Journal of Electronic Testing (2022) 38:453–461
https://doi.org/10.1007/s10836-022-06013-y

Temperature and Humidity Controlled Test Bench for Temperature Sensor Characterization

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Received: 27 April 2022 / Accepted: 24 June 2022 / Published online: 25 July 2022

Abstract

A temperature and humidity-controlled test bench for a wirelessly-powered ultra-low-power temperature sensor IC is presented. It consists of a closed metallic structure of 0.02 m^3, forming a faraday-cage around the design under test (DUT), thermally insulated using Polyethylene foam, to provide electromagnetic interference (EMI) clean and thermally stable test environment with an operating temperature range of -10 °C to 100 °C. The temperature control with a settling accuracy of ± 0.6 °C is achieved with air-cooled 100 W Peltier modules, having fast dynamics to reach 95% of the required temperature within 15 min. The humidity is controlled by air circulation through a desiccant pocket, managed at around 15% to avoid water droplets during defrosting. A controllable vacuum of ~ 1.3 kPa is achieved through a vacuum pump when < 15% of de-humification is needed. The system operates at a lower power consumption of 30 W during the temperature retention phase, with acoustic noise of 58 dB-SPL achieved.

Keywords Electro-Thermal Measurement System · Peltier Cell · Thermoelectric Cooler · Temperature-Controlled Test-Bench

1 Introduction

Vaccine-based immunization is one of the most effective disease control methods in medical sciences. The World Health Organization (WHO) recommends that most vaccines should be stored at temperatures between + 2 °C and + 8 °C until the time of their delivery, especially when they are in the Intermediate and Outreach stages of the cold chain. Almost 30% of vaccines lose their potency due to the temperature fluctuations in the cold chain across manufacturing, transportation, and delivery and it has been listed as one of the major threats to vaccine quality in the VLM. Consequently, every year, more than 20 million children are ineffectively immunized worldwide, potentially exposing them to completely avoidable diseases. The vaccines included in the EPI program in developing countries include both heat (OPV, DPT, TT) and cold (Pentavalent, TT and IPV) sensitive vaccines. The challenge of proper temperature control is worse in developing countries due to poorly working equipment, especially during the last mile in remote areas where health-worker can only reach the recipient on foot. The vaccine drives face severe challenges in the winter and summer seasons

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when extremely hot and cold weather makes the ice-box-based method ineffective [3, 5, 17].

It has been reported that continuous monitoring of the vaccine temperature during storage and delivery helped reduce the temperature excursion by 40%. Still, monitoring the temperature of the transportation box instead of each vial is a shortcoming of the current methods. The currently used color change method is based on the Arrhenius equation used in cold-chain-monitor-cards (CCM) with vaccines from UNICEF. There is one CCM per 3,000 doses of vaccine. Although CCN idea is extended to individual vials as vaccine vial monitor (VVM), this not only increases the cost but this irreversible color change method can only be used to discard the ineffective vaccine, therefore, unable to improve the chain by identifying where the temperature excursion occurred. Moreover, the existing commercial techniques like CCM/VVM are manual. Consequently, they are prone to human error and missed excursions due to limited temperature sampling [1, 4, 6, 15, 16, 18].

A novel custom-designed temperature monitoring ASIC has been proposed in [1, 16]. This developed ASIC is either pasted under or placed inside an individual vaccine vial to monitor its fidelity. This IC which has a targeted temperature range of -10 to + 75 °C and a resolution of ± 0.8 °C, is wirelessly powered up and senses temperature using a nano-Watt on-chip temperature sensor and transmits the measured temperature back wirelessly to an electronic data logging unit in proximity.

