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Real-Time Cooling Rate Characterization in Fused Deposition Modeling Using a Non-Contact Infrared Temperature Sensor

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توصيف معدل التبريد الآني في عملية النمذجة بالترسيب المنصهر (FDM) باستخدام مستشعر حراري بالأشعة تحت الحمراء غير تلامسي

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Abstract

Temperature history during the Fused Deposition Modeling (FDM) process is a critical factor influencing the cooling dynamics of the extruded filament, interlayer adhesion, and final part quality. Traditional contact-based sensors such as K-type thermocouples face limitations including low sampling rate and interference with the process, making them unsuitable for capturing rapid solidification events of materials like PLA. This study presents a real-time experimental investigation of the cooling rate of polylactic acid (PLA) during fused deposition modeling (FDM) using a non-contact infrared sensor, the MLX90614 infrared temperature sensor. A low-cost Arduino-based data acquisition system was developed to monitor the transient thermal behavior of the deposited filament immediately after extrusion. The sensor was positioned in a trailing configuration relative to the nozzle to capture post-deposition temperature evolution without interfering with the printing process. Cooling rate was quantified using numerical differentiation of time-resolved temperature data. The results reveal a highly transient cooling regime characterized by steep initial thermal gradients followed by asymptotic decay. The findings highlight the critical role of early-stage cooling in governing interlayer bonding and provide a practical framework for thermal monitoring and process optimization in FDM.

Keywords: Thyroid Hormones, Chronic Kidney Disease (CKD), Renal Failure, Hemodialysis, Thyroid Dysfunction, Kidney Function.

الملخص

تقدم هذه الدراسة نظاماً للمراقبة الحرارية غير التلامسية لعملية النمذجة بالترسيب المنصهر باستخدام مستشعر درجة الحرارة بالأشعة تحت الحمراء من طراز MLX90614 مدمج مع متحكم دقيق Arduino Uno. الهدف الأساسي هو قياس معدل التبريد لعينات مصنعة من مادة (PLA) في الوقت الفعلي دون حدوث أي تداخل مادي مع عملية الطباعة. بينت النتائج تسجيل بيانات درجة الحرارة مقابل الزمن بدءاً من حالة الترسيب الأولية عند 113.93 درجة مئوية وصولاً إلى 65.63 درجة مئوية، وذلك خلال فترة زمنية بلغت 1409 ثانية تقريباً. علاوة على ذلك، كشف تحليل معدل التبريد العكسي (dT/dt) عن زيادة ملحوظة في المقاومة الحرارية (تصل إلى 15 ثانية/درجة مئوية) مع اقتراب المادة من درجة حرارة التحول الزجاجي (~65 درجة مئوية). تثبت النتائج أن الاستشعار بالأشعة تحت الحمراء غير التلامسي هو وسيلة فعالة وعالية الدقة لمراقبة العملية في الموقع، مما يوفر رؤى جوهرية حول الالتصاق بين الطبقات والتدرجات الحرارية الضرورية لتحسين جودة الطباعة ثلاثية الأبعاد.

الكلمات المفتاحية: هرمونات الغدة الدرقية، مرض الكلى المزمن، الفشل الكلوي، الغسيل الدموي.

