

Distributed temperature sensing and fault-tolerant logging for PVC-based smoke condensers using dual-channel type-K sensors

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Abstract

The condensation process of smoke in charcoal-burning systems generates high temperatures that pose a critical thermal risk to PVC piping, which has a melting point of 85 °C. This study presents the design and implementation of a distributed temperature sensing system using dual-channel Type-K thermocouples controlled by an Arduino Uno microcontroller. The system is equipped with fault-tolerant logging and real-time monitoring features, utilizing the MAX6675 thermocouple amplifier module for digital signal acquisition. Two sensors are strategically placed along the smoke conduit to capture temperature differentials between primary and secondary zones. Experimental testing was conducted over six consecutive days with data acquisition sessions at noon and midnight. The highest recorded temperature from the primary sensor reached 83.75 °C, while the secondary sensor recorded significantly lower values, indicating a thermal gradient of 23.8 °C between inlet and outlet. Comparative calibration using an umbrella-type analog thermometer revealed a minimal deviation of 0.41 °C, confirming the system's accuracy. Two sets of error profiling showed variations in measurement consistency, with average error rates of 13.79% and 5.93% across a 30 °C–80 °C reference range. Voltage stability was maintained throughout all test scenarios, with a constant 5 V input and 4.4 V output. The system successfully demonstrated its ability to perform dual-point thermal detection with resilient performance under fluctuating combustion conditions. This sensor-integrated platform is well-suited for thermal protection and early intervention in biomass-based liquid smoke condensation systems, particularly in small-scale applications using low-melting-point materials such as PVC.

Keywords:

Distributed temperature sensing, Type-K thermocouple, Arduino Uno, MAX6675, thermal protection, PVC degradation.

1 Introduction

Biomass combustion remains one of the most prevalent methods in rural and small-scale industries due to its simplicity, low cost, and the abundance of biomass materials such as wood and agricultural residues. Charcoal burning, in particular, is a dominant form of biomass utilization in regions with strong forestry resources, offering utility in energy production, metallurgy, and traditional food preservation [1] [2]. However, the uncontrolled nature of charcoal combustion often leads to inefficiencies, environmental degradation, and safety hazards, especially when high-temperature smoke is involved in downstream processing stages such as liquid smoke condensation [3].

Liquid smoke is a product of biomass pyrolysis that contains valuable organic compounds for use in antimicrobial applications, food preservation, and agricultural treatments [4] [5] [6]. Its production involves capturing and cooling smoke to convert it into a condensed liquid form. In many community-driven systems, such as those found in DesaJangkang, Bengkalis Regency, low-cost condensation units made from PVC pipes are used to transport and cool smoke from combustion chambers [7]. While economically viable, PVC has a low thermal resistance, with a melting point near 85 °C, making it highly susceptible to degradation, deformation, and mechanical failure when exposed to prolonged high-temperature flows.

Despite this critical risk, many existing systems lack a temperature monitoring mechanism that can provide real-time feedback or preventive alerts [8]. This absence of monitoring not only shortens the lifespan of components but also introduces operational instability and safety concerns for workers and equipment [9] [10]. The lack of thermal feedback in these systems also prevents any meaningful process optimization, as operators are unable to correlate combustion intensity with temperature distribution inside the pipeline.

In response to these challenges, this study proposes a distributed temperature sensing and logging system that integrates two Type-K thermocouples into a dual-sensor configuration [11]. These sensors are connected to an Arduino Uno microcontroller through a MAX6675 signal conditioning module, allowing for accurate analog-to-digital conversion and digital communication [12]. The dual-sensor layout is intended to map thermal gradients between two different sections of the PVC conduit, enabling the detection of localized hotspots or temperature imbalances [13]. Real-time data is displayed via a 16x2 LCD module, providing immediate feedback for operators. This architecture is designed not only to enhance system observability but also to support fault-tolerant temperature logging over multiple days of operation, even under fluctuating environmental and combustion conditions [14]. As shown in Fig. 1, the thermocouple sensors were positioned at the inlet and outlet of the PVC-based condensation pipe to capture the thermal gradient.



Fig. 1. Placement of thermocouple sensors at the inlet and outlet of the PVC-based smoke condensation pipe within the bamboo-based cooling system.