In this paper, we present a low-cost, portable, highly configurable, and robust test system to test the above-mentioned temperature sensing ASIC. The same setup can be used to characterize any temperature sensor with high accuracy. The presented test bench employs Peltier thermo-electric coolers for temperature control along with a microcontroller, similar to a setup proposed in [9] and [2, 7, 8, 10] and it enables electrical testing in a low-noise temperature- and humidity-controlled environment to verify the circuit's performance in the specified temperature range [9]. Achieves a fast-settling time of < 1 min and 0.05 °C temperature setting accuracy; however, it has a very small thermal load that of a single thermostat where the presented test setup handles a thermal load as large as 100 kJ with different settling times [2, 7, 8]. Handle larger thermal loads and therefore their settling times accordingly scale up to several minutes. This test bench also employs a faraday cage-like metallic chamber for isolation from external EMI. The metallic chamber has panel-mounted electrical feed-throughs for robust and vacuum-enabled IO connections. The humidity levels inside the thermal chamber are monitored and actively controlled through a closed loop to keep the frosting/defrosting cycle from creating water droplets over sensitive circuits.

The rest of the paper is organized as follows: Sect. 2 presents the design details of the system; Sect. 3 contains the measurement results while Sect. 4 concludes the paper.

2 Design Description

Figure 1 shows the block-level depiction of the Test-Bench. The details of the individual functional blocks are discussed in the following sub-sections. Figure 2 shows an abstract stepwise construction of the mechanical and thermal aspects of the test bench.

2.1 EMI-Proof Thermal Chamber

The thermal chamber (TC) of the test bench has been constructed as two concentric chambers, with thermal insulation in between. Both chambers are made of aluminum and are grounded to shield the Device Under Test (IC) against the external EMI. These two chambers form the complete EMI-Proof Thermal Chamber.

The inner chamber is constructed with an aluminum sheet of 1.2 mm thickness. The standoffs for the electronic circuits mounted inside the chamber are fixed at the time of assembly of the test setup and locked into place with a thread lock. 18 holes of 3 mm diameter were drilled in the two side walls of the thermal chamber for the electrical feedthrough wires. These holes were set in a pattern, so the mechanical rigidity of the chamber would not be compromised. The Peltier modules for temperature control are attached to the outer

