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OpenTCC: An open source low-cost temperature-control chamber

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ABSTRACT

Microbial electrochemical technologies (MET) are emerging systems for environmental applications such as renewable energy production or pollution remediation. MET research often requires stable temperatures and low levels of electromagnetic interference. Due to the presence of electrical wires and sensors, heating MET using water jacket recirculation can raise safety issues, whereas heating coils may affect the results of electrochemical analyses. The proposed open-source temperature-control chamber (OpenTCC) aims to provide a low-cost solution for controlling temperature (in the range 20–55 °C) while simultaneously reducing the electromagnetic interferences caused by switching mode power supplies. OpenTCC consists of a light and cheap structure, incorporating eight heating pads and two Peltier-cooling modules powered by open-source electronic circuits. Its hardware is controlled by an Arduino microcontroller and a Python interface which provides data-logging and serve as a basis for programable temperature cycles. The system has a modular design to allow stacking several independent modules. OpenTCC provides a reliable and tunable temperature control at lower costs than currently available commercial temperature controllers and provides a platform for field-specific upgrades. Though optimized for MET, Open-TCC can be adapted to other laboratory applications due to its flexible design.

1. Hardware in context

Microbiology research requires accurate temperature control, as temperature affects bioconversion kinetics and microbial community composition and thus, the replicability of the experiments. Microbial electrochemical technologies (MET) is one example of a research field often requiring long-term, temperature-controlled experiments. MET consist of aqueous systems in which electrochemical transformations are mediated by electroactive microorganisms growing on solid electrodes [1]. The electrodes used are often large conductive surfaces potentially acting as antennas for electromagnetic interference (EMI) intense environments [2]. For this reason, Faraday cages are sometimes used in order to reduce the electrical artifacts on electrochemical measurements [3]. Temperature controlled chambers have a high cost and thus, can be a limiting resource in many laboratories. METs require external wiring to connect the bioreactors to the electrical control and measurement devices, and thus conventional temperature-controlled chambers or incubators require special modifications, such as drilling holes. Moreover, if the Faraday cage functionality is required, additional connections to the earth's ground might be necessary to reduce EMI [3]. Such modifications are not possible in commercial temperature-controlled chambers as they invalidate any warranty and may damage the chamber.

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Here, we present an open source temperature-controlled chamber (OpenTCC), designed to reduce costs and open new possibilities for temperature-controlled experiments in microbiology (e.g., constant temperature, simulate temperature cycles, e.g. day-night or seasonal temperature conditions). OpenTCC includes an Arduino microcontroller and a Python interface to obtain a flexible and programmable temperature control and data logging, capable of heating or cooling a volume of 72 L in short time. To the authors knowledge, OpenTCC is the only open-source incubator capable of cooling [4] [Table 1].

OpenTCC can be used in laboratories with limited financial resources, being cheaper than commercially available devices [Table 2]. Although commercial temperature-control chambers such as the Memmert Peltier can set a wider range of temperatures (between 0 and 70 °C), OpenTCC provides temperature control in the range used in most biological experiments (20–55 °C) at 10-times lower cost and offers fully open-source design [Table 3]. Furthermore, OpenTCC facilitates a modular installation with stacked units that can be controlled at different temperatures.

In summary, OpenTCC was designed to meet the following requirements:

1. Temperature control in the range of most biological experiments (20–55 °C)
2. Low cost (less than €400)
3. Portability and stackability (less than 20 kg)
4. Dampening effect on electromagnetic interferences (Faraday cage)
5. Programmable interface

2. Hardware description

The hardware configuration of OpenTCC (Table 3: Structure), and instructions for its assembly, are presented at 1:1 scale in the project repository. The fully open-source and detailed explanation of the working principles and circuitry of OpenTCC (Table 3: Schematic connections) allows for further development or customization of this platform. OpenTCC consists of an aluminium structure which optimize the heat distribution inside the chamber. Due to its inherent conductivity, aluminium can be used to partially reduce the effect of EMI by connecting it to ground as a Faraday cage. This can result in more accurate measurements of the low-voltage and low-current signals typical of MET research, and reduce the effect of EMI on the biological structures [8].

The OpenTCC aluminium structure serves as skeleton for the extruded polystyrene sheets which supply thermal insulation for long periods due to the low water absorption coefficient of the material [9]. The structure has two drilled openings to

Table 1
Specifications table.

Hardware name	OpenTCC
Subject area	• Biological Sciences (e.g. Microbiology and Biochemistry) • Environmental, Planetary and Agricultural Sciences • Educational Tools and Open Source Alternatives to Existing Infrastructure • Electrochemistry
Hardware type	• Laboratory infrastructure • Temperature control / incubator • Faraday cage
Open Source License	CERN OHL
Cost of Hardware	Approx. 400 euros
Source File Repository	https://osf.io/w38t6/ - / https://doi.org/10.17605/OSF.IO/C9JFA.

Table 2
Hardware in context.

Brand	Model	Open source	Temperature range	Dimensions	Datalogging	Extras	Price euro [ref. source]
Incuvers	Iris Tri-Gas incubator	Yes	23–42 °C	20 × 30 × 40 cm (25 L)	Yes	- Control of oxygen and carbon dioxide concentration- Compact and easily transportable- Easy automation to simulate conditions- Live cell imaging- Remote monitoring	6000[4]
FisherSci	Heratherm	No	17–40 °C	29 × 18 × 31 cm (16 L)	No		720 [5]
Memmert	Peltier IPP55	No	0–70 °C	40 × 40 × 33 cm (53 L)	10 year	- Alarm	3,340 [6]
Binder	KMF115	No	−10–100° C	60 × 48.3 × 35.1 cm (101 L)	Computer interface	- Preheating chamber- Humidity control- Alarm	16.467 [7]
OpenTCC	V 1.0	Yes	20-55° C	30 × 60 × 40 cm (72 L)	Computer interface	- Compact, modular and easily transportable- Easy automation to simulate temperature cycles- Connect and program any sensors- EMI noise dampening	400 [This study]

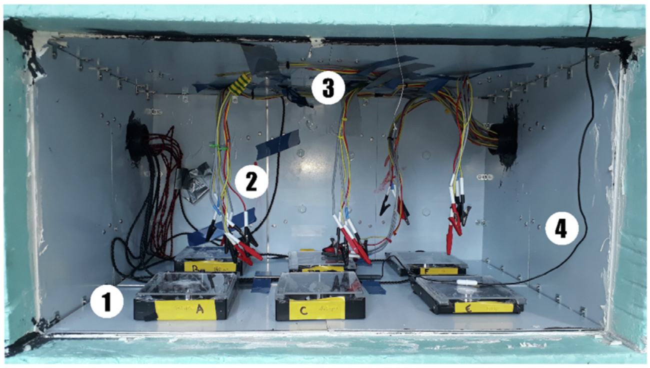

Fig. 1. Picture of the OpenTCC with incorporated old hard drives converted to magnetic stirrers (1), with brushless direct current (BLDC) motor driving electronics, and all the connections necessary for measuring and controlling electrode voltages in MET experiments (2). The image shows the temperature sensor AD22100 hanging from the top of the chamber (3) and the supplementary handheld thermometer (4).

facilitate wiring the reactors and other devices (e.g. stirrers) inside the chamber to the external power sources and measuring devices [Fig. 1]. This modifiable structure allows to implement additional shielding improvements such as specialized EMI connections [10].