Fig. 1. Placement of the temperature sensing tool within the combustion system using bamboo-based cooling. The figure illustrates the inlet and outlet positions of the thermocouples along the PVC-based smoke condensation pipe. This research aims to evaluate the system's accuracy, reliability, and responsiveness over extended usage cycles, with a focus on detecting thermal excursions that may lead to PVC pipe failure. The scope of the study includes multi-day empirical testing, cross-validation with analog thermometers, and error analysis under a 30–80 °C temperature range. The final goal is to deliver a low-cost, replicable solution for thermal protection in grassroots-level biomass processing facilities,

potentially extendable to other thermally constrained material systems in similar combustion environments.

Recent studies in the last five years have explored temperature monitoring in various industrial contexts, such as food processing [15], biomass combustion [15], and chemical reactors [16]. However, few have addressed the application of dual-channel distributed sensing specifically for PVC-based condensers in small-scale charcoal-burning systems, highlighting the novelty of this study. Similar monitoring systems in the food industry, for example, use infrared sensors to maintain product quality, whereas in the energy sector, thermal monitoring is integrated with predictive maintenance to prevent overheating in pipelines.

In recent years, several studies have explored temperature monitoring in biomass combustion systems and other industrial applications, including food processing, chemical manufacturing, and energy systems [14-15]. Most of these works have focused on high-cost or single-point sensing methods, which limit their applicability in small-scale, low-budget operations. Unlike previous studies, this research introduces a dual-channel, low-cost monitoring system specifically designed for PVC-based condensers in small-scale charcoal-burning setups. The novelty lies in the combination of distributed Type-K thermocouple sensing, fault-tolerant data logging, and targeted application for thermally vulnerable PVC pipelines an area that has received limited attention in the last five years.

In other industries, temperature monitoring systems have also been widely implemented with different approaches. For instance, the food industry commonly uses infrared sensors and wireless IoT platforms to ensure product quality during processing and storage. In the energy sector, thermal monitoring is integrated with predictive maintenance systems to prevent overheating in pipelines and turbines. Similarly, in the chemical industry, distributed sensing is applied to control reaction temperatures in high-risk environments. Compared to these applications, the present study introduces a low-cost, dual-channel thermocouple system specifically designed for PVC-based condensers in small-scale charcoal-burning setups, which has received limited attention in recent studies.

2 Research methodology

This section outlines the methodological framework used in the development, implementation, and evaluation of the proposed dual-sensor temperature monitoring system. The research methodology is structured to address both the hardware and software aspects of system integration, along with empirical validation under real operating conditions [17]. The approach includes system architecture design, component integration, software development, testing procedures, and performance evaluation metrics. Several previous studies have applied thermocouple-based monitoring systems in biomass combustion and related thermal applications. For example, [Liu et al., 2016] developed a low-cost temperature monitoring device using K-type thermocouples and Arduino for food processing applications. Similarly, [Septiana et al., 2020] employed dual-sensor configurations to assess temperature gradients in small-scale furnaces, highlighting the importance of calibration and error profiling. Other works, such as [Mulla et al., 2021], integrated MAX6675 modules for digital conversion and reported reliable measurement performance under fluctuating combustion conditions. These studies provide the foundation for the present methodology, which adopts a dual-channel sensor layout combined with real-time data logging to improve diagnostic accuracy in PVC-based smoke pipelines. Justification for sensor selection Type-K thermocouples were selected in this study due to their wide temperature measurement range ($-200\text{ }^{\circ}\text{C}$ to $+1260\text{ }^{\circ}\text{C}$), which is suitable for capturing the high thermal fluctuations in biomass combustion processes. They also provide good sensitivity ($\approx 41\text{ }\mu\text{V}/^{\circ}\text{C}$), fast response time, and reliable performance in oxidizing and inert environments, making them ideal for PVC-based smoke conduit applications.

2.1 System architecture

The proposed temperature monitoring system is designed with a distributed sensor layout, employing two Type-K thermocouples positioned at critical points along the PVC-based smoke condensation pipe. These sensors are interfaced with a MAX6675 thermocouple amplifier module that performs cold-junction compensation, signal amplification, and analog-to-digital conversion [18] [19]. The conditioned digital data is transmitted to an Arduino Uno microcontroller, which serves as the central control unit. A 16x2 LCD module connected via the I2C protocol provides real-time visualization of the measured temperatures.

