

# Preliminary Study on Aerosol Jet Printed Temperature Sensors for Smart Pipes

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**Abstract**—The direct integration of sensors onto the surface of objects is becoming increasingly relevant for applications in smart monitoring, distributed sensing, and industrial Internet of Things. In this work, we present a fabrication method for temperature sensors printed directly onto cylindrical plastic pipes, based on Aerosol Jet Printing (AJP) and photonic sintering. Silver-based temperature sensors were printed and cured on polypropylene (PP) and polyvinyl chloride (PVC) pipes without adhesives, preserving the pipe integrity and ensuring thermal coupling. The fabrication repeatability, calculated on four identical samples, was 10.7% for both materials, in accordance with typical AJP tolerances. Temperature characterization in a climatic chamber over three cycles between  $-10^{\circ}\text{C}$  and  $70^{\circ}\text{C}$  shows a positive, highly linear response on both substrates ( $R\text{-squared}=0.999$ ). The sensitivity, estimated from least-squares fits, is slightly higher on PVC ( $0.0017\ \Omega/\Omega/^{\circ}\text{C}$ ) than on PP ( $0.0014\ \Omega/\Omega/^{\circ}\text{C}$ ). Repeatability and hysteresis remain below 2.1% and 2.4% of the full-scale output, respectively. A stability test (for 8 h at  $-10^{\circ}\text{C}$ ,  $30^{\circ}\text{C}$ , and  $70^{\circ}\text{C}$ ) highlights a material-dependent response, with the PP sensor stabilizing faster at high temperature. These results confirm that AJP in combination with photonic sintering enables robust, directly printed temperature sensing on common industrial pipes, paving the way for distributed thermal monitoring in smart piping systems.

**Keywords**—temperature sensor; aerosol jet printing; resistive temperature detector; Smart piping; industrial monitoring.

## I. INTRODUCTION

Polymer-based piping systems play a critical role in industrial infrastructures due to their low cost, ease of installation, and advanced mechanical properties [1]. However, their long-term reliability is strongly influenced by thermal conditions, making temperature evaluation essential in advanced industrial environments. For example, polyvinyl chloride (PVC) exhibits significant variations in tensile strength, deformation behavior, and overall structural integrity when exposed to different operational temperatures, highlighting the need for accurate thermal analysis in pipeline monitoring [2]. Furthermore, studies on accelerated hydrothermal aging have revealed that PVC undergoes pronounced mechanical degradation under prolonged exposure to elevated temperatures, resulting in reduced flexibility, diminished tensile performance, and shortened service lifetimes. Similar temperature-dependent mechanical trends have been reported for a range of polymeric materials used in piping systems, where variations in temperature affect stress-strain behavior, fracture characteristics, and overall durability [3]. Accurate, distributed temperature measurements are a prerequisite for safe and efficient operation across industrial piping networks that deliver hot and cold potable water, heat-transfer fluids, and gases. Within the framework of Industry 4.0, integrating real-time thermal

monitoring and predictive modeling into pipeline systems enables more accurate forecasting of material degradation and operational failures. This approach not only enhances safety and process continuity but also supports the transition toward smarter industrial networks based on data-driven maintenance and digital twin technologies. [4], [5]

Several strategies and devices have been explored to measure temperature using external instruments mounted on the outside of the pipe, thereby preserving the integrity of polymer piping. External stick-on sensors [6] are common commercial solutions, but they are sensitive to mounting pressure, environmental fluctuations, and imperfect thermal contact. Housing-integrated resistive temperature detectors (RTDs) [7] or thermowells [8] can reduce mounting variability, but they introduce additional components and machining steps that are poorly suited to lightweight plastics. In the industrial context, industrial Internet of Things, or remote-sensing architectures capable of providing distributed measurements of multiple parameters (e.g., temperature, pressure, flow, and vibration) are increasingly required [9], [10]. However, these architectures still rely on discrete transducers whose power and computational consumption, cost, physical size, and wiring constraints can limit spatial resolution and data management. In addition, practical constraints related to long-term stability in field conditions motivates approaches that embed the sensor function directly onto the pipe's outer layer, eliminating intermediate interfaces and improving thermal coupling [11].

Printed electronics provides attractive technologies handling multiple functional material types for the fabricating sensing elements onto various kinds of materials with high design freedom and minimal material waste [12]. Among digital printing techniques, inkjet printing (IJP) has been widely adopted to fabricate resistive temperature sensors using different inks (metal-, carbon-, and polymer-based) on flat polymer substrates. IJP-printed metallic resistive temperature detectors (RTDs) typically exhibit temperature coefficients of resistance (TCR) in the range of  $600\text{--}2800\ \text{ppm/K}^{-1}$ , with hysteresis and non-repeatability below 1.4% of full-scale output in a temperature range up to  $150^{\circ}\text{C}$ . These results confirm that printed metallic networks have metrological performance comparable to conventional thin-film sensors for temperatures up to  $85^{\circ}\text{C}$  [13], [14]. Despite these excellent properties, IJP is inherently limited to planar or quasi-planar substrates and cannot reliably pattern onto three-dimensional components, such as cylindrical pipes. Aerosol Jet Printing (AJP) overcomes this limitation by enabling deposition on curved or non-planar geometries, thanks to its aerodynamically focused aerosol stream that allows non-contact deposition at standoff distances of 1–11 mm, and the creation of sub- $100\ \mu\text{m}$  conductive lines on fully three-dimensional objects [15]. AJP has also enabled

