Adaptation of a Heat Flux Sensor to Raspberry Pi: A Methodological Approach

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ABSTRACT There is an urgent need to evolve practices and materials in the construction sector, which faces increasing pressure to address environmental concerns. Bio-based materials are emerging as promising alternatives, offering potential benefits in terms of sustainability, energy efficiency, and occupant well-being. However, their thermal performance remains incompletely understood especially at building scale due to their complexity. Thus, advanced monitoring techniques are required to provide accurate data in real conditions. This study aims to create a sensor network for monitoring indoor environmental quality, particularly focused on measuring the thermal parameters of insulated walls. The network uses a low-cost module composed of a heat flux sensor (HFS) system connected to a Raspberry Pi. The choice of Raspberry Pi is due to its increased power, enabling more diverse and complex monitoring. This approach raises technical challenges, particularly in terms of signal acquisition and data processing. The study proposes a methodology for integrating and operating laboratory HFS on a Raspberry Pi, focusing on the choice of analog-to-digital converters. Different hardware configurations were evaluated to ensure sufficient sensitivity and accuracy in heat flux measurement.

Keywords Heat Flux Sensor (HFS), building envelope thermal performance, Raspberry Pi, Analog-to-Digital Converters (ADC), Low-Cost Sensor Network (LCSN).

I. INTRODUCTION

Bio-based materials are increasingly being recognized as a feasible alternative to traditional materials due to their low impact on climate change and depletion of non-renewable resources (Jones & Brischke, 2017). These materials are applicable in various uses, both structural and non-structural, especially as insulation, either in their natural state or combined with a binder (Cosentino *et al.*, 2023).

The thermal properties of bio-based materials have been extensively examined at the material level (Gibeaux & Lecompte, 2024). According to Ahmed *et al.* (2019), the thermal conductivity of sheep's and goat's wools, as well as horsehair, rises linearly with temperature. In contrast, Csanády *et al.* (2021) observes a non-linear correlation between density and thermal conductivity in straw bales. For hemp bundles, Kosiński *et al.* (2018) demonstrate that thermal conductivity decreases with density following a polynomial pattern. The model by Costes *et al.* (2017) indicate that both density and thickness affect the thermal conductivity of wheat straw. Experiments on wood wool conducted by Limam *et al.* (2016) using HFMs, and by Colinart *et al.* (2014) using GHP and TPS, showed variations in thermal conductivity values.

The literature review by Gibeaux & Lecompte (2024) emphasized the necessity for data obtained through building-scale measurements. Given the uniqueness of each scenario, it is particularly important to develop a method for acquiring tailored and reference data. However, current monitoring techniques often depend on intrusive and costly equipment, which hinders their widespread use in real-world building conditions.

Indeed, adapting a heat flux sensor with a very low signal to a Raspberry Pi using an analog-to-digital converter (ADC) involves several limitations and challenges. One significant challenge is the low signal strength, which can result in a poor signal-to-noise ratio (SNR). This makes it difficult for the ADC to accurately capture and convert the analog signal into a digital form without significant noise interference, thus affecting measurement accuracy (Vujovic & Maksimovic, 2014).

Another limitation is the need for precise calibration, as low signals often require finer calibration to differentiate between the signal and noise. Calibrating the system to recognize and amplify valid signals while suppressing noise can be complex and may require additional circuitry for signal conditioning, such as amplifiers and filters, to enhance the signal before digitization (Obeidat & Alqudah, 2023). This made crucial the choice of ADC.

The most low-cost ADCs, while compatible with Raspberry Pi and often used in applications for their affordability, may not provide the precision needed for low-signal measurement due to higher inherent noise and limited resolution. Advanced ADCs with features like error correction and correlated-double-sampling could be used to improve accuracy but may increase the system's complexity and cost (Akopyan *et al.*, 2006).

