Thermal verification: does the SHT41 measure the room?

Engineering report ENV1-TR-001 rev A
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VERDICT

+8.3 K ± 0.1
SHT41 self-heating bias · Wi-Fi always on (410 mW)

+2.4 K
ESP-IDF default modem-sleep, DTIM1 (108 mW)

+0.17 K
Fix: Wi-Fi auto light-sleep (7.3 mW) — inside the SHT41's ±0.2 °C typ.

The vent design does not work as a thermal measure. The vent air carries 1.2 % of the heat and 3.8 % leaves as radiation through the slots; 54 % goes out through the shell and 41 % into the wall. Closing every vent changes the bias by only +0.29 K, removing the sensor chamber by -0.20 K (the chamber does not help), a front grille over the chamber by -0.09 K. The whole enclosure warms up, and the SHT41 follows it at about 20 mK per mW dissipated. **Fix (simulated): turn on Wi-Fi auto light-sleep in the firmware.** No hardware change is needed: the reading error falls from +8.3 K to +0.17 K.

1 · QUESTION, MODEL AND INPUTS

The ESP32-C3 module (U1) and the 3.3 V LDO (U3) dissipate inside the closed ENV-1 enclosure. The SHT41 (U4) sits on a slotted PCB island inside a baffled chamber that is vented at the bottom and side. How far does self-heating bias the reading, and do the vents and the chamber prevent it?

Geometry — the real design, nothing redrawn. All 34 parts of the ENV-1 assembly (CAD/STEP, via its GLB export) are voxelised on uniform grids of 0.4, 0.3 and 0.225 mm (finest: 2.99 M cells). That covers the shell with its 1° draft, every vent slot, the baffles and ribs, keys, light pipe, bosses, screws and keyhole pockets. Board outline and isolation slot come from Edge.Cuts. The copper of both layers is rasterised from the Gerbers (61 % / 75 % coverage) as anisotropic conductivity, and all 101 vias count as through-plane copper. A typical USB-C cable (10.5 × 5.5 mm overmold) is plugged in, as it is in use.

Heat source (V_{BUS} 5.0 V, 3.3 V rail)	current	U1 mW	U3 mW	source
Wi-Fi always on (connected, RX listening)	82 mA	270.6	139.7	[1] T6-4
Default modem-sleep, DTIM1 (average)	21.47 mA	70.9	36.8	[2]
Auto light-sleep, DTIM1 (average)	1.4 mA	4.62	2.66	[2]

U1 = 3.3 V × I (all supply power becomes heat; RX radiates nothing). U3 = (5.0 − 3.3) V × I + 5.0 V × 55 µA quiescent [3]. SHT41 0.4 µA average [4]; LED off; PTC/ESD parts < 1 mW — all neglected. The heat is released in the SoC block under the module shield (5 × 5 mm) and in the SOT-23-5 body.

Material (lumped where noted)	k W/m·K	ε
PC/ABS shell, rear housing, keys · PC light pipe	0.20	0.90
FR-4 1.6 mm + 35 µm Cu (390) per Gerber pixel	0.30 + Cu	0.90
Module PCB (in-plane / through) · SoC · shield can	30/2 · 20 · 18	0.9 / 0.1
SOT-23, DFN, passives · USB-C · steel screws · air	3 · 10 · 50 · 0.026	0.9 / 0.15 / 0.6

Surroundings: still room air at 23.0 °C. Outside: natural convection (Churchill–Chu vertical plate [7]; 0.54/0.27·$Ra^{1/4}$ top/bottom), updated with the surface temperatures, plus radiation (ε 0.9) to the room. Rear face on a 12.5 mm gypsum wall (radial-fin solution, 0.2 mm contact gap): G = 31 mW/K. Vents are open boundaries at room pressure, and air enters at 23.0 °C.