multimodal temperature-sensing devices, such as printed thermistors [16], and thermocouples based on graphene/MXene or Au/ITO, achieving thermopower values of  $50\text{--}56\text{ }\mu\text{V }^\circ\text{C}^{-1}$  and stable operation up to approximately  $540\text{ }^\circ\text{C}$  [17]. However, thermocouples inherently require a well-defined cold-junction reference, and when both junctions are printed on the same polymeric component, their condition cannot be guaranteed. Consequently, a secondary temperature measurement remains necessary to obtain absolute values, complicating calibration and reducing suitability for embedded sensing on pipes.

For this reason, AJP-printed RTDs represent a more appropriate solution for conformal temperature monitoring [18]. Studies on AJP-printed silver RTDs could stabilize the TCR near bulk-Ag values (about  $3.8\times 10^{-3}\text{ K}^{-1}$ ), improving long-term reproducibility and illustrating the maturity of resistive temperature sensing within AJP-compatible material systems [15], [19]. However, transferring these methods from flat substrates to real polymer pipes remains challenging due to their low thermal resistance. For thermally sensitive plastics, photonic sintering has emerged as the most viable curing method [20]. Unlike conventional oven-based sintering, photonic sintering enables the sintering of metallic nanoparticle inks within milliseconds, providing optical-thermal energy within the top microns of the printed film. This approach has been proved to produce conductive patterns on temperature-sensitive substrates such as polycarbonate, PVC, and other low glass transition polymers. Ensuring full compatibility across different piping polymers, however, still requires systematic validation of ink wetting, adhesion, curing and TCR stability [21]. Despite these advances, there is a gap between the recent finding and the behavior of printed sensors directly on cylindrical pipes used for air, water, and utility distribution, especially when multi-material validation is required, such as PVC and polypropylene (PP). Our previous works [20] combined Aerosol Jet Printing with photonic sintering to realize conformal piezoresistive sensors on cylindrical PVC conduits at room temperature, demonstrating that direct deposition can attain good adhesion, stable electrical behavior and repeatable geometry without adhesives or thermally aggressive steps.

Building on this previously validated fabrication approach, the present study extends the application of Aerosol Jet Printing combined with photonic sintering to the realization of conformal resistive temperature detectors directly integrated onto industrial polymer pipes. RTDs were fabricated on two technologically relevant substrates — gray polypropylene (PP) and light-gray PVC — widely employed in air, water, and utility distribution networks.

A systematic experimental campaign was conducted to evaluate (i) the electrical performance of the printed sensors, (ii) their temperature response under controlled climatic-chamber conditions, and (iii) fabrication repeatability through the comparison of four nominally identical devices per substrate. By analyzing temperature coefficient of resistance (TCR), linearity, stability, and inter-sample variability, this work aims to assess the feasibility, robustness, and cross-material compatibility of directly printed RTDs for distributed thermal monitoring in real polymer piping systems.

The overall objective is to bridge the gap between laboratory-scale demonstrations on simplified geometries and practical deployment on cylindrical industrial conduits,

advancing the integration of embedded sensing functionalities into next-generation smart piping infrastructures.

## II. TEMPERATURE SENSORS FABRICATION

### A. Materials and Design

Two types of pipes were selected: light gray PVC (25 mm outer diameter, 3 mm wall thickness), and gray PP (32 mm outer diameter, 2 mm wall thickness). The curved geometry and low thermal tolerance of these tubes were considered representative of common industrial piping systems. All tubes were 2 m in length. From each tube, two specimens with a length of 12 cm were cut, and two temperature sensors were printed on each specimen. Genesink Smart Aero (S-CS61308), a silver nanoparticle ink suitable for AJP, was used as received as the active material for the printed temperature sensor. This ink was selected for its good flexibility, strong adhesion to plastic surfaces, and compatibility with rapid photonic sintering, which promotes a proper conductive network in the printed layer without exposing the substrate to high temperatures. Electrical contacts between the sensor pads and the 24-AWG copper wires were created using a silver-based conductive epoxy (CW2400, Chemtronics). RS Pro Printed CCT Board Lacquer was used to form the coating layer for the temperature sensor. The temperature sensor was designed as a serpentine-shaped resistive element (Fig. 1) whose electrical resistance varies with temperature. The active area of the printed temperature is  $121.27\text{ mm}^2$ .

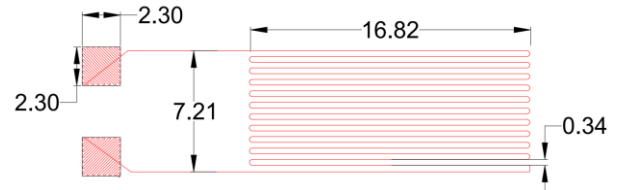


Fig. 1. Schematic representation of the printed sensor geometry with main dimensions (in mm).