The main purpose of OpenTCC is an accurate temperature control inside the chamber, to avoid thermal variations affecting the experimental results. A set of eight heating pad resistors (Table 4: Pad) were installed at the base of the chamber as heating devices, and two thermoelectric Peltier (Table 5: Pelt) modules were installed on the back side of the chamber for cooling. The compact heating pad resistors are covered with aluminium sheets to increase heat distribution and homogenize the temperature inside the chamber. The thermoelectric Peltier cooling modules are characterized by lower maintenance cost and lower weight compared to the commonly applied compressor-type cooling systems [11,12]. Both heating pads and Peltier modules are DC devices with limited EMI generation.

In OpenTCC, heating and cooling elements are powered by a 12 V power supply. The eight heat pads (8 Ω resistance each) can conduct up to 1.5 A per unit at 12 V if an appropriate heatsink (an aluminium sheet in this case) is supplied to transfer the generated heat. Each thermoelectric (Peltier) unit has a limit of 6 A, therefore 24 A are necessary to power at full potential all the eight heating and two cooling elements installed. However, since the modules never work all simultaneously, any power supply that supplies at least 10 A, such as a typical computer ATX power supply or the one specified in Table 4 (Designator: Pow) can be used. In this work, the power supply was recovered from an old computer to power OpenTCC. A more efficient and nowadays popular power supply is the switching-mode power supply (SMPS), which regulate its output to supply a constant voltage. However, SMPS is characterized by a high level of EMI radiation, and thus, should be placed outside and distant from the chamber (Supplementary material: EMI).

In OpenTCC, the heating and cooling modules are controlled by an Arduino microcontroller (Table 5: Ardu) which opens or closes the energy supply to the heating or cooling elements depending on the temperature measured in comparison to the set temperature, using logic-level N-channel power MOSFETs (Table 5: Mosf). OpenTCC incorporates two different temperature sensors: a Pt-100 resistance temperature detector (RTD) as the external temperature sensor and an AD22100 integrated circuit (IC) as the internal temperature sensor. The Pt-100 circuit (Table 5: RTD) comprises a Wheatstone bridge and a differential/instrumental amplifier built from simple op-amps (Table 5: Opa). The voltage difference is then measured by the Arduino analog-to-digital converter (ADC). The AD22100 consists of a low-cost proprietary-RTD IC (Table 5: Therm) measuring the temperature inside OpenTCC using the Arduino as a power source and an ADC without any additional circuit requirements. Other types of sensors can be installed based on the user's needs and possibilities.

3. Design files

Table 3
Design Files Summary.

Design file name	File type	Open source license	Location of the file (https://osf.io/w38t6/)
WhatstoneRTD	.png	CERN OHL	/Schematics/Wheatstone.png and Fig. 4
AD22100	.png	CERN OHL	/Schematics/ AD22100.png and Fig. 5
MOSFETSwitching	.png	CERN OHL	/Schematics/MOSFETSwitching.png and Fig. 6
Arduino	.ino	GNU GPLv3	/Software/Arduino.ino and SupplementaryMaterial code 1
PySerialGUI	.py	GNU GPLv3	/Software/PySerialGUI.py and SupplementaryMaterial code 2
Structure	.fcstd .step	GNU GPLv3	/Schematics/Structure.fcstd and Fig. 2.

4. Bill of materials

Table 4
Bill of Materials – OpenTCC – electronics (total = 315 euro).

Designator	Component	Number	Cost per unit (Euro)	Total cost (Euro)	Source of materials [ref. link]	Material type (purpose)
Ardu	Arduino uno	1	20.57	20.57	Radionics [13]	Micro controller and USB wire to communicate with the PC (or Raspberry Pi)
Pelt	Peltier Module with Fan	2	31.01	62.02	Sparkfun [14]	Cooling element
Pad	Heat pad	8	4.32	34.56	Sparkfun [15]	Heating element
Mosf	N-channel MOSFET	6	0.85	7.10	Sparkfun [16]	Switching
Res	Resistor kit	1	7.14	7.14	Sparkfun [17]	Wheatstone bridge and instrumentation amplifier components
LED	Leds (green, red, yellow)	3	0.3	0.9	Radionics [18]	Visualize the state of the power circuitry
Str	Stripboard	1	4	4	Radionics [19]	PCB for the circuits
Pro	Protoboard	1	7 (2 units)	3.5	Sparkfun [20]	PCB for Pt-100 circuit
Opa	Dual operational amplifier	2	1	2	Radionics [21]	Building blocks for the instrumentation amplifier
RTD	RTD Pt-100	1	18.11	18.11	Radionics [22]	Temperature sensing resistor
Therm	Thermometer IC (AD22100)	1	5	5	Digikey [23]	Temperature sensing IC
W	Wire 30 AWG	2	10	20	Radionics [24]	Wiring
Opt	Opto-coupler	2	0.5	1	Radionics [25]	Circuit isolation (Arduino-ATX)
Dio	Flyback diode	1	0.2	0.2	Sparkfun [26]	Flyback diodes to avoid inductive voltage peaks during switching
Pow	Power supply	1	21	21	Radionics [27]	ATX power supply to power up the system
Keyb	Keyboard	1 (if PC not available)	13.1	13.1	Radionics [28]	USB keyboard to interact with Raspberry Pi
Mous	Mouse	1 (if PC not available)	7	7	Radionics [29]	USB mouse to interact with Raspberry Pi
Screen	Screen	1 (if PC not available)	53	53	Radionics [30]	Screen to visualize Raspberry Pi information
Rasp	Raspberry Pi	1 (if PC not available)	30	30	Radionics [31]	Datalogging Python script
Plug	UK socket	1	2	2	Radionics [32]	Earth's grounding for the aluminium structure

Table 5
Bill of Materials – OpenTCC – mechanical (Total = 107 euro).

