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Development of a Thermocirculator Applied to the Sous Vide Culinary Technique

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ABSTRACT

This paper addresses the theory, design, and execution of a thermocirculator, developing its electronic circuits, printed circuit boards (PCBs), plastic structure, and equipment assembling. The developed thermocirculator is based on 3 previous prototypes, with the first one being created in 2019. The ESP32 microcontroller was used as the basis for the electronic circuits. MicroPython was chosen as the programming language, and a web server was developed to connect the user and the equipment via Wi-Fi, allowing monitoring of the equipment from anywhere. An On-Off controller was implemented to keep the water temperature constant. The plastic structure was made of ABS plastic, and manufactured by 3D printing, with lateral dimensions of 7 x 7 cm and 18.5 cm of height, divided into upper portion, medial cover, lower portion, and lower covers. The device has a manufacture cost around US$56 per unit, and a selling price estimated around US$140. After the equipment was assembled, tests were made to verify its operation, which consisted of preparing foods such as a NY strip steak at 55 ºC. In contrast to previous works, its design integrates a complete Wi-Fi monitoring system and ensures portability and compactness. The developed thermocirculator effectively maintained a stable water temperature and achieved cooking results comparable to commercial products, fulfilling the objectives established by this paper.

Keywords: 3D printing. ABS Plastic. Electronics. ESP32. MicroPython.

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1. INTRODUCTION

The term Sous Vide originates from French, translated into English as under vacuum (Baldwin, 2012). The culinary technique itself involves cooking food that's vacuum-sealed in a non-toxic plastic bag and placed in a container of water at a low and controlled temperature (Borges, 2019). This culinary technique was first applied in 1970 by chef George Pralus at the Troisgros restaurant, who was trying to develop a method to cook foie gras (translated from French: duck liver) without altering the original texture of the food (Ramos, 2004).

The bag’s vacuum-sealing allows for more efficient heat transfer between water and food and prevents the dilution of its flavors into the water (Borges, 2019). The original taste, nutrients, and natural juices of the food are preserved using the Sous Vide technique, resulting in a cooking quality impossible to achieve through traditional methods. Additionally, this technique eliminates problems related to color, taste, and texture commonly associated with frozen food. Furthermore, its application eradicates the risk of bacterial contamination since during the cooking process, the food is fully pasteurized and isolated from the external environment through vacuum-sealing (Ramos, 2004).

What captures the public and professional chefs’ attention regarding the use of the Sous Vide culinary technique is its precision in cooking food to the desired doneness, irrespective of its thickness (Creed; Reeve, 1998). Foods prepared using this technique retain their organoleptic and nutritional properties and become much softer and more flavorful than when prepared using conventional methods (Baldwin, 2012).

Hence, the use of the Sous Vide technique, due to the precision and stability of the water temperature, results in an even cooking throughout the food. In comparison, traditional methods of cooking cuts of meat, such as grilling at high temperatures, often result in overcooked edges and undercooked center (Borges, 2019).

The Sous Vide technique consists of four stages: seasoning, packaging, cooking, and finishing (Borges, 2019).

As for the first stage, this culinary technique amplifies the flavor of seasonings and condiments, requiring careful measurement of quantities used. Subsequently, the food is placed in a non-toxic and heat-resistant packaging, and vacuum-sealed (Borges, 2019).

The food is then placed in a container with water at a controlled temperature. The temperature and cooking time varies according to the food being prepared, with, for example, a recommended 1.5 hours per inch of thickness for beef (Borges, 2019).

When cooking food according to the Sous Vide culinary technique, the Maillard reaction does not occur on its surface. This process involves a chemical reaction between an amino acid or protein and a reducing carbohydrate, producing products that give flavor and color to food. The golden-brown appearance after baking or grilling a steak is result of this reaction (Francisquini et al., 2017). Therefore, a quick sear using a torch or grill is necessary to achieve the perfect exterior while maintaining the interior's ideal temperature. This step mainly aims to enhance the food's appearance (Borges, 2019).