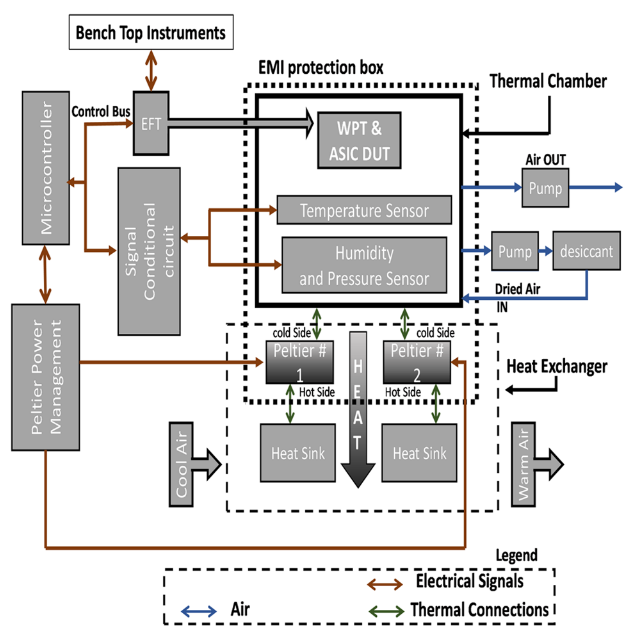

Fig. 1 System Block Diagram

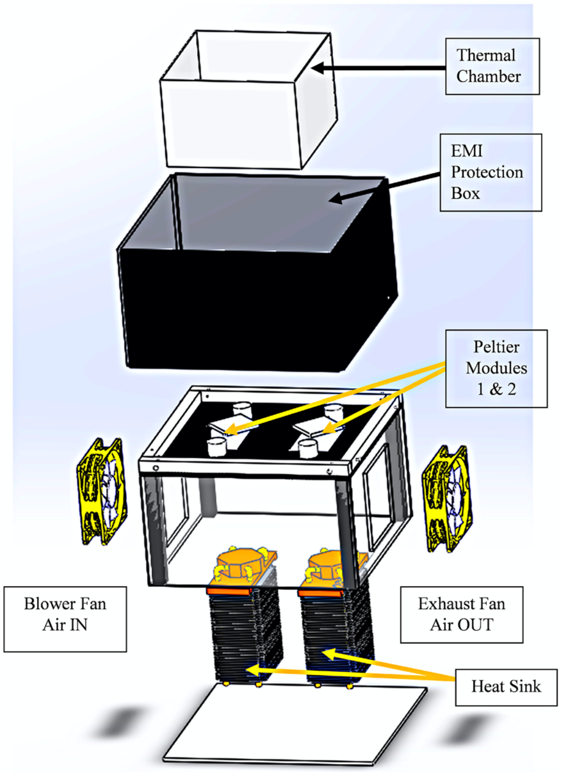

Fig. 2 Abstract Stepwise View of the Thermal and Mechanical Structural Aspects of the Test-Bench

wall of the inner chamber through screws with thermal paste in between.

The outer chamber consists of 4 mm thick sheet aluminum, for the necessary robustness and mechanical stability to sustain electrical feed-through mounting, constructed with shear-cut plates held together using square rods as braces with 4 mm screws tapped in to hold the structure in place.

The space between the two chambers, containing the Peltier modules and feed-through cables, is filled with 20 mm polyurethane foam, reducing the thermal conductivity to 0.037 W/m°C. Therefore, the only significant thermal input or output inside the inner thermal chamber can come through the Peltier modules while electrical feed-throughs also contribute to negligible thermal leakage.

2.2 Temperature-Controlled Equipment

The absorbed heat from the internal environment is to be pumped out using a cooling mechanism. The available choices were:

- Ice bath
- Combination of Liquid Nitrogen-based cooling with heaters
- Vapor compression cycle-based cooler
- Cool water running through copper tubing or water body.
- Thermo-electric cooler (Peltier modules)

The ice bath was not employed as during the electrical testing phase of the ASIC having ice and water close to the test setup could be hazardous. Also, it would be difficult to absorb the amount of heat required to lower the temperature to -10 °C and to sustain the temperature at one point for a reasonable time to have extended testing of the IC. Liquid nitrogen-based open-loop coolers would provide the temperature range required, but their operational intricacies while dealing with LN2 would make the setup hazard-prone. Vapor compression cycle-based coolers are popular cooling methods available, with low operating costs, and a reasonable coefficient of refrigeration. However, it would require a rather bulky copper tubing of the evaporator to be attached to the thermal chamber along with other disadvantages of the presence of moving parts and circulating liquid inevitably leading to leaks [1, 6, 14].

The presented system employs Peltier modules or solid-state heat pumps for temperature control. Peltier modules comprise n-type and p-type dopes materials connected thermally in parallel while electrically in series, joined through thermal conducting plates on both sides. Whenever current passes through the Peltier module it absorbs the heat from the cold side and transfers it to the hot side to counterbalance the potential difference applied to it. This effect is known as the Peltier Effect which is the reverse phenomenon of the Seebeck Effect [12, 13]. Subsequently, heat from the hot side must be extracted using a heat sink system, which in turn dissipates the heat into the environment. The critical benefits offered by Peltier modules are compact size, no moving parts resulting in longer part life, and the ability to reverse the heat, i.e. by switching the electrical polarity of the Peltier module, heat can be put into the cold chamber instead [11]. This offers a unique advantage as no additional heating mechanism is required to raise the temperature of the chamber. However, critical disadvantages of thermoelectric coolers are constant power consumption and low thermal efficiency. As electrical input is removed from these modules, they become thermal short, where hot and cold environments are thermally shorted and considerable thermal leakage takes place in a short time [11]. Table 1 includes the dimensions of the thermal control chamber along with the properties of the materials used and the testing operating conditions.