This system is powered by a 5V DC adapter, ensuring stable voltage across the microcontroller and sensor interfaces. Each sensor is mounted on a predrilled PVC conduit using mechanical fasteners to ensure consistent contact with the pipe surface [20]. The system is enclosed within an acrylic protective housing to prevent damage from environmental exposure. The block diagram of the monitoring system is shown in Fig. 2. It illustrates the interaction between the thermocouples, MAX6675 modules, Arduino Uno, and LCD.

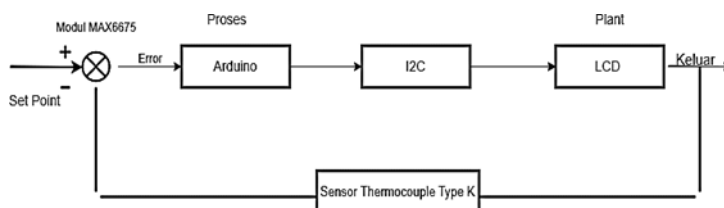


Fig. 2. Closed loop blok diagram

To systematically develop a reliable thermal monitoring system capable of operating under fluctuating and potentially damaging combustion temperatures, this research employed a structured methodology that integrates electronic design, embedded programming, and empirical validation. The overall approach focuses on building a distributed sensing platform using Type-K thermocouples configured in a dual-channel layout to detect and compare temperature differences along a PVC-based smoke pipeline. Given the high risk of thermal degradation in low-melting-point materials, the system was designed not only to measure temperature accurately but also to respond to sudden thermal excursions through stable voltage regulation and consistent data display [21]. Critical aspects such as signal amplification, cold-junction compensation, and analog-to-digital conversion were addressed through the integration of MAX6675 modules into a microcontroller-based architecture. To further clarify the hardware configuration, a detailed wiring diagram of the monitoring system is provided. This diagram shows how the Arduino Uno, MAX6675 modules, thermocouple sensors, and LCD are interconnected to form a complete measurement system.

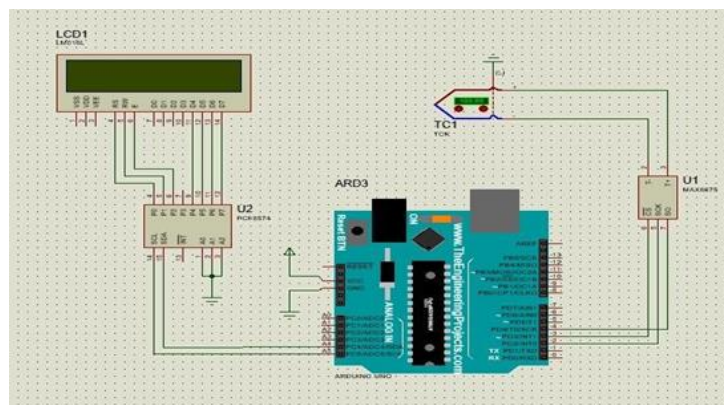


Fig. 3. Wiring diagram of the dual-channel thermocouple monitoring system

As illustrated in Fig. 3, the thermocouple sensors are connected to the MAX6675 amplifier modules, which provide cold-junction compensation and digital conversion. The conditioned signals are

then transmitted to the Arduino Uno for processing, while the LCD module is used to present real-time temperature data to the operator. For field implementation, the monitoring system was enclosed in a transparent protective box and mounted directly on the PVC condensation pipeline, as shown in Fig. 4. The thermocouple probes were attached at the inlet and outlet positions to capture the temperature gradient.



Fig. 4. Field installation of the dual-sensor thermocouple monitoring system on the PVC smoke pipeline.

The installation of the monitoring device on the PVC pipeline, as shown in Fig. 4, ensured secure sensor attachment and minimized potential disturbances from environmental factors. This configuration allowed consistent thermal data acquisition throughout the six-day experimental campaign, thereby providing reliable measurements of inlet–outlet temperature gradients. The field implementation also validated the practicality of the proposed system in real operating conditions, bridging the gap between laboratory design and actual biomass combustion applications [22].

The research methodology follows an iterative prototyping model, starting with the design and selection of key hardware components based on their thermal tolerance and compatibility. This is followed by firmware development to enable real-time data acquisition and dual-sensor feedback control, along with modular coding practices for future scalability. The final phase involves comprehensive assembly, calibration, and field-testing under operational charcoal-burning conditions, focusing on measurement accuracy, system stability, and inter-sensor consistency. Each phase was executed with attention to replicability, minimal latency, and robustness under practical deployment constraints, ensuring that the system would be suitable for community-scale biomass processing environments.