A thermocirculator can be used to control the water temperature and requires a water-containing vessel to allow its operation. The vessel should have dimensions such that the equipment is not entirely submerged but also not excessively above the water level. Additionally, a motor with a propeller or a pump is responsible for circulating the water, as the heater alone doesn't ensure uniform temperature throughout the container. A thermocirculator is considered an economical and compact device, easily transportable and suitable for small and amateur kitchens. Some models have Wi-Fi or Bluetooth modules, enabling remote control and monitoring of the equipment. (Borges, 2019).

When it comes to 3D printing, three materials typically stand out: Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and Polyethylene Terephthalate Glycol (PETG). Their main characteristics are shown in Table 1.

Table 1. Characteristics of the most used materials for 3D printing.

Properties	PLA	ABS	PETG
Density	1.24 g/cm3	1.04 g/cm3	1.27 g/cm3
Melting temperature	185 ºC	220 ºC	240 ºC
Glass transition temperature	60 ºC	100 ºC	85 ºC
Leakage tension	66 Mpa	38 Mpa	51 Mpa
Bending resistance	130 Mpa	66 Mpa	72 Mpa
Elasticity	4350 Mpa	2200 Mpa	2120 Mpa
Price per kilogram	US$ 19.60	US$ 13.18	US$ 21.40
Finishing quality	Low	High	Medium

Source: Own authorship.

ABS is a petroleum-based thermoplastic widely applied for its mechanical strength, slight flexibility, and resistance to moisture and temperature. Due to these characteristics, it is suitable for industrial prototypes and components subjected to mechanical loads and impacts (Galvani, 2019).

On the other hand, PLA is a biodegradable material of plant origin, derived from corn starch, sugarcane or potato starch. This material is sensitive to heat and requires to be stored in cool and dry places (Galvani, 2019).

PETG, is considered a premium material for 3D printing due to its high mechanical and chemical resistance characteristics, and is temperature resistant like ABS (Galvani, 2019).

This paper presents the design and development of a thermocirculator, encompassing its structural and electronic components, the creation of a MicroPython embedded algorithm, and the implementation of an On-Off controller for water temperature control. The proposed equipment was conceived to be a low-cost alternative to commercial models and is based on the prototype designed and executed by Marcotti and Nascimento (2021), introducing improvements and correcting issues identified by the authors, such as the excessive number of connector cables that made the equipment assembly impossible.

2. MATERIALS AND METHODS

Initially, a literature review was conducted, studying topics related to the Sous Vide culinary technique, applications of the thermocirculator to it, as well as subjects related to electronics, microcontrollers and programming languages.

As a reference for the design of all electronic circuits in this paper, the ESP32 microcontroller was chosen. It is a component manufactured by Espressif Systems, featuring Wi-Fi connectivity at a 2.4 GHz frequency and Bluetooth, enabling various applications. This microcontroller has a built-in 40 MHz crystal oscillator, eliminating the need of an external component. Its operating voltage can range from 3 to 3.6 V, with an average operating current of 80 mA, and it can work in temperatures between -40°C and +85°C. Additionally, it is a compact component with dimensions of 18 x 25.50 x 3.10 mm. It communicates through the I2C and SPI standards. When summing all its digital pins, the ESP32 can deliver an output current of up to 1.1 A (Espressif Systems, 2021).

The electronic circuits were designed using the EasyEDA software and then grouped into Printed Circuit Boards (PCBs), which were ordered from the manufacturer JLC PCBs.

For programming the ESP32 microcontroller, the high-level programming language MicroPython was used, derived from Python 3. It includes several subfunctions from the standard Python libraries but optimized to work with microcontrollers.

Subsequently, the peripherals communicating with the microcontroller, sending information or being controlled by it, were chosen and acquired: water heater, water level sensor, probe temperature sensor, direct current (DC) motor, and fan.

With the definition and acquisition of the peripherals, the plastic structure of the thermocirculator was developed using Autodesk Inventor software, ensuring the secure placement of all PCBs and peripherals.

ABS was chosen for the plastic structure due to its moisture resistance and high glass transition temperature (100°C), in addition to its cost-effectiveness.

The printed circuit boards and peripherals were placed in the thermocirculator structure. Subsequently, using the Thonny development environment, a MicroPython language programming algorithm was developed to control the chosen microcontroller (ESP32), communicate with the equipment user via a web server using Wi-Fi, and implement an On-Off controller to stabilize the water temperature during the equipment's operation period.