Designator	Component	Number	Cost per unit (Euro)	Total cost (Euro)	Source of materials [ref. link]	Material type (purpose)
Screw	Screws assembling (M3)	115	0.1	11.5	Radionics [33]	Assembly aluminium structure
Angle	Angle bracket	26	0.25	6.5	Radionics [34]	Assembly aluminium structure
Straight	Straight bracket	14	0.42	5.88	Radionics [35]	Assembly aluminium structure
Nut	Nuts (M3)	115	6.17 (250 units)	5.75	Radionics [36]	Assembly aluminium structure
Al	Aluminium sheet	20	2.4	48	Radionics [37]	Structural component (Aluminium)
Extru	Extruded polystyrene	1.2	17	20.4	Build4less [38]	Isolation material
Neop	Neoprene sheet	0.2	3	0.6	Radionics [39]	Neoprene rubber sticker sheet
Sil	Silicone	1	8.66	8.66	Radionics [40]	Silicone to seal the junctions of the chamber
Nyl	Nylon screw (M8)	10	0.272	2.72	Radionics [41]	Handle and Peltier module installation
Nylnut	Nylon nut (M8)	10	0.1	1	Radionics [42]	Handle and Peltier module installation
Pas	Thermal paste	1	2	2	Sparkfun [43]	Thermal paste for adequate thermal transfer between Peltier unit and aluminium sheet
Tub	Plastic tube	1	2	2	Radionics [44]	Plastic tube to pass the wiring inside the chamber

5. Build instructions

5.1. Chamber construction

OpenTCC is constructed by assembling 18 aluminium sheets (Table 4: Al) joined by a combination of straight (Table 4: Straight) and corner (Table 4: angle) aluminium guides fixed with screws (Table 4: Screw). The aluminium sheets provide the cage structure over which the other components are installed. The design is low-cost and flexible, with customizable dimensions adaptable to the specific experiment or other use. The aluminium sheets are joined through pre-drilled holes, which match the screw size and position required for the aluminium sheets, corners and brackets. The aluminium structure acts as the OpenTCC skeleton and the internal side of the chamber is chemically resistant and easy to clean. The extruded polystyrene sheets (Table 4: Extru) are cut to size as seen in the 3D model [Fig. 2]. These sheets are relatively thick (60 mm) to ensure thermal insulation capabilities while conferring additional structural support. Due to its inert nature, extruded polystyrene can be used in the presence of acids, bases and alcohols, but not with hydrocarbons due to its solubility in organic solvents [45]. The spaces between the polystyrene sheets were filled with silicone rubber to reduce heat losses (Table 4: Sil). Besides thermal conductivity, the aluminium structure provides electrical conductivity which plays a role in EMI dampening. For this reason, a copper cable was connected to the chamber with a screw and grounded, improving the Faraday cage properties of the chamber [46].

5.2. Temperature control elements

5.2.1. Heatpads

A set of eight flat heating pads (Table 5: Pad) was installed at the base of the chamber to optimize the space footprint. The heating pads are designed to produce heat by dissipating energy in a resistive element in low voltage applications (5 V). However, they can handle up to 12 V, and drain up to 1.5 A, if the heat dissipation is optimized by means of a heatsink. Thus, four aluminium sheets were installed as heatsink above the heating pads (built by the same method described in Section 5.1), which were supplied with 12 V, considerably decreasing the heating time of OpenTCC. The heating pads were connected in parallel to achieve maximum heating capabilities under the voltage supplied (12 V).

5.2.2. Thermoelectric Peltier units

The cooling system consisted of two thermoelectric Peltier modules (Table 5: Pelt) installed at the back of OpenTCC to optimize the heat transfer [47]. The thermoelectric cooling modules are not as efficient as the compressor-type refrigeration system typically installed on commercial incubators [11]. However, they provide enough refrigeration for controlling the temperature in the range required for most microbiology experiments (20–55 °C). Furthermore, Peltier modules can be used intermittently, are light and do not have compressors which could cause strong vibrations. Thermoelectric units act as temperature pumps, thus, when the current flows in one direction, the heat is transferred from one side to the other of the module (e.g. from inside to outside the chamber), and the opposite when the current is inverted [11]. The thermoelectric element can provide a maximum temperature difference of 220–240 °C between the hot and cold side, which might cause failure of the unit if exceeded. For this reason, an appropriate cooling system was provided at the warm side (outside the chamber) by the addition of a prebuilt unit with an integrated heatsink and fan (Table 5: Pelt). Since sudden changes in temperature can harm the Peltier components [48], the modules can be only used under continuous voltage, denying the use of pulse width

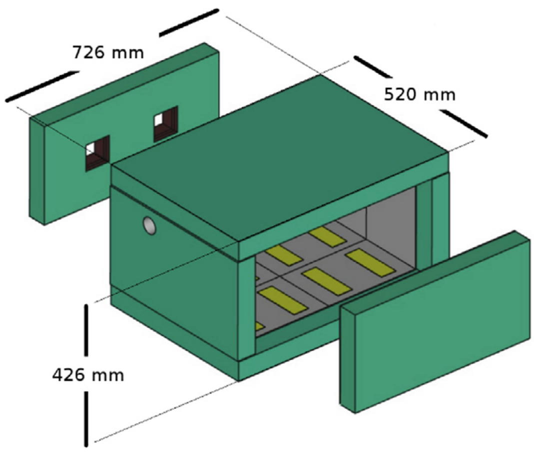

Fig. 2. 3D model of the OpenTCC that can be downloaded in format. fcstd and visualized using Freecad open source software. An additional. STEP file is provided for Autocad users.

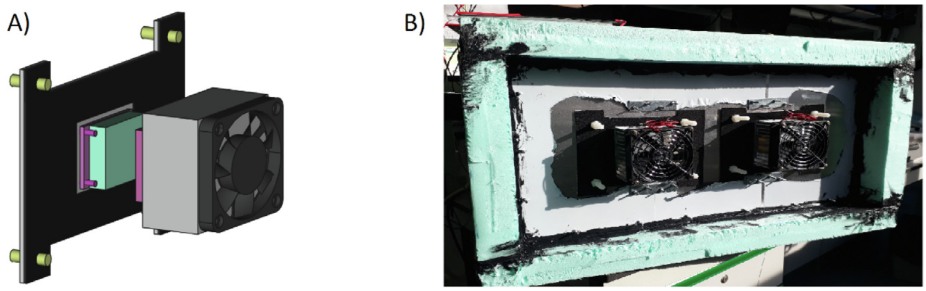

Fig. 3. A) Detail of the installation of the Peltier thermoelectric modules. This can be downloaded from the /Schematics/structure. fcstd file on the repository of the project and visualized using Freecad open source software. B) Picture of the two Peltier modules installed at the back of OpenTCC.