1. Introduction

Fused Deposition Modeling (FDM) is one of the most widely used additive manufacturing technologies due to its low cost, operating simplicity, and suitability for rapid prototyping and functional part production [1]. The polylactic acid (PLA) considered one of the most thermoplastic materials used in FDM because of its low melting temperature, biodegradability, and ease of processing, making it ideal for rapid prototyping and engineering applications [2,3]. The quality of FDM-printed parts strongly depends on the thermal history experienced by the extruded filament during and immediately after deposition. In addition, the temperature evolution plays a decisive role in critical outcomes such as interlayer bonding, residual stress formation, crystallization behavior, and dimensional accuracy, making thermal control a precarious factor in process optimization [4-6]. Recent studies have publicized that heat transfer and its management significantly affect the properties of the printed parts, for example rapid cooling immediately after extrusion significantly affects interfacial diffusion between adjacent layers and ultimately determines the mechanical integrity of printed PLA structures [7, 8]. Therefore, understanding and quantifying cooling rate has become a significant research direction in polymer additive manufacturing. Conventional thermal monitoring methods in FDM commonly rely on contact-based sensors such as thermocouples and thermostats, which measure temperature by direct physical contact. These methods suffer from several limitations, including physical interference with the printing process, delayed thermal response, and difficulty in capturing fast transient thermal events occurring at the extrusion stage. To overcome these limitations, non-contact thermal sensing techniques have gained increasing attention in recent years. Infrared-based monitoring approaches have demonstrated strong capability for in-situ thermal characterization of FDM processes, enabling real-time observation of temperature evolution without disturbing the deposited filament. However, high-resolution thermal cameras remain relatively expensive and are not always suitable for low-cost laboratory implementations [9-11]. Low-cost infrared sensing systems represent an attractive alternative for localized real-time thermal monitoring in FDM environments. In this study, a low-cost, non-contact infrared sensor (MLX90614), is employed to record localized surface temperature vs. time during printing. The proposed experimental setup enables real-time cooling-rate characterization with high temporal resolution, providing practical insight into early-stage thermal behavior and supporting future process optimization and quality prediction in FDM 3D printing.

2. Methodology

An MLX90614 infrared temperature sensor was integrated with an Arduino Uno microcontroller to enable real-time, non-contact temperature measurement during the FDM printing process. The sensor was positioned at a fixed distance and orientation to monitor a predefined location on the surface of PLA printed specimens. Temperature data were continuously recorded at a defined sampling interval and stored for post-processing. The acquired temperature–time data were analyzed to determine cooling rates during the solidification phase. The proposed setup avoids physical contact with the printed part, ensuring minimal disturbance to the printing process.

2.1 Materials and Equipment

The experimental investigation was conducted using a material extrusion additive manufacturing system. The following materials and equipment were employed:

FDM 3D printer:

- Bambu Lab A1, FDM 3D printer , Nozzle diameter 0.4 mm
- Filament: PLA (Polylactic acid), Melting range approx. 200–220 °C.
- Printing parameters (example): nozzle temperature 220 °C, bed temperature 65 °C, Printing speed 500mm/s

Temperature Measurement System:

- Infrared sensor: MLX90614 infrared temperature sensor
- Microcontroller: Arduino Uno

2.2 Experimental Setup

A non-contact temperature measurement system was developed to monitor the thermal evolution of the extruded PLA filament during printing. The infrared sensor was interfaced with the Arduino Uno via the I²C communication protocol. Real-time temperature data were acquired and transmitted to a computer through serial communication. The mounting configuration was designed using SolidWorks software to avoid interference with the printer's motion system (Figure 1).The sensor was mounted in a trailing configuration relative to the nozzle to capture the temperature of the filament immediately after deposition, as shown in Figure 2.

Key positioning parameters:

- Distance from deposition point: 3–5 cm
- Orientation angle: ~45° relative to the build surface
- Measurement target: freshly deposited filament

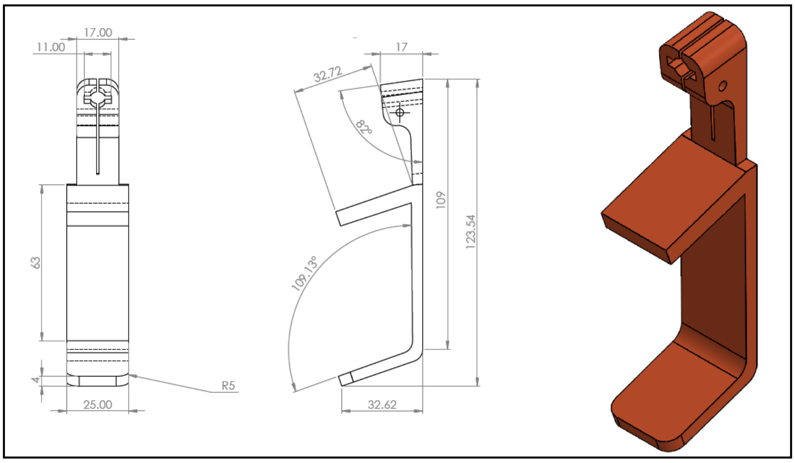

Figure 1. CAD-based design of the custom 3D-printed holder.

