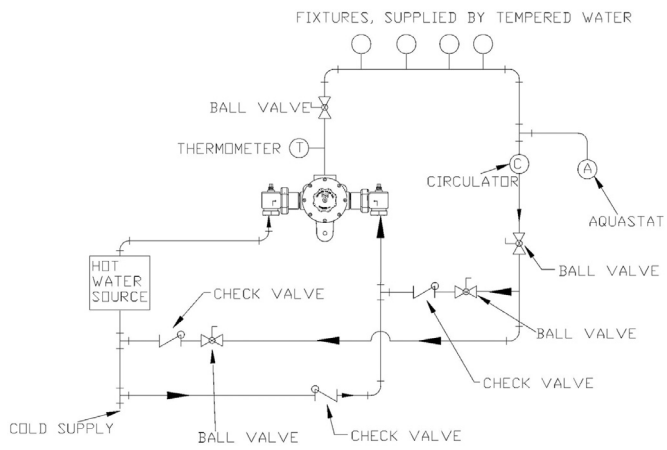


Fig. A2. Engineering drawing for the TMV system.

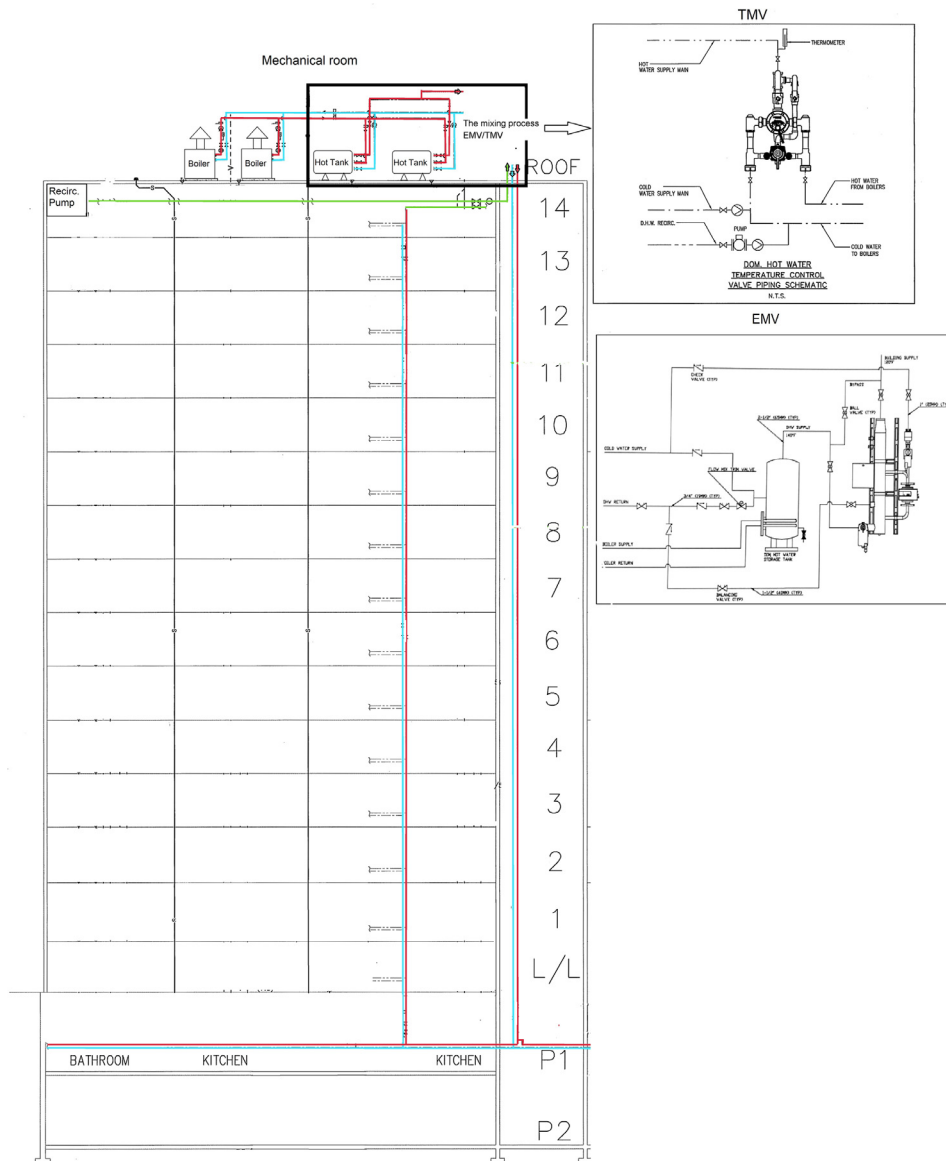


Fig. A3. Engineering drawing of the entire building.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at [10.1016/j.enbuild.2020.109830](https://doi.org/10.1016/j.enbuild.2020.109830).

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