Instrumentation System for a Rapid-Recovery Water Heater

Sistema de Instrumentación para un Calentador de Agua de Rápida Recuperación

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Abstract

This work presents an instrumentation system developed for the experimental acquisition and monitoring of the main thermal and hydraulic variables of a rapid-recovery water heater. The system uses two externally mounted NTC thermistors to measure inlet and outlet pipe temperatures, a Hall-effect sensor to measure water flow, an STM32 microcontroller for data acquisition, an NI TC-01 module for reference temperature measurement, and a LabVIEW interface for real-time visualization and data storage. The experimental procedure considered heating, steady-state, and cooling conditions combined with zero, low, and high water-flow levels. We acquired 120 experimental records at 5 Hz, collecting 1200 samples during each 240 s test. The measurements captured the water heater's thermal and hydraulic behavior under different operating conditions without modifying the original water path. The resulting dataset provides a structured basis for subsequent analysis of outlet-temperature behavior and future temperature-estimation strategies.

Keywords: Rapid-recovery water heater; experimental instrumentation; temperature sensing; water flow measurement; data acquisition; LabVIEW.

Introduction

Thermal systems such as water heaters require measurements to observe their operating conditions. Temperature and water flow are two main variables for this purpose, as changes in these variables directly relate to the system's thermal response. In experimental studies, researchers usually record several operating variables simultaneously to describe better the process and its behavior under different conditions (Bellanco *et al*., 2021). Similar measurements have been used to characterize heating system operation under various conditions (Chesser *et al*., 2021).

Temperature is a key variable in water-heating applications. Inlet and outlet temperatures change with the heat supplied and the flow through the system. Therefore, temperature sensors are commonly used to monitor and control water-heating processes. However, measurement reliability depends not only on the sensor but also on its calibration and installation. For example, experimental tests on a water heater used a DS18B20 sensor with a reference thermometer to evaluate differences between measurements (Rahmadini *et al*., 2023). More comprehensive testing platforms have integrated temperature measurements with water supply, outlet flow, data acquisition, communication, and software subsystems to evaluate water-heater performance (Yu *et al*., 2018). These examples show that temperature measurement is closely linked to the rest of the system's instrumentation.

Selecting and installing temperature sensors becomes particularly relevant when measurements are taken from flowing water in pipes. A sensor's physical location, its thermal contact with the measured surface, and its mounting configuration can influence the measurement response. Experimental work on temperature measurement in district-heating pipe networks shows that sensor type, installation position, thermal response, stability, and measurement uncertainty must be considered when selecting a measurement configuration (Fester *et al*., 2025). Likewise, studies on temperature sensor design and experimental validation report that the measurement arrangement can affect the resulting temperature and should therefore be considered during validation (Yang *et al*., 2021). These aspects are especially relevant when installing a sensor inside the water path is inconvenient or requires modifications to the original system.

Water flow is also an important variable in water heater operation. The amount of water entering the system can change the outlet temperature, particularly when the heating power remains relatively constant. For this reason, measuring flow together with inlet and outlet temperature makes it possible to relate changes in water movement to the thermal response observed during an experiment. Experimental thermal systems have used temperature sensors and flow meters, along with data acquisition systems, to record these variables under transient and steady-state conditions (Salimi Khanghah *et al*., 2025). This type of measurement is particularly useful for rapid-recovery water heaters, where flow changes can be reflected in outlet temperature.

Another challenge is obtaining reliable measurements without substantially modifying the equipment's normal operation. Installing a sensor directly inside a water stream may require modifications to the hydraulic circuit and can affect the system under study. This issue has motivated the development of alternative measurement strategies that use accessible physical variables to estimate variables that are difficult to measure directly. For example, (Cosoli *et al*., 2020) developed a soft sensor to estimate the temperature near the water outlet of a professional coffee machine because installing a physical sensor there could interfere with normal operation. More broadly, researchers have studied physical and virtual sensing approaches as alternatives when direct measurement is difficult or impractical (Paepae *et al*., 2021). These approaches also show the importance of having a suitable physical instrumentation system from which the required process variables can be obtained (Jinasena *et al*., 2022).

Real-time data acquisition helps characterize a thermal system's behavior experimentally. By continuously recording temperature and flow, researchers can observe changes during heating, steady-state, and cooling without relying only on measurements at individual points. Automated testing systems for water heaters combine data acquisition, communication, and software-based monitoring to evaluate system performance (Yu *et al*., 2018). A similar approach allows the measurements obtained during the experiments to be displayed and stored for later analysis.