Power consumption is also a concern, especially in wireless sensor networks where energy efficiency is vital. The integration of additional components to condition the low signal can lead to increased power usage, potentially impacting the viability of the Raspberry Pi as a low-power sensor node (Vujovic and Maksimovic, 2014; Komarizadehasl *et al.*, 2022).

Progress in wireless sensor networks (WSNs) and Low-cost Sensor Networks (LCSNs), along with the miniaturization of sensors, microcontrollers, and electronic components, make them effective tools for monitoring the built environment. Very recently, WSN prototypes for measuring envelope thermal performances have been developed using both commercial (Rosti *et al.*, 2025) and homemade (Lazaro *et al.*, 2022) Heat Flux Sensor (HFS).

In light of the promise shown by biobased thermal insulation solutions and the necessity for extended research in practical construction settings, this study aims to design an affordable and minimally disruptive method for real-time monitoring of the thermal performances of building envelopes.

II. MONITORING SYSTEM

The monitoring sensor network, which is cost-effective, utilizes a Raspberry Pi 4B (RPi) as its main processing unit. Raspberry Pi is particularly advantageous for monitoring the quality of indoor environments. Its ability to run a complete operating system allows for the implementation of advanced software and integration with the cloud for real-time data uploading and storage. The processing capabilities, operating system support, and networking features of Raspberry Pi make it an excellent choice for indoor environmental monitoring (Ibrahim *et al.*, 2015 ; Princy & Nigel, 2015). A HFS is linked to an ADC to measure heat flux (Fig.FIGURE 1). The ADC includes four analog buses, which can connect either two HFS or one HFS and a thermocouple to determine surface temperature.

The Raspberry Pi's built-in Wi-Fi supports wireless data transmission, while its processing power allows for real-time data analysis and storage (Fig.FIGURE 1). InfluxDB, a time-series database designed for efficient data storage and retrieval, has been successfully implemented on an Amazon Web Services (AWS) instance for effective data management. Grafana, a platform for creating interactive and visual data displays, is used to present information in real-time. This setup enables users to immediately view and comprehend data as it is collected, without waiting for updates or reports. The cloud-based setup allows for flexible resource allocation, ensuring optimal performance during high-demand periods. Additionally, data is stored on the Raspberry Pi's SD card as a backup to prevent data loss due to signal fluctuations or network issues (Hajji & Tso, 2016).

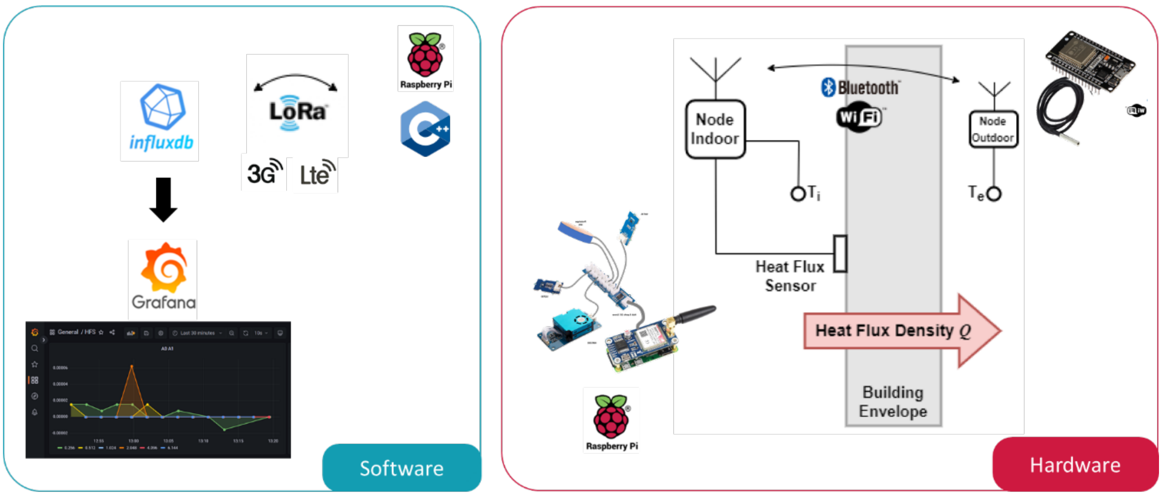

FIGURE 1. Software and hardware parts overview of the designed monitoring system (inspired by Lazaro *et al.*, 2022).

