International Journal of Advanced Engineering Application (IJAEA)
Volume 3 Issue 11 Nov 2026
ISSN :3048-6807

Fuzzy Logic Based Liquid Thermal Management of a Lithium-Ion Battery Pack for Electric Vehicles

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Abstract

The temperature of a lithium-ion battery decides how much power it can deliver, how safe it is and how long it lasts, and uneven heating inside the pack shortens its life further. This paper presents the design of a liquid-cooled thermal management system for a 24 V, 10 Ah lithium-ion pack built as seven series groups of four parallel cells (7S4P), together with the prototype assembled from it. An aluminum panel carries heat from the pack to a copper tube, and a 12 V pump moves an inhibited propylene-glycol/water coolant from the tube to a fan-cooled radiator. Six DS18B20 sensors read the pack temperature and an ACS758 sensor reads the battery current. An ESP32 runs a PID controller whose gains are scaled by a fuzzy supervisor using the highest temperature, its rate of rise and the load current, and it drives the pump and fan with PWM signals. A separate check sets full cooling and raises an alert on overtemperature or a sensor fault. Design calculations put the pack heat at about 5 W at 10 A and 47 W at 30 A, which needs only 0.04–0.4 L/min of coolant. In a lumped thermal-model run with the load falling from 10 A to 5 A at 30 °C ambient, fuzzy–PID control peaked at 32.77 °C, 0.77 °C above the 32 °C set-point, and ended at 31.98 °C, while the uncooled pack reached 36.51 °C. In the same model ON/OFF control held the temperature closer to the set-point but used about 42 % more auxiliary energy, and at 30 A the cooling saturated with the pack settling at 38.0 °C. These values come from a model and not from measurements. The prototype has been assembled and its display reports a normal-temperature status, but systematic measurements on it are still to be done.

Keywords: ***Battery thermal management, Fuzzy logic, Lithium-ion battery, Liquid cooling, PID control***

1. INTRODUCTION

Most electric vehicles (EVs) use lithium-ion (Li-ion) batteries because the cells store a lot of energy for their size. How well a pack performs, and how long it lasts, depends heavily on its temperature, which is why thermal management of EV batteries remains an active research area [1]. In the cold the reactions slow down and the available power drops. When the pack runs hot, ageing speeds up, and if the heat cannot be removed the cells can go into thermal runaway. Studies on air-cooled modules report an optimum range of roughly 15–35 °C [2], and a spread of about 5 °C inside a module is a common target. A cooling system therefore has to remove heat, keep temperature differences small and use as little energy as it can.

Air cooling is simple and cheap, but air carries little heat, so it struggles at high current. A liquid coolant has a much higher heat capacity and keeps the cells closer in temperature, at the cost of a pump, a radiator, tubing and some risk of leakage. That cost makes control worth getting right. A thermostat that switches the pump and fan fully on or off wastes energy and lets the temperature swing around its limit. PID control gives accurate closed-loop regulation, and fuzzy logic can capture nonlinear thermal behavior in simple rules; studies that combine the two report faster and smoother temperature control [3], [4].

Fuzzy and other intelligent controllers have also been applied to energy management in hybrid vehicles [5] and to the charging of Li-ion batteries [6], although neither addresses pack temperature directly.

This paper presents the Phase I design of a liquid-cooled system for a 24 V, 10 Ah pack arranged as seven series groups of four parallel cells (7S4P). Its main features are six-point temperature sensing, battery current as an early signal of load, a fuzzy supervisor that adapts the PID gains, pulse-width-modulated (PWM) control of the pump and radiator fan, and a

separate safety check, all on one ESP32 board. A prototype has been assembled and is shown here, but the temperature results reported are model-based, and systematic measurements on the prototype are planned next.

2. RELATED WORK

Fuzzy PID control has been studied for battery cooling in several forms. Ma *et al.* applied it to a liquid-cooled power battery and found, in simulation, a shorter regulation time, a smaller temperature difference inside the pack and better rejection of current disturbances than a conventional PID controller [3]. Liu *et al.* paired an optimized fuzzy PID algorithm with switchable thermoelectric devices and liquid cooling. Their hot pack went from 63.5 °C to 25 °C in 280 s, and the control time was about 76 % shorter than with multi-channel liquid cooling [4]. Both studies support combining rules with feedback, but their results depend on their own cooling hardware and cannot be carried over to this pack.

Other work covers fuzzy logic with particle-swarm optimization (PSO) on an Arduino Uno [7], thermoelectric cooling [8], hybrid air–water cooling [9] and physics-informed machine learning for pack temperature prediction [10]. The Arduino implementation was limited by the computing power of the board, the thermoelectric system by its cooling energy and its behavior at high load, and the hybrid design by its extra hardware and energy use. The machine-learning approach needs training data and more computation. A recent review of EV thermal management [1] gives the wider background for choosing a cooling method.

The gap addressed here is a low-cost, liquid-cooled system built as real hardware for a pack of practical size. It uses a simple copper-tube loop on an aluminum panel, several temperature points and the battery current, and it runs an adaptive fuzzy–PID controller on a capable microcontroller. Fuzzy PID control and multi-point sensing are not new in themselves. The contribution is their integration on one low-cost platform, with a model-based comparison against ON/OFF and conventional PID control in this paper and a measured comparison in the next phase.

3. PROPOSED SYSTEM ARCHITECTURE

The battery is a 7S4P pack rated at 24 V and 10 Ah (240 Wh), which means 28 cells of 2.5 Ah each. Its voltage runs from about 21 V at cut-off to 29.4 V when fully charged. Heat passes through a thin, electrically insulating but thermally conductive interface into an aluminum spreading panel. A copper tube is secured to the outer face of the panel and carries an inhibited propylene-glycol/water coolant. A 12 V DC pump pushes the coolant through a liquid-to-air radiator, where a 12 V fan blows air across the core, and the coolant then returns to the tube (Fig. 1).