### B. Fabrication Method

A schematic representation of the proposed fabrication method is shown in Fig. 2. Prior to printing, the pipe surface was cleaned with isopropyl alcohol and dried with compressed air. The AJP system (Optomec AJ-300) was programmed starting from a 2D CAD layout corresponding to the sensor geometry (Fig. 1). In (1), the ink was atomized in a nitrogen carrier gas and subsequently focused by a nitrogen sheath flow. A nozzle of  $750\text{ }\mu\text{m}$  was used, with a printing speed of  $2\text{ mm/s}$  and a fixed nozzle-to-surface distance of  $4\text{ mm}$ . Owing to the cylindrical shape of the pipes, a constant working distance could be maintained along the entire printing path. During deposition, process parameters were optimized to ensure a uniform trace width of approximately  $0.1\text{ mm}$ . Each sensor pattern was printed twice to increase line thickness and obtain the nominal design resistance. After printing, the samples were placed in a static oven at  $70\text{ }^\circ\text{C}$  for  $1\text{ h}$  to promote controlled solvent evaporation. In (2), the pipes were transferred to a photonic sintering system (PulseForge 1300, NovaCentrix), where a high-energy light pulse was applied to cure the conductive ink. The pulse energy profile, selected based on preliminary optimization, enabled sintering of the metallic film without causing thermal degradation of the underlying polymer. In (3), electrical

contacts and wiring were formed using a silver-based conductive epoxy cured at room temperature. Finally, a thin protective coating was spray-applied to shield the printed structures from oxidation and environmental exposure. Some examples of printed temperature sensors on PVC and PP pipes are shown in Fig. 3.

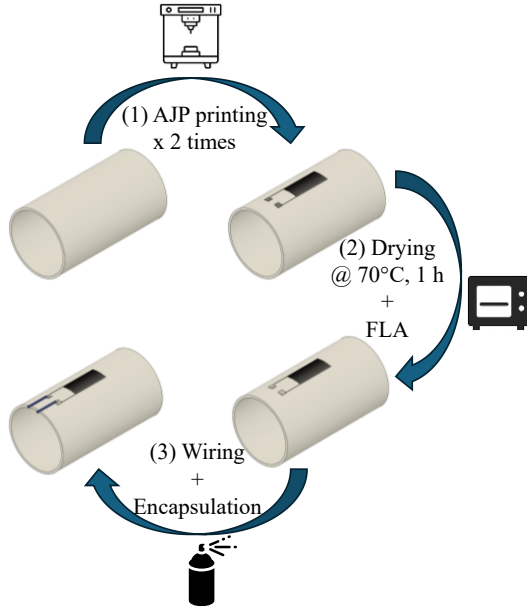


Fig. 2. Schematic representation of the fabrication process for the printed temperature sensor on a polymeric pipe.

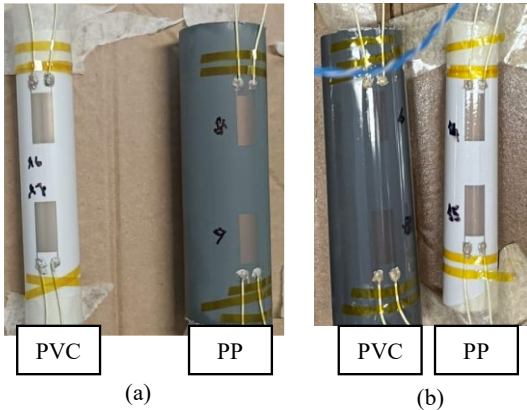


Fig. 3. Photograph of the two tubes made of PVC (sample #1) and PP (sample #4), each instrumented with two sensors, (a) before coating and (b) after coating.

### C. Morphological and Electrical Analysis

The line aspect of the printed sensors before the coating (Fig. 4) was observed on an optical microscope with a  $2\times$  magnified view (Orma Scientific), equipped with a camera connected to a laptop. The measured width was  $(0.19 \pm 0.02)$  mm in all sensors.

The resistance of the eight printed sensors was measured to determine their nominal resistance at room temperature and to assess the deposition uniformity achievable on the two materials. Measurements were performed using Keysight 34465A  $6\frac{1}{2}$  digit multimeter, providing an accuracy better than 0.002% of the reading  $\pm 0.005 \Omega$ . For the PVC tubes, the mean resistance,  $R_{\text{mean}}$ , was  $352 \Omega$ , with a minimum and maximum resistance,  $R_{\text{max}}$  and  $R_{\text{min}}$ , of  $321 \Omega$  and  $389 \Omega$ , respectively.

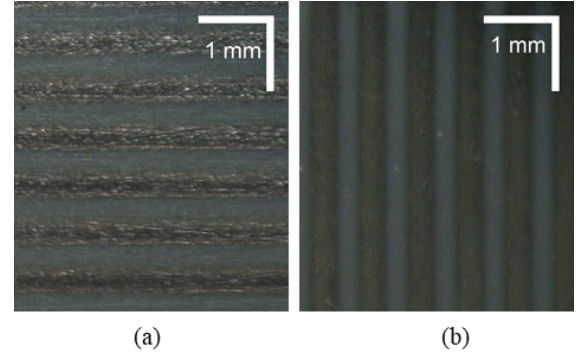


Fig. 4. Photograph at the microscope of a portion of the temperature sensor on (a) PVC and (b) PP.