III. HEAT FLUX MEASUREMENTS METHODOLOGY USING ADC

Equation (1) theoretically illustrates the heat flux values across a building envelope, given a known U-value and the temperature differential between indoor and outdoor.

$$\varphi = U \cdot \Delta T \quad (1)$$

with φ the heat flux in $W.m^{-2}$, U the thermal insulation coefficient in $W.m^{-2}.K^{-1}$ and ΔT the the temperature difference between indoor and outdoor air in K. The Fig.FIGURE 2 shows the ranges of theoretical heat flux values depending on the U-value of the surface and the temperature difference between indoor and outdoor.

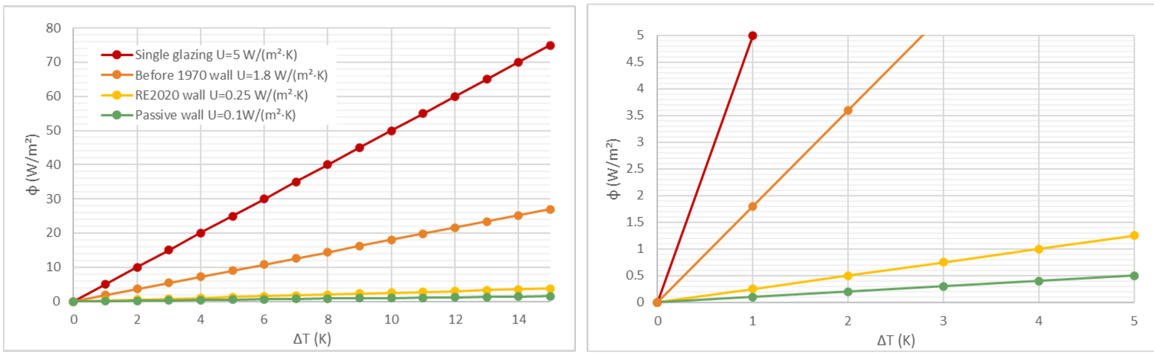

FIGURE 2. Theoretical heat flux in function of monitored surface and temperature gradient.

The linear relationship between heat flux and U-value has significant implications for building energy efficiency and thermal performance measurements. For a given temperature difference, the heat flux through building elements with vastly different U-values can vary by orders of magnitude. This is exemplified by the comparison between a passive wall (U=0.1 $W.m^{-2}.K^{-1}$) and simple glazing (U=5 $W.m^{-2}.K^{-1}$), where the heat flux through the well-insulated wall would be 50 times lower than that through the glazing (Fig.FIGURE 2).

The operational principle of a HFS in conjunction with an ADC is as follows. An HFS is composed of thermocouples and generates an analog voltage signal corresponding to a tension differential between two terminals, one positive and one negative. This signal is continuous, rendering it unrecognizable by the Raspberry Pi. The function of the ADC is to convert this continuous signal into a discrete or digital signal. For instance, a 16-bit ADC possesses 2^{16}, or 65,536, possible measurable levels. This implies that to measure a voltage ranging from 0 to 4.096V, the interval is divided into 65,536 steps, resulting in a theoretical step size or Least Significant Bit (LSB) of 62.5 µV. Subsequently, the Raspberry Pi scripts apply equation (2) to convert bits into voltage.

$$V_m = \frac{\mathrm{RD}}{2^{\mathrm{N}-1}} \times V_{\mathrm{ref}} \quad (2)$$

With V_m the tension differential in V, RD the measured raw data in bits, N the ADC resolution and V_{ref} the reference voltage in V which can be internal of the ADC or external.