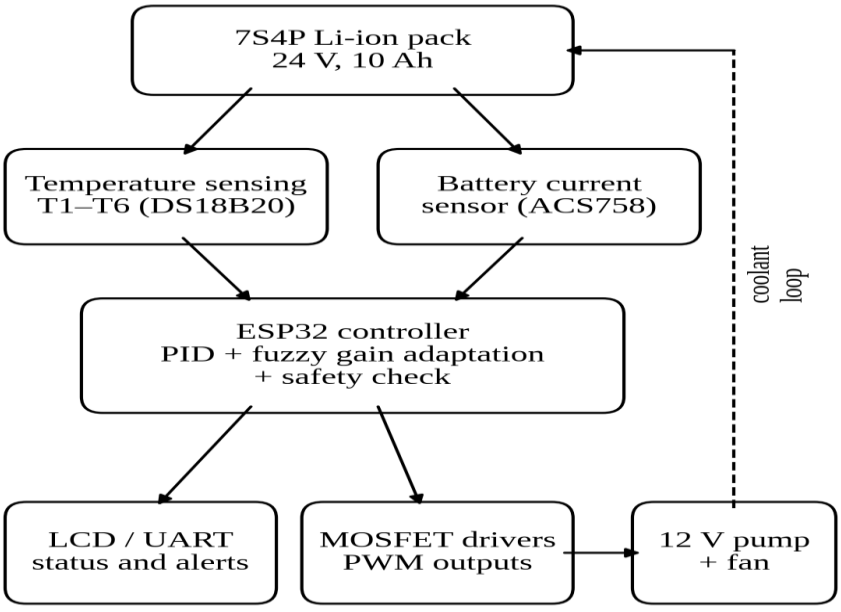


Fig. 1. Proposed battery thermal management architecture.

Six DS18B20 sensors (T_1–T_6) are fixed at six points on the pack to cover its seven series groups. An ACS758 sensor in the negative battery lead measures current, which indicates the load and therefore the heat that is about to be produced. The ESP32 reads these signals once per second, finds the highest pack temperature, the spread between sensors and the rate of change, and sends PWM commands to the pump and fan through two MCP1415 gate drivers and 2N6660 MOSFETs. One 12 V buck converter, rated above the 29.4 V full-charge voltage, supplies the pump, fan and drivers and, through the board regulator, the controller, sensors and display. A 16 × 2 LCD and a serial link show temperatures, current, cooling commands and alarms.

The set-point is 32 °C, inside the 15–35 °C window, and the critical limit is 40 °C. Both are design values to be checked against the cell datasheet. In the first tests the pump will run at a fixed safe speed and only the fan will be controlled. Pump speed control can be added later. The radiator can only cool the coolant toward the ambient air temperature, so the system cannot hold the pack below ambient, and the 32 °C set-point is reachable only when the surroundings are sufficiently cooler.

The prototype built from this design is shown in Fig. 2. It carries the battery pack with its protection board, a 12 V diaphragm pump, a fan, the coolant tubing, an ESP32 development board and a 16 × 2 LCD on an insulating panel. The ESP32 is wired on a breadboard, and a soldered perfboard holds part of the electronics. The LCD in the photograph shows the status message "Normal Temp".

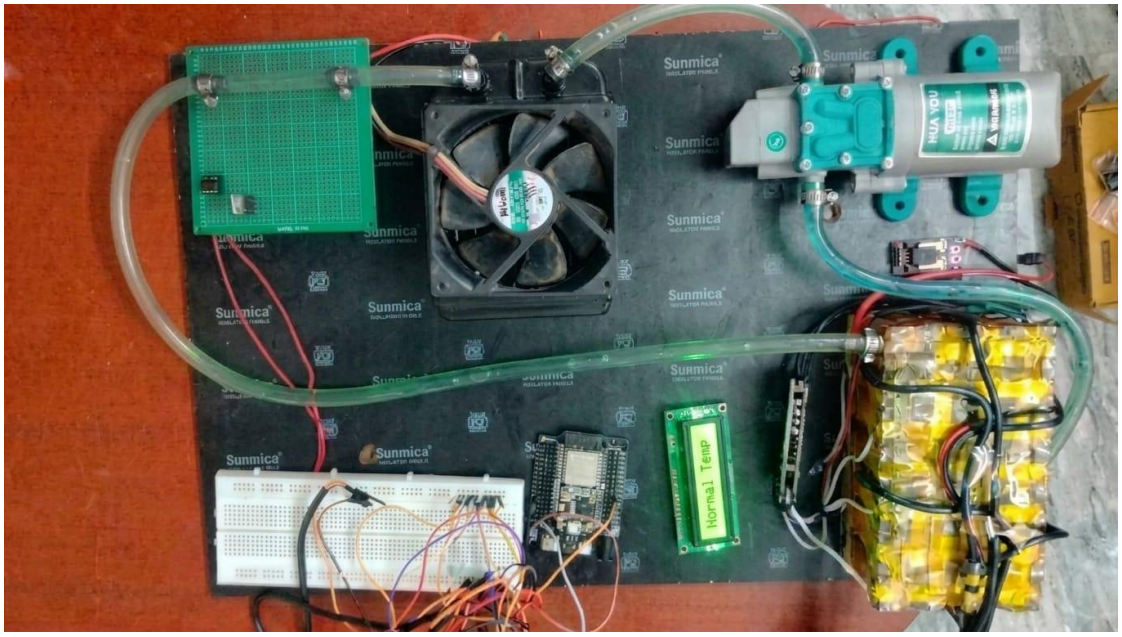


Fig. 2. Assembled prototype of the liquid-cooled battery thermal management system.