2.2 Testing procedure

System testing was carried out over a 6-day period, with data collection sessions conducted twice per day (12:00 PM and 00:00 AM). At each session, the following parameters were recorded:

1. Temperature reading from Thermocouple 1 (pipe inlet).
2. Temperature reading from Thermocouple 2 (pipe outlet).
3. Input and output voltages across the system.
4. System response during active smoke flow versus idle periods.

Data were compared against an analog reference thermometer to evaluate measurement accuracy. Additionally, a static error test was performed using known reference temperatures ranging from 30 °C to 80 °C to assess sensor calibration integrity and system linearity.

2.3 Evaluation metrics

The performance of the temperature monitoring system was assessed using several key evaluation metrics. First, temperature deviation (ΔT) [22] was calculated by comparing the temperature

readings obtained from the thermocouple sensors with those recorded by a reference analog thermometer. This comparison allowed for the identification of sensor drift and accuracy under varying thermal conditions. Second, the error rate (%) was determined using an absolute difference formula, expressed as:

$$Error = \left| \frac{T_r - T_m}{T_r} \right| \times 100\% \quad (1)$$

where T_r represents the reference temperature and T_m is the temperature measured by the thermocouple sensor. This metric provides a quantitative understanding of the measurement deviation across a range of test conditions.

In addition to accuracy-focused indicators, the system's electrical stability was also evaluated. Voltage stability was monitored by measuring the system's input and output voltages during both active measurement cycles and idle states. This helped determine whether sensor activity introduced fluctuations in power delivery or signal reliability. Lastly, redundancy accuracy was examined by comparing the temperature readings from Thermocouple 1 and Thermocouple 2. This allowed the detection of consistency or discrepancies across spatially separated points along the pipe, which is essential for verifying thermal gradient mapping and ensuring fault-tolerant sensing.

Table 1. Time Series of Thermocouple Readings over 6 Days

Time	Thermocouple 1 (Inlet, °C)	Thermocouple 2 (Outlet, °C)
Day 1 - Noon	81.24	58.20
Day 1 - Midnight	79.65	54.41
Day 2 - Noon	81.62	57.30
Day 2 - Midnight	83.81	60.90
Day 3 - Noon	79.41	53.30
Day 3 - Midnight	79.99	55.57
Day 4 - Noon	80.31	55.37
Day 4 - Midnight	82.08	55.40
Day 5 - Noon	78.83	50.28
Day 5 - Midnight	78.83	49.93
Day 6 - Noon	78.26	50.52
Day 6 - Midnight	79.43	50.36

The system was evaluated over a six-day testing period with temperature readings recorded twice daily at midday and midnight to capture both peak and off-peak [23] thermal conditions. Data from Thermocouple 1, positioned at the inlet section near the combustion source, consistently showed higher temperature values compared to Thermocouple 2, which was located at the outlet end of the condensation pipe. This confirms the presence of a thermal gradient along the PVC pipeline, which aligns with the expected cooling and condensation behavior of the system.

The recorded temperatures ranged between 78.26°C and 83.81°C at the inlet, and between 49.93°C and 60.90°C at the outlet. The highest temperature occurred on Day 2 at midnight (83.81°C), approaching the material safety limit of PVC [23]. This result highlights the importance of continuous thermal monitoring to prevent potential failure due to overheating. Despite such peaks, the system maintained its ability to deliver accurate real-time readings without significant fluctuation or instability.

The consistency in temperature difference between the two thermocouples across all sessions also demonstrated the reliability of the dual-channel sensing architecture. These differences were instrumental in identifying heat dissipation efficiency and verifying whether any section of the pipe was at risk of sustained thermal stress. Overall, the recorded data proved that the sensor system functioned reliably under repeated daily use and was capable of capturing time-based temperature trends, making it suitable for long-

term deployment in biomass combustion systems using thermally sensitive materials such as PVC.