Where the 410 mW go	mW	%
outer shell (convection + radiation)	221	54
into the wall (rear face)	168	41
radiation out through the vents	15.7	3.8
carried out by the vent air	**5.1**	**1.2**

Rise above room, Wi-Fi on	K
ESP32-C3 SoC (hottest cell)	+22.8
board, mean	+15.2
inside air, mean	+9.5
SHT41 reading	**+8.3**
air in front of the SHT41	+7.5
outer surface, area mean	+4.8

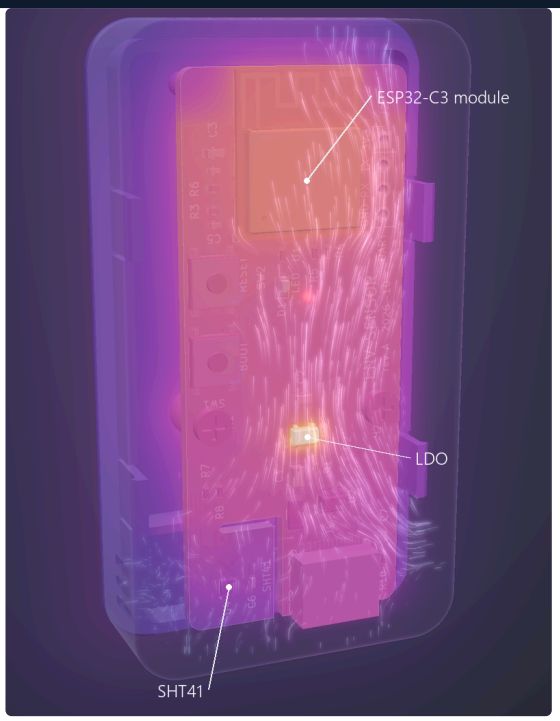

Fig. 1 Steady state, Wi-Fi always on: simulated surface temperatures on the real CAD geometry, plus air tracers from the computed flow (front shell drawn as glass). Same colour scale as Fig. 2.

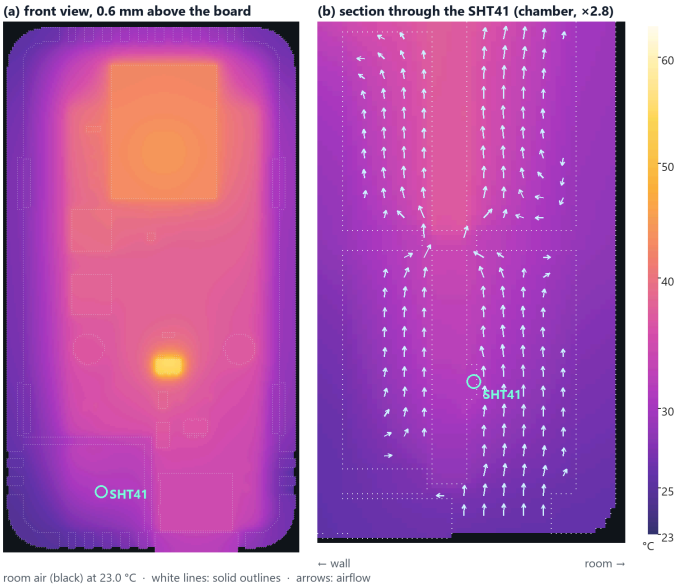

Fig. 2 Exact cell temperatures on the finest grid, Wi-Fi always on. (a) A plane 0.6 mm above the board; (b) a section through the SHT41 with the in-plane airflow (max 13 mm/s). Room air does enter the chamber from below, but the chamber walls, the board island and the air are all part of one warm enclosure.