4. CONTROL STRATEGY

4.1 Sensing and Control Variables

Let $T_1,\ldots,T_6$ be the six pack temperatures. The highest of them is the controlled variable:

$$T_{max} = \max(T_1, T_2, \ldots, T_6) \tag{1}$$

With a set-point T_{ref} = 32 °C the error is $e(k) = T_{max}(k) - T_{ref}$, where k is the sample index, so a positive error means the pack is hotter than the set-point. The rate of rise is estimated as

$$\frac{dT_{max}}{dt} \approx \frac{T_{max}(k) - T_{max}(k-1)}{T_s} \tag{2}$$

where T_s is the 1 s sampling interval. The battery current I serves as an early indicator of load, because Joule heating grows roughly with I^2 and the current changes before the temperature does. It is not a direct measure of heat, since cell resistance varies with temperature and age and the reversible heat is ignored.

4.2 Fuzzy Supervisor

The fuzzy supervisor takes T_{max}, I and dT_{max}/dt and returns a cooling demand D between 0 and 100 %. The temperature has four sets: Normal (up to 29 °C), Warm (centered at 33 °C), Hot (centered at 37 °C) and Very Hot (from 41 °C). The current has three: Low (up to 5 A), Medium (centered at 15 A) and High (from 25 A), as shown in Fig. 3. The demand has five sets, from Very Low to Very High. Table I lists the twelve rules; for example, if the temperature is Warm and the current is High, the demand is High.

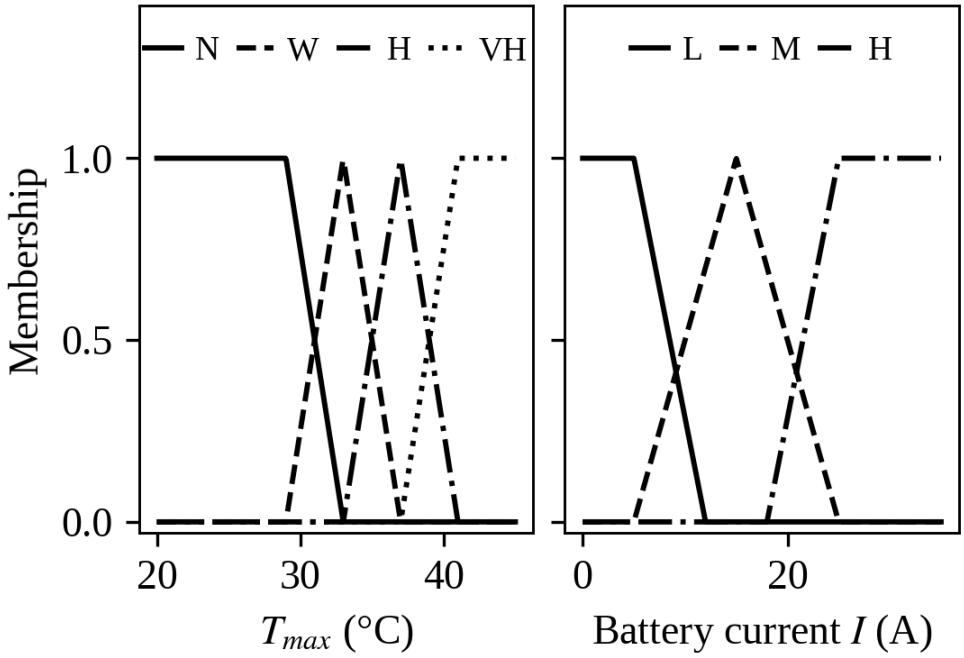


Fig. 3. Membership functions of the highest temperature (N, W, H, VH) and the battery current (L, M, H).

TABLE I: FUZZY RULE BASE FOR THE COOLING DEMAND

Temperature	Low (≤ 5 A)	Medium (15 A)	High (≥ 25 A)
Normal (≤ 29 °C)	VL	L	M
Warm (33 °C)	L	M	H
Hot (37 °C)	M	H	VH
Very Hot (≥ 41 °C)	VH	VH	VH

In each sampling period the memberships of T_{max} and I are found. Every rule fires with the smaller of its two input degrees, and the outputs are combined by a weighted average of the output levels, taken as 0, 20, 50, 75 and 100 % for Very Low to Very High. The rate of rise then corrects the result. When dT_{max}/dt is above +0.05 °C/s the demand is raised by 25 points. When it is below −0.05 °C/s it is lowered by the same amount, so cooling starts early on a rising load and eases off as the pack cools.

4.3 Adaptive PID and Safety Check

The PID layer acts on the temperature error. In discrete form

$$u_{\mathrm{PID}}(k) = K_p e(k) + K_i T_s \sum_{i=0}^{k} e(i) + \frac{K_d \Delta e(k)}{T_s} \tag{3}$$

where K_p, K_i and K_d are the proportional, integral and derivative gains and $\Delta e(k) = e(k) - e(k-1)$. The fuzzy demand does not drive the actuators directly. It scales the gains instead:

$$K_x = K_{x0}\left(0.5 + \frac{D}{100}\right) \tag{4}$$

with x = p, i or d. The gains are therefore half their base values at $D = 0$ and one and a half times their base values at $D =$ 100 %. The base gains in the firmware, $K_{p0} = 8$, $K_{i0} = 0.10$ and $K_{d0} = 20$, are starting values, as are the membership limits, and both will be tuned during commissioning. The PID output is limited to 0–100 % and sets the fan duty; anti-windup stops the integral term from growing while the output is saturated. The coolant loop responds slowly because of its thermal mass, so the sampling period and the integral action must suit that slow response.

