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Smart Adaptive Water Tap Based on Ambient Temperature: A Review of Temperature Sensing, Thermoelectric Conditioning and Embedded Control Techniques

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Abstract—The temperature of tap water changes with the seasons. In summer, water stored in rooftop tanks and exposed pipes can become uncomfortably warm, while in winter it can feel too cold for washing or drinking. Users often wait for the water to change temperature or depend on separate coolers and heaters, which wastes water and energy. A smart adaptive tap addresses this by sensing the ambient conditions, deciding a comfortable water temperature and conditioning the water automatically. This paper reviews the technologies required for such a device. It covers temperature sensors for air and water, flow sensing to detect when the tap is in use, cooling and heating methods with emphasis on thermoelectric Peltier modules and resistive heaters, and control strategies from hysteresis to PID and fuzzy logic. Basic heat-transfer relations are used to estimate the power needed to change the temperature of flowing water, showing why a small conditioned reservoir is more practical than instantaneous cooling for most household flows. A system architecture and control flow are proposed in which a microcontroller maps ambient temperature to a target water temperature, compares it with the measured value and drives cooling or heating only while water is drawn. Applications, safety requirements, limitations and future enhancements such as user profiles and IoT monitoring are discussed.

Index Terms—Smart water tap, ambient temperature, water temperature control, thermoelectric cooler, Peltier module, flow sensor, embedded controller, energy efficiency.

I. INTRODUCTION

Water is used many times a day for drinking, washing hands and face, cooking and cleaning. The comfort of these activities depends on water temperature. In much of India, summer air temperatures are high, and water in overhead tanks and exposed pipes absorbs heat from the sun and surroundings, so tap water may feel warm. In winter, the same supply can feel very cold, especially in the early morning. People respond by letting water run until it becomes acceptable, by storing water in earthen pots or refrigerators, or by using electric geysers. These practices waste water, take time and consume energy.

A smart adaptive water tap is an embedded system that measures the ambient temperature and the water temperature and automatically conditions the water to a comfortable level. When the water is warmer than desired, a cooling mechanism is activated; when it is already suitable, the conditioning stays off; and when it is too cold, a heater can be switched on. A flow sensor ensures that the system operates only while the tap is actually in use, avoiding standby energy waste.

This paper reviews the technologies required to design such a tap. Its contributions are:

- A review of thermal comfort considerations and the heat-transfer principles that govern conditioning of flowing water.
- A review of sensors, cooling and heating methods and control strategies suited to a tap-mounted device.
- A proposed system architecture, control algorithm and design calculations.
- A comparison of conditioning methods and a discussion of challenges and future enhancements.

Section II gives the background, Section III reviews sensing, Section IV reviews conditioning methods, Section V reviews control strategies, Section VI presents the proposed system,

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Section VII compares approaches, Section VIII discusses challenges, and Section IX concludes.

II. BACKGROUND

2.1 Thermal Comfort

Thermal comfort describes the condition in which a person is satisfied with the thermal environment. Fanger developed a quantitative approach to comfort based on heat balance of the human body [1], and ASHRAE Standard 55 defines conditions for acceptable indoor thermal environments [2]. Although these works address air rather than water, they show that perceived comfort depends on ambient conditions. Water that feels refreshing at an air temperature of 38 °C can feel unpleasantly cold at 15 °C. This motivates using ambient temperature to choose the target water temperature rather than a single fixed set-point.

2.2 Heat Required To Condition Flowing Water

The thermal power Q needed to change the temperature of water flowing at mass flow rate $\dot{m}$ by ΔT is given by the steady-flow energy balance [3]:

$$Q = \dot{m} \cdot c_p \cdot \Delta T \quad (1)$$

where $c_p \approx 4186$ J/(kg·K) is the specific heat of water. For a typical washbasin flow of 4 L/min (about 0.067 kg/s), lowering the temperature by 5 K requires roughly 1.4 kW of cooling. This is far beyond the capacity of small cooling devices that can fit in a tap, and has a major influence on system design, as discussed in Section VI.

2.3 Safety And Hygiene

Drinking-water quality must not be compromised by materials or stagnant storage within the device [4]. Appliances that heat water with mains electricity must meet electrical safety requirements for insulation, earthing and protection against overheating [5].

III. TEMPERATURE AND FLOW SENSING

3.1 Temperature Sensors

The ambient sensor measures air temperature near the tap, and the water sensor measures the temperature of water in the reservoir or pipe. The LM35 provides an analog output of 10 mV/°C and is easy to read with a microcontroller ADC [6]. The DS18B20 is a digital sensor available in waterproof stainless-steel probes and offers resolution up to 12 bits over a single-wire bus, which makes it convenient for immersion in water [7]. Thermistors are inexpensive and fast but non-linear, while thermocouples are unnecessary for this temperature range [8]. Table I compares these options.