2.3 Theoretical Framework for Thermal Analysis

Based on the above-mentioned chamber dimensions, a theoretical thermal analysis is presented in the following text to gauge the requirements of the Peltier modules. The

Table 1 Data and parameters

Operating Conditions	
Temperature	25 °C
Pressure	101.3 kPa
Humidity	-
Target Temperature	-10 °C
Box Parameter	
Internal Volume	147.6 × 147.6 × 98.8 mm^3
Wall Thickness	1.2 mm (uniform)
Box Thermal Properties	
Aluminum Grade	1060
Density	2.7 g/cm^3
Thermal Conductivity	234 Wm^{-1} K^{-1}
Specific Heat Capacity	0.9 $kJkg^{-1}$ K^{-1}
Air Thermal Properties (During Testing)	
Density	1.1839 kg/m^3
Thermal Conductivity	26.24 mWm^{-1} K^{-1}
Specific Heat Capacity	1.006 kJ kg^{-1} K^{-1}

study, briefly presented below, is carried out considering the entire system as a closed system to calculate the total energy needed to be taken out of the system to achieve a temperature drop of ± 40 °C. The vapor content of the ambient air is neglected as the box is intended to be used in a controlled environment.

2.3.1 Total Energy

Aluminum:

Mass of walls:

$$[2(100 \times 150 \times 1.2) + 2(100 \times 147.6 \times 1.2)$$
$$+(147.6 \times 147.6 \times 1.2)] \times 0.0027 = 0.26343\ kg$$

Required energy removal:

$$Q_M = mC\Delta T = -8.298\ kJ$$

Air:

Mass of contained air:

$$(0.1476 \times 0.1476 \times 0.0998) \times 1.1839 = 0.00255\ kg$$

Required energy removal:

$$Q_A = mC\Delta T = -0.090\ kJ$$

Total energy removal:

$$Q_u + Q_A = -8.388\ kJ$$

Table 2 Settling Time

# Of Peltier Modules	Required Time to Achieve ΔT
1	19.2 min
2	9.6 min

2.3.2 Rate of energy removal

The employed Peltier modules, because of local-market availability, have a power wattage of 100 W with 10% surface losses. With these Peltier modules and the above-mentioned thermal load, the following Table 2 lists the time required to achieve the required temperature gradient. However, the following calculations do not include any thermal leakages of any heat generated by the DUT itself. Based on this table, it is reasonable to use two Peltier to decrease the settling time.

2.4 Humidity Control Equipment

The water content of the air inside the thermal chamber needs to be monitored and kept below the condensation point to avoid the frosting/defrosting cycle creating water droplets over the IC or other electronics. Two approaches were considered: 1) a passive approach employing Silica Gel beads inside the thermal chamber; however, this would add to the thermal load and dampen the response of the system without any accurate control over the humidity levels. 2) an active approach with close-loop air-circulation through two silicon hoses was placed inside the thermal chamber by a flapper valve pump, passing through an external container that has silica gel beads while measuring the humidity through an off-the-shelf humidity sensor and controlling the pump through a microcontroller. The second active approach is employed in the presented system. Again, the pump is kept out of the Thermal chamber to avoid electromagnetic interference.

2.5 Electrical Feed Throughs

Panel-mounted SMA connectors, mounted on the external Aluminum box, are used as the electrical feed-throughs. They are routed to the internal DUT break-out board using appropriate wires and cables.

2.6 Temperature Control Loop

The temperature controller regulates the inside temperature of the chamber through the Peltier modules. The control loop

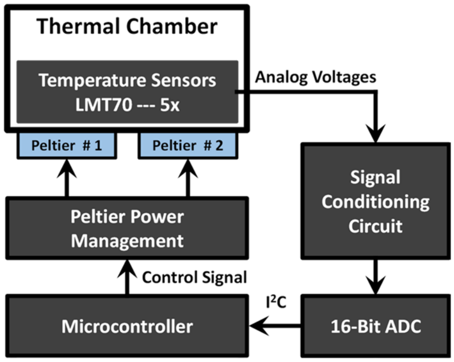

Fig. 3 Thermal Control Loop

is shown in Fig. 3. The temperature sensors used for the temperature control loop are LMT70. Five LMT70 sensors are used inside the thermal chamber, to sense the temperature of each separate surface like PCB, internal air, metal body, and the break-out board housing the IC. Multiple temperature sensors provide the capability to observe the consistency of the thermal profile inside the thermal sensor and to avoid the creation of hot and cold spots. To filter out spurious glitching in the temperature management loop, the signal conditioning circuitry routed the output of the LMT70 sensors through a second-order low-pass filter. The filtered signal is subsequently digitized using the 16-bit ADC modules. The Atmega2560 microcontroller then controls the Peltier modules in accordance with the temperature data measured.