A safety check runs independently of the normal control demand. If $T_{\max}$ reaches 40 °C, or a sensor is missing or reads outside −20 °C to 100 °C, the pump and fan go to 100 % and the display and serial link show an alert. Fig. 4 shows the control sequence.

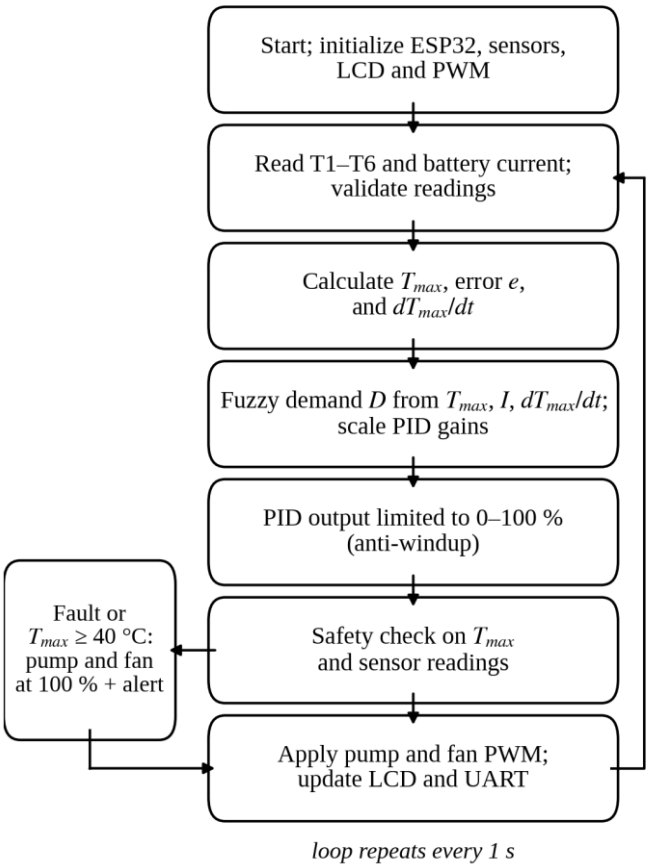


Fig. 4. Control sequence of the ESP32 firmware. The safety check overrides the PID output.

5. DESIGN ESTIMATES AND ENGINEERING CONSTRAINTS

Heat generation is estimated from Joule heating with an assumed cell resistance of 30 mΩ. Four cells in parallel and seven groups in series give a pack resistance of 7 × (30 mΩ / 4) = 52.5 mΩ, so

$$Q_{\text{gen}} = I^2 R_{\text{pack}} \tag{5}$$

where R_{pack} is the equivalent pack resistance. This gives 1.31 W at 5 A, 5.25 W at 10 A, 21 W at 20 A and 47.25 W at 30 A (Table II). The coolant flow needed to carry this heat with a temperature rise ΔT_c follows from a heat balance:

$$\dot{m} = \frac{\dot{Q}}{c_p \Delta T_c} \tag{6}$$

where $\dot{Q}$ is the heat passed to the coolant and c_p is its specific heat; dividing by the density gives the volume flow. With ρ = 1030 kg/m^3, c_p = 3600 J/(kg·K) (typical assumed values for a propylene-glycol/water mixture) and ΔT_c = 2 K, the flow is about 0.49 L/h per watt, or 0.04–0.4 L/min over the 10–30 A range. That is far below the 1–3 L/min target of the pump. At 1 L/min the coolant warms by only about 0.8 K at 47.25 W, so flow is not the limit. The heat still has to travel from the cells through the interface, panel and tube, and the radiator has to reject it. Holding the coolant 8 K above ambient at 47.25 W needs a radiator conductance of about 47.25/8 ≈ 5.9 W/K, which will be checked by test.

TABLE II: ESTIMATED HEAT GENERATION AND COOLANT FLOW (ΔT_c = 2 K)

Load current (A)	C-rate	Heat (W)	Coolant flow (L/min)
5	0.5C	1.31	0.011
10	1C	5.25	0.042
20	2C	21.0	0.170
30	3C	47.25	0.382

The electronics and actuators draw about 16.3 W with the pump and fan at full speed. At an assumed converter efficiency of 85 % that is about 19.2 W (0.8 A) from the battery, or 19.2 Wh over one hour, which is 8.0 % of the 240 Wh pack. Lower duty cycles reduce this overhead further.

The cell resistance and coolant properties are assumed values and will be replaced by measured ones. Before the pack is energized, the team should verify battery management system compatibility, fuse and wire ratings, MOSFET dissipation, pump and fan starting current, coolant compatibility with copper and aluminum, electrical isolation and leak integrity. Table III summarizes the main design parameters.