In the case of PP, the measured values were  $R_{\text{mean}} = 710 \Omega$ ,  $R_{\text{min}} = 640 \Omega$ , and  $R_{\text{max}} = 791 \Omega$ . Considering the four sensors fabricated on each substrate, the dispersion of the nominal resistance was quantified in terms of the coefficient of variation (CV). Since the sample size is limited, the standard deviation was estimated from the resistance range ( $R_{\text{max}} - R_{\text{min}}$ ) using the  $d_2$  constant ( $d_2 = 2.059$  for  $n = 4$ ). The resulting CV is approximately 9.4% for PVC and 10.3% for PP, confirming comparable fabrication repeatability within each substrate group. According to our previous works and to findings reported in the literature, the tolerance of AJP typically remains within 15% [22]. Conversely, the mean resistances of the two groups differ significantly. As found in our earlier study [23], the final resistance is strongly influenced not only by the printing parameters but also by the substrate characteristics and the sintering mechanism. In the present work, the efficiency of photonic curing was found to be dependent on substrate-related parameters, including polymer type and, importantly, surface color. Although both PVC and PP are thermoplastic polymers, their different colors lead to different optical absorption during photonic sintering, resulting in the observed shift in nominal resistance.

### III. EXPERIMENTAL SETUP

The eight sensors were characterized in a climatic chamber (DY200 C, Angelantoni Test Technologies) at the same time. A Pt100 element was positioned near the printed sensor to measure the temperature close to the printed sensors, and all sensors were measured using three modules of NI9219 connected to cDAQ 9174 (National Instruments) and a personal computer to store the data. The expected resistance accuracy is  $1.9 \Omega$ , according to National Instruments. The specifications of the equipment are reported in Table I.

TABLE I. EQUIPMENT FOR SENSOR CHARACTERIZATION

| Component                | Model                      | Main Specifications                                                                                                                                                             |
|--------------------------|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Climatic chamber         | DY200 C                    | Temperature range: $-40^\circ\text{C}$ to $180^\circ\text{C}$ ; maximum temperature fluctuation: $\pm 0.3 \text{ K}$                                                            |
| Reference sensor         | Pt100 RTD (M 222, Heraeus) | Nominal TCR: 3850 ppm/K; Tolerance $\pm 0.1 \text{ K}$                                                                                                                          |
| Devices under test       | Eight printed sensors      | Four sensors printed on PVC and four on PP pipes                                                                                                                                |
| Data acquisition modules | Three NI 9219              | 4 analog input channels; 4-wire resistance measurements; accuracy: $\pm(0.1\% \text{ of reading} + 1.2 \Omega)$ ; Pt100 accuracy: $\pm(0.1\% \text{ of reading} + 0.24 \Omega)$ |
| DAQ chassis              | cDAQ-9174                  | Multi-module data acquisition platform for synchronous measurements of NI 9219 modules                                                                                          |

The temperature response of each sensor was investigated in the climatic chamber over a controlled thermal cycle ranging from  $-10\text{ }^{\circ}\text{C}$  to  $70\text{ }^{\circ}\text{C}$ . This temperature range falls within the operating temperature range specified for PVC and PP. As shown in Fig. 5, the temperature was increased in  $10\text{ }^{\circ}\text{C}$  steps with adequate stabilization intervals (40 minutes), and the same cycle was repeated three times to assess sensitivity, drift, hysteresis, and repeatability. To assess the long-term stability of the printed temperature sensors, another thermal profile was applied inside the climatic chamber.

Each sample was first exposed to  $-10\text{ }^{\circ}\text{C}$  for 8 h, followed by a transition to  $30\text{ }^{\circ}\text{C}$  for 8 h and then to  $70\text{ }^{\circ}\text{C}$  for an additional 8 h. At the end, the chamber temperature was abruptly returned to  $-10\text{ }^{\circ}\text{C}$ . This sequence was designed to evaluate sensor stability across low, intermediate, and high temperatures, as well as their ability to recover their initial baseline following a sharp thermal excursion.

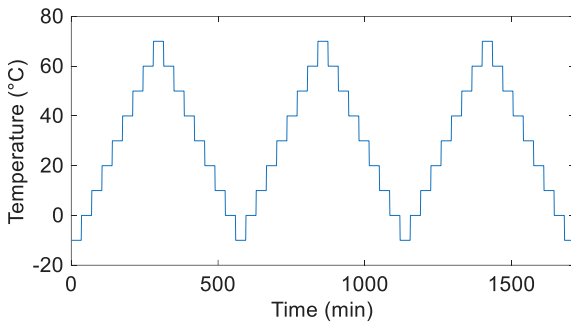


Fig. 5. Temperature profile used to control the climatic chamber for the temperature characterization.