2.7 Humidity Control Loop

The thermal energy inside the thermal chamber is transmitted through three mechanisms, conduction, convection, and radiation. For faster and efficient thermal transmission inside, an adequate level of humidity should be present. That, however, raises another issue. With too much humidity, the testing towards lower ranges of the temperature may result in frosting, de-frosting, and then eventual water droplet build-up on electronics. Therefore, proper humidity control is required to keep the dew point away from the test temperature range.

Figure 4 shows the humidity control loop, which achieves the control through the flapper vane pump and uses the DHT-11 humidity sensor for feedback. To remove the humidity silica gel beads were identified as the most convenient option. As these beads change color gradually as they become saturated with moisture and can easily be recharged by heating in an oven.

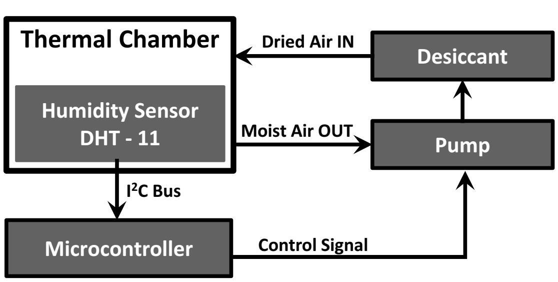

Fig. 4 Humidity Control Loop

3 Measurement Results

The following Fig. 5 shows the evolution of test-bench construction at different phases. Figure 6 shows the open-loop large-signal temperature control test results with the Peltier modules fully on for two hours and then turned off for two hours. Figure 6 shows the temperature profile of different elements on the test bench. The testing starts at 09:57 Hrs. from the graph it can be seen that the response of the Peltier modules is very fast, taking around less than 3 min to descend below zero degrees from room temperature while the air inside the thermal chamber takes 8 min to descend below zero and 30 min to achieve 95% of the final required value equilibrium.

Closed-loop small-signal testing started at around 12:57 Hrs. by subjecting the device to an On–Off control using an Arduino microcontroller. The control variable was the thermal

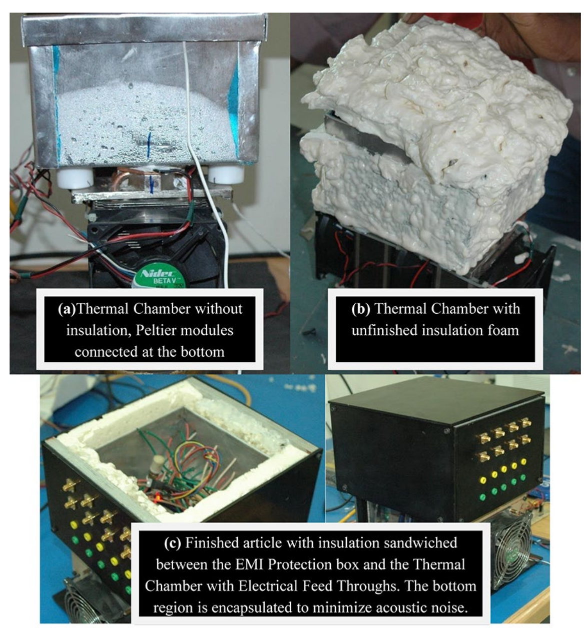

Fig. 5 The thermal chamber **a** with no insulation. **b** covered in polyurethane insulation and **c** Final assembly installed within the EMI protection box with 20 mm insulation between the two aluminum structures, and electrical feedthroughs mounted on the outside box

