5th YEAR INNOVATIVE PROJECT

Characterization of an Earth Brick for Natural Air Conditioning`

Authors:
Léa Beghin, Nathan Brugière, Alexandre Masson, Hugo Michel and Maxime Valentin

5th Year PTP Innovative Smart System
2024 - 2025

Tutors: Nathalie Bruyère, Matthieu Labat, Thierry Monteil.

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Introduction

With rising temperatures and more heatwaves, an increasing number of households are equipping themselves with air conditioners to keep cool and comfortable. In the 1980s, there was only one heatwave every 5 years on average, compared to today when there is at least one every year according to the French Ministry of Ecological Transition. This has resulted in a dramatic expansion in the air conditioner market, from 350,000 units sold in France in 2015 to around 800,000 in 2020. In 2016, only 14% of households were equipped with air conditioning, but by 2020, this figure had doubled to 25% of French homes. This growth varies by region: nearly 47% of households in the South-East and Corsica have an air conditioner, while only 11% of those in Brittany do [1].

However, the growing popularity of air conditioning is not without consequences. Residential sector air conditioners alone consume 4.9 TWh of electricity per year, while tertiary sector air conditioners consume 10.6 TWh, particularly in offices and shops [1]. To give an order of magnitude, 15 TWh, the sum of air conditioning consumption in the tertiary and residential sectors, represents the annual electricity consumption of three cities the size of Toulouse.

Even more alarming, the refrigerants used in these appliances are responsible for greenhouse gas emissions that are twice as high as those generated by the electricity consumed by air conditioners. In France today, air conditioning accounts for around 5% of building CO_2 emissions, and this figure could rise if solutions are not found and implemented quickly.

In response to these environmental challenges, it is essential to adopt innovative solutions. One such solution, which we aim to characterize in this study, has the potential to transform air conditioning usage by reducing our dependence on traditional systems, while simultaneously enhancing energy efficiency and minimizing the greenhouse gas emissions linked to refrigerants. By developing this solution, we can contribute to a more sustainable future in air conditioning.

This solution is found in an earth brick with a specific design shape that allows it to cool down a room. More specifically, the structure of the brick serves to optimize the flow of air through it, thereby reducing the temperature of the space. This characterisation is part of our innovative final-year project, the PTP Innovative Smart System.

1. Project description

1.1. Project objectives

The main objective of this project is to characterise the cooling properties of the earth brick in order to determine its ability to reduce ambient temperature. This characterisation has to be carried out under specific conditions and in a controlled environment so as to obtain consistent and usable results. In addition, real-life scenarios will be simulated to test the brick's performances in practical applications and ensure that its efficiency goes beyond theoretical assumptions.

The aim is to show whether the brick's structure enables it to significantly cool the space in which it is installed. A comparison between the analyses conducted on the brick and conventional cooling methods such as air conditioning or fans is useful in order to determine whether the brick offers added value compared with basic methods.

On a more technical level, our role is to set up a test bench enabling us to carry out precise and reliable measurements required for the characterisation. Detailed protocols are put in place for each use case, therefore ensuring that all experiments respect scientific standards and that they can be reproduced.

The test process uses a variety of sensors to monitor key parameters such as temperature, humidity and airflow. These sensors are integrated into the test structure to collect data that is analysed to produce useful information. An interface is put in place to facilitate the visualisation of the data in real-time and enable the results to be interpreted correctly.

1.2. Possible applications

Having outlined the main objectives of this project, we are now going to look at the possible applications of the brick, for both indoor and outdoor environments, to better understand its potential utility.

1.2.1. Indoor use

One possible use for brick could be as an integrated element of interior design, for example, part of a piece of furniture, a partition wall, or any other interior material. In this use-case, the brick could be humidified manually, using a spray bottle, whenever the temperature rises too much for the user's comfort. Then, all we would need to do is place an interior fan that would blow towards the bricks, and the cooling effect would take place. This solution would allow localised cooling, making it adapted for specific indoor zones, such as a room, a workspace or a relaxation area.

1.2.2. Outdoor use

For outdoor use, these bricks could form part of the wall of a terrace, pool house or any other outdoor space requiring a more comfortable temperature. The bricks could be connected to a continuous humidification system, potentially using rainwater or a recycled source of water to even further go into energy efficiency. Under the effect of the wind, the bricks could provide passive and ecological cooling, effectively reducing ambient heat. This ventilated wall would also provide a climatic barrier against hot winds, while creating a refreshing breeze. This second use-case could make the brick particularly useful for enhancing outdoor comfort in warm climates.

2. Organisation

2.1. Agile method

The project was organised around the Agile method, a dynamic and iterative approach to project management. The Agile method is designed to bring flexibility, enhance performance and provide a solid framework for efficiently managing projects. This approach is essentially based on communication, which ensures that stakeholders, especially customers, are actively involved in the product's development.

In this context, sprint periods have been set up to focus on short-term objectives. Each sprint has clearly defined goals, and team members work collaboratively to address tasks and deliverables within the set timeframe. To ensure alignment with the project goals, frequent review meetings are conducted. During these sessions, the team shares updates on completed activities, progress made, and challenges faced. These presentations serve as checkpoints for evaluating the sprint's outcomes. They are a time for exchange where the teachers give their opinions and advice on the work done, just as clients would do on their project.

The Agile method helped us to maintain focus while allowing for real-time adjustments. Regular meetings enabled an open exchange of ideas, improving the overall quality of the work done. This approach also ensured not only the project's success but also enhanced the team's ability to work collaboratively in a professional environment. It highlighted the value of iterative development, constant feedback, and the importance of communication in achieving project objectives.

2.2. Gantt diagram

As part of the Agile method, we have organised our activities in the form of a Gantt chart. This tool serves as a base for organizing and visualizing the timeline of tasks, ensuring that the project progresses efficiently. By distributing tasks among team members, we have aimed to maintain a high level of collaboration throughout the project. Each activity is assigned to one or more team members based on their expertise and availability. Depending on its importance and complexity, tasks are scheduled on specific dates in the project timeline and lasts for varying lengths of time.