TABLE III: SUMMARY OF PROPOSED SYSTEM PARAMETERS

Parameter	Design value	Verification needed
Battery pack	24 V, 10 Ah; 7S4P; 21–29.4 V	Confirm cell chemistry, ratings and BMS limits
Temperature sensing	6 × DS18B20 (T_1–T_6)	Calibration, mounting and fault detection
Current sensing	ACS758 (±50 A) at 3.3 V; 26.4 mV/A	Zero offset, range and accuracy
Controller	ESP32; 1 s sampling	Timing and fault behavior
Cooling actuators	12 V pump (1–3 L/min target); 12 V fan; PWM	Flow in the assembled loop, current draw, minimum duty
Set-point / critical limit	32 °C / 40 °C	Validate against the cell datasheet
Power supply	One 12 V buck converter; input above 29.4 V	Current margin, including start-up current

6. MODEL-BASED RESULTS AND DISCUSSION

6.1 Thermal Model and Test Condition

The pack response was evaluated with a lumped, single-node thermal model in which the whole pack is one body of heat capacity C at temperature T:

$$C\frac{dT}{dt} = I^2 R_{\text{pack}} - G(u)(T - T_{\text{amb}}) \tag{7}$$

where R_{pack} = 52.5 mΩ is the pack resistance of Section 5, T_{amb} is the ambient temperature and $G(u)$ is the overall conductance from the pack to the ambient air. The conductance rises linearly with the fan duty u (%):

$$G(u) = G_{\text{nat}} + (G_{\text{max}} - G_{\text{nat}})\frac{u}{100} \tag{8}$$

where G_{nat} is the conductance with the fan off and G_{max} is the value at full duty. Eq. (8) lumps the heat path through the cells, interface, panel, tube and radiator into one conductance, so it ignores the temperature drop inside the pack and the lag of the coolant loop; the temperatures it gives are for the pack as a whole and are likely to be optimistic for the hottest cell. The model is integrated with a 1 s forward-Euler step. The controller is the control law of Section 4 with the base gains given there, and the pump is held at a 40 % duty. Table IV lists all the parameters, so that the runs can be reproduced.

TABLE IV: PARAMETERS OF THE LUMPED THERMAL MODEL

Parameter	Value and basis
Pack resistance R_{pack}	52.5 mΩ (7 × 30 mΩ / 4; assumed cell resistance)
Heat capacity C	1035 J/K, fitted so that the uncooled pack reaches 36.51 °C at sample 50 (28 cells of about 45 g at about 0.9 kJ/(kg·K) would give about 1.1 kJ/K)
Conductance, fan off G_{nat}	0.15 W/K (assumed natural convection from the enclosure)
Conductance, fan at 100 % G_{max}	5.9 W/K (design target of Section 5)
Ambient temperature T_{amb}	30 °C
Initial pack temperature	29.2 °C (10 A to 5 A run); 30 °C (constant-current runs)
Set-point / critical limit	32 °C / 40 °C
Fuzzy–PID controller	K_{p0} = 8, K_{i0} = 0.10, K_{d0} = 20; rule base of Table I; 1 s sampling
Fixed-gain PID	Same as above with the gain scale s = 1 in Eq. (4)
ON/OFF controller	Fan at 100 % above 32 °C and off below 31 °C; pump at 40 %
Auxiliary power at 100 % duty	Fan 3.6 W, pump 12 W; taken as proportional to duty
Sensors	Ideal: no noise and no quantization

The load current falls from about 10 A to 5 A, with random variation of roughly 0.5 A between neighboring samples, and is interpolated linearly between the one-minute samples. Current, highest temperature and fan duty were recorded once per minute for 50 samples, with an ambient temperature of 30 °C and the set-point at 32 °C. A sample is labeled Rise or Fall when T_{max} changes by more than +0.05 °C or −0.05 °C from the previous sample, and Normal otherwise. All values in this section come from the model, not from the hardware.

6.2 Temperature and Cooling Response

Fig. 5 shows T_{max} climbing from 29.50 °C at the first sample to a peak of 32.77 °C at the 17th sample, while the current is still above 8 A. The fan stays off until T_{max} passes the 32 °C set-point, because the PID output is limited at zero while the error is negative, so the temperature overshoots the set-point by 0.77 °C before the cooling catches up. It then eases down to 31.98 °C as the load falls toward 5 A. T_{max} is above the set-point for about 16.9 min in total and stays inside the 15–35 °C window throughout. The temperature trails the current because of the thermal capacity of the pack: a sudden dip in current, for example at samples 3 and 20, produces no matching dip in temperature.

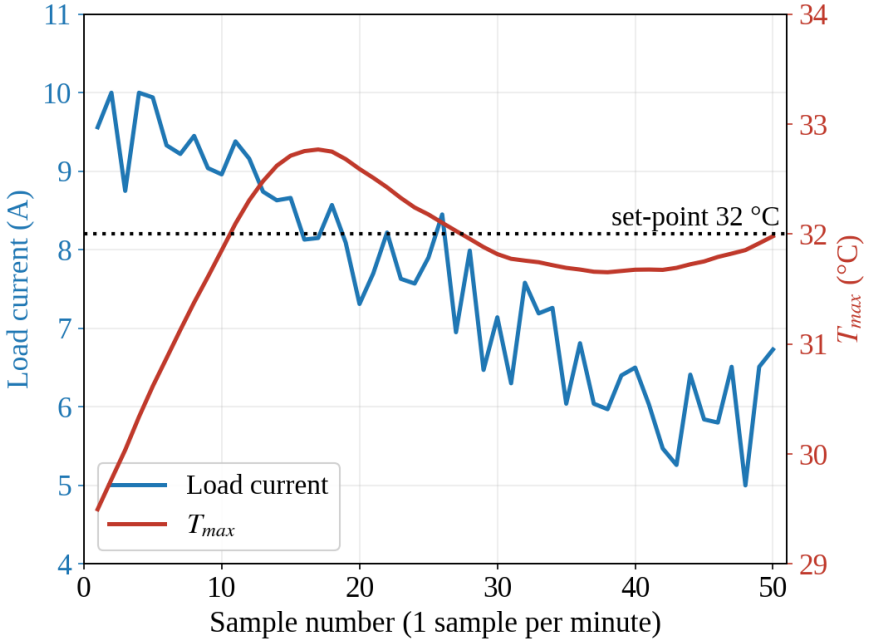


Fig. 5. Load current and highest battery temperature T_{max} against sample number (model).