#### IV. RESULTS AND DISCUSSION

The temperature response of the printed sensors was evaluated inside a climatic chamber over three complete heating-cooling cycles, in the range from  $-10\text{ }^{\circ}\text{C}$  to  $70\text{ }^{\circ}\text{C}$ . For both PVC and PP substrates, the sensors exhibited the characteristic behavior of RTD, showing a positive and highly linear change in resistance with increasing temperature. Representative results for one sensor printed on PVC and one printed on PP are reported in Fig. 6 and Fig. 7, respectively; these are representative of the consistent behavior observed across all fabricated sensors, independently of the tube material. Temperature ( $T$ ) values on the x-axis were obtained from the four-wire resistance ( $R$ ) measurement of a calibrated Pt100 ( $T = (R_T - R_{0^{\circ}\text{C}})/(R_{0^{\circ}\text{C}} \cdot \text{TCR})$ ), while the error bars represent the estimated measurement uncertainty derived from the declared NI 9219 accuracy. In all cases, the curves corresponding to the three heating and cooling cycles show good superposition, confirming the stability and repeatability of the printed devices throughout thermal cycling. This effect is particularly evident for the PP samples, where the overlap of the curves is perfect over the entire temperature range. For the PVC-based sensors, a slight drift can be observed at temperature extremes. At  $70\text{ }^{\circ}\text{C}$ , the resistance measured during the second and third heating cycles decreases by approximately 0.1% with respect to the first cycle. A similar deviation is visible at  $-10\text{ }^{\circ}\text{C}$ , where the resistance in the third cycle is marginally lower than in the previous cycles. Despite this, the overall response remains linear ( $R$ -squared = 0.998-0.999), and the magnitude of the drift is limited. In contrast,

the PP sensor shows negligible drift, with the curves from the three cycles overlapping exactly both at low and high temperatures. This improved stability could be justified by the low thermal stress of the PP. Overall, these results confirm that the printed sensors behave as reliable RTD-like devices across the tested temperature range, with stable, linear responses and minimal hysteresis, and that the fabrication method ensures consistent performance regardless of the substrate type, with only minor drift observed in the case of PVC.

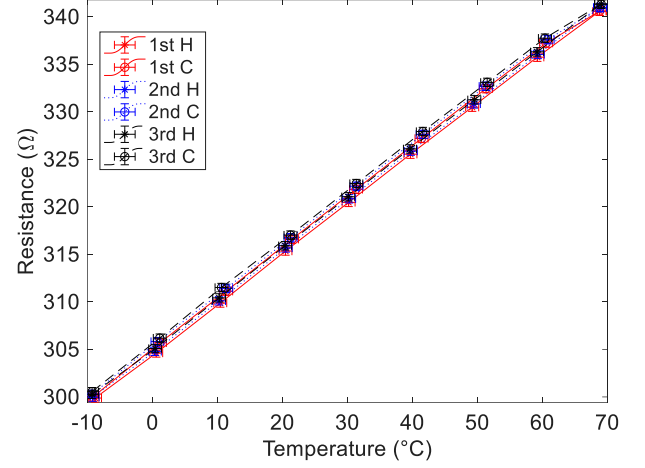


Fig. 6. Resistance of a sensor printed onto PVC (sample #1) as a function of the temperature over three heating-cooling cycles. Temperature is obtained from Pt100 resistance measurements using the nominal TCR. Error bars correspond to the estimated resistance uncertainty ( $k = 1$ ), derived from the NI 9219 declared gain and offset accuracy assuming a rectangular distribution.

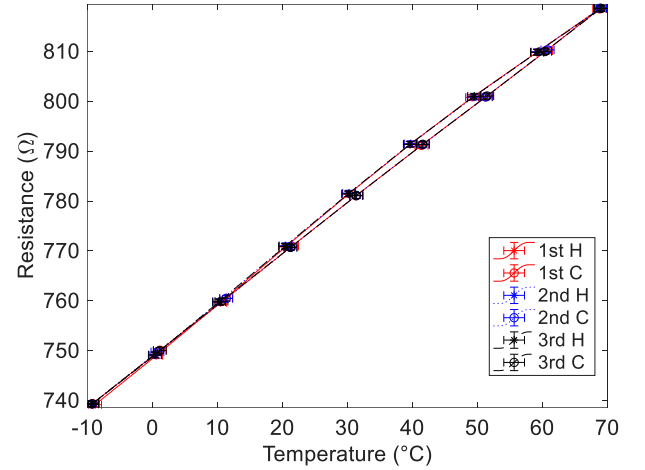


Fig. 7. Resistance of a sensor printed onto PP (sample #4) as a function of the temperature over three heating-cooling cycles. Temperature is obtained from Pt100 resistance using the nominal TCR. Error bars correspond to the estimated resistance uncertainty ( $k = 1$ ), derived from the NI 9219 declared gain and offset accuracy assuming a rectangular distribution.

To complement the representative thermal responses shown in Fig. 6 and Fig. 7, Table II reports several metrological indicators extracted from the experimental data for all eight printed sensors (from sample #1 to sample #8), grouped by tube material. All sensors — both on PVC and on PP — exhibited the same linear and repeatable behavior already discussed for the representative cases. By

approximating the relationship between temperature and the fractional resistance change with respect to the resistance at 0 °C ( $\Delta R/R_0$ ) using a least-squares linear fit, it is confirmed that the temperature dependence is highly linear for all samples, as indicated by the coefficient of determination  $R^2$ , which remains between 0.998 and 0.999. The relative uncertainties of the slope and of the intercept, obtained from the confidence intervals of the linear regression and expressed as one-sigma standard deviations, are below 0.13% and 0.75%, respectively, for all the sensors. The analysis of the slope, which can be considered equal to TCR, shows that sensors printed on PVC have a slightly higher sensitivity, with slopes exceeding 0.0017  $\Omega/\Omega/^\circ\text{C}$ , although still about half the value typical of platinum-based RTDs. The fitted curves display a small offset in the intercept, attributable to hysteresis effects and minor time-dependent drift observed during thermal cycling. Sensor repeatability, evaluated across the three heating–cooling cycles by computing half the dispersion among the six measurements at a given temperature (worst case), remains below 2.1% of the full-scale output (FSO).