The initial Gantt chart can be seen in Figure 1. This diagram provides us a clear overview of the project's key activities.

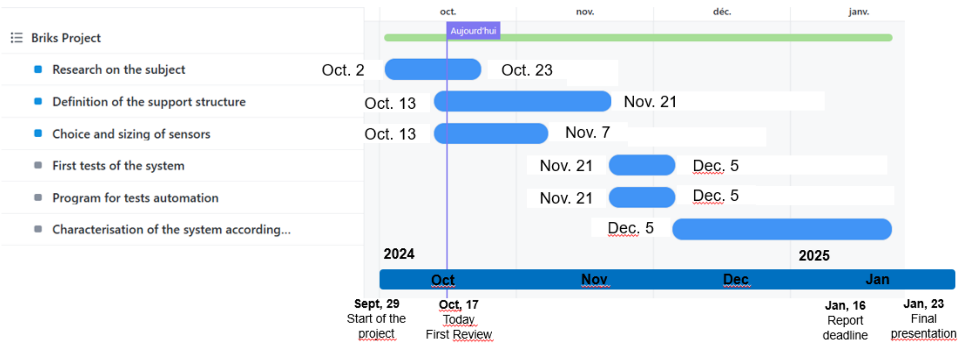

Figure 1: Initial Gantt diagram (16th, October 2024).

As the project progresses, the Gantt chart is adjusted according to the advancement of activities and problems encountered. In this way, the diagram has evolved throughout the semester, enabling us to keep the objectives for the period in mind while allowing us to find solutions to any difficulties identified.

Table 1 summarizes the activities carried out during the different sprint periods. This table is representative of the changes made to the initial Gantt chart.

	Sprint 1	Sprint 2	Sprint 3	Sprint 4
Test structure	Reflecting on materials and the structure itself.	Adapting materials and structures to the problems encountered.	Validation of the equipment list and ordering.	Setting up the test bench and testing the prototype.
Sensors	Consideration of the measurements to be taken, the accuracy of the sensors to be used and the organisation of the sensors within the structure.	Finding the right sensors to meet our needs.	Sensor ordering and humidity sensor testing.	Testing of all sensors, calibration and installation on the test bench.
User interface			Start of user interface development in Python using the Qt library.	Finalisation of the interface, with the option of viewing the progress of measurements live and recording data.
Measurements			Start of acquisition of values measured by the sensors.	Acquisition and storage of measurements taken in accordance with defined protocols.
Results analysis				Characterisation of the brick according to the results obtained.

Table 1: Activity schedule.

3. Test environment

3.1. Testing problematics

In order to characterize the brick properly, we have set up a test structure containing various types of sensors and actuators. The aim of these tests is to assess the brick's cooling capacity under a variety of real-life conditions (indoors, outdoors). This means measuring its efficiency while taking into account the intrinsic parameters of the brick's environment, such as humidity, ventilation and ambient temperature.

These tests are thus based on the assumption that the brick should be able to lower the air temperature as a function of humidity and the air flow passing through it. In fact, when humidified, the brick has the property of cooling the ambient air by evaporating the water it contains. When water evaporates, it absorbs heat from its surroundings. This process, known as evaporative cooling, lowers the temperature of the air around the brick. These tests are therefore designed to measure this capacity under various conditions defined in the protocol section.

3.2. Sensors used

For accurate testing, we chose various sensors to measure and control key environmental parameters which we present here.

3.2.1. Humidity sensor

To monitor the humidity in the structure, we used the Grove humidity and temperature sensor 101020019 (shown in Figure 2) based on the DHT22. This sensor, manufactured by Seeed Studio, is one of the most accurate humidity sensors we have found. It offers a measurement range of 5 to 99% relative humidity with an accuracy of ± 2%, and -40 to 80°C with an accuracy of ± 0.5°C. Moreover, this sensor is easy to integrate into our system because it uses digital communication via a single data pin. As a result, it takes up less space. Its features include the internal conversion of analogue signals into digital data using an integrated microcontroller, which makes data processing easier. It can also transmit data over distances of up to 20 metres, making it ideally suited to our application, where the structure will be just over 3 metres long. [2]

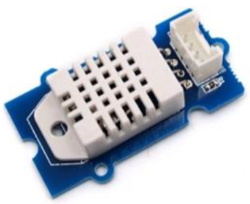

Figure 2: Grove Temperature and Humidity Sensor.

However, this sensor is based on the DHT22 which has a relatively high power consumption compared to other similar sensors. As a result, it does not fully comply with our need to design a low-energy system. In choosing it, we made a compromise between energy and accuracy.

The Grove sensor has been ordered from the distributor Mouser with the reference 713-101020019. We use two in our test prototype.

3.2.2. Temperature sensor

Although the humidity sensor has the functionality to measure temperature, we decided to add a temperature sensor to give us a second measurement of this parameter. We therefore chose to use the TMP117 sensor from Adafruit. This sensor is a high-precision temperature measurement device developed by Texas Instruments and integrated into the Adafruit module. This digital sensor uses an I^2C interface to facilitate its integration into various electronic systems such as ours. We chose it specifically because it offers a remarkable accuracy of ±0.1°C over a temperature range of -20°C to +50°C, making it ideal for our application given that the temperature will not exceed 40/45°C. In addition, its low power consumption of up to 3.5 µA in standby mode makes it an excellent choice for ensuring that our system is energy efficient. Given that we want precise measurements, this sensor is also an asset because it has a high resolution of 16 bits. As a result, it is capable of taking precise and detailed measurements. [3] The TMP117 also has built-in features such as programmable temperature alarms. These features are an added bonus which, time permitting, will enable us to go further in automating our test and integrate alarms when the desired maximum temperature has been reached.