The cooling effort follows the load (Fig. 6). The fan is off for the first 10 samples, while T_{max} is still below the set-point. Its duty then rises to a maximum of 34 % at sample 25, shortly after the temperature peak, and falls to about 9 % by the end as the current drops to 5–6 A. Starting the cooling below the set-point, or using larger initial gains, would reduce the overshoot and is left for the tuning stage.

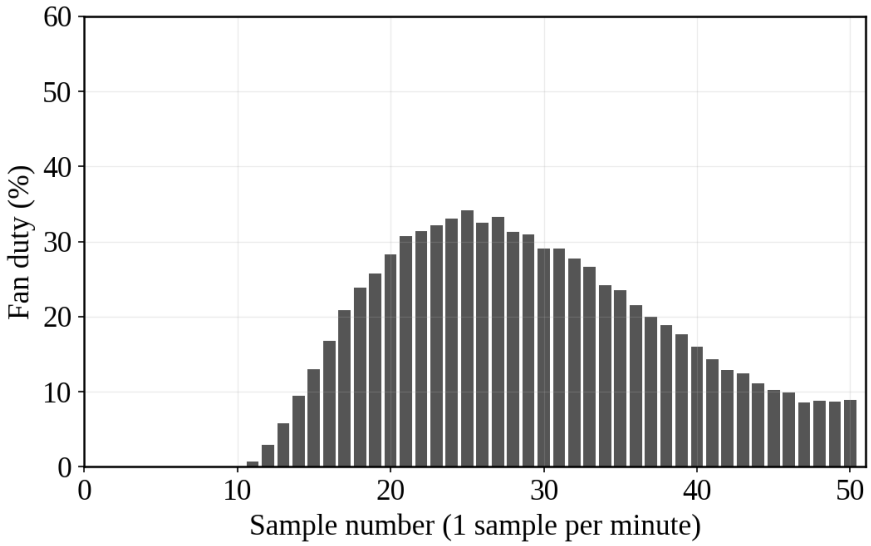


Fig. 6. Pump and fan duty against sample number (model).

6.3 Comparison with No Cooling

Fig. 7 compares the same load with and without cooling. Without cooling, T_{max} keeps rising, passes 35 °C at about the 29th sample and reaches 36.51 °C at the 50th, outside the recommended window. With cooling it is 31.98 °C at that point, which is 4.53 °C lower. Table V summarizes the run.

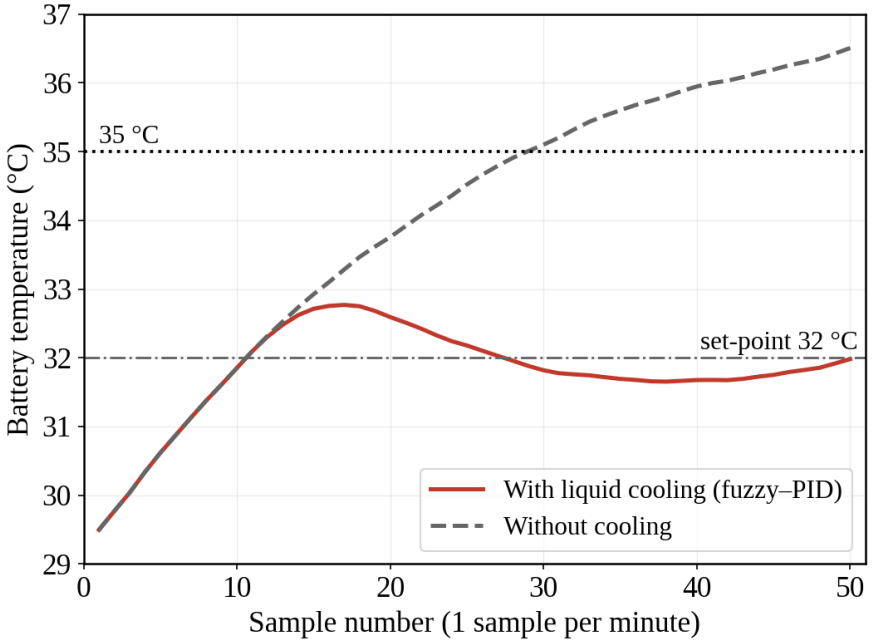


Fig. 7. Battery temperature with and without liquid cooling for the same load (model).

TABLE V: SUMMARY OF THE MODEL-BASED RESULTS

Parameter	**Result**
Load current	5.00–10.00 A (mean 7.61 A)
T_{max} with cooling	29.50–32.77 °C (mean 31.78 °C)
Highest temperature	32.77 °C at sample 17 (set-point 32 °C)
Samples Rise / Fall / Normal	17 / 12 / 21
Pump and fan duty	0–34 % (pump at its 40 % minimum)
T_{max} at sample 50	31.98 °C with cooling; 36.51 °C without

The model shows fuzzy–PID control holding T_{max} within 0.8 °C of the set-point while the load falls from 10 A to 5 A, and cutting the cooling as the load eases.

6.4 Comparison of ON/OFF, PID and Fuzzy–PID Control

Fig. 8 and Table VI compare ON/OFF, fixed-gain PID and fuzzy–PID control on the same model and the same 10 A to 5 A load. All three use the same set-point and pump rule, and the fixed-gain PID uses the base gains without the fuzzy scaling of Eq. (4).