Table I Comparison Of Temperature Sensors For A Smart Tap

Sensor	Interface	Suitability	Note
LM35 [6]	Analog	Ambient air	Needs ADC and sealing for water
DS18B20 [7]	Digital 1-Wire	Water and air (probe)	Waterproof probes available
NTC thermistor	Resistance	Fast water sensing	Non-linear, needs calibration
Thermocouple	Millivolt	Not required	Suited to high temperatures

3.2 Flow Sensing

A flow sensor detects whether water is being drawn and measures its rate. Turbine-type Hall-effect flow sensors produce pulses whose frequency is proportional to flow rate and can be counted by a microcontroller interrupt [8]. Detecting flow allows the system to switch conditioning on only during use and to estimate the required thermal power from (1).

IV. COOLING AND HEATING METHODS

A. Thermoelectric (Peltier) Cooling

A thermoelectric cooler (TEC) is a solid-state heat pump based on the Peltier effect. When current passes through junctions of n-type and p-type semiconductor elements, heat is absorbed at one face and released at the other [9]. TECs have no moving parts or refrigerant, are compact and can switch between cooling and heating by reversing current. Their main weakness is low efficiency; the coefficient of performance, defined as

$$COP = Q_c / P_{in} \quad (2)$$

is typically well below 1 for useful temperature differences, much lower than that of vapour-compression systems [10], [11]. The hot side needs a heat sink and often a fan, because it must reject both the absorbed heat and the electrical input. Zhao and Tan reviewed thermoelectric cooling materials, modelling and applications, and Riffat and Ma discussed applications including small refrigerators and water coolers [10], [11].

3.3 Vapour-Compression Cooling

Compressor-based refrigeration, used in water dispensers and refrigerators, is more efficient and can provide larger cooling capacity, but it is bulky, noisy and costly for a tap-mounted device [3]. It is more appropriate for a central chilled-water unit serving the tap.

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3.4 Resistive Heating

Electric resistance heaters convert electrical energy to heat with nearly 100% efficiency at the point of use and are easy to control with a relay or solid-state relay. Instantaneous heaters for full flow require several kilowatts, while low-power heaters suit small reservoirs [5]. A TEC operated in reverse can also provide mild heating.

3.5 Passive And Hybrid Methods

Insulating pipes and tanks reduces the temperature rise in summer and drop in winter at no running cost. Hybrid designs can use a small insulated reservoir pre-conditioned slowly by a TEC, so that the first litres delivered are already near the target temperature.

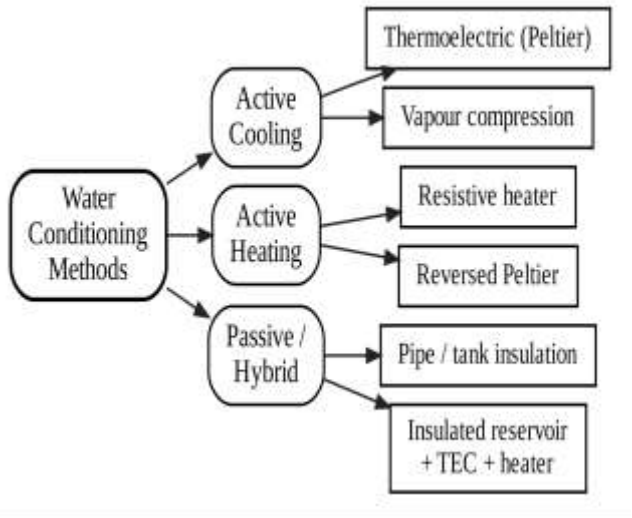


Fig. 1. Classification of water temperature conditioning methods for a smart tap.

3.6 Control Strategies

3.7 Target Temperature From Ambient Conditions

The controller first maps ambient temperature T_a to a target water temperature T_w^*. A simple piecewise rule, for example a cooler target in hot weather, a neutral target in moderate weather and a warmer target in cold weather, can be adjusted by the user through a knob. More refined mappings can draw on comfort principles [1].

3.8 On–Off With Hysteresis

The simplest control switches the TEC or heater on when the water temperature deviates from the target by more than a band and off when it returns, preventing rapid cycling [12].

3.9 Pwm And Pid Control

TEC power can be varied with PWM through a MOSFET or H-bridge driver, allowing proportional control of cooling or heating. A PID controller can hold the reservoir temperature close to the target with little overshoot [12], [13].

3.10 Fuzzy Logic

Fuzzy logic expresses rules such as "if ambient is hot and water is warm, cool strongly", and can blend ambient and water readings smoothly without an exact model [14].

IV. PROPOSED SYSTEM

4.1 Architecture

Fig. 2 presents the proposed architecture. The ambient sensor and the water sensor feed a microcontroller such as an ATmega328 or ESP32. A flow sensor indicates when the tap is used, and a button or knob on the tap lets the user select the mode or adjust the target. The controller drives a TEC through an H-bridge so that it can cool or heat, a heat-sink fan, and optionally a resistive heater through a solid-state relay. An LED or small display indicates the mode and temperature.