2 · METHOD

Air: steady, laminar, incompressible Navier–Stokes with Boussinesq buoyancy (cell Re < 1), on staggered (MAC) finite volumes with central differences and no-slip at every voxel face. Pseudo-time marching (Chorin artificial compressibility [8]) is followed by an exact discrete projection (AMG-CG), so the velocity that carries heat is divergence-free to 10^{-12}. **Heat:** one conservative finite-volume equation for every cell — air and all solids together (conjugate). Harmonic-mean face conductances and hybrid central/upwind convection; solved implicitly (BiCGSTAB + smoothed-aggregation AMG, residual < 10^{-10}). **Radiation inside:** grey-diffuse surface-to-surface exchange on ~6 000 two-millimetre patches. View factors come from Monte-Carlo ray tracing (1.2–2.1 M rays, exact voxel traversal), with reciprocity enforced and the radiosity solved directly; rays that leave through a vent reach the room. **Coupling:** flow, energy, radiation and outside coefficients are iterated until the SHT41 changes by < 0.2 mK per K twice in a row. **Transient:** variable-step BDF2 with real heat capacities (Δt 2 → 120 s); airflow, radiation and outside coefficients are re-solved every step. The SHT41 reading is the mean temperature of its package cells.

3 · RESULTS

Case (steady, room 23.0 °C)	grid mm	P mW	SHT41 K	air K	SoC °C	vent %	mm³/s
Wi-Fi always on, as drawn (finest grid)	0.225	410.3	**+8.32**	+7.46	45.8	1.2	766
Wi-Fi always on, as drawn	0.4	410.3	**+8.28**	+7.27	45.6	1.4	856
— every vent closed	0.4	410.3	**+8.57**	+7.63	45.6	0.0	0
— sensor chamber removed	0.4	410.3	**+8.08**	+6.83	45.6	2.0	1184
— front grille over the chamber	0.4	410.3	**+8.19**	+7.14	45.6	1.4	878
Default modem-sleep (DTIM1)	0.4	107.6	**+2.38**	+2.14	29.1	0.4	238
Fix: Wi-Fi auto light-sleep	0.4	7.3	**+0.17**	+0.16	23.4	0.0	17

SHT41 / air: rise above the room; vent %: share of the heat carried out by the vent air; mm³/s: exhaust flow. The design studies use the 0.4 mm grid (compare them with its own baseline, +8.28 K).

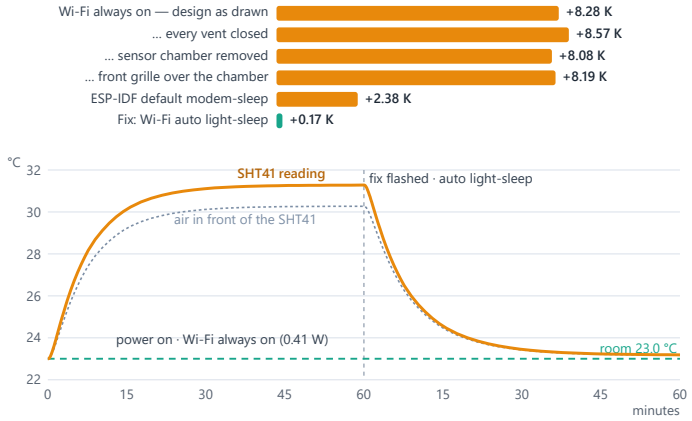

Fig. 3 Power-on transient (Wi-Fi always on, 0.4 mm grid, BDF2), then the light-sleep firmware is flashed. The reading reaches 90 % of its error after ≈16 min and returns to within 0.2 K of the room within the hour after the fix.

Assumptions and limits: still air (drafts lower the bias); rear face on a gypsum wall (a stand-off mount raises the bias); module internals and contact resistances lumped; average currents (TX bursts add short peaks); laminar flow; no sun or radiant room loads.