Finally, knowing the HFS sensitivity, the script can calculate the heat flux in function of the measured tension differential thanks to the following equation (3).

$$\varphi = V_m \times S_{\mathrm{HFS}} \quad (3)$$

with φ the heat flux in $W.m^{-2}$, V_m the tension differential in V and S_{HFS} the HFS sensitivity in $V.m^2.W^{-1}$.

IV. ADC CHOICE

A. Key parameters

In this study, two primary parameters significantly influence the selection of the ADC component: its resolution and the internal programmable gain amplifier (PGA).

The resolution refers to the number of bits used to represent the analog signal, indicating that a higher resolution allows the ADC to detect smaller variations, thereby enhancing the precision and detail of the measurements. However, high resolution is associated with certain limitations, such as increased sensitivity to electrical noise, higher power consumption, and a reduced sampling rate.

The gain facilitates the amplification of small input signals prior to digitization. This parameter optimizes the resolution, improves the signal-to-noise ratio (SNR), and enables the detection of minor voltage changes. Similar to resolution, the PGA must be carefully managed, as excessive signal amplification can result in noise amplification, signal saturation, offset errors, and bandwidth reduction.

B. 16 bits ADC - ADS1115

The ADS1115 is an ADC notable for its 16-bits resolution, and a PGA up to 16 times the reference voltage range (Texas Instruments, 2024). The ADS1115 uses an I2C interface for communication. This feature facilitates integration with microcontrollers and single-board computers like the Raspberry Pi, allowing seamless data acquisition and processing.

Rosti *et al.* (2025) showed that integrating the HFS with an RPi and ADS1115 closely matched its performance in a lab-grade setup, particularly in measuring low heat flux rates on interior glazing. Findings indicate the EcoDAQ system can achieve lab-grade accuracy for heat flux measurements using the HFP01 sensor, with maximum discrepancies of 7% for U-value. HFS systems by Rosti *et al.* (2025) and Lazaro *et al.* (2022) were tested only on glass surfaces. Significant differences exist in heat flux resolution through glazing and walls due to unique thermal properties as shown on Fig.FIGURE 2. Even with high-sensitive HFS, with a sensitivity around 50μV.m^2.W^{-1}, the heat flux resolution would vary between 0.13 and 1.3 mW.m^{-2} (Fig.FIGURE 3).

C. 24 bits ADC - ADS1220

The ADS1220 is a highly integrated 24-bit ADC designed for precision measurement applications (Texas Instruments, 2013). It features an on-chip low-drift oscillator, a four-channel multiplexer, a PGA, and a built-in voltage reference. Its low power consumption and ability to operate at a low supply voltage make it suitable for battery-powered devices such as the Raspberry Pi. It uses a Serial Peripheral Interface (SPI) protocol communication.

The PGA can be configured to amplify the signal up to 128 times, ensuring it falls within the optimal input range of the ADC and allowing a theoretical heat flux resolution between 40 and 400 μW.m^{-2} depending on the HFS sensitivity (Fig.FIGURE 3).