Finally, the equipment's testing phase started, involving the preparation of New York strip using the Sous Vide culinary technique.

3. RESULTS AND DISCUSSION

The electronic circuits of the developed thermocirculator were divided into three different circuits: the main circuit, the power circuit, and the alternating voltage control circuit.

The main circuit is responsible for processing information collected by the buttons and sensors (water level and temperature), controlling the OLED display, DC motor, and cooling fan, and maintaining the wireless connection with the user. This circuit was based on the ESP32 microcontroller and its datasheet. The main purpose of this circuit is to reduce the connection cables inside the equipment. Figure 1 shows the necessary connections for the proper operation of the microcontroller, obtained from the component's datasheet.

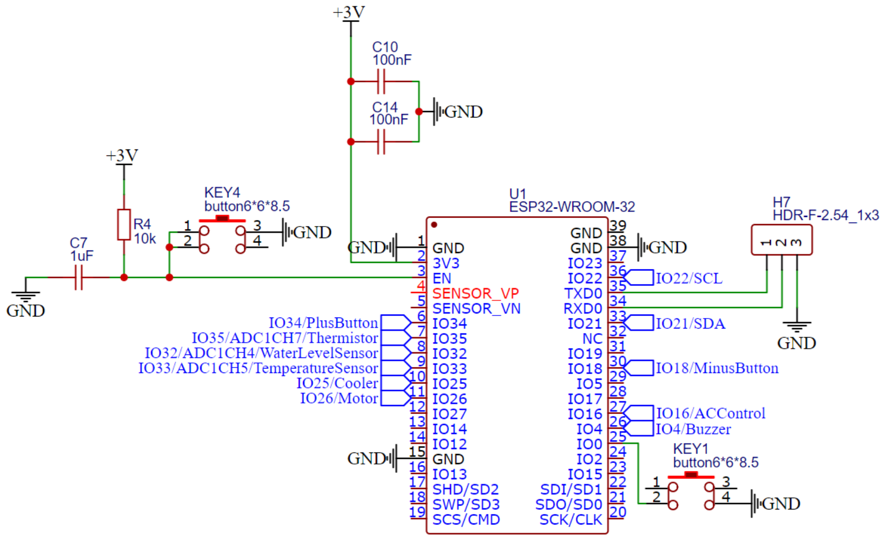

Figure 1. Connections with the ESP32 microcontroller (Own authorship).

Regarding the microcontroller programming, two buttons were required: one to assign a low logic signal to its digital port 0, allowing the microcontroller to enter boot mode, which enables the sending of firmware and algorithms to it, and another button to assign a low logic signal to its EN pin, resetting the microcontroller's state. Additionally, the TXD0 and RXD0 ports allow communication with a computer through a USB to UART bridge.

Furthermore, two positive poles (3.3V and 5V) and a GND pole power the microcontroller and the other components of the main circuit. Its digital pin 4 (IO4) connects to a resistor and an active buzzer, responsible for emitting an audible warning to alert the equipment user if it is turned on outside of water, avoiding accidents.

The microcontroller connects to the alternating voltage control circuit through its digital pin 16 (IO16) and two male sockets (main board) and two female sockets (control and power board).

Its digital pins 21 (IO21/SDA) and 22 (IO22/SCL) connect to the OLED display, allowing communication with this component and enabling it to show text messages.

To collect temperature values from an NTC thermistor, a voltage divider circuit was used and connected to ESP32's digital pin 35 (IO35), which has an analog-to-digital converter.

A green LED connected to a resistor is placed between the 3V and GND poles, indicating if the main board is powered or not.

A pull-up resistor is connected to the digital pin 34 (IO34), representing the temperature increment button. The digital pin 18 (IO18) is directly connected to the button since it supports internal pull-up or pull-down resistors via software, representing the temperature decrement button.

The control of the DC motor and fan occurs through two NPN transistors model 2SC1815, connected to the microcontroller's digital pins 26 (IO26) and 25 (IO25), respectively (Figure 2).