In this work, we develop an instrumentation system for a rapid-recovery water heater based on external temperature measurements, water-flow measurement, an STM32 microcontroller, and a LabVIEW-based monitoring interface. Two NTC thermistors are installed externally on the copper pipe to measure inlet and outlet temperatures, while a Hall-effect flow sensor measures water flow. An immersion-type K thermocouple serves as the reference temperature measurement during the experimental tests. The STM32 acquires the NTC and flow signals, while LabVIEW provides real-time visualization, data logging, and experimental monitoring. This configuration records the main thermal and hydraulic variables without modifying the water path.

This work aims to design and implement an instrumentation system for real-time acquisition and monitoring of the main operating variables of a rapid-recovery water heater. The main contributions are: (i) the development of an external temperature measurement configuration for the inlet and outlet pipes without modifying the water path; (ii) the integration of the temperature and flow sensors with an STM32-based data-acquisition system; (iii) the implementation of a LabVIEW interface for real-time monitoring and data logging; and (iv) the generation of an experimental dataset under heating, steady-state, cooling, and different water-flow levels. The resulting platform provides the measurements needed to characterize the water heater's thermal behavior and establishes a basis for future development of indirect temperature-estimation strategies.

Instrumentation system description

A. System Architecture

The experimental system was implemented on a rapid-recovery water heater to measure the main thermal and hydraulic variables during operation. The instrumentation measures water temperature at the heater inlet and outlet, as well as the water flow rate. An additional temperature measurement was included as a reference for the outlet temperature. The system consists of the sensors, signal-conditioning circuits, an STM32 microcontroller, an NI TC-01 module, and a LabVIEW-based monitoring and data-acquisition platform.

The water heater has two water connections: an inlet and an outlet. The inlet temperature is measured on the inlet pipe, before the water enters the heating section. At the same time, the outlet temperature and water flow are measured on the outlet pipe after heating. Two NTC thermistors are mounted directly on the external surface of the copper pipes. This arrangement allows temperature measurement without direct contact with the water or modifying the hydraulic path. A Hall-effect flow sensor is installed in the outlet line to measure the

water flow rate. In addition, a Type-K immersion thermocouple is installed at the outlet to provide a reference water-temperature measurement.

Figure 1 shows the sensor locations and the remaining instrumentation on the experimental test bench.

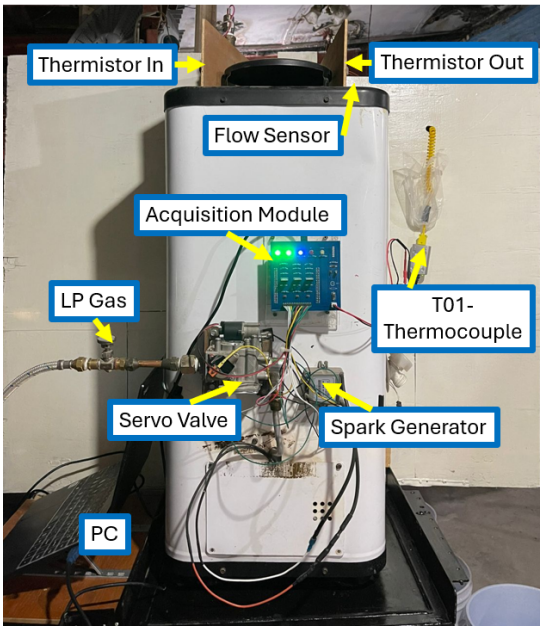


Figure 1. Experimental test bench and instrumentation system of the rapid-recovery water heater.
Source: Authors' elaboration.

The experimental test bench comprises the rapid-recovery water heater, temperature and flow sensors, signal-conditioning circuits, the STM32 acquisition unit, the NI TC-01 module, and a computer for monitoring and data storage. The sensors were installed at the inlet and outlet pipes according to the variables to be measured. No changes were made to the original water path. The two NTC thermistors were placed on the outer surface of the copper pipes, so the water temperature could be measured without introducing a sensor into the flow.