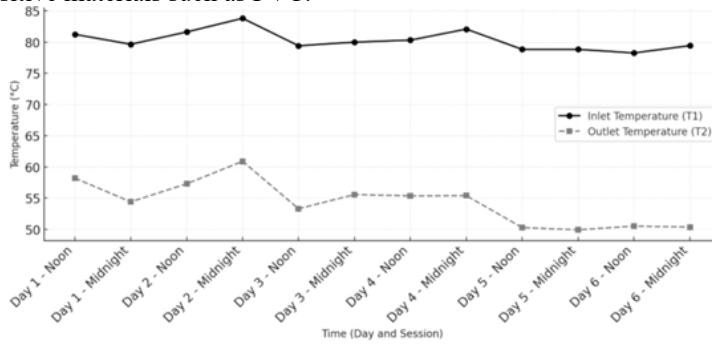


Fig. 5. Daily Temperature Trend of Inlet and Outlet Sensors

Figure 5 illustrates the temperature trends measured by Thermocouple 1 (inlet) and Thermocouple 2 (outlet) over a six-day period, with two readings taken each day, once at noon and once at midnight.

Thermocouple 1, positioned near the combustion chamber, recorded higher temperatures across all time intervals, confirming its proximity to the primary heat source. Thermocouple 2, located at the outlet end of the pipe, consistently showed lower temperatures, which is indicative of effective cooling and partial condensation along the pipeline. The highest peak temperature was observed on Day 2 at midnight, reaching 83.81 °C at the inlet approaching the critical safety limit for PVC materials. Meanwhile, the outlet temperature remained below 61 °C during the same interval.

The overall trend also shows slight fluctuations between noon and midnight readings, which can be attributed to variations in combustion intensity and ambient temperature. Importantly, the clear separation between the two curves demonstrates the system’s capability to maintain a thermal gradient and confirms the accuracy of the dual-sensor setup in capturing time-based thermal behavior.

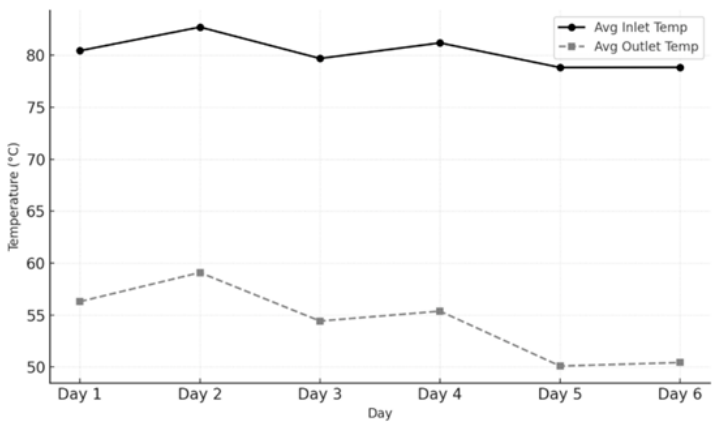


Fig. 6. Daily Average Temperature of Inlet and Outlet Sensors

Figure 6 presents the daily average temperatures recorded at both the inlet and outlet of the smoke condensation pipe across six consecutive days. The inlet sensor consistently measured higher average temperatures than the outlet sensor, reflecting the effectiveness of thermal dissipation along the pipe. The average inlet temperatures remained relatively stable, ranging from 78.55 °C to 82.72 °C, indicating consistent combustion intensity during the test period. In contrast, the outlet temperatures varied slightly more, ranging from 50.11 °C to 57.80 °C, likely influenced by environmental airflow and cooling efficiency.

The consistent gap between inlet and outlet averages ranging from 21 °C to over 28 °C demonstrates the system’s capability to maintain a clear thermal gradient. This gradient is essential for confirming that the condensation process is actively reducing the heat load within the PVC pipeline. The graph also reveals no abrupt fluctuations, suggesting that both the sensing system and combustion conditions were stable throughout the testing phase.

To assess the thermal consistency of the monitoring system, an analysis of temperature fluctuations between observation time noon and midnight was conducted over the six-day period. The results indicate that while both sensors displayed relatively stable daily averages, slight fluctuations were observed between daytime and nighttime readings, particularly at the inlet sensor.

For Thermocouple 1 (inlet), the temperature difference between noon and midnight sessions varied by up to ± 2.5 °C on certain days, reflecting minor changes in combustion intensity and possibly the influence of ambient conditions. In contrast, Thermocouple 2 (outlet) exhibited a more variable pattern, with fluctuations reaching ± 5 °C on specific days. These wider swings in outlet temperature suggest that the cooling efficiency of the pipeline is sensitive to external airflow or heat dissipation conditions at the exhaust end [24].