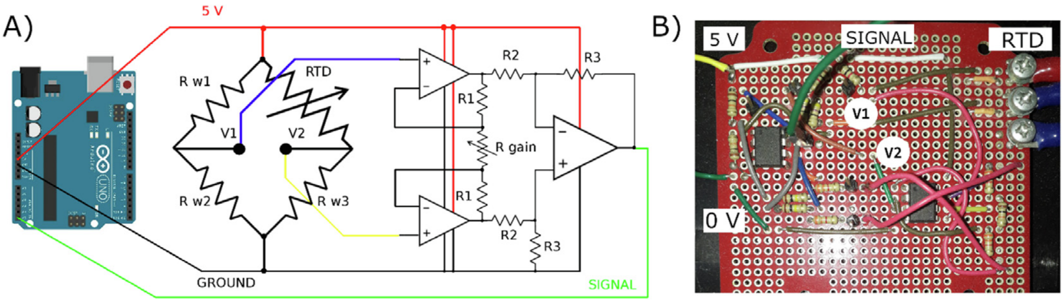

Fig. 4. Circuit schematic for the Pt-100 temperature meter. Wheatstone bridge and instrumentation amplifier to obtain voltage differences between the reference voltage (between R w1 and R w2) and the divider (between RTD and R w3). The voltage difference is amplified by an instrumentation amplifier consisting of 3 op-amps to obtain a signal read on the analog input of the Arduino (A). Picture of the circuit designed for environmental temperature monitoring with two double op-amp ICs (B).

modulation (PWM) driving circuits. Additionally, intermittent powering mode can damage the modules in the long term and thus, enough time should be given between on–off switching operation [47].

The Peltier elements and the attached fans were installed on an aluminium plate supported by nylon screws (Table 4: Nyl) [Fig. 3A], since metal screws could act as temperature "shorts" between the inside and outside of the chamber. Thermal paste (Table 4: Pas) was applied to improve temperature transfer between the chamber and the cooling side of the thermoelectric element, and a thin neoprene sheet (Table 4: Neop) was applied to reduce unwanted heat transfer between the warm side of the unit and the chamber. The cooling side of the Peltier elements was installed outside, at the back of OpenTCC, to reduce EMI from the thermoelectric elements [49]. Details on the dimensions and placement of these modules can be found on the attached Freecad schematics (Table 3: Structure) and on Fig. 3.

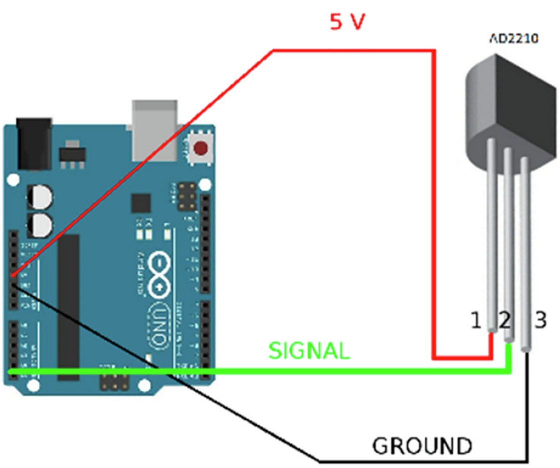

Fig. 5. Connections required to obtained temperature measurements from the AD22100.

5.3. Circuits

5.3.1. Temperature sensing

OpenTCC uses two different circuits for temperature sensing: a resistance temperature detector (RTD) Pt-100 (Table 5: RTD) and an IC sensor with integrated amplification (Table 5: Therm). The Pt-100 RTD and IC thermometers were utilized to monitor the temperature outside and inside the OpenTCC, respectively. Other temperature measuring options, such as the ubiquitous ISP/I2C digital communication modules used in other Arduino projects [50], can be installed to OpenTCC. However, the RTD and IC sensors are simple, low-cost alternatives, and do not cause EMI due to digital communications.

In Pt-100, the RTD-dedicated Wheatstone bridge allows measuring differences of potential on the RTD and associate them with temperature based on a linear correlation between temperature and RTD resistance. The signal obtained is amplified using an instrumentation amplifier comprising of three op-amps, using two double op-amp ICs (Fig. 4). The Pt-100 has indeed a resistance of 100 Ω at 0 °C that increases with temperature until 138.5 Ω at 100 °C [51]. It can be set as 2-wire, 3-wire or 4-wire configurations, each of them with a different linear response in the voltage output for temperature. OpenTCC was equipped with the simplest 2-wire electronic circuit. This circuit consists of a Wheatstone bridge supplied with a constant voltage of 5 V from the Arduino, which results in a variable output voltage depending on the RTD resistance (Fig. 4: V2). This potential has no common ground with the circuit and thus, a potential difference is measured between the RTD and the voltage reference set by a voltage divider (Fig. 4: V1). However, the potential difference is small and signal amplification is required. The instrumentation