Two separate paths acquire the measurements. The STM32 receives the signals from the two NTC thermistors and the Hall-effect flow sensor after signal conditioning. The Type-K thermocouple follows a different path and is connected directly to the NI TC-01 module. This measurement was used as the reference for the outlet water temperature. The computer handled both paths simultaneously in LabVIEW.

The STM32 acquires TempIn, TempOut, and WaterFlow. The acquired signals are converted into their corresponding physical variables and transmitted to the computer through the serial interface. LabVIEW receives the STM32 data and displays the variables during the experiment, while also saving the measurements for subsequent analysis.

The STM32 acquisition program converted each NTC thermistor's resistance into temperature using the thermistor characteristic.

B. Variables and Instruments

The instrumentation system considered four variables. TempIn corresponds to the temperature measured at the heater inlet pipe, while TempOut corresponds to the temperature measured at the external surface of the outlet pipe. WaterFlow represents the water flow rate through the outlet line. Finally, TempReal corresponds to the reference outlet temperature measured with the Type-K immersion thermocouple. Table I lists the sensors and their respective measurement locations.

Table I. *Main variables and instrumentation used in the experimental system.*

Variable	Symbol	Instrument	Measurement Location
Inlet water temperature	TempIn	NTC 3950 MF52, 100 kΩ, ±1%, −55 to 125 °C	External surface of inlet copper pipe
Outlet water temperature	TempOut	NTC 3950 MF52, 100 kΩ, ±1%, −55 to 125 °C	External surface of outlet copper pipe
Water flow rate	WaterFlow	Hall-effect flow sensor, 1–30 L/min, 1.75 MPa max. pressure	Outlet water pipe
Reference water temperature	TempReal	Immersion-type Type-K thermocouple, −50 to 300 °C	Inside outlet water pipe

C. Sensor Signal Conversion

We connected the NTC thermistors to the STM32 analog-to-digital converter (ADC) through a voltage-divider configuration. We used a 12-bit ADC with a nominal 3.3 V supply. The measured ADC value was converted into voltage according to:

$$\boldsymbol{V_{NTC} = \frac{ADC_{NTC}}{4095} V_{ADC}} \qquad \textbf{(1)}$$

Where $\boldsymbol{ADC_{NTC}}$is the digital value obtained from the ADC channel, and $\boldsymbol{V_{ADC}}$is the ADC reference voltage, nominally 3.3 V

The STM32 also acquired a reference-voltage channel. The thermistor resistance was calculated from the measured NTC voltage and the reference voltage as:

$$\boldsymbol{R_{NTC} = R_{REF}\left(\frac{V_{REF}}{V_{NTC}} - 1\right)} \qquad \textbf{(2)}$$

Where $\boldsymbol{R_{REF}}$is the reference resistance and $\boldsymbol{V_{REF}}$is the measured reference voltage.

The thermistor resistance was then converted into temperature using the Steinhart–Hart equation:

$$\boldsymbol{\frac{1}{T} = C_0 + C_1 \ln(R_{NTC}) + C_2 [\ln(R_{NTC})]^3} \qquad \textbf{(3)}$$

where $\boldsymbol{T}$is the absolute temperature in kelvin, $\boldsymbol{R_{NTC}}$is the thermistor resistance, and $\boldsymbol{C_0}$, $\boldsymbol{C_1}$, and $\boldsymbol{C_2}$are the Steinhart–Hart coefficients. The resulting temperature was converted to degrees Celsius by subtracting 273.15. The same conversion procedure was applied to both TempIn and TempOut.

The water flow rate was measured using a Hall-effect flow sensor. The STM32 determined the pulse frequency generated by the sensor and converted it into liters per minute using the conversion factor implemented in the acquisition program:

$$\boldsymbol{WaterFlow = \frac{60f}{480.81}} \qquad \textbf{(4)}$$

where $\boldsymbol{f}$is the pulse frequency in pulses per second and 480.81 is the sensor conversion factor in pulses per liter. The resulting water flow rate is expressed in L/min.

Experimental setup and procedure

A. Experimental Setup

We obtained the measurements with the rapid-recovery water heater installed on the laboratory test bench. We used the instrumentation described in Section II throughout the experiments. We varied water flow and burner operation according to the test condition and recorded the sensor signals during each run.

Before each measurement, we checked the signals in the LabVIEW interface. This included the two NTC thermistors installed on the inlet and outlet pipes and the Hall-effect flow sensor. We also checked the Type-K immersion thermocouple through the NI TC-01 module and used it as the reference for outlet water temperature.