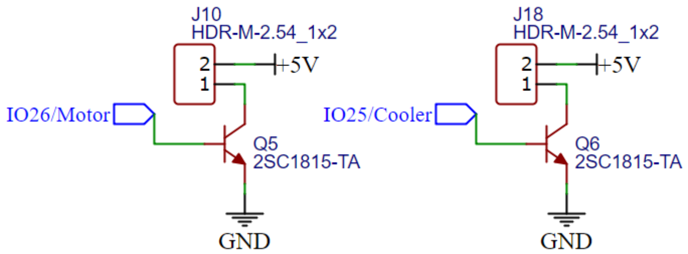

Figure 2. DC motor control circuit (left) and fan control circuit (right) (Own authorship).

The water level and the temperature sensor are connected to digital pins 32 (IO32/ADC1CH4) and 33 (IO33/ADC1CH5), respectively, interacting with the analog-to-digital converter 1 and its channels 4 and 5. Additionally, the temperature sensor requires a 4.7 kΩ resistor in a pull-up configuration (Figure 3).

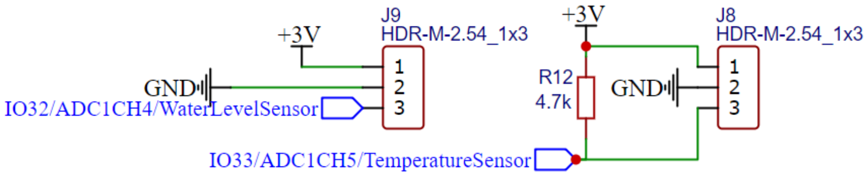

Figure 3. Microcontroller connection with the water level sensor (left) and the temperature sensor (right) (Own authorship).

As a power source for the microcontroller and other electronic components, a 110 AV - 5 DV converter with 10 W of power was used. This converter is basically composed of a transformer, rectifier bridge, capacitors, and resistors. The complete power supply circuit is shown in Figure 4.

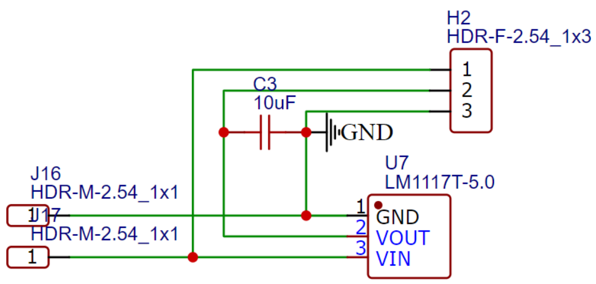

Figure 4. Schematic of the power supply circuit (Own authorship).

To reduce the 5V from the AC-DC converter to 3.3V, a fixed voltage regulator LM1117-3.3 was used, positioned at the component's output (J16 connected to GND and J17 to the 5V pole).

The alternating current control circuit (Figure 5), responsible for the proper operation of the water heater was based on Borges (2019) and is basically composed of a TRIAC (BTB12) and an optocoupler (MOC3023), specifically designed for driving TRIACs connected to the electrical network. The optocoupler acts as an isolator between the microcontroller and the electrical network voltage and, upon receiving the high logic signal from the microcontroller, triggers the TRIAC. This allows the flow of alternating current through the heater, connected to the control and power board through terminal connectors (U8).

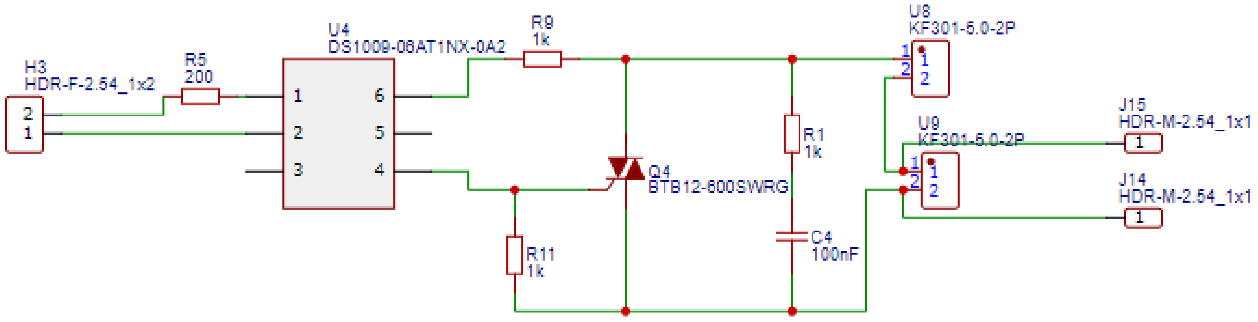

Figure 5. Schematic of the alternating current control circuit (Own authorship).