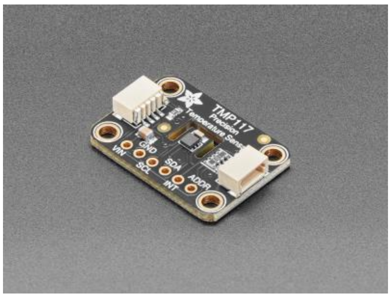

Figure 3: TMP117 Temperature Sensor.

The TMP117 sensor has been ordered from the distributor Mouser with the reference 485-4821. There will be two in our test prototype.

3.2.3. Pressure sensor

To measure the speed of the air in the structure, we used a Pitot tube. This is an instrument designed to measure the velocity of a moving fluid by exploiting the difference between total pressure and static pressure. It is commonly employed in hydrodynamic applications to evaluate the velocity of flow in pipes. By applying Bernoulli's equation, the velocity of the fluid is calculated from the difference between the total pressure and the static pressure. This simple and effective principle makes the Pitot tube an important tool in our application to study air velocity and ensure that it remains uniform throughout the structure. [4]

However, this pressure gauge did not fit properly into the test structure. Indeed, it was too small to be placed directly on the pipes. We were therefore afraid we would not get a good representation of the air flows in the section. In this way, we added two pressure sensors "Grove - High Precision Barometric Pressure Sensor (DPS310)": one at the beginning of the structure before the brick and the other at the end. This sensor is designed to measure pressure accurately over a range from 300 to 1200 hPa, with an accuracy of ±1 hPa. [5] The pressure difference measured will be small in the prototype, so sensors with an acceptable level of accuracy, such as this one, are needed to obtain results that are consistent with reality. In addition, this sensor communicates via an I^2C interface, making it easy to integrate into our electronic system. Designed in Grove format, it is most suitable for use with an Arduino microcontroller. In terms of energy consumption, its low power consumption makes it perfect for developing energy-efficient systems.

Figure 4: DSP310 Pressure Sensor.

The DSP310 sensor has been ordered from the distributor DigiKey with the reference 1597-101020812-ND. There will be two in our test prototype.

3.3. Actuators structure

Actuators are added to the test bench to recreate conditions aligned with the defined use cases. For this setup, we aimed to control the airflow speed by installing a ventilator at the entrance of the tube. Additionally, to regulate the temperature, we included a heating element positioned after the fan.

3.3.1. Ventilator

The choice of the ventilator was based on the previous use cases. For maximum performance, we needed an airflow corresponding to outdoor wind speeds of up to 30 km/h. Considering that our tube had an uniform diameter of 20 cm, this requires an air flow rate of approximately 900 m^3/h.

However, obstacles like the brick and the reduction in tube diameter slow the air down. By modeling the reduction as a transition from 20 cm to 5 cm in diameter, similar to a Venturi tube, we calculated that the ventilator needed a static pressure of around 4000 Pa to overcome these effects. This high value is mainly due to friction losses in the narrower section of the tube.

After searching through our available product catalogs, we did not find any ventilators capable of meeting these requirements within our format constraints. Initially, we tried using a portable high-power ventilator, but it was not sufficient. Given the time limitations, the best solution was to use four hair dryer fans in parallel. This setup generates enough airflow, although the pressure is insufficient to fully achieve maximum test conditions.

Figure 5: Four hair dryer fans in parallel.

To adjust the airflow, we implemented a current control system using a MOSFET driven by a PWM signal from the microcontroller. The control law was simple: proportional with an experimentally determined offset.

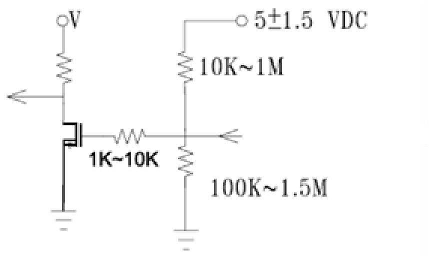

Figure 6: Current control schema using a MOSFET.

Figure 7 is a picture of the control law implemented.

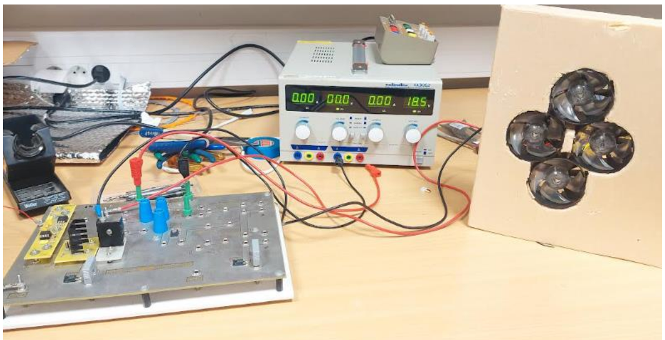

Figure 7: Picture of the control law.

3.3.2. Heating resistor

To select the heating system, we used the same approach as previously explained. Here, our goal was to reach a maximum temperature of 40°C under an airflow at 30 km/h, starting from an initial temperature of 25°C. Assuming uniform heating and perfect tube insulation, this would require 1000 W of heating power.

However, we could not find any components in our available catalogs that met these specifications. The best option we found was a finned resistor from RS rated at 200 W. We thus decided to take two of them, which allowed us to reach a maximum temperature of approximately 30°C at 30 km/h. While this was below our target, it was sufficient for our testing purposes.

Figure 8: Acim Jouanin Finned Tubular Heater, 200 W, 230 V ac.

These resistors operate on mains power, so they cannot be directly controlled by the microcontroller. To address this, we employed an AC Dimmer 8A 1 Channel module. This module enabled us to modulate the mains voltage using a PWM signal from the microcontroller. It supports up to 8A, which was sufficient enough for our use case.

Figure 9: AC Dimmer 8A 1 Channel module.

The temperature regulation system was implemented as a closed-loop system. A temperature sensor placed before the brick provided feedback, and the control law used was a proportional-integral (PI), in order to minimize the steady-state error.