The sensor positions, hydraulic connections, and acquisition hardware were kept the same for all tests. Only the heater operating condition and water flow changed between runs. This provided a consistent measurement setup across all experiments.

B. Operating Conditions

The experiments covered three thermal conditions: heating, steady-state operation, and cooling. For the heating tests, the burner was turned on, and the outlet water temperature increased. Once the heater reached its normal operating range, the steady-state tests were carried out with the burner switching on and off according to its regular operation. For the cooling tests, the burner remained off, and the water temperature was allowed to decrease.

The resulting dataset contains 60 records from the heating condition, 40 from steady-state operation, and 20 from cooling, for a total of 120 experimental records. The experiments were organized into 12 operating-condition combinations based on the water heater's thermal state and the water and gas flow levels. Each combination was repeated ten times. Table II summarizes the distribution of experimental conditions.

Table II. *Experimental operating-condition combinations.*

Water State	Water Flow	Gas Flow	Combinations	Repetitions	Records
Heating	Zero; Low; High	Low; High	6	10	60
Steady	Low; High	Low; High	4	10	40
Cooling	Low; High	Zero	2	10	20
Total			12		120

Each experimental record was identified using a structured file name, such as C01_R01_SH_FZ_GL. The code C01 identifies one operating-condition combination, while R01 indicates the repetition number. SH, SS, and SC denote the Heating, Steady, and Cooling states, respectively. FZ, FL, and FH indicate zero, low, and high water flow, while GZ, GL, and GH indicate zero, low, and high gas flow, respectively.

We changed the water flow between tests to three levels: zero, low, and high. We carried out the low-flow tests at approximately 4–7 L/min, whereas the high-flow tests were performed at approximately 12–15 L/min. We obtained the zero-flow condition by closing the outlet valves.

Not every combination of thermal and flow conditions was physically applicable to the heater. For example, we carried out the cooling tests with the burner off. Similarly, we used zero-flow tests only when the absence of water circulation was possible. The laboratory temperature during the tests was approximately 25 ± 2 °C.

C. Data Acquisition Procedure
During each test, the STM32 acquired the signals from TempIn, TempOut, and WaterFlow and sent them to the computer through the serial interface. At the same time, the NI TC-01 read the Type-K thermocouple. LabVIEW displayed and stored the four variables during the experiment, as shown in Figure. 2.

Data were sampled at 5 Hz. Each run lasted 240 s and produced 1200 samples. With 120 runs, the complete experimental set corresponds to approximately 8 h of data acquisition.

For each run, the stored data included the time vector and the four measured variables: TempIn, TempOut, WaterFlow, and TempReal. Each record was identified according to the thermal condition and water-flow level used during the test. This organization produced a structured experimental dataset in which measurements can be grouped by operating condition. The complete dataset contains 120 experimental records, with 1200 samples per record, resulting in 144,000 samples acquired during the experiments.

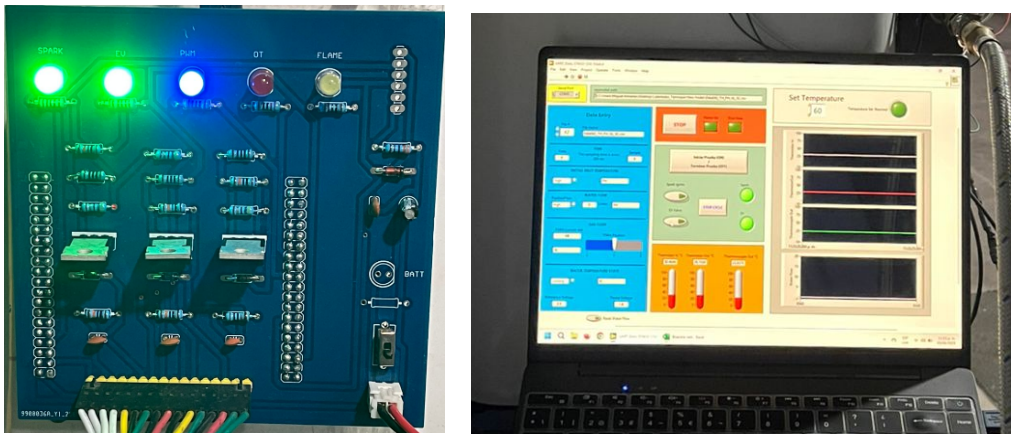


Figure 2. Experimental data acquisition system: (a) data acquisition board and (b) computer with the LabVIEW interface for real-time visualization of the measured variables.
Source: Authors' elaboration.