U9 connects to the voltage from the domestic electrical network via a conventional outlet, which also connects to the inputs of the AC-DC converter.

Considering the complete equipment manufacturing, the three designed circuits were grouped into 2 printed circuit boards, with designs aimed at minimizing the thermocirculator's dimensions and reducing the number of connecting cables inside it.

Regarding the control and power board, it is important to highlight the calculus related to the width of its tracks connected to the heater and to the alternating voltage network, ensuring that a certain current can be conducted without causing overheating or damage to the board. Therefore, based on the technical standard IPC-2221A, Equation 1 describes the track width (L), in millimeters, for a certain temperature rise (ΔT) when carrying a current (I), where k is a constant that varies according to the track's location, equals to 0.048 for external tracks, and E refers to the copper thickness, which is 1 ounce (oz), or 28.4 g, for standard manufacturing through the manufacturer JLC PCBs (IPC, 2003).

$$L = 0.0254 * \frac{\left(\frac{I}{k * \Delta T^{0.44}}\right)^{\frac{1}{0.725}}}{1.378 * E} \quad (1)$$

For this project, considering external tracks, a temperature change (ΔT) of 10°C, and a current (I) of 6 A, the track width was calculated as 3.5 millimeters.

Both designed PCBs have the same lateral dimensions: 5 cm x 5 cm, allowing their positioning in a tower format (one on top of the other) using hexagonal nylon screws, employed to reduce the mass of the upper region of the thermocirculator. Male and female sockets were used to connect the PCBs. The printed circuit boards were ordered through the manufacturer JLC PCBs, and their PTH (Pin Through Hole) electronic components were assembled using a conventional soldering iron.

The structure of the developed thermocirculator was divided into 4 parts, aiming to facilitate its assembly and manufacturing: upper part, lower part, middle lid, and lower lids 1 and 2. The upper part was designed to contain and protect the circuit boards stacked inside it, in addition to the fan, DC motor, OLED display, and buttons. On its rear face, there's an opening for the entry of the alternating current wires and its sides have gaps for the exit of hot air. It has lateral dimensions of 7 x 7 cm and a height of 5.5 cm.

The middle lid was designed to fix the DC motor and the fan and to connect the upper and lower portions of the thermocirculator. It has lateral dimensions of 7 x 7 cm and a thickness of 3 mm.

The lower part is the largest part of the thermocirculator, accommodating the water heater, the temperature sensor, the water level sensor, and the propeller. This part has lateral dimensions of 7 x 7 cm and a height of 12.5 cm.

Finally, there is the lower lid, which consists of two parts and contains neodymium magnets (with dimensions of 16 x 24 x 2 mm) responsible for fixing the thermocirculator. This piece seals the bottom of the equipment, has openings that allow water to enter, has lateral dimensions of 7 x 7 cm and a combined thickness of 5 mm.

All these parts were designed for 3D printing and are made of black and gray ABS plastic, which was chosen due to its good mechanical resistance, with a melting point higher than the water temperature during equipment operation (maximum of 80°C). Thus, the structure of the developed thermocirculator has lateral dimensions of 7 x 7 cm and a total height of 18.5 cm.

The On-Off controller was chosen because it showed a low water temperature oscillation during the tests, ranging between values of 59.8 to 60.4 °C for a desired temperature of 60 °C, representing an oscillation between 0.2 and 0.4 °C around the setpoint, which is acceptable for culinary purposes. Therefore, the application of a PID controller for such a small oscillation around the desired value was considered unnecessary.