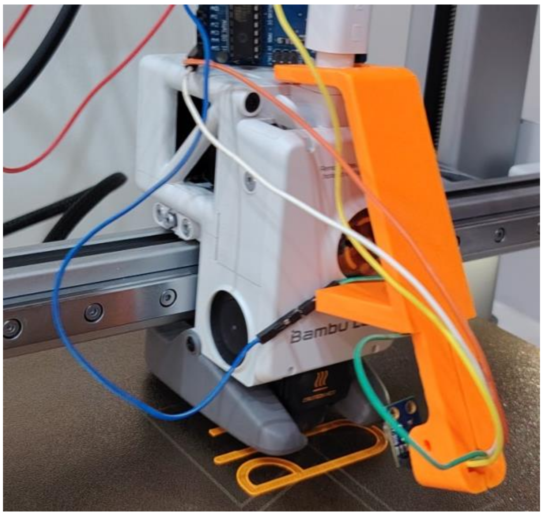

Figure 2. Experimental setup showing the infrared sensor rigidly mounted to the print head assembly in close proximity to the nozzle using a custom-designed 3D-printed holder.

2.3 Data Acquisition

The Arduino Uno was programmed using embedded C to interface with the MLX90614 infrared temperature sensor via the I²C protocol. Table 1 shows the technical specifications of the MLX90614 Sensor.

Table 1: Technical specifications of the MLX90614 temperature sensor [12].

Parameter	Value
Measurement Range (Object Temperature)	-70 °C to 380 °C
Ambient Temperature Range	-40 °C to 125 °C
Accuracy	±0.5 °C (typical)
Resolution	0.02 °C
Supply Voltage	3.3–5 V
Communication Protocol	I²C
Field of View (FOV)	35° (MLX90614-BAA version)
Response Time	Approximately 100 ms
Emissivity Setting	0.95

Prior to the experiments, the sensor was calibrated using reference temperature measurements obtained from the printer nozzle and heated PLA samples. Since the accuracy of infrared temperature measurements depends strongly on the emissivity of the target surface, an emissivity value of 0.95 was adopted, which is commonly reported for matte PLA surfaces. The sensor was positioned at a fixed distance and angle relative to the deposited filament to minimize measurement variability associated with changes in viewing geometry. The Field of View (FOV) of the sensor was considered during the design of the measurement setup. To reduce the influence of surrounding hot components, particularly the nozzle heater block, the sensor was mounted in a trailing configuration and equipped with a shielding structure that restricted its observation area to the freshly deposited filament. However, the data collection was intentionally concluded at the temperature threshold corresponding to the heated bed temperature of the 3D printer. Measurement uncertainty may arise from variations in filament emissivity, sensor alignment, ambient environmental conditions, and the presence of nearby heat sources.

The hardware configuration of the temperature measurement system is illustrated in Figure 3. The MLX90614 infrared temperature sensor was interfaced with the Arduino Uno using the I²C communication protocol, enabling real-time acquisition of temperature data, Figure 4. Temperature measurements were acquired at the maximum effective sampling rate of the MLX90614 infrared sensor. Based on the sensor's internal thermal response characteristics, a sampling interval of approximately 63 ms (≈16 Hz) was selected to ensure that each recorded data point represents an independent and physically meaningful temperature measurement. Because the sensor's internal thermal time constant limits the effective update rate, and higher sampling frequencies do not provide additional thermal information. The selected sampling rate ensured that the recorded temperature data accurately captured the rapid cooling behavior of PLA without temporal oversampling. This approach maximized the sensor's effective thermal bandwidth and avoided redundant measurements caused by internal signal filtering. Temperature data were streamed to a PC via Serial Monitor and recorded for post-processing. All measurements were performed in a controlled ambient environment with minimal airflow to reduce thermal disturbance.