3.3.3. Challenges and Solutions

In the end, it was quite difficult for us to reproduce the maximum test conditions corresponding to our use cases. To solve these problems, we saw three potential solutions. The first would be to reconsider our use cases and work with less extreme conditions, what we have done. The second option would be to have access to specialized distributors, which is particularly complicated in a university setting. The third option would have been to miniaturize the prototype to reduce the impact of external factors. By testing smaller bricks, we could have reduced the size of the test bench and made better choices in our components, allowing us to test the desired conditions more effectively.

3.4. Test structure

We use the sensors mentioned above to carry out our measurements. One of each will be placed before and after the brick. The aim is to be able to compare the measurements at the brick's input and output, to see if there is any cooling effect or any other parameters modifications.

The brick will be placed in an insulated box. The air will flow via some pipes that will also be insulated. We also chose to reduce the cross-section after the brick with insulated pipes of different sections, in order to achieve a better flow rate and more accurate measurements on the output sensors. In addition, we will print a 3D air flow cutoff grid and put it in the entrance of the pipes to homogenise the air flow and to prevent air turbulence in the structure. The box will be insulated with expanding foam and polystyrene. For the pipes, an insulating blanket is required.

Figure 10 is a diagram of the wanted structure.

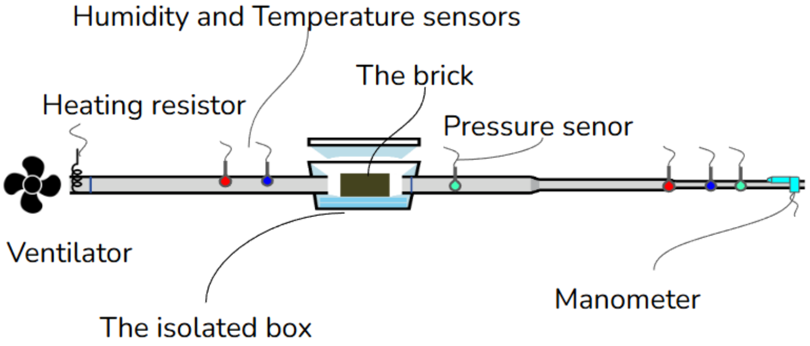

Figure 10: Image of the test bench.

Below, Figure 11 shows the first prototype of the brick test structure created.

Figure 11: Picture of the prototype.

3.5. Tests protocols

The test protocols will enable us to establish a well-defined framework for the experiments we are going to carry out on the brick. The aim is to precisely characterise the behaviour of the wet brick in different situations by adjusting environmental parameters.

1. **Calibration Phase**

Before proceeding with the main tests, it is essential to conduct a calibration phase to guarantee the reliability and accuracy of the measurements. This phase comprises several stages. An initial test will be carried out without any interaction with the brick, under controlled conditions. The objective is to ensure that the measurement system operates correctly without any external influence. Next, the structure used to support the brick and sensors will be examined to check its stability and compliance with the experimental requirements. This stage involves checking the effectiveness of the insulation in order to minimise external thermal or environmental interference, thereby guaranteeing reliable and representative results.

2. **Protocol for Indoor Use**

In this protocol, the experiment simulates the conditions of use of the brick inside a room. The following steps will be applied. Firstly, the brick will be humidified by spraying water directly onto it by the user. This method will simulate a one-off application of water to the brick. In addition, the tests will be carried out at three temperature levels: 20°C, 25°C and 30°C. These values have been chosen to represent realistic conditions encountered inside a home. With regard to ventilation, a moderate airflow will be applied, corresponding to a typical air current in an interior space. The speed of this flow is set at 5 m/s, which reproduces the effect of a slight air circulation.

3. **Protocol for Outdoor Use**

Here, outdoor conditions will be simulated in order to assess the brick's performance in these applications. The brick will be continuously humidified by immersion using a sprinkler system. This system can be either autonomous or supplied by a natural source, such as a fountain. This configuration maintains the brick in a constant state of humidity, similar to prolonged outdoor exposure. Again, the tests will take place at three temperature levels: 30°C, 35°C and 40°C. These values represent warm climatic conditions typical of outdoor environments. A strong air flow will be simulated by the fan, representing a current of outside air with a speed of 30 km/h. This intensity corresponds to winds that can be encountered outdoors.

4. Data acquisition

4.1. Connection via ESP-32

To retrieve data from the sensors and manage the actuators, we needed a microcontroller. We first thought of using an Arduino board, but it did not have enough pins to connect all the needed sensors. We finally opted to use 2 ESPs: one to retrieve the test bench's input data, and the second to collect the brick's output data. We needed to use two of them because, given the size of the test bench (~5 m), the input and output sensors of the brick were too far apart.

4.2. Communication with the Raspberry Pi

4.2.1. The role of the Raspberry Pi

To make the solution as portable as possible and as easy to implement, we decided to add a Raspberry Pi 4. Its role will be to run the Python scripts for analysis and data collection, the graphical interface and to manage communication with the two ESPs.

4.2.2. Communication between ESP and Raspberry Pi

To ensure reliable communication between the two ESPs and the Raspberry, we implemented the MQTT protocol. This is a wireless communication protocol based on the publish/subscribe principle. We opted for this option because this protocol is practical in our solution, as we separated the transmissions from the various sensors, actuators, etc. to different topics. In this way, the Raspberry Pi will act as a broker on which the two ESP boards will subscribe to topics and send their measurements.

5. Implementation of the interface

To ensure efficient management of the test bench and its data, it was necessary to design an interface that met a number of requirements. The aim was to provide an ergonomic application that would be easy for operators to use, while ensuring a degree of robustness. In addition, the interface had to be versatile, allowing for future development according to the needs of the project. In other words, we needed to design a tool that would centralise data collection and analysis, while standardising the experimental process to ensure reproducibility.