TABLE II. PERFORMANCE OF THE PRINTED SENSORS

| Sample | Metrological Indicators        |                 |                     |                   |                   |
|--------|--------------------------------|-----------------|---------------------|-------------------|-------------------|
|        | Slope                          | Intercept       | Repeat <sup>b</sup> | Hysteresis        | Drift             |
|        | $\Omega/\Omega/^\circ\text{C}$ | $\Omega/\Omega$ | %FSO <sup>a</sup>   | %FSO <sup>a</sup> | %FSO <sup>a</sup> |
| S1 PVC | 0.0017                         | 0.0027          | 1.8%                | 2.1%              | −0.22             |
| S2 PVC | 0.0017                         | 0.0028          | 1.9%                | 2.0%              | −0.24             |
| S3 PVC | 0.0018                         | 0.0082          | 1.3%                | 0.9%              | −0.25             |
| S4 PVC | 0.0018                         | 0.0027          | 1.7%                | 2.1%              | −0.21             |
| S5 PP  | 0.0014                         | 0.0016          | 1.2%                | 1.7%              | −0.08             |
| S6 PP  | 0.0014                         | 0.0018          | 1.3%                | 1.7%              | −0.06             |
| S7 PP  | 0.0014                         | 0.0017          | 1.0%                | 1.5%              | −0.06             |
| S8 PP  | 0.0014                         | 0.0009          | 2.1%                | 3.7%              | −0.03             |

<sup>a</sup> FSO = Full-scale output

<sup>b</sup> Repeat=Repeatability

Similarly, hysteresis — computed as the maximum deviation between heating and cooling branches over the full temperature range — remains below 2.4% of the FSO. Focusing on drift, defined here as the variation of resistance at 70 °C, between the first and third cycles, the data confirms a larger drift for sensors printed on PVC. The PVC sensors (S1–S4) show drift values of lower than −0.25 % of the FSO (mean = −0.23 % of the FSO), whereas the PP sensors (S5–S8) remains markedly lower at −0.08 % of the FSO in the worst case (mean = −0.06 % of the FSO). This finding is consistent with the trend observed in Fig. 6 and Fig. 7, where the PVC device displays a slight end-point relaxation across cycles, while the PP device shows near-perfect superposition. These results confirm that the deposited structures behave as stable and reliable RTD like elements on both polymeric substrates, with only small performance differences attributable to the substrate thermal efficiency.

Regarding the response time and the stability, sensors printed on PVC and PP exhibited different behaviors under the imposed thermal profile. As shown in Fig. 8, at 30 °C all sensors—including the Pt100 reference—reach a stable value within comparable time interval, between 540 min and 980 min. After the initial rise, all devices maintain their steady-state value with deviations below 0.25% of their final value (at 980 min), confirming a stable behavior in this temperature range. At 70 °C, however, the PP-based sensor

(S5) stabilizes more rapidly than both the PVC sensor (S1) and the Pt100 reference, as visible in the plateau reached shortly after the temperature shift at 1030 min. In the interval from 1030 min to 1475 min, sensor S5 displays the highest stability, with fluctuations confined to 0.0061% (standard deviation computed over 450 samples). In contrast, sensor S1 exhibits a drift, ending the 70 °C plateau with a resistance approximately 1% higher than its value at the beginning of the interval, while the Pt100 reference shows a smaller but measurable increase of about 0.7%. The reduced thermal expansion coefficient of PP, and the consequently weaker influence of piezoresistive strain on the metallic printed layer, may account for the improved stability of S5 compared to the PVC-based sensor. When the temperature is subsequently decreased to −10 °C, the two printed sensors display opposite behaviors. The PVC sensor (S1) does not return to its initial baseline; instead, it stabilizes at a slightly higher resistance value (+0.64% relative to its −10 °C reference). Conversely, the PP sensor (S5) settles at a value below its initial baseline (−0.49%). These two devices (S1 and S5) are representative of the consistent behavior observed across all sensors fabricated on the same tube material. The Pt100 reference, in contrast, rapidly returns to its original baseline (+0.3%), indicating that the observed offsets and asymmetries are attributable to the printed structures and substrate-induced effects rather than chamber instability or instrumentation drift. This comparison highlights the differing settling behaviors and baseline shifts between sensors printed on PVC and PP.