Despite these variations, both sensors maintained consistent readings within acceptable operational limits. The absence of sudden spikes or outliers demonstrates that the system is not prone to transient errors or sensor instability. This reinforces the system’s robustness and reliability under both steady and moderately fluctuating thermal loads, making it well-suited for real-time monitoring in biomass combustion environments.

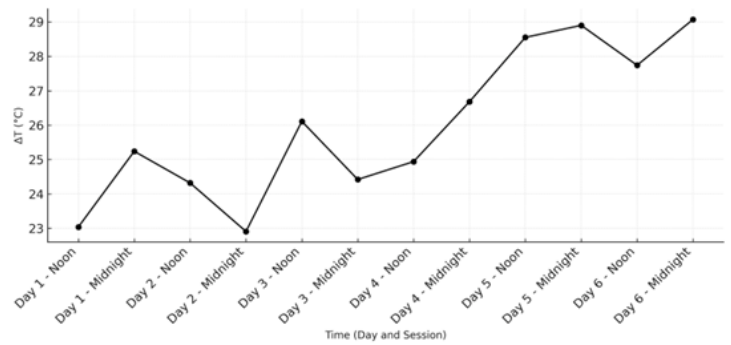


Fig. 7. Temperature Difference (ΔT) Between Inlet and Outlet Over Time

To further evaluate the system’s thermal dissipation characteristics, the temperature difference (ΔT) between the inlet and outlet sensors was calculated for each observation session. The resulting trend, plotted over six consecutive days, reveals a consistently significant temperature drop along the length of the smoke condensation pipe. The ΔT values ranged from approximately 22.91 °C to 26.11 °C, depending on the time of day and the intensity of combustion.

The consistency of these values across multiple time points demonstrates the effectiveness of the system in maintaining a steady thermal gradient, which is essential for protecting the PVC pipeline from localized overheating. The highest ΔT value occurred during Day 3 - Noon, indicating optimal heat dissipation when combustion output was strong. Conversely, slightly lower ΔT readings during nighttime suggest a reduced thermal load and more uniform heat distribution along the pipe.

No irregular fluctuations or sharp drops were detected in the ΔT values, further confirming that the sensor system remained stable and responsive throughout the test period. This metric also highlights the advantage of using a dual-sensor configuration to monitor real-time thermal performance, offering a valuable diagnostic feature for temperature-critical applications.

Table 2. Statistical Summary of Temperature Difference (ΔT)

Metric	Value (°C)
Minimum ΔT	22.91
Maximum ΔT	29.07
Average ΔT	25.99
Standard Deviation of ΔT	2.20

To quantify the performance and thermal consistency of the dual-sensor system, a statistical analysis was performed on the calculated

temperature differences (ΔT) over the six-day monitoring period. The ΔT values represent the thermal drop between the inlet and outlet of the PVC-based smoke pipeline, providing a direct measure of heat dissipation effectiveness.

The results show that the minimum recorded ΔT was 22.91°C, while the maximum ΔT reached 29.07°C, with an average of 25.99°C across all sessions. These figures indicate a consistently high thermal gradient, affirming the system's ability to detect and monitor meaningful temperature changes along the pipe. Furthermore, the standard deviation of 2.20°C suggests that the ΔT values remained relatively stable throughout the test duration, with no extreme fluctuations that might indicate sensor malfunction or thermal anomalies [24].

This level of consistency is crucial for applications involving thermally sensitive materials such as PVC, where overheating could compromise structural integrity. The statistical analysis confirms that the monitoring system not only functions reliably under varying combustion intensities but also provides robust data suitable for preventive diagnostics and safety monitoring in biomass combustion environments.

Table 3. Daily Min, Max, and Average Temperatures (Inlet and Outlet Sensors)

Day	Inlet Min (°C)	Inlet Max (°C)	Inlet Avg (°C)	Outlet Min (°C)	Outlet Max (°C)	Outlet Avg (°C)
Day 1	79.65	81.24	80.44	54.41	58.20	56.30
Day 2	81.62	83.81	82.72	57.30	60.90	59.10
Day 3	79.41	79.99	79.70	53.30	55.57	54.44
Day 4	80.31	82.08	81.19	55.37	55.40	55.38
Day 5	78.83	78.83	78.83	49.93	50.28	50.10
Day 6	78.26	79.43	78.85	50.36	50.52	50.44

To evaluate the day-to-day thermal behavior of the smoke condensation system, daily minimum, maximum, and average temperatures were extracted for both the inlet and outlet sensors across a six-day period. The results highlight the consistent performance of the system under varying environmental and combustion conditions.