5.1. Interface Development

To address the challenges of making the interface ergonomic and adaptable, we decided to develop it using Python and the Qt library with PyQt. Python seemed like the best choice because it is simple to use, has a lot of useful libraries, and can handle data processing pretty well. Using PyQt made it easier to create a graphical user interface (GUI) that was both interactive and visually appealing.

Throughout development, the emphasis was on usability. We wanted to ensure that users, even if they were not very familiar with the technology, could easily find their way around the interface and use its main functions. PyQt gave us the flexibility to add important things like real-time data visualization, adjustable controls, and a modular structure. This helped make the interface more user-friendly and efficient overall.

Another important priority was making the interface adaptable. We built it in a modular way so that it could be updated or expanded in the future without too much trouble. For example, it is ready to support new analysis tools, extra hardware, or improved visualization features if needed later on.

Standardizing the experimental workflow was also really important. The idea was to centralize data collection, processing, and analysis in one place, so results would stay consistent and easy to reproduce. Operators just have to follow a set process, which makes everything more organized and reduces the chances of mistakes.

Finally, we wanted the interface to be reliable, so we tested it a lot under different conditions. This included making sure the hardware connection was solid, and checking how it handled errors. Thanks to this testing, the interface turned out to be pretty robust and ready to handle the test bench and all its data efficiently.

5.2. Design and Objectives of the Interface

The interface was designed to meet three primary objectives:

1. **Ease of Navigation**: A main menu was added to give users quick and easy access to the most important features, like viewing protocols or tracking measurements in real-time. The layout was kept simple to avoid unnecessary complexity and make the interface more user-friendly.
2. **Effective Data Visualization**: Sensor data is shown in both tables and graphs, making it easy to quickly understand the measurements. These visualizations are updated in real-time so users can keep track of what is happening during experiments without any delay.
3. **Integration with the testbench hardware**: The interface is built to connect smoothly with the test bench, ensuring reliable communication for collecting and processing data. This strong connection allows the interface to act as the main control hub for the entire system, making operations more efficient and dependable.

5.3. Core Components of the Interface

To achieve the three main goals mentioned earlier, the interface was split into different modules that work together. Each part focuses on a specific task to make the system easy to use and efficient for managing the test bench.

5.3.1. Main menu

The main menu is like the home screen of the application. It is the first thing the user sees and gives quick access to the main features. There are only two buttons: one for accessing protocols and the connection guide, and the other for data acquisition.

The layout is really simple, with a clear title at the top and easy-to-spot buttons in the center. The goal was to keep everything straightforward so that even someone new can find their way without any confusion.

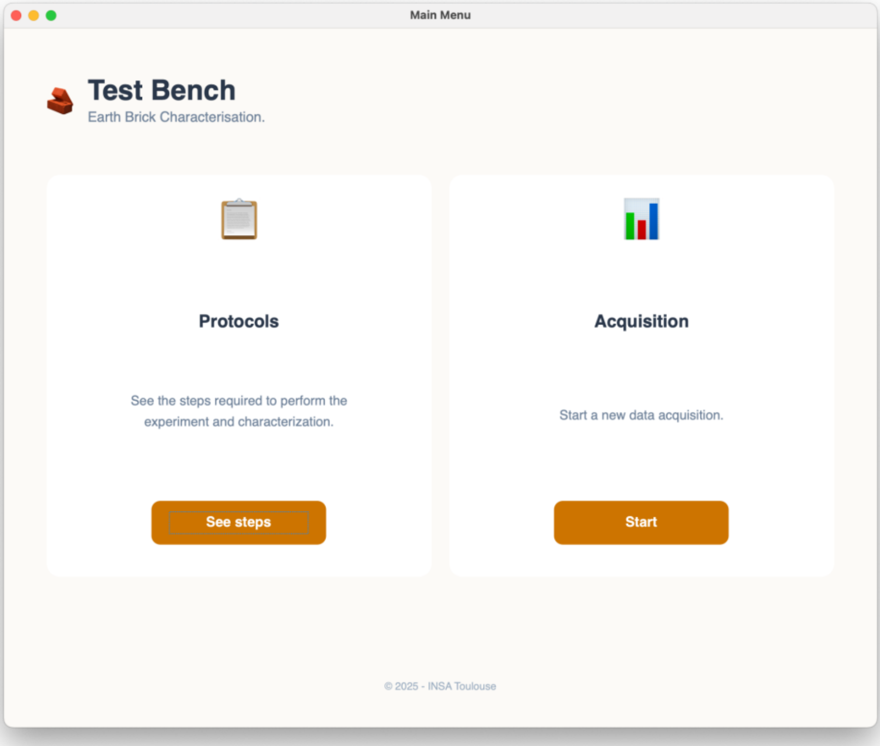

Figure 12: Main menu of the test bench application.

5.3.2. Protocol and user guide

This section is all about guiding the user step by step. It explains how to set up the test bench and connect the hardware to the interface. The instructions are simple and focus on ensuring everything is done properly before starting the tests.

The page has two main parts. One explains the protocols for setting up and using the test bench, and the other gives the verifications to make before starting an acquisition.