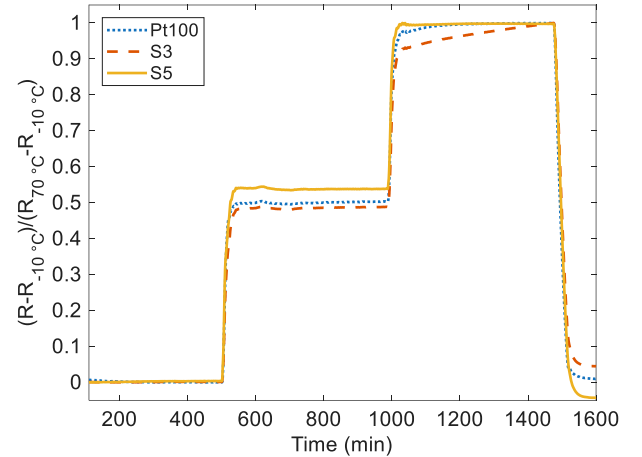


Fig. 8. Printed sensors on PVC (S1) and PP (S5) compared with a Pt100 reference, when the chamber was set to −10 °C, 30 °C, and 70 °C for 8 h at each step, then abruptly returned to −10 °C. Curves are normalized to the individual span: 0 corresponds to the initial resistance at −10 °C and the maximum at 70 °C, respectively.

## V. CONCLUSIONS

This work demonstrates that Aerosol Jet Printing (AJP) combined with photonic sintering enables the direct fabrication of RTD-like temperature sensors on cylindrical polymer pipes that are commonly used in industrial networks. Sensors were successfully printed and cured on PVC and PP tubes without adhesives or intermediate carriers, preserving the integrity of the piping and ensuring intimate thermal coupling at the surface. The fabrication repeatability within each material group was satisfactory: considering the four sensors per substrate, the resistance deviation was of 10.7% for both PVC and PP, in line with typical AJP tolerances for conformal prints. Between materials, nominal resistance

differed significantly, due to combined effects of substrate surface energy, local wetting, and photonic-curing efficiency. Sensor performance was consistent with an RTD response on both substrates. Across three climatic-chamber cycles from  $-10\text{ }^{\circ}\text{C}$  to  $70\text{ }^{\circ}\text{C}$ , all devices exhibited a positive, highly linear dependence of resistance on temperature, with R-squared coefficients of 0.999. The TCR was slightly higher on PVC, but less than TCR of Pt100, according to the literature. Repeatability and hysteresis over three heating-cooling cycles were low. The average drift at  $70\text{ }^{\circ}\text{C}$  between the first and the third cycle was slightly higher for PVC, confirming the lower drift and enhanced high-temperature stability on PP. A stability assessment highlighted a material-dependent behavior, especially at  $70\text{ }^{\circ}\text{C}$ , where the PP sensor stabilized faster than both the PVC sensor and the reference, indicating reduced thermal relaxation in PP. From an application perspective, the proposed process provides direct-on-pipe sensing suitable for distributed thermal monitoring in industrial systems. The combination of digital AJP patterning and photonic curing offers a scalable, flexible, and substrate-compatible route to integrate temperature sensing onto real components with minimal effort. Future developments will focus on extending the proposed approach toward fully distributed sensing architectures. This includes the investigation of long-term stability under real operating conditions, the integration of multiple printed sensors on the same pipe section with low-power wireless readout electronics as a promising direction for condition-based monitoring of industrial piping networks.