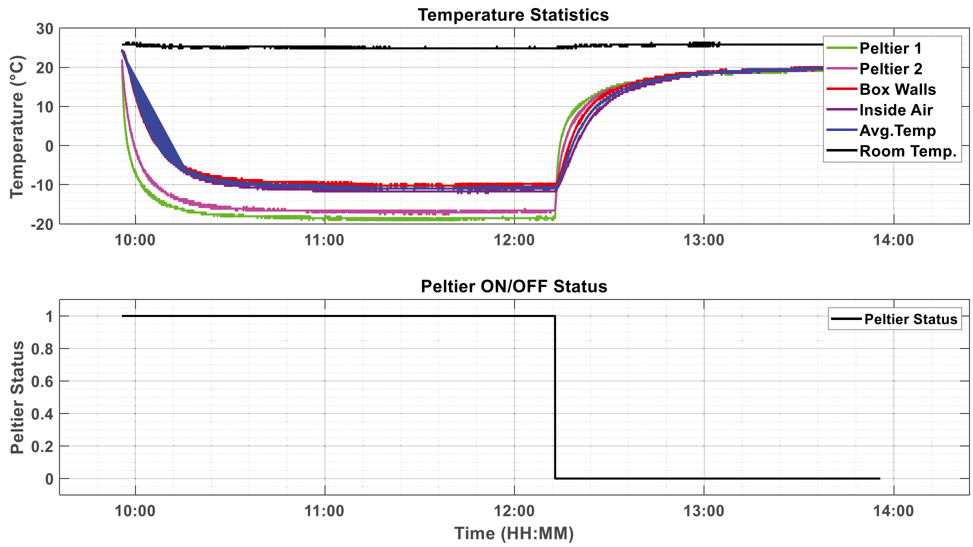

Fig. 6 Open-loop Large-Signal Thermal Testing of the Test-Bench

chamber air temperature. The results are shown in Fig. 7 when the desired temperature is set at -5 °C and the temperature is just 5 °C, i.e. starting from -10 °C. The closed-loop settling time is approximately 15 min to 99% of the desired value, as can be seen by the Average Temperature graph in Fig. 7. It can also be seen that humidity is settled to the desired value of 25% after 15 min through the closed-loop circulation through desiccant. In Figs. 6 and 7 the x-axis refers to the absolute time in 24-Hour format as the temperature, humidity, and Peltier status data are logged in absolute time.

Figure 8 zooms into the final thermal settling after 15 min and shows the steady-state response with percentage errors for two cases; with and without a bi-quad electrical low-pass filter in the thermal control closed-loop. It can be seen that there is significant noise in the measurement, which results in unnecessary switching of the Peltier modules and a degraded thermal settling accuracy of ± 20% without electrical filtering. Bi-quad low-pass analog filters at a cut-off frequency of 100 Hz and discarding of LSB of the controller's ADC along with a moving average digital filter with a span of 100 samples were subsequently used to post-process the acquired signal before turning on and off the Peltier modules. The improved percentage error of ± 4% with an electrical filter can be seen in Fig. 8, which demonstrates a settling accuracy within ± 0.6 °C of the desired temperature.

Figure 9 shows the sampled acoustic and electrical noises inside the EMI-protected thermal chamber. It can be seen that the EMI protection is providing a noise floor below -80 dBV of electrical noise, which is limited by the noise measuring instrumentation, nevertheless, it demonstrates that the setup is adequate for 12-bit measurements. This proves the feasibility of the Faraday cage, insulating the internal