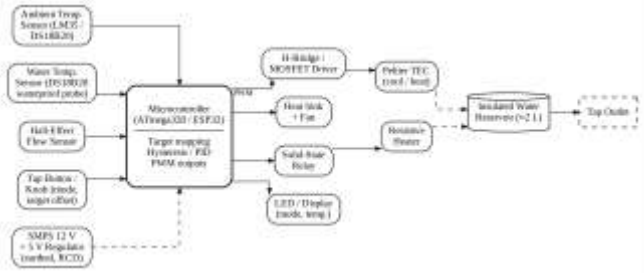


Fig. 2. Block diagram of the proposed smart adaptive water tap based on ambient temperature.

4.2 Control Algorithm

The control flow is shown in Fig. 3. The system remains in a low-power state until flow is detected or a periodic check is due. It then reads the ambient and water temperatures, computes the target, and compares the measured value with it. Cooling is activated if the water is warmer than the target by more than the hysteresis band, heating if it is colder, and neither if it is within the band. The loop repeats while water flows, and the reservoir is maintained at a moderate duty cycle between uses.

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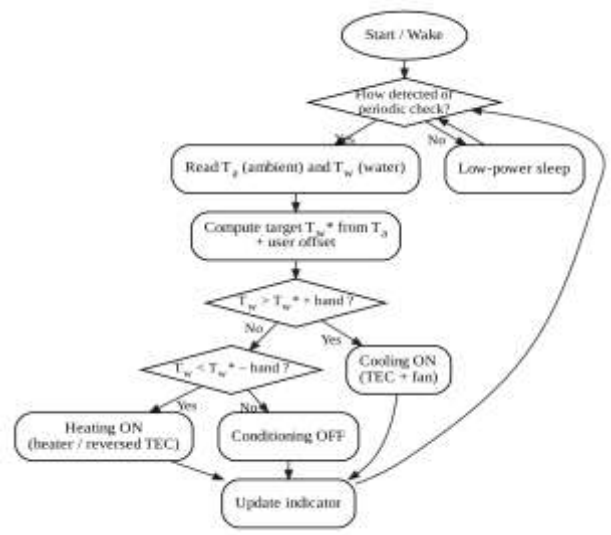


Fig. 3. Control flowchart of the smart adaptive water tap.

4.3 Design Calculations

Equation (1) shows that cooling flowing water instantly needs about 1.4 kW for a 5 K drop at 4 L/min, while a single TEC module typically pumps only tens of watts. Instantaneous thermoelectric cooling of full flow is therefore impractical. A more realistic design uses a small insulated reservoir, for example 2 L, that is conditioned gradually. Cooling 2 L by 5 K requires about 42 kJ of heat removal, which a TEC pumping 40 W can achieve in roughly 18 minutes, neglecting losses. The tap then delivers conditioned water for the first part of each use, which covers typical hand-washing and drinking, and the flow sensor prevents the reservoir from being drained unnecessarily. Because COP is low, the electrical input may exceed the heat removed, so the heat sink and fan must be sized for the total rejected heat [10].

V. COMPARATIVE ANALYSIS

Table II compares water conditioning options for the smart tap.

Method	Capacity	Efficiency	Size and Noise	Cost	Suitability for Smart Tap
Thermoelectric (Peltier) [9]	Low (tens of W)	Low COP	Compact, silent (fan only)	Low	Good with small reservoir
Vapour compression [3]	High	High COP	Bulky, some noise	High	Central chiller unit only
Resistive heater [5]	High	Near 100% at use	Compact	Low	Good for heating mode
Passive insulation	None (prevents drift)	No energy	No impact	Very low	Always recommended
Hybrid (insulated reservoir + TEC + heater)	Moderate effective	Moderate	Compact	Moderate	Most practical design

VI. CHALLENGES AND FUTURE DIRECTIONS

Several challenges must be considered. The limited capacity and low COP of thermoelectric modules restrict how much water can be cooled and make energy use significant [10], [11]. Hot-side heat rejection requires adequate airflow, which may be restricted near a washbasin. Condensation on cold surfaces must be drained and electronics protected from water. Hygiene requires food-grade materials and prevention of stagnation in the reservoir [4]. Electrical safety demands proper insulation, earthing and residual-current protection in a wet location [5]. Sensor placement affects accuracy, because a sensor in stagnant pipe water may not represent the delivered temperature. Future enhancements include user profiles that remember preferred temperatures, solar-powered operation, IoT connectivity for monitoring energy and water use, learning algorithms that predict usage times to pre-condition the reservoir, and integration with existing solar water heaters or central chillers.

VII. CONCLUSION

A smart adaptive water tap can improve comfort and reduce wasted water and energy by delivering water at a temperature suited to the surrounding conditions. This review has examined the sensors, conditioning methods and control strategies that make such a device possible. Thermoelectric modules offer compact, silent cooling and heating, while resistive heaters provide efficient warming, and a microcontroller with ambient, water and flow sensors coordinates their operation. Heat-transfer calculations show

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that a small insulated reservoir conditioned between uses is the most practical design for household flows. The architecture and control algorithm presented here provide a basis for the hardware design, component selection and implementation of the proposed system.

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