#### ACKNOWLEDGMENT

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#### REFERENCES

- [1] J. Tamošaitienė, S. Parham, H. Sarvari, D. W. M. Chan, and D. J. Edwards, "A Review of the Application of Synthetic and Natural Polymers as Construction and Building Materials for Achieving Sustainable Construction," *Buildings*, vol. 14, no. 8, p. 2569, Aug. 2024, doi: 10.3390/buildings14082569.
- [2] M. K. Khan *et al.*, "Experimental and Simulation Stress Analysis of PVC Pipe Under Different Operational Temperatures," in *Proceedings of the 5th International Conference on Metal Material Processes and Manufacturing*, D.-W. Jung, Ed., Singapore: Springer Nature Singapore, 2024, pp. 63–72. doi: 10.1007/978-981-97-1594-7\_9.
- [3] H. Bennis, R. Elkor, A. Hachim, K. El Had, A. El Maliki, and S. Sandabad, "Determining the impact of accelerated hydrothermal aging on the mechanical properties of polyvinyl chloride and chlorinated polyvinyl chloride," *Journal of Polymer Research*, vol. 32, no. 2, p. 40, Feb. 2025, doi: 10.1007/s10965-025-04266-7.
- [4] R. Kerkeni, S. Khlif, A. Mhalla, and K. Bouzrara, "Digital Twin Applied to Predictive Maintenance for Industry 4.0," *J. Nondestruct. Eval. Diagn. Progn. Eng. Syst.*, vol. 7, no. 4, Nov. 2024, doi: 10.1115/1.4065875.
- [5] Z. Huang, Y. Shen, J. Li, M. Fey, and C. Brecher, "A Survey on AI-Driven Digital Twins in Industry 4.0: Smart Manufacturing and Advanced Robotics," *Sensors*, vol. 21, no. 19, p. 6340, Sep. 2021, doi: 10.3390/s21196340.
- [6] Harold G. Schaevitz Industries LLC, "SSP-RTD Surface Mount Stick On RTD Sensor - PT100 3-Wire." Accessed: Jan. 29, 2026. [Online]. Available: <https://www.hgsind.com/product/ssp-rtd-surface-mount-stick-rtd-sensor-pt100-3-wire?v=57>
- [7] DwyerOmega, "Series-S2-4 Weatherproof Pipe Temp Assembly." Accessed: Jan. 29, 2026. [Online]. Available: <https://www.dwyeromega.com/en-us/weatherproof-pipe-temp-assembly-strap-on-twist-off-11-output-options/p/series-s2-4>
- [8] Emerson, "Rosemount™ 214C RTD Temperature Sensor, 248R Transmitter and 114C Thermowell," 2026. Accessed: Jan. 29, 2026. [Online]. Available: <https://www.emerson.com/en-it/catalog/rosemount-pkg-214c-sensor-248r-transmitter-and-114c-thermowell-en-gb>
- [9] Y. Cao, "Design and implementation of multi-sensor integrated intelligent alarm based on Arduino," *IET Conference Proceedings*, vol. 2024, no. 24, pp. 73–78, Jan. 2025, doi: 10.1049/icp.2024.4457.
- [10] S. Sun, H. Lin, J. Ma, and X. Li, "Multi-sensor distributed fusion estimation with applications in networked systems: A review paper," *Information Fusion*, vol. 38, pp. 122–134, Nov. 2017, doi: 10.1016/j.inffus.2017.03.006.
- [11] S. H. Abdulhussain *et al.*, "A Comprehensive Review of Sensor Technologies in IoT: Technical Aspects, Challenges, and Future Directions," *Computers*, vol. 14, no. 8, p. 342, Aug. 2025, doi: 10.3390/computers14080342.
- [12] J. Zikulnig, S. Lengger, L. Rauter, L. Neumaier, S. Carrara, and J. Kosel, "Sustainable Printed Chitosan-Based Humidity Sensor on Flexible Biocompatible Polymer Substrate," *IEEE Sens. Lett.*, vol. 6, no. 12, 2022, doi: 10.1109/LSSENS.2022.3224768.
- [13] J. Jäger, A. Schwenck, D. Walter, A. Büla, K. Gläser, and A. Zimmermann, "Inkjet-Printed Temperature Sensors Characterized according to Standards," *Sensors*, vol. 22, no. 21, p. 8145, Oct. 2022, doi: 10.3390/s22218145.
- [14] M. Georgas, P. Selinis, G. Zardalidis, and F. Farmakis, "Temperature Sensors by Inkjet Printing Compatible With Flexible Substrates: A Review," *IEEE Sens. J.*, vol. 23, no. 1, pp. 21–33, Jan. 2023, doi: 10.1109/JSEN.2022.3213072.
- [15] M. Tursunniyaz, V. Agarwal, A. Meredith, and J. Andrews, "Hybrid nanomaterial inks for printed resistive temperature sensors with tunable properties to maximize sensitivity," *Nanoscale*, vol. 15, no. 1, pp. 162–170, 2023, doi: 10.1039/D2NR04005K.
- [16] T. Fapanni, S. Bellotti, M. Borghetti, E. Sardini, and M. Serpelloni, "Preliminary Results on Carbon-Based Thermistors Produced by Aerosol Jet Printing," in *2023 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT)*, IEEE, Jun. 2023, pp. 239–243. doi: 10.1109/MetroInd4.0IoT57462.2023.10180174.
- [17] M. Saeidi-Javash and others, "All-Printed MXene-Graphene Nanosheet-Based Bimodal Sensors for Simultaneous Strain and Temperature Sensing," *ACS Appl. Electron. Mater.*, 2021, doi: 10.1021/acsaelm.1c00218.
- [18] T. Fapanni, E. Sardini, M. Borghetti, M. Serpelloni, and S. Bellotti, "Preliminary Results on Fully-Printed and Silver-Based Temperature Sensors for Aerospace Industry," in *2023 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT)*, IEEE, Jun. 2023, pp. 200–204. doi: 10.1109/MetroInd4.0IoT57462.2023.10180153.
- [19] Y. Sui, L. Tsui, A. J. Thibodeaux, and J. M. Lavin, "An Aerosol Jet Printed Resistance Temperature Detector-Micro Hotplate with Temperature Coefficient of Resistance Stabilized by Electrical Sintering," *Adv. Mater. Technol.*, vol. 8, no. 12, Jun. 2023, doi: 10.1002/admt.202202053.
- [20] M. Borghetti, M. Serpelloni, and E. Sardini, "Printed strain gauge on 3D and low-melting point plastic surface by aerosol jet printing and photonic curing," *Sensors (Switzerland)*, vol. 19, no. 19, Oct. 2019, doi: 10.3390/s19194220.
- [21] L. Mo *et al.*, "Silver Nanoparticles Based Ink with Moderate Sintering in Flexible and Printed Electronics," *Int. J. Mol. Sci.*, vol. 20, no. 9, p. 2124, Apr. 2019, doi: 10.3390/ijms20092124.
- [22] M. Borghetti, E. Sardini, and M. Serpelloni, "Voltage-based balancing technique for half printed Wheatstone bridges," *Measurement (Lond.)*, vol. 260, 2026, doi: 10.1016/j.measurement.2025.119809.
- [23] T. Fapanni, S. Bellotti, M. Borghetti, E. Sardini, and M. Serpelloni, "Preliminary Results on Carbon-Based Thermistors Produced by Aerosol Jet Printing," in *2023 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT)*, IEEE, Jun. 2023, pp. 239–243. doi: 10.1109/MetroInd4.0IoT57462.2023.10180174.