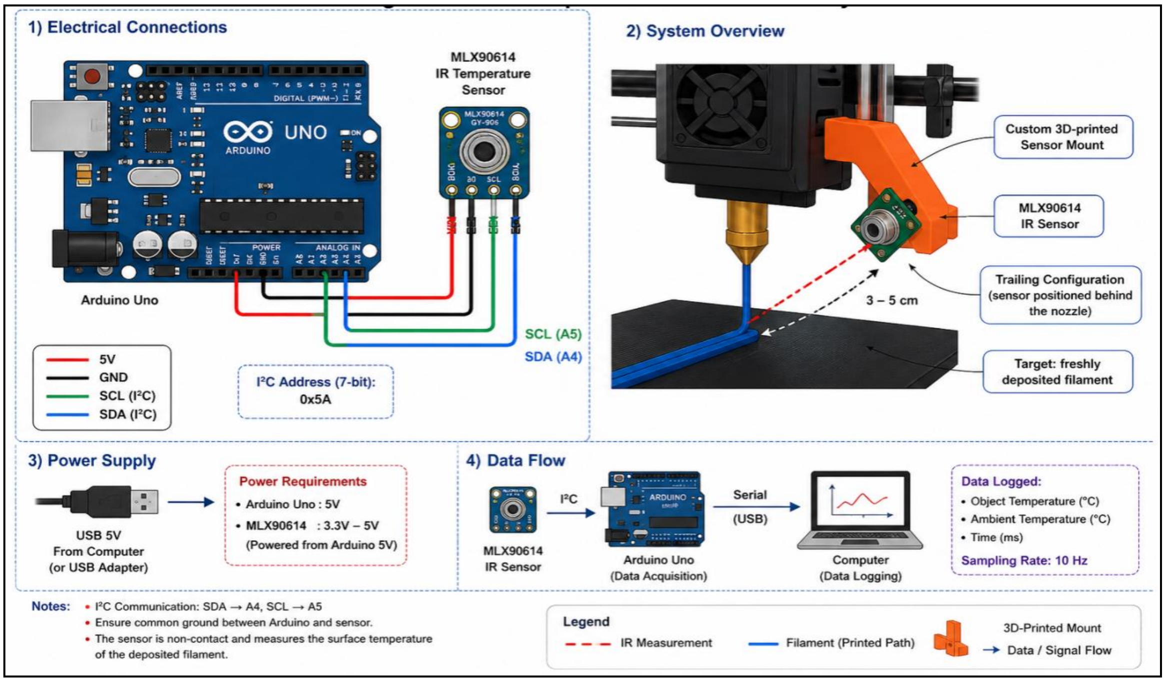

Figure 3. Hardware setup showing the connection between the MLX90614 infrared temperature sensor and the Arduino Uno

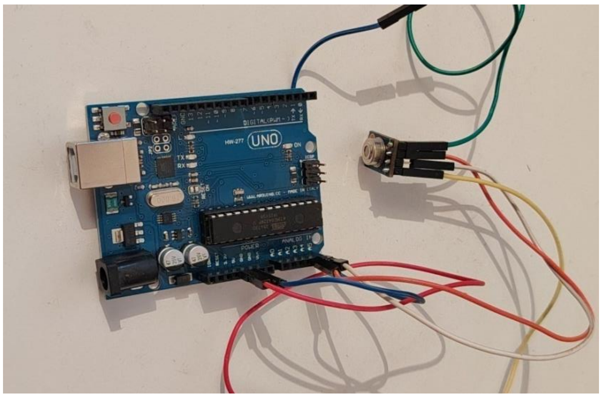

Figure 4. Hardware configuration of the Arduino-based infrared temperature measurement