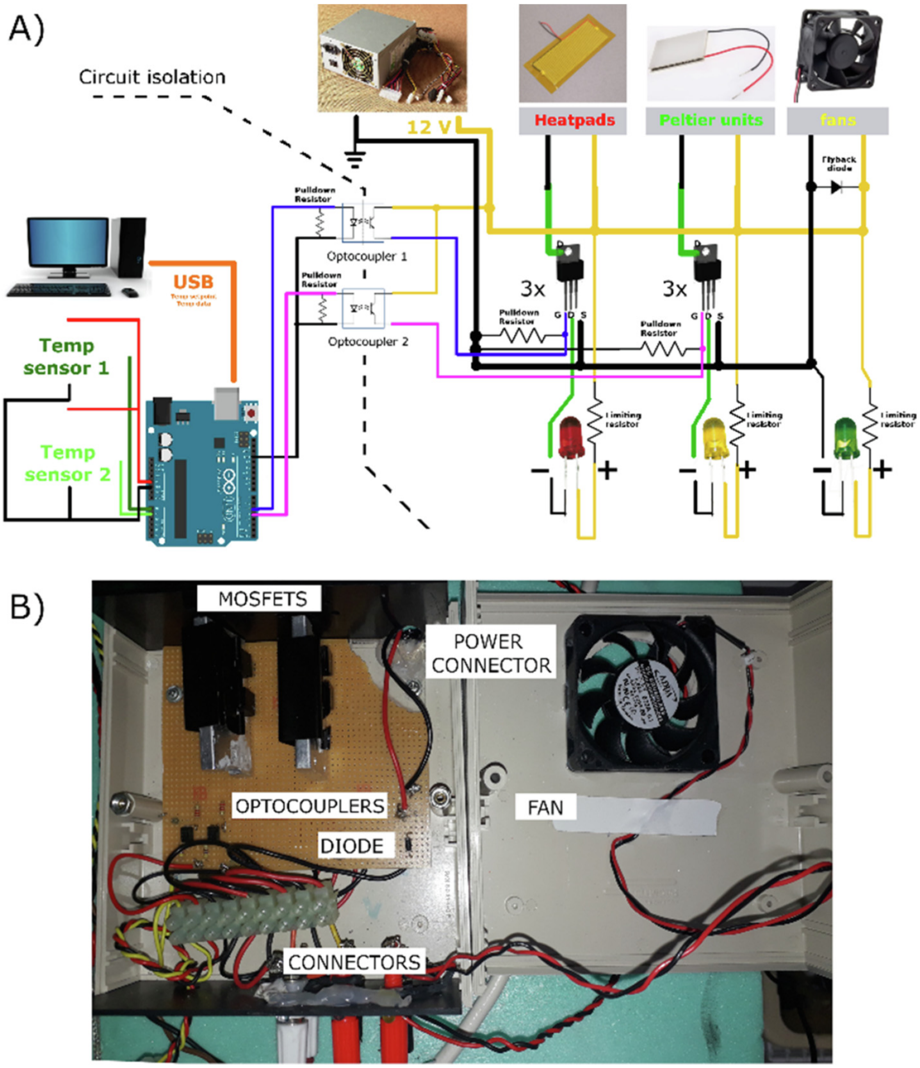

Fig. 6. Schematics of the connections required to combine the switching control signals of the Arduino with the ATX power supply and heating/cooling modules (A). Two optocouplers isolated the Arduino circuitry from the MOSFET and power supply circuit. Limiting resistors were placed for the indicator LEDs. A flyback Schottky diode was placed across the fans to avoid inductive spikes during on/off operation. Pull-down resistors were placed at each of the MOSFET gates to avoid half-opened gates. Picture of the switching power circuitry box (B).

amplifier combines a differential amplifier with the inputs buffered by a combination of operational amplifiers (Fig. 4). This circuit translates the floating potential difference between V1 and V2 (Fig. 4) to the ground in the Arduino.

Due to the limited linearity in the 2-wire configuration of the Pt-100, the calibration was optimized in the range 20–55 °C. To obtain the temperature value, the voltage reading was averaged by means of an Arduino "for loop" [code 1] and a calibration was performed with the help of an external handheld thermometer with an accuracy of 1 °C (ATP Thermometer AST-9258) and a bench pH Meter with a Pt-100 detector with 0.1 °C accuracy (WTW pH526). The inner temperature of OpenTCC was changed and kept stable for at least 30 min at each calibration point, after which, the potential obtained from the Arduino analog was assigned to the temperature reading from the Pt-100 detector thermometer. This was hard-coded on the Arduino microcontroller using the built-in "map" function [code 1]. This process was reiterated until obtaining the best linear response in the range 20–30 °C corresponding to ambient temperatures (Supplementary material: code1 lines 34–48).

The temperature sensing IC AD22100 (Therm) is a temperature sensor based on the same principle of RTD. However, the amplification circuit of this device was already built into the sensor package, and therefore no additional circuit was required. The sensor was powered by the Arduino, after which, it produced an analog signal proportional to the change in temperature. This analog signal was read by the 10-bit Arduino analog-to-digital converter (ADC). This sensor does not require a calibration as the relation between temperature and potential can be directly applied from the manufacturer's datasheet [52]. The mathematical relationship was included in the Arduino code (Supplementary material: code 1 line 64).

Other temperature sensing solutions can be used, depending on the purpose (e.g. education or lab application) and the available materials. As an example, the Wheatstone bridge and instrumental amplifier op-amp configuration can be helpful to illustrate the basic understanding of processing a temperature signal from an RTD, while the easy wiring of the AD22100 sensor and its low cost is a good example of how IC circuitry can simplify electronics for the final user. Alternative solutions such as digital thermometer modules with ISP or I2C digital protocol communication can be installed as an upgrade [see Section 8].

5.3.2. Switching circuitry

The Arduino can read the temperature signal, but it needs an energy supply and means to control the cooling and heating elements. To reduce costs, an ATX power supply from an old computer was recycled to power OpenTCC. The ATX standard is

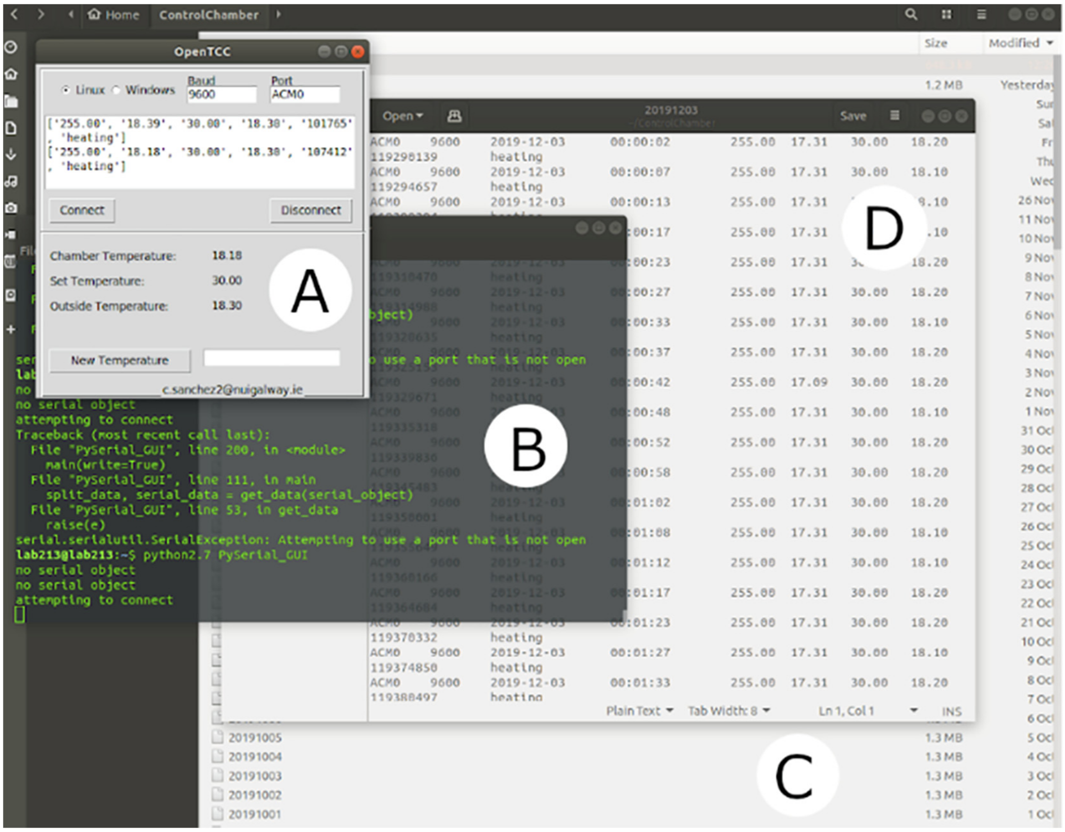

Fig. 7. Screenshot of the OpenTCC in operation. The phyton graphical user interface [A] shows the readings for internal and external temperature from the Arduino and allow to set the internal temperature by clicking in "New temperature". The python program is run from the command line [B] where serial information serves for error handling. The python program creates a folder [C] and records the information from the Arduino in a new file each day, with related timestamps for posterior data analysis [D].

a popular SMPS in computers. To utilize the ATX, an embedded switch needs to be activated. For the ATX standard, this is achieved by shorting the green wire to ground. Only the 12 V line was required to power the heating and cooling components and thus, any power supply with 12 V and generating at least 10 A current can be used [table 4: Pow]. The ATX power supply may require a minimum load to maintain a constant output voltage. This can be obtained using a power resistor connected in parallel with the power rail used for OpenTCC.