References: [1] Espressif, ESP32-C3-MINI-1 & MINI-1U Datasheet v2.2, Tables 6-4, 6-6, 6-7. [2] Espressif, ESP-IDF Programming Guide v6.1, "Introduction to Low Power Mode in Wi-Fi Scenarios" (ESP32-C3): average 21.47 mA (modem-sleep, DTIM1), 1.4 mA (auto light-sleep, DTIM1). [3] Diodes Inc., AP2112 datasheet DS39724 Rev. 2-2: I_Q 55 µA, θ_{JA} 184 °C/W (SOT25). [4] Sensirion SHT41 product data / SHT4x datasheet (04/2025): typ. accuracy ±0.2 °C, average supply current 0.4 µA. [5] G. de Vahl Davis, Int. J. Numer. Meth. Fluids 3 (1983) 249–264. [6] I. B. Celik et al., J. Fluids Eng. 130 (2008) 078001. [7] S. W. Churchill, H. H. S. Chu, Int. J. Heat Mass Transfer 18 (1975) 1323–1329. [8] A. J. Chorin, J. Comput. Phys. 2 (1967) 12–26.

ENV-1 and its company context are illustrative: the product story and all business data are invented, and no real company is involved. Component figures come from the public datasheets cited. These are simulation results, not measurements. Simulation, verification, film and report: AILA.

4 · VERIFICATION

Natural-convection benchmark [5]	Nu 64²	Nu 128²	ref.	error
Ra 10^3	1.118	—	1.118	+0.03 %
Ra 10^4	2.251	2.246	2.243	+0.15 %
Ra 10^5	4.562	4.532	4.519	+0.29 %

The benchmark uses the same solver code as the enclosure. The error falls at roughly second order as the grid is refined, and the hot- and cold-wall Nu agree to 10^{-10} (exact conservation).

Grid study [6]	0.4 mm	0.3 mm	0.225 mm	convergence	uncertainty
SHT41 bias, K	8.28	8.17	8.32	oscillatory	±0.10 K
air at SHT41, rise K	7.28	7.48	7.46	oscillatory	±0.13 K
ESP32-C3 SoC, rise K	22.61	22.68	22.82	monotonic, not asymptotic	±0.26 K

The SHT41 bias converges oscillatorily within ±1 % (staircase voxels on a 1.5 mm package and 0.4 mm gaps), so no extrapolation is made. The uncertainty is 1.25 × the half-range, and the headline is +8.32 ± 0.10 K. The LDO body temperature is grid-sensitive (62.8 / 61.6 / 57.4 °C; lumped SOT-23 shape): treat it as indicative only.

Further checks	result
Energy balance, every case (in = shell + wall + vent air + radiation through vents)	**closed to ≤ 0.04 %**
Iterative convergence (remaining change of the SHT41, geometric estimate)	**≤ 1.6 mK in every case**
Time step Δt vs Δt/2, power-on transient 0–30 min	≤ 168 mK (2.0 %); t_{90} 17.5 vs 16.2 min
Transient after 60 min vs steady solution (same grid)	**+8.280 vs +8.283 K**
Hand calculation: isothermal box (Churchill–Chu + radiation + wall fin)	**surface +5.35 K vs simulated mean +4.79 K**
Hand calculation: chimney, 21 mPa head over laminar 1.1 mm slots (upper bound)	**≤ 2117 mm³/s; simulated 766 mm³/s**

The transient carries a first-order coupling lag (the flow is re-converged once per step). It shifts the warm-up curve by ≤ 2 % and does not affect any steady result.

5 · VERDICT AND RECOMMENDATIONS

- **Self-heating bias:** +8.3 ± 0.1 K with Wi-Fi always on, +2.4 K with the ESP-IDF default modem-sleep, +0.17 K with auto light-sleep. The reading needs ≈16 min after power-on to reach 90 % of its error.
- **Vents and chamber:** they work as a chimney (766 mm³/s), but at this size they cannot remove 0.4 W. Vent design changes move the bias by ≤ 0.3 K out of 8.3 K.
- **Fix:** ship the firmware with Wi-Fi power management on (*esp_pm_configure*, light_sleep_enable = true, DTIM ≥ 1; [2]). That gives a bias ≤ 0.2 K at 7.3 mW. Read the SHT41 before the radio wakes. Keep the average dissipation under about 8 mW (≈24 mK/mW at low power).
- Do **not** rely on a fixed software offset in always-on builds: it would change with Wi-Fi traffic, drafts and mounting.