2.4 Data Analysis

The cooling behavior of the deposited PLA filament was analyzed using Newton's Law of Cooling, which assumes that the rate of heat loss is proportional to the temperature difference between the object and the surrounding environment. The governing differential equation is expressed as, [13]:

$$\frac{dT}{dt} = -k(T - T_a) \quad (1)$$

Where:
(T) is the filament temperature (°C),
(T_a) is the ambient temperature (°C),
(t) is the time (s),
(k) is the cooling constant (s^{-1}).

3. Results and Discussion

The experimental data obtained from the non-contact monitoring system reveals a sophisticated thermal profile of the FDM-printed PLA specimen, as illustrated in the initial cooling curve (**Figure 5**).

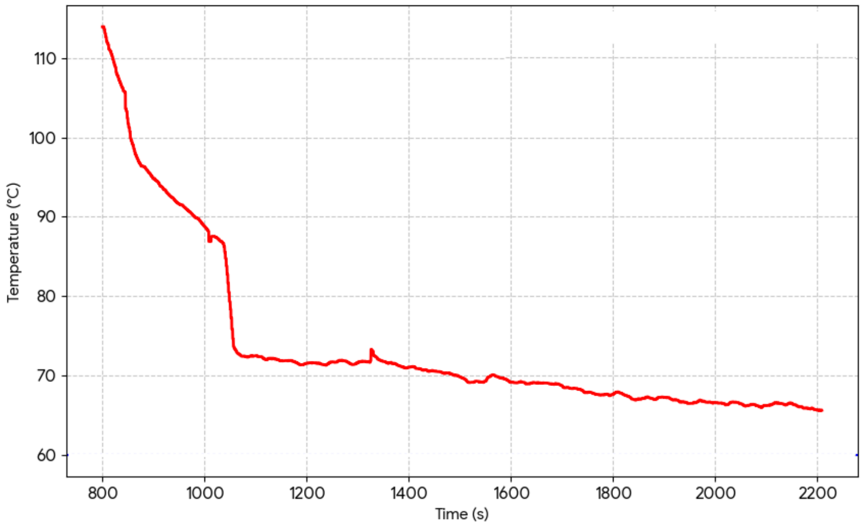

Figure 5: FDM Specimen Cooling Curve (Temperature vs. Time).

Upon deposition, the material recorded a peak surface temperature of 113.93°C, which was followed by a non-linear decay characteristic of thermoplastic extrusion. A significant temperature difference was noted between the nozzle set temperature of 220°C and the first measured filament surface temperature of 113.93°C. This discrepancy arises from several factors in the FDM process and infrared measurement techniques. The nozzle temperature indicates the internal heat of the extrusion system, while the MLX90614 sensor measures the surface temperature post-extrusion. The filament cools rapidly through convection, conduction, and radiation before measurement. Additionally, the sensor's trailing position behind the nozzle captures a temperature after a brief cooling period. Infrared measurements reflect surface temperature, which can be affected by factors such as emissivity and sensor angle. The observed reduction to about 114°C aligns with findings from prior thermal studies, which noted significant cooling just after filament deposition.

The observed difference between the nozzle set temperature and the first measured filament surface temperature is consistent with previously reported thermographic investigations of material extrusion additive manufacturing. It is important to note that the nozzle temperature corresponds to the molten polymer inside the hot-end, whereas the infrared sensor measures the surface temperature of the deposited filament after extrusion and partial cooling [14]. The integration of the MLX90614 sensor successfully captured a maximum cooling rate of 10.30°C/s during the primary solidification phase. This high-velocity thermal loss is consistent with existing literature regarding the steep gradients encountered in additive manufacturing, where the temperature difference between the molten filament and the ambient environment is at its maximum [15]. The statistical validity of the cooling process was further examined using Ordinary Least Squares regression (**Figure 6**).