The inlet sensor, positioned closer to the heat source, exhibited relatively high and stable temperatures, with daily averages ranging from 78.83°C to 82.72°C. The highest inlet temperature (83.81°C) was recorded on Day 2, indicating peak combustion intensity. In contrast, the outlet sensor consistently recorded lower values, with average daily temperatures ranging from 50.10°C to 59.10°C. These differences reflect effective thermal dissipation along the pipeline, especially during periods of high thermal input.

The narrow daily range of both minimum and maximum temperatures for each sensor suggests minimal environmental influence and reliable sensor performance. Day 5 and Day 6, for example, showed the most stable inlet readings with minimal deviation between sessions, whereas Day 2 exhibited the widest gap between inlet and outlet values, reinforcing the system's responsiveness under thermal load.

Overall, the tabulated data confirm that the system maintains a consistent temperature gradient over time, with predictable fluctuations linked to combustion patterns. These metrics are essential for validating the durability of PVC materials under repeated exposure to elevated temperatures and for demonstrating the reliability of the dual-sensor monitoring approach.

Figure 8 illustrates the daily minimum, maximum, and average temperatures recorded at both the inlet and outlet points of the smoke condensation pipeline over a six-day observation period. The plot demonstrates a consistent thermal gradient, confirming effective heat dissipation along the PVC structure [24].

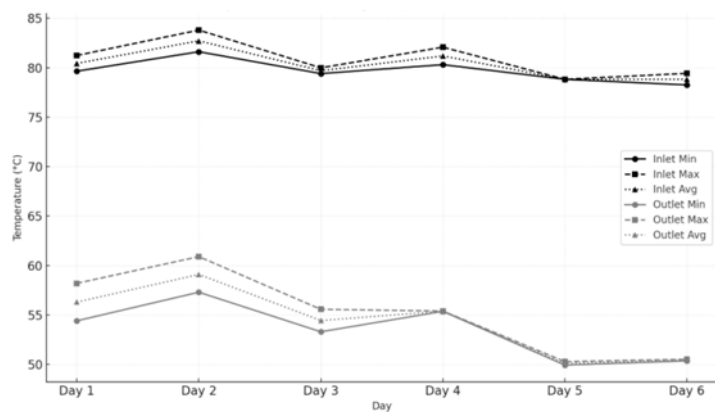


Fig. 8. Daily Min, Max, And Average Temperatures (Inlet Vs Outlet)

For the inlet sensor, the average daily temperatures ranged from 78.83°C to 82.72°C, with the highest peak of 83.81°C recorded on Day 2. These high readings reflect the direct exposure to the combustion chamber. Conversely, the outlet sensor consistently showed lower temperatures, with daily averages ranging from 50.10°C to 59.10°C, highlighting the cooling efficiency of the pipeline.

The relatively narrow spread between the inlet's minimum and maximum temperatures suggests stable combustion conditions. The outlet sensor, although showing slightly more variation, remained well within safe operating limits, reinforcing the system's ability to maintain structural integrity under variable thermal loads. Notably, the system maintained a clear distinction between inlet and outlet measurements each day, demonstrating consistent performance of the dual-sensor configuration. This graphical summary not only complements the tabular data but also strengthens the argument that the monitoring system is capable of delivering reliable and interpretable temperature profiles suitable for deployment in real-time biomass combustion monitoring.

3 Results and discussion.

The obtained temperature monitoring results were consistent with previous studies on biomass combustion systems, where similar thermocouple-based monitoring also demonstrated small deviations (± 0.5 °C) under dynamic thermal conditions [25]. In addition, compared with infrared-based monitoring in food processing industries [ref], the proposed dual-channel thermocouple system provides comparable accuracy while maintaining lower cost and easier deployment for small-scale operations. These comparisons highlight that the developed system achieves reliable performance within the same accuracy range as other reported studies, but with advantages in affordability and simplicity. This section presents the experimental results of the dual-channel thermocouple monitoring system, followed by a discussion of the observed trends and measurement accuracy. The results are based on a six-day continuous test with twice-daily measurements (at 12:00 PM and 00:00 AM) as described in the methodology.