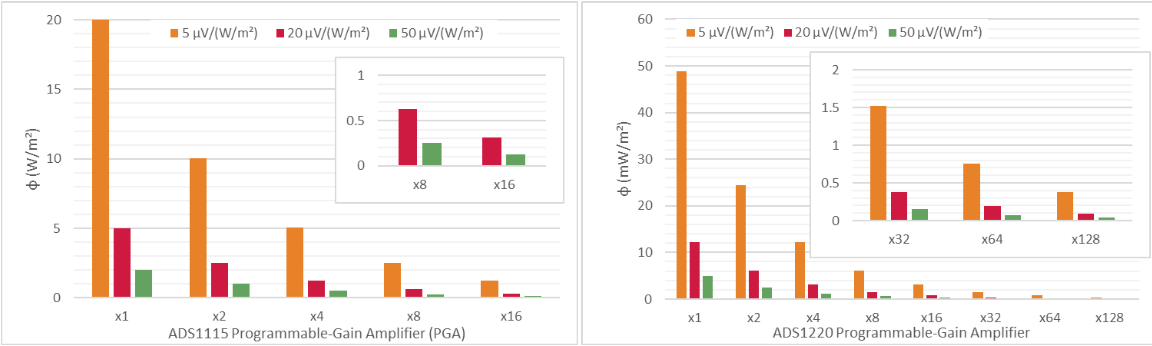

FIGURE 3. Smallest measurable heat flux values in function of HFS sensitivity and PGA with the ADS1115 (left) and with the ADS1220 (right).

V. PRELIMINARY RESULTS AND TECHNICAL ISSUES

Preliminary laboratory tests involved installing a heat flux sensor (HFS) connected to an ADS1115 and a Raspberry Pi, alongside an identical HFS connected to a lab-grade Keithley datalogger. Both sensors were placed on an earth-hemp wall coated with earth plaster, located between two temperature-controlled chambers. A temperature gradient of 2°C was maintained for 24 hours, after which it was increased to 5°C and kept constant until thermal stabilization was achieved (Fig.FIGURE 4).

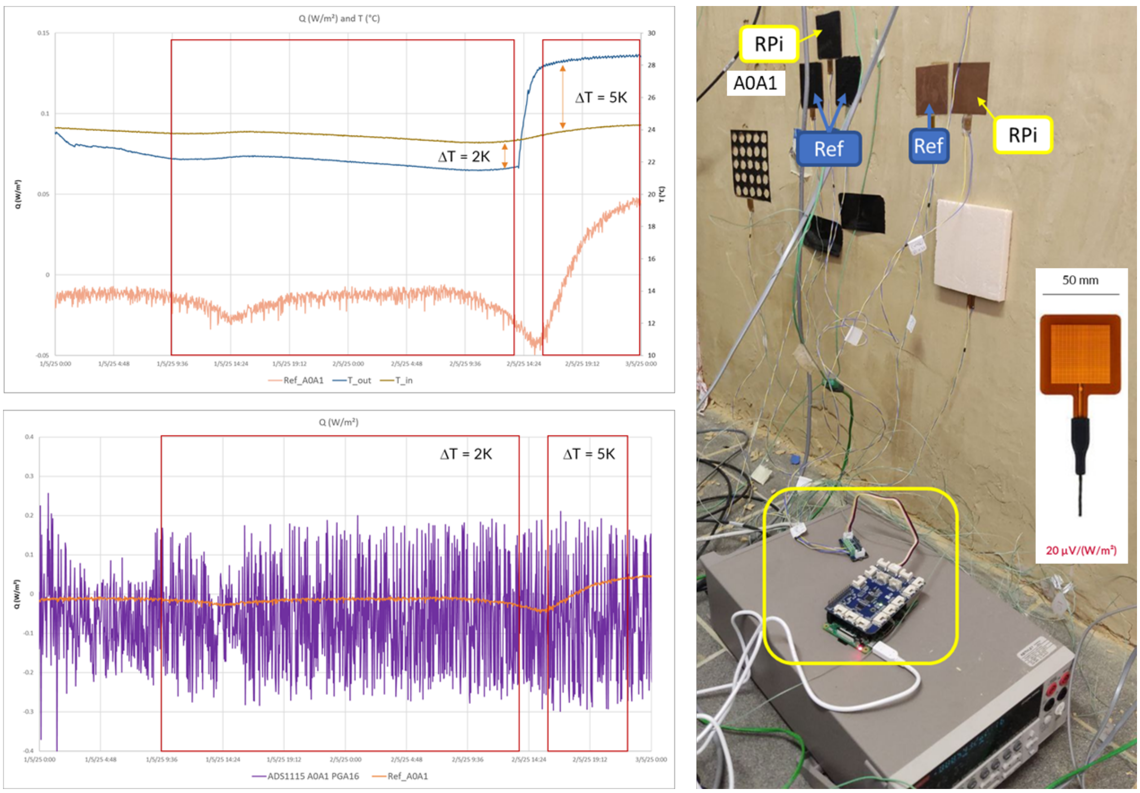

FIGURE 4. First tests with the ADS1115 in a climatic chamber on a raw earth wall.