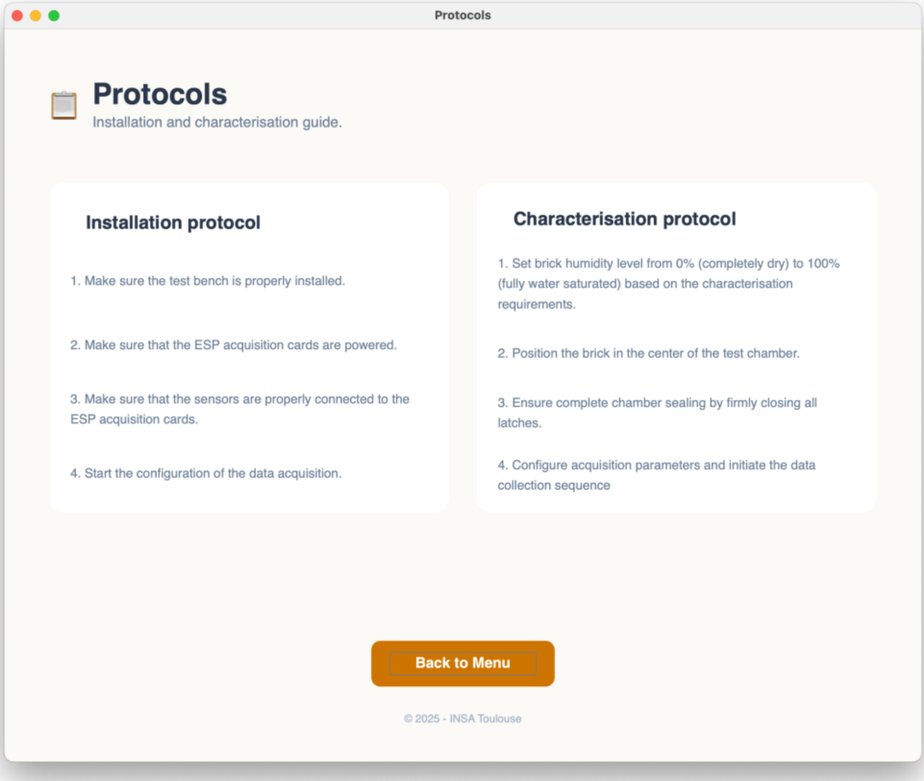

Figure 13: User guide page of the application.

5.3.3. Data acquisition and visualisation

This is probably the most important part of the interface because it is where all the real work happens. It lets users monitor sensor measurements in real-time, adjust certain parameters, and save the results when the experiment is over.

5.3.3.1. Setting the initial condition of the test

This window simply allows the user to enter the initial conditions of the test they want to carry out. Using the three sliders, they can choose the temperature, wind speed and humidity level at which they have placed the brick. At the top of the window, there is also a reminder of the checks to be made before launching an acquisition, to make sure things are done right. This window can be seen in Figure 14.

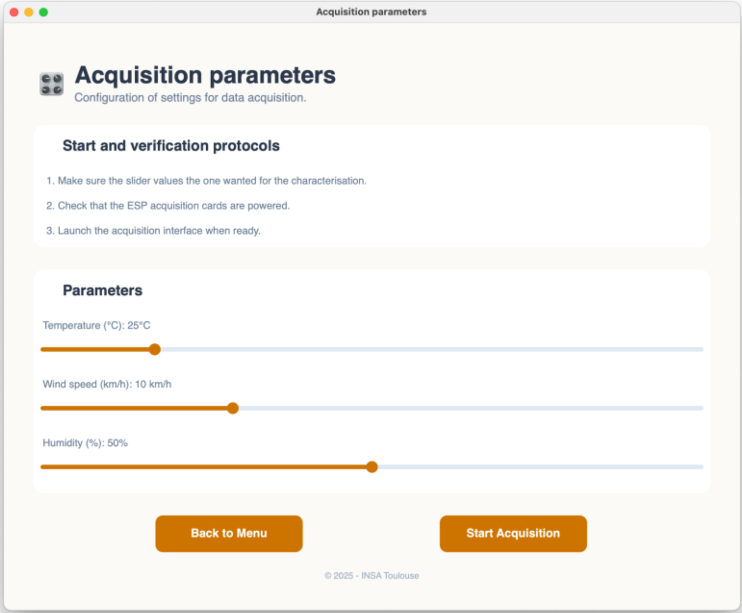

Figure 14: Acquisition Parameter window.

5.3.3.2. Waiting Data Acquisition window

Once the user has entered the required parameters, the window shown in Figure 15 appears. In this window, you can see a graph with a dotted blue line, which corresponds to the temperature the user has just entered. Here, all the user has to do is wait for the temperature measured (red line, not in the image) in the tube to rise to the desired temperature. Once this has been done, data acquisition can begin.

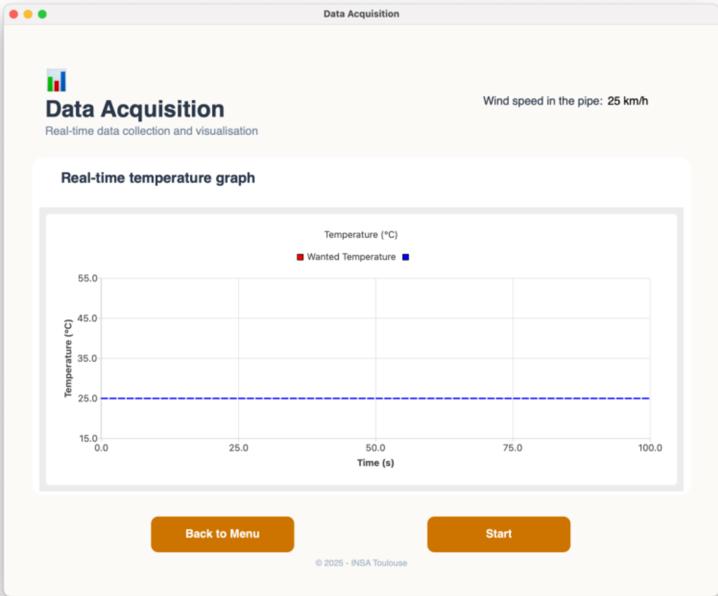

Figure 15: Waiting Data Acquisition window.

5.3.3.3. Data Acquisition window

Finally, the main data acquisition window can be seen in Figure 16. Several important elements can be seen in this window. Firstly, on the left-hand side, there are two tables. The top table shows the measurements taken before the brick, and the bottom table shows the measurements taken after the brick. The graphs on the right display the data measured before and after the brick, for a more practical visualisation of the data.

At the bottom of the window, there are control buttons that allow the user to manage data acquisition efficiently. All these buttons have fairly transparent names, but we are going to go into a little more detail about the data export button because it contains some interesting features that we would like to present.