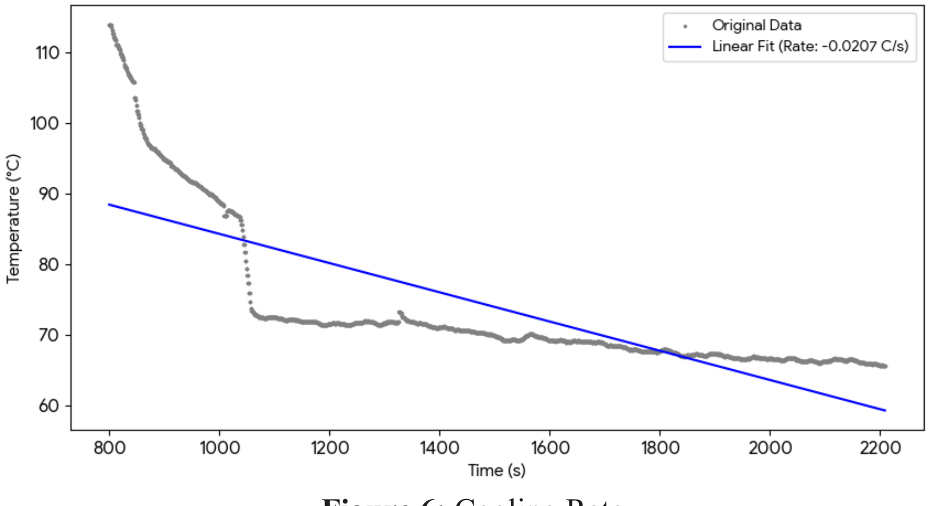

Figure 6: Cooling Rate

The inverse cooling rate, or dt/dT analysis (**Figure 7**), highlights critical transitions in the material's state as it approaches its final recorded temperature of 65.63°C. In the high-temperature range between 110°C and 90°C, the thermal inertia remained low, reflecting rapid solidification. However, as the specimen reached the 73°C to 65°C window, the dt/dT value surged to approximately 15 s/°C, indicating a significant increase in the time required for the material to drop each subsequent degree. This plateau effect occurs as the PLA nears its glass transition temperature, where molecular mobility decreases and the thermal driving force diminish. This extended residence time in the leathery phase is critical for ensuring adequate interlayer bond strength and molecular diffusion, though it requires careful management to prevent structural sagging in complex geometries. These findings confirm that non-contact infrared thermography provides a reliable, high-resolution digital footprint of the printing process, aligning closely with established thermo-mechanical research in the field.

To estimate the empirical cooling constant (k) using Ordinary Least Squares (OLS) linear regression, Equation (1) was integrated with respect to time from the initial deposition boundary state (t_0, T_0), yielding the explicit non-linear exponential decay function:

$$T(t) = T_a + (T_0 - T_a)e^{-k(t-t0)} \ldots\ldots\ldots\ldots (2)$$

This exponential framework was subsequently linearized by isolating the temperature differential and applying a natural logarithmic transformation:

$$\ln\left(\frac{T_{(t)} - T_a}{T_0 - T_a}\right) = -k(t - t_0) \ldots\ldots\ldots\ldots (3)$$