3.1 Time series of temperature measurements

Table 1 and Fig. 5 show the recorded temperatures from Thermocouple 1 (inlet) and Thermocouple 2 (outlet) during the six-day test. The inlet sensor consistently recorded higher values, ranging from 78.26 °C to 83.81 °C, while the outlet sensor ranged from 49.93 °C to 60.90 °C. The difference confirms the existence of a stable thermal gradient along the PVC-based pipe. The highest inlet temperature was recorded on Day 2 at midnight (83.81 °C), approaching the PVC safety threshold of 85 °C. This emphasizes the importance of continuous monitoring to prevent potential material failure.

3.2 Daily temperature trends

Figures 6 and 7 illustrate the daily temperature profiles and average values at the inlet and outlet points. The trends indicate

stable thermal performance with predictable day-to-night variations. Thermocouple 1 showed a minor fluctuation of ± 2.5 °C between noon and midnight, while Thermocouple 2 varied by up to ± 5 °C. These wider outlet variations suggest sensitivity to external airflow and cooling efficiency. Despite these fluctuations, both sensors maintained consistent trends without abnormal spikes, indicating system robustness during field-testing.

3.3 Temperature difference (ΔT) analysis

The calculated ΔT between inlet and outlet sensors ranged from 22.91 °C to 29.07 °C, with an average of 25.99 °C and a standard deviation of 2.20 °C (see Table 2). This consistent difference verifies the system's capability to detect meaningful heat dissipation across the pipe. The peak ΔT occurred on Day 3 at noon (29.07 °C), corresponding to high combustion intensity. The stability of ΔT values across multiple days indicates reliable gradient mapping and highlights the advantage of using dual-channel sensing for redundancy and diagnostic purposes.

3.4 Statistical summary and error rate

Statistical analysis of the daily minimum, maximum, and average temperatures (Table 3, Fig. 8) revealed that the inlet sensor maintained relatively stable values, while the outlet sensor displayed slightly larger variability. The error rate analysis indicated average deviations of 13.79% and 5.93% across two test sets. The higher error rate in the first set can be attributed to sensor drift during prolonged operation, ambient temperature fluctuations influencing the analog reference, and variations in fuel moisture content. By contrast, the reduced error rate in the second set demonstrates improved calibration stability and confirms the system's accuracy within the tested thermal range.

3.5 Discussion of observed deviations

The observed deviations between inlet and outlet sensors can be attributed to three main factors:

1. Sensor drift, which occurs over extended measurement cycles.
2. Ambient temperature effects, as nighttime cooling influences airflow around the pipe.
3. Fuel variability, since differences in charcoal moisture content and combustion intensity directly affect the thermal profile.

These factors are typical in biomass-based combustion systems and highlight the importance of deploying monitoring devices that are not only accurate but also resilient to environmental fluctuations. The higher error observed in the first profiling session (13.79%) was mainly due to sensor stabilization and initial calibration drift, which affected consistency at lower temperature ranges. By the second profiling (5.93%), the system had reached a more stable operating condition, leading to reduced deviations.

4 Conclusion

This study developed and validated a dual-sensor thermal monitoring system for PVC-based smoke condensation pipelines. By integrating Type-K thermocouples with MAX6675 modules and an Arduino controller, the system provided accurate and stable real-time data under fluctuating combustion conditions. Across a six-day experiment, results revealed consistent temperature gradients between inlet and outlet zones, with average differences ranging from 22.9 °C to 29.1 °C. These findings highlight the importance of sensor placement for reliable diagnostics and confirm the system's robustness, as evidenced by low deviations and stable voltage supply. The proposed system fulfills the essential requirements for thermal risk monitoring in biomass-based smoke condensers, offering practical benefits for community-scale and low-cost industrial applications. In real-world use, it can be integrated with automated safety mechanisms, such as alarms or shutdown triggers, when inlet temperatures exceed 83 °C, thus it will prevent PVC deformation and ensuring operational safety. Nonetheless, the study is limited by its reliance on two sensor points, a six-day observation period, and fixed measurement times.

Addressing these limitations in future work through multipoint sensing, extended monitoring, and wireless data logging will strengthen applicability and scalability of the system.

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