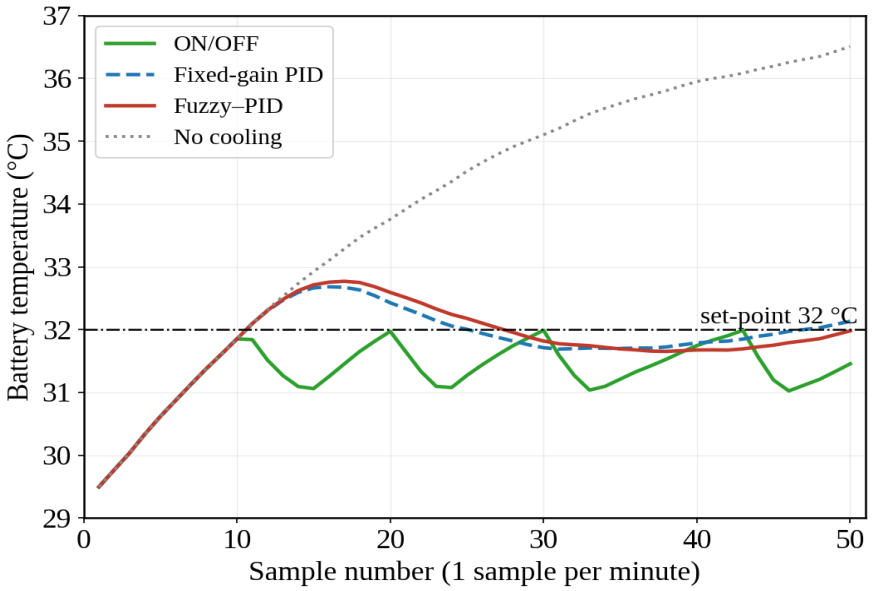


Fig. 8. Battery temperature under ON/OFF, fixed-gain PID and fuzzy–PID control for the same load (model).

TABLE VI: COMPARISON OF CONTROL METHODS (10 A TO 5 A RUN, MODEL)

Controller	Peak T_{max} (°C)	Time above 32 °C (min)	Mean fan duty (%)	Auxiliary energy (Wh)
No cooling	36.51	39.4	—	—
ON/OFF	31.99	< 0.1	26.4	6.37
Fixed-gain PID	32.68	17.7	15.6	4.47
Fuzzy–PID	32.77	16.9	15.9	4.48

ON/OFF control holds T_{max} closest to the set-point (peak 31.99 °C), but the fan switches fully on and off in about 4 cycles in the 50 min, the temperature swings by about 1.0 °C and the auxiliary energy is 6.37 Wh, which is 42 % more than the 4.48 Wh of fuzzy–PID control. The fixed-gain PID and fuzzy–PID controllers vary the fan smoothly and use less energy, but because they act only above the set-point they overshoot it by 0.68 °C and 0.77 °C. In this run the fuzzy scaling does not lower the peak (32.77 °C against 32.68 °C). It shortens the time above the set-point by about 0.9 min and ends 0.15 °C lower (31.98 °C against 32.13 °C), at essentially the same energy. A small difference is expected at this load: the load changes slowly, the gains are scaled only between 0.5 and 1.5 of their base values, and the rate correction of Section 4.2 never acts (see the limits below).

6.5 Higher Load Currents

Because the heat grows with I^2, the 10 A to 5 A run is the easy case. Two further constant-current runs were made with the same model: 20 A for 30 min and 30 A for 20 min. Each equals one full discharge of the 10 Ah pack and starts at the 30 °C ambient temperature. Fig. 9 shows the fuzzy–PID response and Table VII lists all three controllers.

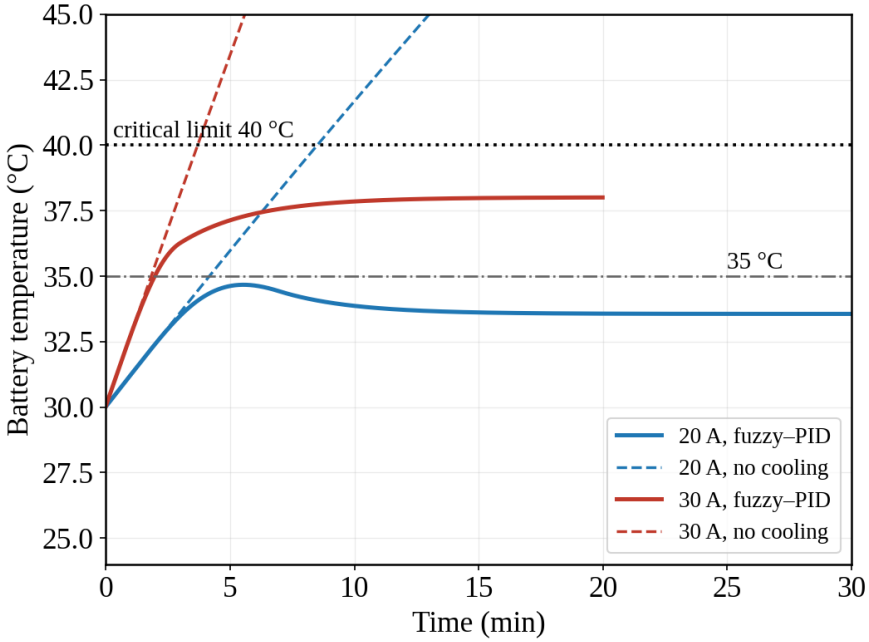


Fig. 9. Battery temperature at constant 20 A and 30 A with fuzzy–PID control and without cooling (model).