A power of 5 V was supplied to the Arduino *via* USB connection to a computer. Due to the presence of two independent power supplies and two different type of electronic requirements (sensing *vs.* powering), two optocouplers [Fig. 4: Opt] were installed between the Arduino pins and the gate of the MOSFET circuit to protect the Arduino and avoid generating ground loops and the resulting EMI. The power MOSFET switches included a pull-down resistor to avoid a floating gate that could generate half-open switches [Fig. 6]. Two MOSFET were installed for each channel (heating/cooling) to reduce the heat stress over the MOSFET mechanisms in the long term. Additionally, an aluminium block was fixed to the MOSFETs with clamps to improve the heatsink capabilities. A 12 V channel was also installed to continuously power the fans dissipating the heat accumulated on the hot side of the Peltier elements (see Section 5.2.2). This channel was also used to power a small fan for cooling the box containing the switching circuitry [Fig. 6B].

5.4. Software

5.4.1. Arduino controller

The Arduino receives the analog input from each of the temperature sensors and executes a loop for signal averaging to improve the signal-to-noise ratio and thus, the accuracy of the temperature measurements. The Arduino controller compares the measured temperature to the set temperature. If the temperature is lower than required, it applies a signal to optocoupler (5 V Arduino), which in turn applies a signal to the MOSFET's gate (12 V power supply) powering the heating circuit. Conversely, if the temperature is higher than the set temperature, the optocoupler starts conducting (5 V Arduino) and turns on the MOSFETS controlling the Peltier modules. No specialized mathematical algorithm was implemented in order to minimize the switching frequency of the power circuitry. Proportional-Integral-Derivative (PID) controllers are often utilized to control the temperature in small volumes, but the large volume of OpenTCC make their use unnecessary. A programmable temperature hysteresis was applied to keep the temperature within a certain range (±0.2 °C) and avoid continuous switching between heat and cooling. The Arduino code includes a function to translate the messages from the PC to program new set temperatures by using the "serial.read" function.

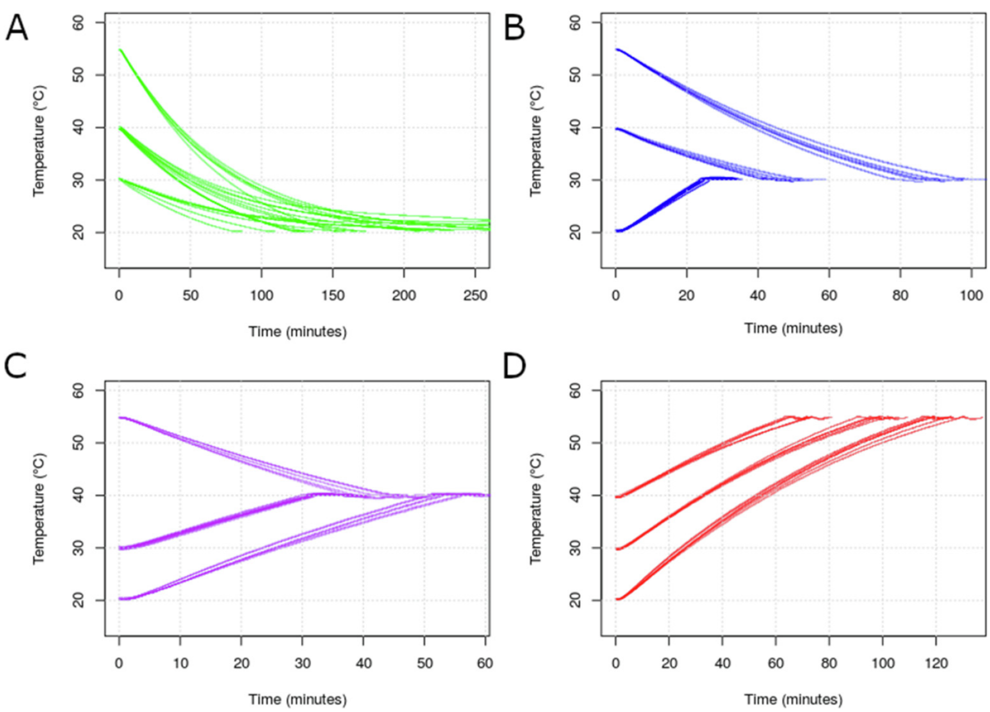

Fig. 8. Time required to achieve the set temperature of 20 (A), 30 (B), 40 (C) or 55 °C (D) from different initial temperatures (20, 30, 40 or 55 °C). Data was plotted applying R programming scripts to the raw data obtained from the PySerial_loop programs (repository: Plotting).

5.4.2. Python interface

In OpenTCC, the temperature values are communicated by a graphical user interface (GUI) written in Python [Fig. 7]. The GUI shows also the current temperature inside and outside OpenTCC. The GUI allows quick changes in the set temperature without the need of reprogramming the Arduino or changing any variable in the programs. Additionally, the GUI includes a routine program that creates a folder and generate a new .txt file with the temperatures recorded by OpenTCC each day. This allows to analyze the temperature outside and inside OpenTCC and study the temperature changes in the long term by plotting the data in a software of choice (e.g. R).

6. Operation instructions

In OpenTCC, the temperature required inside the chamber can be set from the computer once the program is uploaded, and it is automatically maintained by the Arduino equipped with the conditional switching control and hardware circuitry. To run the GUI, the installation of the free and open-source software Python 2.7 is required. The PythonGUI runs the serial communication and records the logs obtained from the Arduino by creating a folder in the same directory where the Python-GUI script is located. In this example, the OpenTCC interface is connected to a computer running Ubuntu 18.04 and the GUI is run from the Linux terminal (Fig. 7). A pc is required to set the program and exploit the datalogging capabilities of the software. The OpenTCC interface can also be run using a low-cost raspberry pi computer, whose price averages around 35 euro [31] with the same functionality of a pc. The raspberry pi 3 provides additional functionalities such as the automatic wi-fi card, which can be a step towards the implementation of the internet of things (IoT).