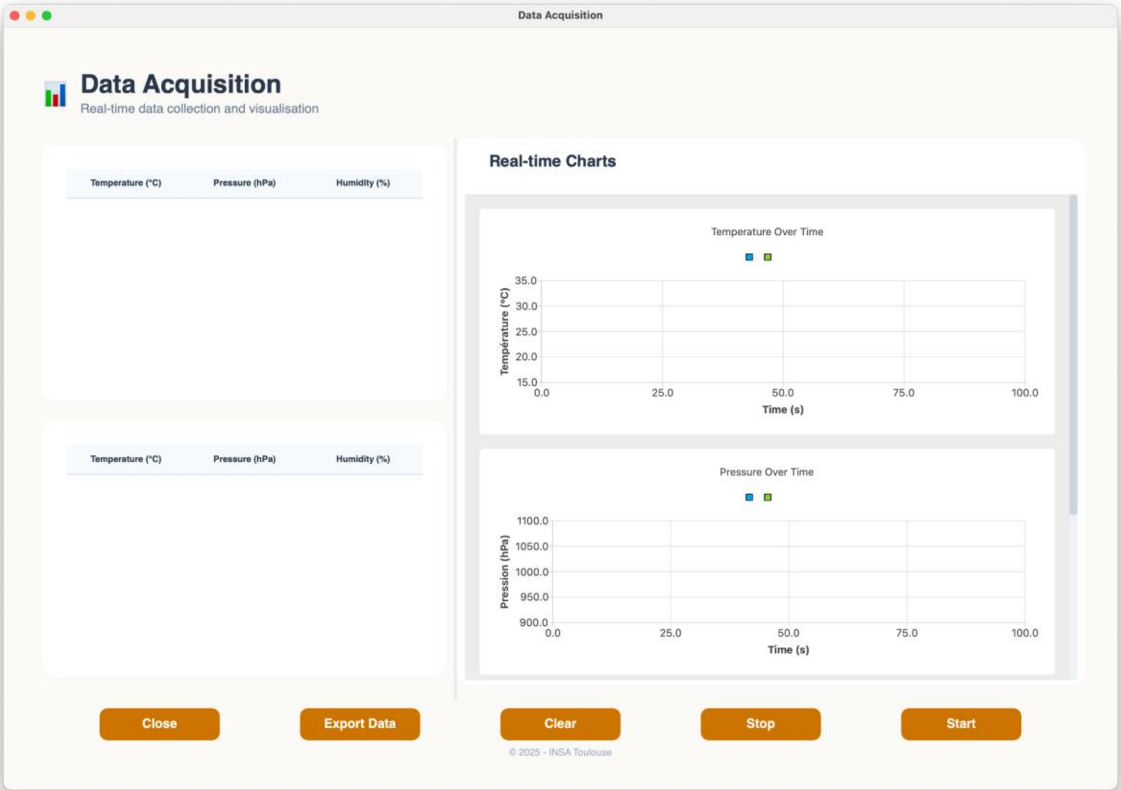

Figure 16: Data Acquisition window.

5.3.4. Export

After finishing the experiment, it is important to save the results properly. The export feature makes this really easy by putting everything together in a single .zip file, so it is simple to find and share later.

The .zip file includes:

1. **CSV File**: This is a spreadsheet with all the recorded data. You can open it in Excel or other tools to analyze the numbers.
2. **PNG Graphs**: The graphs created during the experiment are saved as images. They are perfect for reports or presentations without needing extra editing.

3. **PDF Report**: A full document that brings together everything: data, graphs, and the test setup. It is great for keeping a complete record or sharing the results with someone else.

With just one click on the export button, all these files are generated and zipped together. It is simple, fast, and makes sure nothing gets lost or forgotten.

6. Conclusion

This project was particularly interesting for our team. Of course, it would be wrong to say there were no ups and downs, but that is often part of an engineer's journey.

Throughout this project, we explored the human and relational aspects of our future profession, especially by working with stakeholders who had diverse and complementary expertise. This allowed us to better define and understand the challenges of our project in a multidisciplinary context. However, we were somewhat disappointed by the lack of structured follow-up and project oversight from the partner company. While they communicated the objectives, they did not provide proper monitoring or clear guidance, which reduced some of the value of working on a project proposed by an external organization.

We also encountered some knowledge limitations, which encouraged us to seek information from external sources. This experience helped us improve our skills and learn how to work more effectively as a team.

One of the strengths of this project was the engineering reflection it required. We consistently questioned our choices and applied critical thinking to our goals and results. These reflections allowed us to clearly identify the project's limitations and explore ways to improve its performance.

For example, it would have been helpful to have defined use cases and a pre-established testing structure from the beginning. This would have allowed us to focus our efforts on selecting sensors and actuators, their control, automating operations, and wired or wireless communication, while also integrating safety aspects relevant to our field.

Another possible improvement would have been to redefine the project's purpose. Instead of limiting the scope to material characterisation, we could have aimed to develop an autonomous system that allows users to test these materials easily and repeatedly.

Finally, if building the full-scale test bench was unavoidable, it might have been more practical to create a scaled-down model. This would have reduced challenges related to material procurement and improved portability while still yielding relevant results.

The goal was not to abandon the initial objectives but to adapt the project to better align with the expectations and expertise of our field. This would have meant reducing the focus on simulating physical properties and managing material orders, and instead prioritizing innovation and connectivity.

Beyond the project itself, it is important to consider its broader context: optimizing a technology that exploits the physical principles of thermal transfer. During our research into use cases to size the system, significant doubts emerged about the potential of the material under study. Its efficiency appeared relatively low compared to other materials, while its size and weight were significantly higher. Our task, therefore, was to create a system that could confirm or refute these observations by providing reliable and well-documented data.

If this test bench produces promising results, it could pave the way for further development of this technology and its integration into applications that fully exploit its potential.