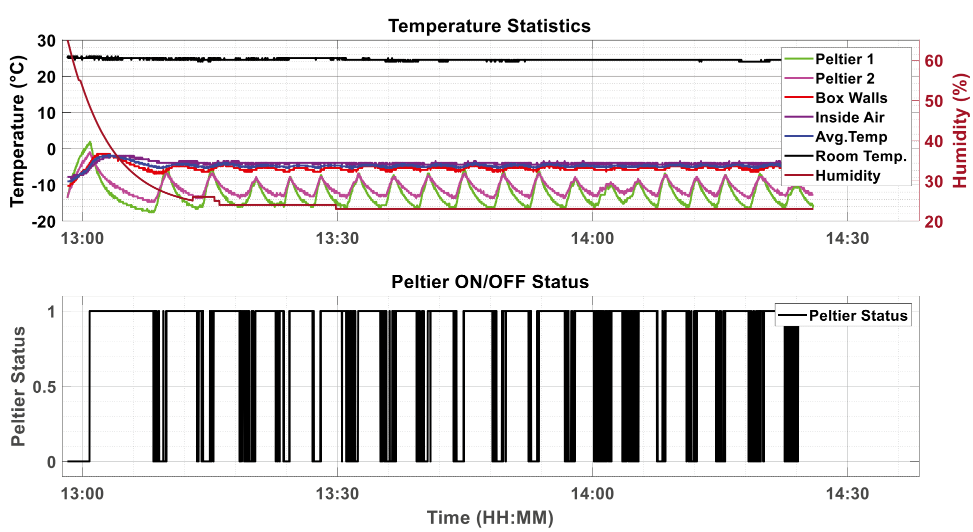

Fig. 7 Closed Loop Testing

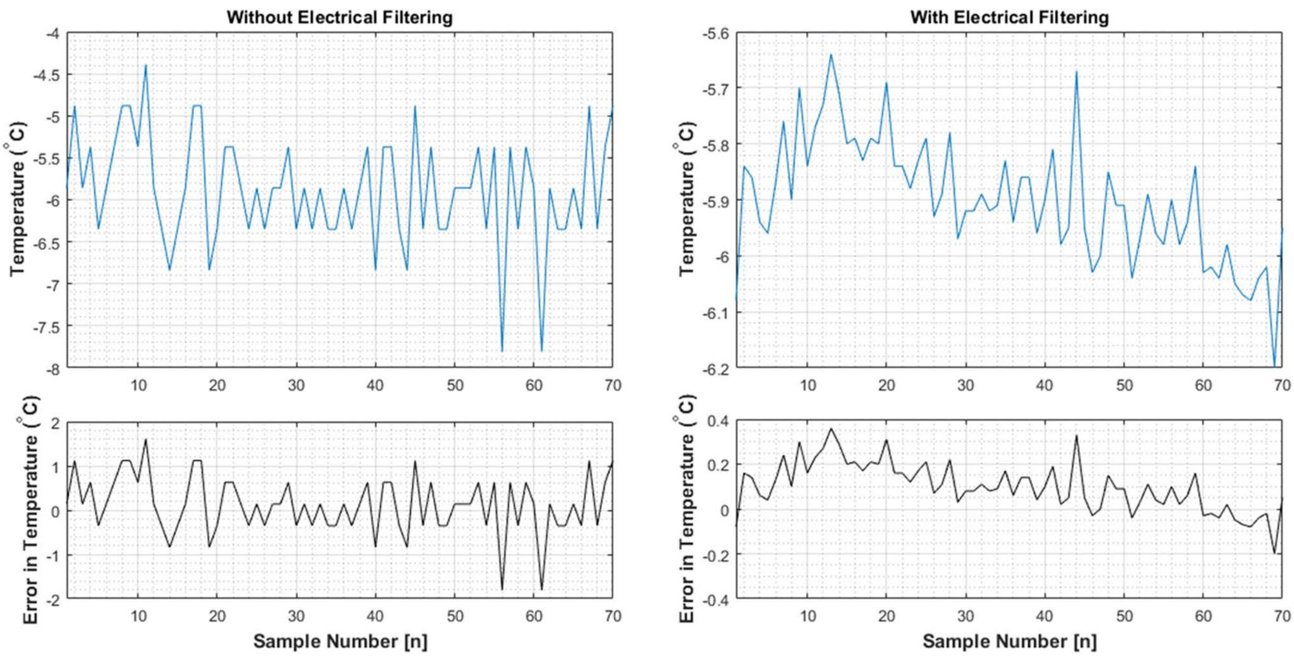

Fig. 8 Thermal Steady State Measurements—with and without Electrical Filtering – when the desired temperature is -6 °C