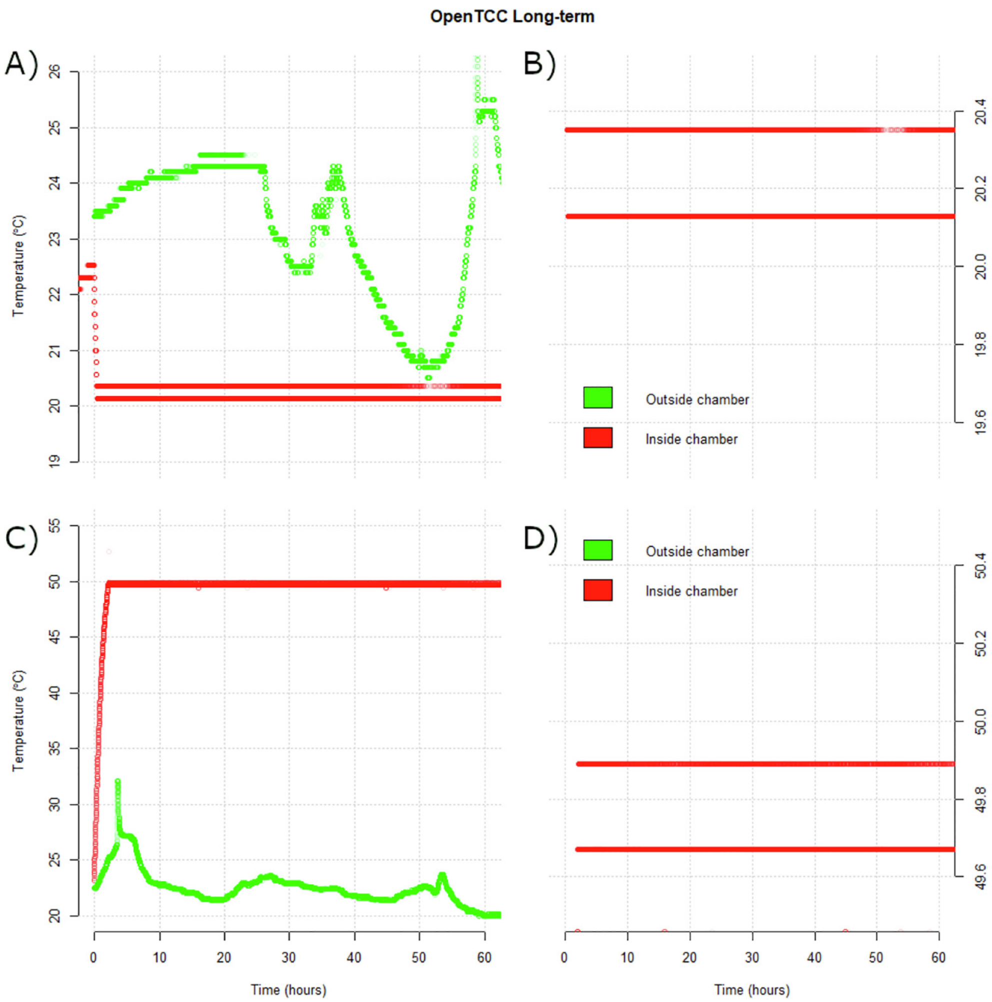

Fig. 9. Long-term (60 h) temperature control inside OpenTCC at 20 °C (A) or 50 °C (C) with the respective magnifications (B, D). Temperatures were registered inside (red) and outside (green) the chamber at 5 s intervals. The temperature inside the chamber shows steps between the temperature values corresponding to the data conversion of the temperature sensor around the hysteresis of the Arduino. Data was plotted applying R programming scripts to the raw data obtained from the PySerial_GUI program (OSF repository: Plotting). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7. Validation and characterization

The validation of the platform was done by (i) controlling the time required for heating and cooling to a stable temperature, (ii) verifying the long term stability of the temperature control, and (iii) evaluating the EMI mitigation inside the chamber. The temperature plots were obtained from data generated by Arduino through the installed thermometers, calibrated by benchtop thermometer, while the EMI measurements were obtained using the Aaronia Spectran NF-5035 equipped with a 3D EMI antenna.

7.1. Heating and cooling times

For the temperature control validation, a Python script (repository: Python and Arduino programs/PySerial_loop) was used to program OpenTCC to loop 10 times over selected set temperatures inside the chamber (20, 30, 40 and 55 °C). The data from these 10 loops was used to analyze the time required to reach the set temperatures inside the chamber using the AD22100 temperature sensor [Fig. 8]. The heating process was quicker (120 min to increase temperature from 20 to 55 °C) than cooling (250 min to decrease temperature from 55 to 20 °C). Similarly, less than 30 min were necessary for heating from 20 to 30 °C, while nearly 100 min were necessary for cooling from 30 to 20 °C. If required, the heating and cooling