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Annex 1: Detailed Calculation of actuators dimensionnement

This section provides the calculations involved in determining the required air flow and pressure, as well as the thermal dissipation needed for the system.

1.1 1. Maximum Air Flow Calculation

Step 1: Calculating the Tube Cross-Section Area

The area A of the circular tube is calculated as:

$$A = \pi \times \left(\frac{d}{2}\right)^2$$

Where $d = 0.1\,\mathrm{m}$ (converted from 10 cm):

$$A = \pi \times \left(\frac{0.1}{2}\right)^2 = \pi \times (0.05)^2 = 0.00785\,\mathrm{m}^2$$

Step 2: Calculating the Volumetric Flow Rate Q

Using the air speed $v = 8.33\,\mathrm{m/s}$, we calculate the volumetric flow rate Q:

$$Q = v \times A = 8.33 \times 0.00785 = 0.0654\,\mathrm{m}^3/\mathrm{s}$$

Step 3: Conversion to $\mathbf{m^3/h}$

To convert the flow rate into cubic meters per hour:

$$Q = 0.0654 \times 3600 = 235.44\,\mathrm{m}^3/\mathrm{h}$$

Result: The required air flow for a 10 cm diameter tube to achieve a speed of 30 km/h is approximately 235.4 $\mathrm{m^3/h}$.

1.2 2. Maximum Air Pressure Calculation

Given a tube that narrows progressively from a 20 cm diameter to 10 cm, then 5 cm, we calculate the pressure losses for each section.

Step 1: Volumetric Flow Rate Calculation

In the first section with $D_1 = 20\,\mathrm{cm} = 0.2\,\mathrm{m}$:

$$A_1 = \pi \times \left(\frac{D_1}{2}\right)^2 = \pi \times (0.1)^2 = 0.0314\,\mathrm{m}^2$$

$$Q = A_1 \times v_1 = 0.0314 \times 8.33 = 0.2615\,\mathrm{m}^3/\mathrm{s}$$

This volumetric flow rate is constant throughout the tube.

Step 2: Air Speeds in Each Section

For section 2 $D_2 = 10\,\mathrm{cm} = 0.1\,\mathrm{m}$:

$$A_2 = \pi \times \left(\frac{D_2}{2}\right)^2 = 0.00785\,\mathrm{m}^2$$

$$v_2 = \frac{Q}{A_2} = \frac{0.2615}{0.00785} = 33.3\,\mathrm{m/s}$$

For section 3 $D_3 = 5\,\mathrm{cm} = 0.05\,\mathrm{m}$:

$$A_3 = \pi \times \left(\frac{D_3}{2}\right)^2 = 0.001963\,\mathrm{m}^2$$

$$v_3 = \frac{Q}{A_3} = \frac{0.2615}{0.001963} = 133.2\,\mathrm{m/s}$$

Step 3: Friction Losses in Each Segment

The pressure losses from friction ΔP_f are calculated as:

$$\Delta P_f = f \times \frac{L}{D} \times \rho \times v^2$$

Where $f = 0.02$ is the friction coefficient for PVC, $\rho = 1.2\,\mathrm{kg/m^3}$, and the air velocity varies per section.

For Segment 1 ($L_1 = 2\,\mathrm{m}, D_1 = 0.2\,\mathrm{m}, v_1 = 8.33\,\mathrm{m/s}$):

$$\Delta P_f 1 = 8.33\,\mathrm{Pa}$$

For Segment 2 ($L_2 = 1\,\mathrm{m}, D_2 = 0.1\,\mathrm{m}, v_2 = 33.3\,\mathrm{m/s}$):

$$\Delta P_f 2 = 133.33\,\mathrm{Pa}$$

For Segment 3 ($L_3 = 1\,\mathrm{m}, D_3 = 0.05\,\mathrm{m}, v_3 = 133.2\,\mathrm{m/s}$):

$$\Delta P_f 3 = 4260.25\,\mathrm{Pa}$$

Step 4: Losses Due to Contractions

The pressure losses due to contractions ΔP_c are calculated as:

$$\Delta P_c = K_c \times \rho \times v^2$$

Where $K_c = 0.4$ for the contractions:

From $D_1 = 0.2\,\mathrm{m}$ to $D_2 = 0.1\,\mathrm{m}$:

$$\Delta P_c 1 = 16.65\,\mathrm{Pa}$$

From $D_2 = 0.1\,\mathrm{m}$ to $D_3 = 0.05\,\mathrm{m}$:

$$\Delta P_c 2 = 266.67\,\mathrm{Pa}$$

Step 5: Total Static Pressure Required

The total static pressure is the sum of the friction and contraction losses:

$$\Delta P = 8.33 + 133.33 + 4260.25 + 16.65 + 266.67 = 4685.23\,\mathrm{Pa}$$

Result: The total static pressure required to achieve a speed of 30 km/h in this tube is approximately 4685 Pa (or 46.85 mbar).

1.3 3. Maximum Thermal Dissipation Calculation

To determine the power needed to heat the air from $25°C$ to $40°C$, the following steps are used.

Step 1: Volumetric and Mass Flow Rates

The volumetric flow rate was calculated earlier as $Q = 0.0654\,\mathrm{m}^3/\mathrm{s}$.

The mass flow rate $\dot{m}$ is:

$$\dot{m} = \rho \times Q = 1.2 \times 0.0654 = 0.07848\,\mathrm{kg/s}$$

Step 2: Energy Required for Heating

The energy required to heat the air is calculated using:

$$P = \dot{m} \times c_p \times \Delta T$$

Where:

$$c_p = 1005\,\mathrm{J/(kg{\cdot}K)} \quad \text{(specific heat capacity of air)}, \quad \Delta T = 40 - 25$$

Thus:

$$P = 0.07848 \times 1005 \times 15 = 1183.3\,\mathrm{W}$$

Result: The power required to heat the air from $25°C$ to $40°C$ is approximately 1183 W (or 1.18 kW). This assumes negligible thermal losses and uniform heating.