By executing an OLS linear regression on the transformed experimental variables, the slope of the resulting fit directly determined the negative value of the cooling constant (-k). Through this mathematical procedure, the regression yielded a highly localized cooling constant of k = 0.0004 s^{-1} with a coefficient of determination (R^2 = 0.670). The empirical thermal profile of the FDM-deposited PLA specimen exhibits a multi-stage transient cooling behavior that validates the integrated mathematical model while highlighting distinct process transitions. Upon initial deposition, the PLA material recorded a peak surface temperature of 113.93°C. During this opening interval (800 s to 1040 s), the temperature dropped rapidly and non-linearly down to approximately 87°C, capturing a maximum cooling rate of 10.30°C/s. Physically, this extreme initial gradient occurs because the temperature differential at its absolute maximum. According to Newton's Law of Cooling, the rate of heat transfer (dT/dt) is directly proportional to this difference, forcing aggressive, high-velocity energy loss dominated by convection and radiation. This phenomenon is thoroughly supported by Sun et al. [16], who demonstrated that extruded polymer filaments experience an almost instantaneous thermal drop upon exiting the nozzle due to immediate exposure to the lower ambient environment. The non-linear decay profile observed here is also consistent with the numerical simulations presented by Zhang and Chou [17], confirming that the initial layer deposition stage introduces highly transient, non-linear thermal cycles where the cooling velocity peaks at the outer boundary layers before internal conduction stabilizes.

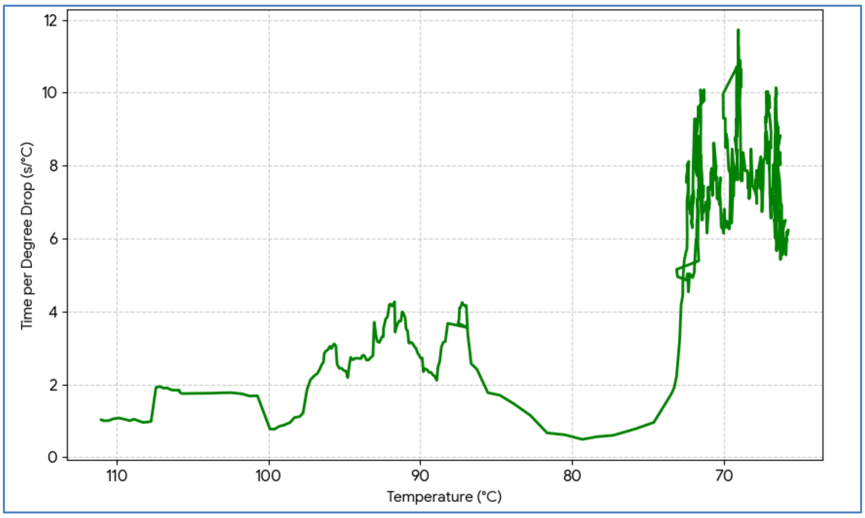

Figure 7: Inverse Cooling Rate (dt/dT) vs. Temperature.

However, the experimental results produced smooth temperature–time curves showing the evolution of PLA surface temperature immediately after extrusion. In addition, the non-contact MLX90614 sensor successfully captured subtle changes in surface temperature over time, demonstrating the feasibility of monitoring thermal history in real time without physical contact. This is significant because traditional thermocouples with slower response times and intrusive placement cannot adequately capture such rapid cooling events. The results also correlate well with literature that highlights the challenges of temperature sensor installation and response time in FDM thermal measurement. The derived cooling rates can be used to understand how printing parameters such as speed, nozzle temperature, and cooling fans affect thermal behavior and material bonding. This experimental insight can facilitate the development of thermal models and guide parameter settings aimed at improving mechanical performance and print quality.

4. Conclusion

The experimental investigation leads to the following conclusions:

- The infrared temperature sensor (MLX90614) can effectively monitor localized surface temperature during FDM printing of PLA material.
- The integration of the MLX90614 sensor provided a robust, non-invasive method for capturing high-resolution thermal data. The setup avoided the mechanical disturbances and cooling artifacts typically associated with thermocouple contact.
- The specimen exhibited a maximum cooling rate of 10.30°C/s during the initial solidification phase.
- The dt/dT analysis identified a critical slow-cooling zone near 73°C to 65°C, where the material spends significantly more time per degree of temperature drop. This phase is vital for promoting molecular diffusion and improving bond strength between layers, although it also marks the region where structural stability must be maintained as the polymer nears its glass transition point.

Overall, the proposed monitoring framework provides a reliable digital footprint of the printing process, enabling better control over the thermo-mechanical properties of the final printed parts.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.