As highlighted by Fig.FIGURE 4, in laboratory conditions, with a gain range of ±0.20625 V (PGA x16) the resolution heat flux reached 300 $mW.m^{-2}$ instead of the theoretical value of 130 $mW.m^{-2}$ (Fig.FIGURE 3). The heat flux resolution is lower in real-life conditions due to another parameter to take into account in the voltage fluctuation: the Raspberry Pi electrical noise. The electrical noise contribution in voltage measurements from an ADC connected to a Raspberry Pi can arise from various sources, which impact the accuracy and reliability of the data being measured.

Firstly, thermal or resistor noise is a common source of electrical noise which is introduced by the measuring circuit itself. It can affect the precision of the voltage measurements as it adds a random component to the signal, which might lead to erroneous readings, especially in sensitive measurements (Sriram *et al.*, 2005). High-frequency noise also poses a significant challenge. This is typically due to electromagnetic interference from external sources such as radio broadcasts or carrier wave communications. These signals can couple into the ADC circuit electromagnetically, especially if proper shielding and grounding practices are not employed. Such noise can distort the measurements, making it difficult to accurately capture low-level signals (Sriram *et al.*, 2005).

An important aspect of mitigating noise impact involves signal conditioning. Techniques like amplification and filtering are crucial to ensure that the signal remains within the desired frequency range and is free from noise as much as possible. For instance, in applications like electrocardiogram (ECG) monitoring using Raspberry Pi, proper signal conditioning is essential to obtain clean signals that can yield reliable health indicators (Obeidat & Alqudah, 2023). Achieving a good signal-to-noise ratio (SNR) involves balancing various design considerations, such as the choice of components and circuit layout, to minimize these noise sources. Connecting an additional low-noise amplifier between the HFS and the ADC, such as INA333, could help to limit and control this disturbance (Babusiak *et al.*, 2014).

The ADS1220 offers several advantages over the ADS1115, particularly in terms of noise reduction and measurement precision. However, the implementation of the ADS1220 presents a significant challenge in programming due to its more complex feature set. Indeed, it operates on an SPI interface, which can be a bit more challenging to configure compared to I2C due to the need to manage multiple lines (MISO, MOSI, SCLK, CS) and the intricacies of the SPI protocol. Additionally, utilizing the extra features of the ADS1220, such as its internal temperature sensor or the ability to perform continuous conversions, may require a better understanding of ADCs and their configuration.

VI. CONCLUSION

The large variation in heat flux across different building elements presents challenges for accurate measurement and analysis. The choice of ADC and the sensitivity of the HFS become critical factors in ensuring precise heat flux measurements across a wide range of U-values. For elements with low U-values, such as well-insulated walls, the heat flux will be relatively small, requiring more sensitive equipment to detect and measure accurately. Conversely, for elements with high U-values, like simple glazing, the heat flux will be much larger. This highlights the need for careful consideration of measurement tools and methodologies when assessing the thermal performance of diverse building components. The 16-bit ADC, such as the ADS1115, is suitable for applications involving significant temperature variations on poorly insulated surfaces. However, for the monitoring of energy-efficient and passive buildings, the low measured heat flux necessitates the use of higher resolution converters, specifically those with at least 24 bits, such as ADS1220, which can be integrated with external low-noise amplifiers.

RESOURCES

The programming scripts and the presented data are available and can be shared on request.

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