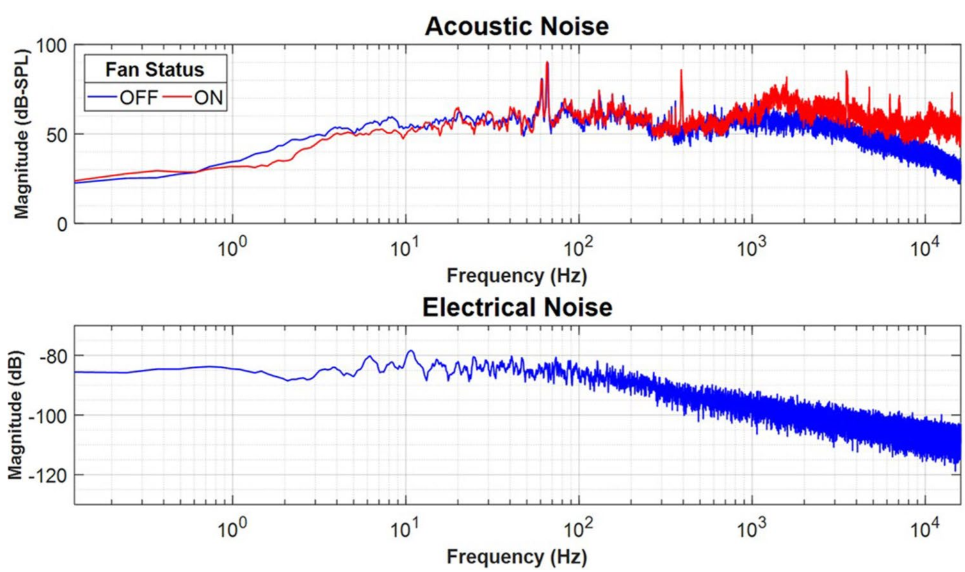

Fig. 9 Electronics and Acoustic Noise inside the Thermal Chamber

chamber from the noise of cooling fans, Peltier modules, and power supplies. Figure 9 also shows the acoustic noise due to the Peltier cooling fans outside the measurement setup at a distance of 1 m. The acoustic noise level is below 65 dB-SPL even when the fans are operating at their maximum RPM, which is a reasonably comfortable level to work on the testing setup for longer durations without any headphones. The features of the Test-bench are summarized in the Table 3 below.

4 Conclusion

A test bench for temperature-controlled measurements of a wirelessly powered ultra-low-power temperature sensor IC was presented with a temperature range from -10 °C to 100 °C. The test bench can control temperature, and humidity and provides a low-noise internal chamber for DUT testing. It has a volume of 0.02 m^3, forming a Faraday cage around the IC, thermally insulated using Polyethylene foam. The temperature control was

Table 3 Summary of the Characterized Test-Bench Features

Features	Value
Average power consumption	180 Watts
Temperature range	-10 to 100 °C
Humidity control range	Above 5 %
Vacuum level	~1.3 kPa
Acoustic noise level	64 dB-SPL at 1 m distance
EMI protection	-80 dBV within 1-10 KHz Band
Temperature settling time	< 15 mins
Temperature settling accuracy	± 0.6 °C
Volumetric capacity	0.0025 m^3
Cooling technology	Thermo-electric cooler

demonstrated through two air-cooled 100 W Peltier modules with a settling accuracy of ± 0.6 °C, and a settling time of 15 min to reach 95% of the required temperature. The test bench demonstrated humidity by air circulation through a desiccant pocket. The peak total power of the complete system is 300 Watts and the audio noise level generated by the cooling fans at maximum RPM is ~ 64 dB-SPL at 1 m from the system. The total electrical noise inside the thermal chamber is -80 dBV, which is adequate for 12-bit instrumentation. The overall thermal, electrical, and acoustic specs of the test bench make it an adequate setup for a wide range of temperature sensor characterization.

5 Funding

The data that support the findings of this work are available and can be made available from the authors upon reasonable request.

Acknowledgements The authors would like to show appreciation towards EDCAS Research Group for supporting the ASIC and its test setup manufacturing; and the Karachi Institute of Economics and Technology (KIET) for providing research facilities.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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