TABLE VII: CONSTANT-CURRENT RUNS AT HIGHER LOAD (MODEL)

Load	Controller	Peak T_{max} (°C)	T_{max} at end of run (°C)	Mean fan duty (%)
20 A, 30 min	ON/OFF	33.56	33.56	94.4
20 A, 30 min	Fixed-gain PID	34.92	33.56	84.2
20 A, 30 min	Fuzzy–PID	34.67	33.56	85.5
30 A, 20 min	ON/OFF	38.00	38.00	96.3
30 A, 20 min	Fixed-gain PID	38.01	38.01	88.4
30 A, 20 min	Fuzzy–PID	38.00	38.00	90.2

Without cooling the pack would pass 35 °C after 4.2 min and 40 °C after 8.5 min at 20 A, and after 1.8 min and 3.7 min at 30 A. With cooling, the fuzzy–PID fan reaches full duty after about 7.0 min at 20 A and 3.0 min at 30 A, and from then on the controller can do no more. The pack settles where the heat generated equals $G_{max}(T - T_{amb})$, at 33.56 °C for 20 A and 38.00 °C for 30 A, so the 32 °C set-point cannot be held at either current when the ambient temperature is 30 °C. The 30 A result stays below the 40 °C critical limit, but only by 2.0 °C, and above the 35 °C window. Holding 35 °C at 30 A would need an overall conductance of about 9.4 W/K instead of the 5.9 W/K design target. At 20 A the fuzzy supervisor gives a peak of 34.67 °C against 34.92 °C for fixed-gain PID, which is consistent with the larger gains it applies at high demand. At 30 A the three controllers give the same result because the fan is saturated. The 5.9 W/K radiator target is therefore adequate up to about 20 A at this ambient temperature and has to be increased for sustained 3C loads.

6.6 Predicted Response for the Planned Prototype Test

Testing of the assembled prototype (Fig. 2) is planned for the next phase. Table VIII gives the model prediction for the planned test: a constant discharge current of 10 A for 20 min at a 30 °C ambient temperature, with the pump at a fixed speed and the fan under fuzzy–PID control.

TABLE VIII: MODEL-PREDICTED RESPONSE FOR THE PLANNED PROTOTYPE TEST

Time (min)	Current (A)	Predicted T_{max} (°C)	Predicted fan duty (%)
0	10.0	30.01	0
5	10.0	31.49	0
10	10.0	32.77	12
15	10.0	32.89	38
20	10.0	32.38	47

These results have clear limits. All of them come from one lumped model whose heat capacity was fitted to the uncooled end point of the 10 A to 5 A run and whose conductances are assumed, so they are not identified from measurements. The rate correction of Section 4.2 never acted: the heating rate in the model is below 0.005 °C/s in the 10 A to 5 A run and below 0.046 °C/s even at 30 A without cooling, against the ±0.05 °C/s threshold, so the threshold must be reset from measured data.

7. LIMITATIONS AND FUTURE WORK

This paper covers the design stage and the assembly of a prototype. The prototype has not yet been tested systematically, so there are no measured temperatures, flow rates or repeatability data, and the results above are model-based. Cell resistance, membership limits, PID gains, actual coolant flow and radiator capacity are design values that must be confirmed by measurement. The loop also adds leak risk, weight and an auxiliary electrical load.

The next phase will instrument the assembled prototype and test it under charging, discharging and changing loads. The proposed controller should be compared with ON/OFF, conventional PID and standalone fuzzy control on the same battery, coolant, radiator, ambient condition and load profile, logging T_1–T_6, current, pump and fan duty, ambient temperature and fault events. Peak temperature, temperature spread, settling time, overshoot and auxiliary energy should be reported together over repeated runs, because a lower temperature is of little value if it costs more pump and fan energy. Fault tests should include a disconnected sensor and a stopped pump or fan. Later work may tune the membership functions and gains with an optimization method such as PSO, extend the rule base to the full three-input form, estimate the state of charge, add pump speed control and combine liquid cooling with phase-change material for higher-power packs.

8. CONCLUSION

A liquid-cooled thermal management system has been designed for a 24 V, 10 Ah (7S4P) Li-ion pack. An ESP32 combines six-point temperature sensing, battery current measurement, a PID controller whose gains are adapted by a fuzzy supervisor, PWM control of the pump and radiator fan, and a separate safety check. The pack heat is estimated at about 5 W at 10 A and 47 W at 30 A, which needs only 0.04–0.4 L/min of coolant, well within the 1–3 L/min pump target. In a model run with the load falling from 10 A to 5 A, fuzzy–PID control kept the highest temperature within 0.77 °C of the 32 °C set-point, with a peak of 32.77 °C, while the uncooled pack reached 36.51 °C by the end of the run, and the cooling duty followed the load. In the same model ON/OFF control held the temperature closer to the set-point but used about 42 % more auxiliary energy, the fuzzy scaling gave only a small gain over fixed-gain PID at this load, and at 20 A and 30 A the 5.9 W/K radiator target saturated and left the pack at 33.6 °C and 38.0 °C. Because these results are model-based, the next step is to test the assembled prototype and measure temperature regulation, temperature spread and auxiliary energy against ON/OFF and PID control.

ACKNOWLEDGMENT

The authors thank the Department of Electrical and Electronics Engineering, K. Ramakrishnan College of Technology (Autonomous), for academic support during this project work.

AI ASSISTANCE DISCLOSURE

An AI assistant (Claude, Anthropic) was used to help draft and edit the text of this manuscript, to write and run the thermal-model simulations and to prepare its figures from the authors' project report and data. The authors reviewed and verified the content and take full responsibility for its accuracy and integrity.

CONFLICT OF INTEREST

The authors declare that they have no known conflict of interest.

DATA AVAILABILITY

The model-based data and the simulation script behind Tables IV–VII and Figs. 5–9 are available from the corresponding author on reasonable request. No human or animal subjects were involved in this work.

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