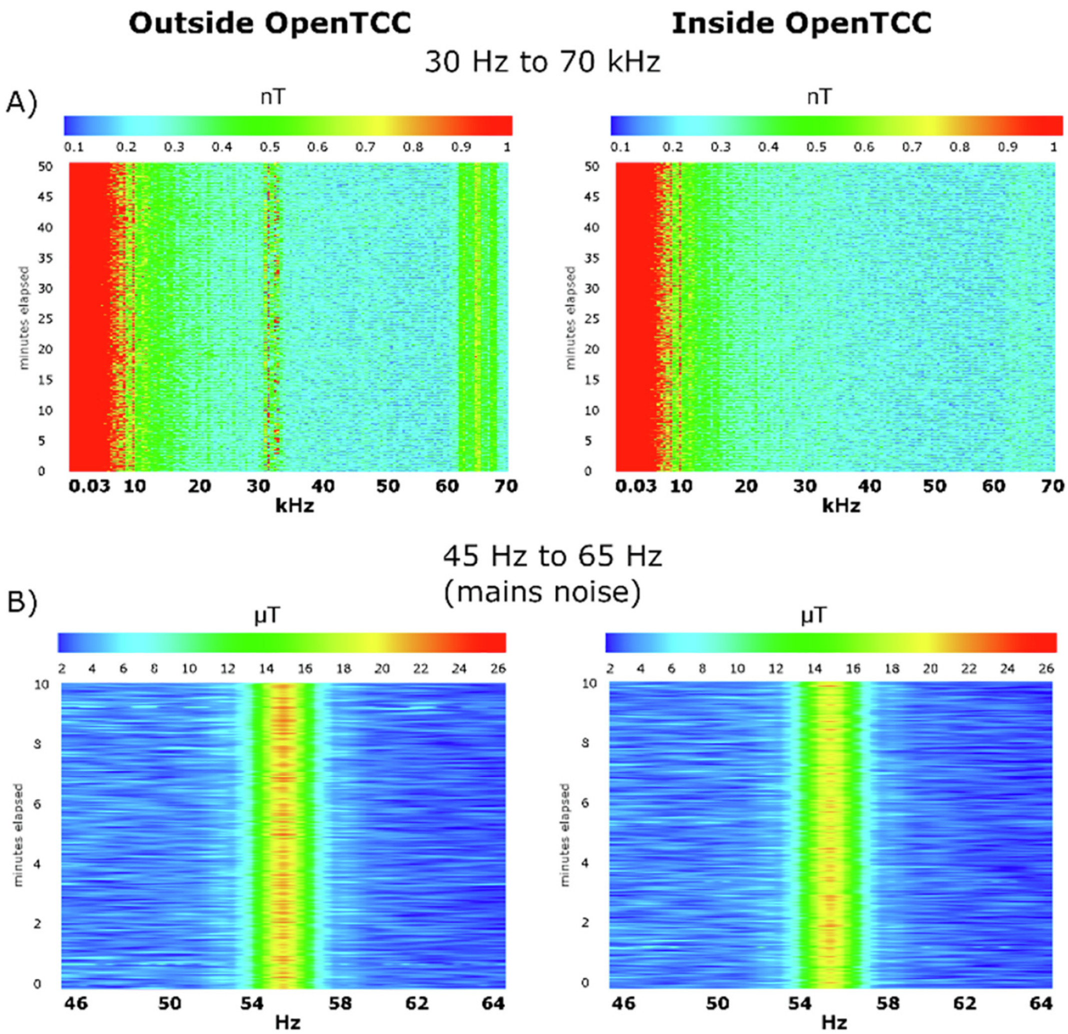

Fig. 10. Electromagnetic interference (EMI) inside and outside OpenTCC. Plot A shows the frequencies rejected by the aluminium structure of OpenTCC between 30 and 35 kHz and 60–70 kHz. Plot B shows that the mains noise (50–60 Hz) is slightly dampened, but still present inside the OpenTCC. The plots were obtained by collecting screenshots from the Linux version of Aaronia Spectrum Analyzer software [56] and cleaning and placing up the figures with GIMP software.

times can be shortened and the temperature range widened by increasing the number of modules or improving the heat transfer and dissipation on the Peltier elements.

7.2. Long-term stability

The long-term stability characterization was performed controlling the temperature at 20 °C (±0.2) or 50 (±0.2) for 60 h while the ambient temperature outside OpenTCC oscillated between 20 and 26 °C [Fig. 9]. The AD22100 temperature readings inside the chamber show a step-change of about 0.2 °C [Fig. 9] due to the limited resolution of the 10-bit ADC of the Arduino. Nevertheless, this experiment showed that OpenTCC can maintain a constant temperature effectively despite the ambient temperature oscillations.

7.3. Electromagnetic interference mitigation

The EMI mitigation (Faraday's cage) properties of OpenTCC were analyzed comparing the electromagnetic spectrum inside and outside the chamber using a 3D sensor detector (Aaronia Spectran NF-5035). The measurements were recorded over several minutes to account for changes in EMI over time, in what is known as waterfall plots of magnetic flux density measured in Tesla (T) versus frequency [Fig. 10]. Several scans were obtained for increasingly shorter frequency ranges (Supplementary material: EMI). The aluminium structure of OpenTCC effectively suppressed the EMI in the range 30–70 kHz, corresponding to the frequency of switching power supplies. Bands at frequencies around 32 kHz and 60 kHz, with magnetic flux densities around 0.8 nT outside the chamber, were strongly mitigated inside the chamber to background values below 0.3 nT. However, OpenTCC failed mitigating the main sources of EMI in our environment, i.e. a high frequency band at 4 MHz (Supplementary Material: EMI), and a low-frequency band (55 Hz) corresponding the mains frequency (Fig. 10). However, the grounded aluminium structure attenuated the EMI from devices powered from the same power line (Supplementary material: EMI), highlighting the capacity of OpenTCC for EMI and electrical noise mitigation.

The EMI dampening effect depends on the material and the thickness of the conductive layer, according to the skin-depth effect [53,54] . If required, the EMI mitigation capability of OpenTCC can be improved by increasing the thickness of the aluminium layer, adding more layers, or using special EMI dampening materials like the mu-metal rather than aluminium [49,53,55]. This could represent a solution in experiments where EMI rejection is strictly necessary, e.g. when dealing with EMI sensitive environments, or when using EMI sensitive equipment, but would unavoidably increase the overall cost of the chamber.

8. Potential applications and possible upgrades

OpenTCC is a low-cost platform for temperature-controlled experiments, aimed for laboratories with less economical resources. The popular Arduino platform used by OpenTCC allows an easy expansion of its software and hardware capabilities, and other function can be added to upgrade OpenTCC to perform different types of experiments. If required, both analog [57] and digital (I2C/ISP) [58] sensors can be installed to detect important environmental variables (e.g. humidity, carbon dioxide and/or oxygen concentration). OpenTCC also represents a sensor-actuator example, and this general idea could be extended for other type of sense and control purposes, such as switching solenoid valves [59,60] or peristaltic pumps [61,62]. For biological experiments, when sterile conditions are necessary, an UV lamp can be installed to sterilize the chamber without affecting the aluminium structure [63].

The current version of OpenTCC effectively control temperature in the range 20–55 °C. Increasing the power of the heating and cooling elements would decrease the response time, but can result in oscillations derived from overshooting the set conditions. In this case, additional software control (PID algorithms) might be required. However, PID algorithms produce PWM signals, which can be detrimental for the Peltier elements and other power electronics [48]. The cooling power of the Peltier elements is not as efficient as the heating power of the heating pads. Addition of thermoelectric elements is required to improve the cooling rate of Open TCC, which would require additional consideration for heat displacement from the hot side. Liquid refrigeration systems could be used to considerably increase the thermal transfer in the thermoelectric units [64].

The EMI dampening effect of OpenTCC was not appropriate to mitigate low frequency (large λ) and high frequency (small λ) EMI, which are difficult to reject due to the charge absorption and the gaps in the isolation layer, respectively [55]. Use of materials like mu-metal or increasing thickness of the conductive walls may help mitigating EMI in a wider frequency range. If PWM signals are produced, they generate EMI. Voltage or current-regulated high-power linear power supplies might mitigate such an issue. A possible solution is the use of linearly regulated Darlington transistors [65], or chopper filtering methods to the high frequency PWM signals [66]. However, these solutions might be complicated due to the interaction of analog signal with high power actuators, and the need to keep circuits isolated.

9. Conclusions

OpenTCC provides affordable temperature control, simple to build with easily available and/or recycled materials. Integration with GUI allows to easily change the set temperature during the experiments. The temperature sensing and the switching circuit with a microcontroller intermediate can be modified and upgraded to satisfy the user' s necessities. OpenTCC provides an initial platform for open-source, low cost temperature control. Its strengths and limitations are comprehensively discussed, and possible upgrades are suggested to facilitate its use and expand its capabilities. The educational value of OpenTCC should be also considered, as it gives an overall idea of temperature control, ranging from programming and electronics to materials selection and engineering.

10. Human and animal rights

NA

Declaration of Competing Interest

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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Appendix A. Supplementary data

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