Thus, based on the graphs describing the operation of the developed thermocirculator and the logic followed by its On-Off controller, it can be concluded that the heater is active during approximately 50% of the equipment's operation time. Therefore, for continuous operation of 1 hour, it is active for 30 minutes. Therefore, as the heater has a power of 680 W, its energy consumption is calculated as 340 Wh.

To manufacture one unit of the developed thermocirculator, it's estimated a manufacturing cost of US$41.00 for the electronics circuits and US$15.00 for the plastic structure. Furthermore, to be considered a fair comparison with the equipment available on the market, it is required to also consider taxes and sales profits. Therefore, regarding a fictious manufacturing company, the taxes on its final sales value includes ICMS (19%) and IPI (6.5%), resulting in an estimated selling price of US$140 with a gross margin of 34.50% (Marcotti, Miranda & Nascimento, 2025).

To evaluate the developed thermocirculator properties, a comparison was made with entry-level equipment from the manufacturers Anova Culinary, Cetro and Chefsteps, based on their public available characteristics, as shown in Table 2.

Table 2. Comparison between the developed thermocirculator and its market competitors.

Characteristics	This paper	Anova Precision Cooker Nano	Chefsteps Joule	Cetro SV95
Price (US$)	140.00	260.00	640.00	260.00
Power (W)	680	750	1100	1200
Voltage (V)	127	120	120	220
Side dimension (cm)	7 x 7	7,8 x 10,5	4,83 x 4,83	14,5 x 13
High (cm)	18.50	32.50	27,94	32.00
Weight (kg)	0.40	0.63	0,58	-
Monitoring via Wi-Fi	Yes	Yes	Yes	No
Control via Wi-Fi	No	Yes	Yes	No
Control via Bluetooth	No	Yes	Yes	No
Fastening type	Magnetic base	Support	Magnetic base	Support
Display and physical buttons	Yes	Yes	No	Yes

Source: Own authorship.

The thermocirculator developed in this work has some physical advantages in comparison to its market competitors: it is shorter than all of them and thinner and lighter than two of them. Furthermore, it features Wi-Fi monitoring, display and buttons, which are absent in some commercial models. But it also has some disadvantages: its magnetic base doesn't allow the equipment to operate inside all types of vessels as the support does, and it doesn't feature wireless control (limited to physical buttons).

The testing period of the developed thermocirculator included the validation of its operation and adjustments of its electronic circuits and algorithm, as well as the preparation of a New York strip.

Fetterman et al (2016) established 55 °C as the temperature corresponding to a medium-rare beef, 60 °C to medium, and 65 °C to medium-done. Therefore, to prepare a rare New York strip, 55 °C was chosen as the desired temperature.

Following the suggestions of Fetterman et al (2016), and as the cooked beef had a 1-inch thickness, its cooking lasted for 1 hour, finalized by using a gas torch to create the Maillard reaction. As a result, a medium-rare beef was prepared, as expected (Figure 6).

Figure 6. Medium rare New York strip prepared 55 °C (Own authorship).

4. FINAL CONSIDERATIONS

With the completion of this project, all initially established objectives were achieved, including the development and execution of the electronic circuits and plastic structure of the thermocirculator, as well as the programming of a MicroPython embedded algorithm with an On-Off controller.

As a result, a compact and low-cost device was obtained, smaller than its market counterparts, capable of maintaining a constant water temperature. The device can be controlled through physical buttons and monitored via a web server, a feature absent in some commercial models (Cetro SV95).

Unlike the previous prototypes developed by Marcotti and Nascimento (2021), the present device is a functional thermocirculator suitable for the Sous Vide culinary technique. In contrast to Borges (2019) water oven, its design integrates a complete Wi-Fi monitoring system developed in MicroPython and ensures portability and compactness.

For future work, the web server could be improved, allowing not only temperature monitoring but also remote control of the equipment. Other potential upgrades include substituting the propeller and motor with a water pump, replacing the 680 W heater with one exceeding 1000 W and applying another kind of water level sensor, as the current one doesn't emit a voltage equal to zero when removed from water due to residual moisture on its surface. Additionally, replacing the physical buttons and OLED display with a touchscreen-supported display would align the thermocirculator with its market counterparts.

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