Experimental results

The experimental data were used to observe the response of the temperature and flow measurements under the different operating conditions. The recorded temperature signals were analyzed under heating, steady-state, and cooling conditions. The external outlet temperature measurement was also displayed together with the reference temperature obtained from the Type-K thermocouple.

A. Temperature Measurements
Figure 3 presents temperature data recorded during heating, steady-state operation, and cooling. When the burner was turned on, TempOut increased as the water was heated. TempIn changed more gradually since it was measured at the heater inlet and depended mainly on the incoming water temperature.

After the heater reached its normal operating range, TempOut stayed within a narrower range. Small changes in the signal during this period are related to the burner's on/off operation. When the burner was turned off, the outlet temperature decreased progressively during the cooling period.

The two NTC thermistors remained in contact with the outer surface of the copper pipes during the tests. Therefore, the sensors acquired temperature signals without being inserted into the water. The TempOut signal provided the external outlet temperature measurement used to observe the thermal changes at the heater outlet throughout the different tests.

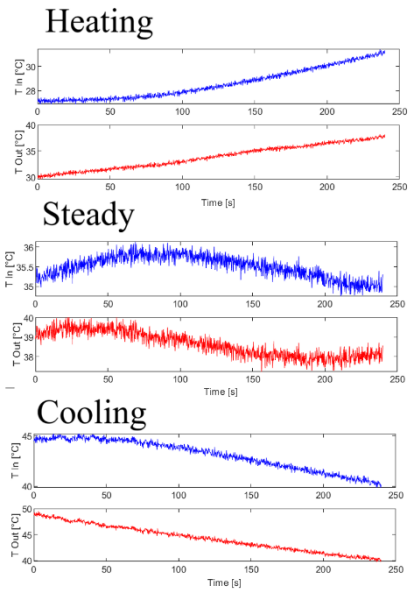


Figure 3. Representative temperature measurements during heating, steady-state, and cooling conditions.
Source: Authors' elaboration.

B. Flow Measurements

Figure 4 shows the water-flow signal for the three flow levels used in the experiments. With the outlet valves closed, the signal remained at zero flow. Opening the water path produced the low-flow condition, with measured values of approximately 4–7 L/min. The high-flow tests reached approximately 12–15 L/min.

The difference between these three cases is evident in the recorded signal. The flow sensor also remained connected to the outlet line for all tests, so its position did not change when the flow condition changed.

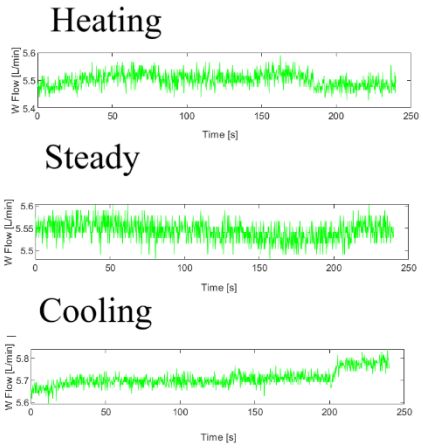


Figure 4. Representative water-flow measurements for zero, low, and high flow conditions.
Source: Authors' elaboration.

C. Comparison of Outlet Temperature Measurements

TempOut and TempReal were recorded simultaneously to observe the outlet temperature behavior using the two measurement configurations. TempOut was obtained with the NTC thermistor mounted on the outlet pipe's external surface, whereas TempReal was measured with the Type-K immersion thermocouple connected to the NI TC-01.

Figure 5 shows an example of the two outlet temperature measurements. Both signals increase during heating and decrease after the burner is turned off. During steady-state operation, the measurements remain within a similar temperature range, although their values are not identical.

The difference between the two measurements is associated with their different installation configurations. The NTC thermistor is attached to the external surface of the copper outlet pipe, whereas the Type-K thermocouple is immersed in the water. Therefore, the two sensors do not measure the temperature at the same physical location or through the same measurement mechanism. This comparison shows the corresponding temperature evolution recorded by both measurement configurations rather than establishing direct accuracy equivalence between the two sensors.

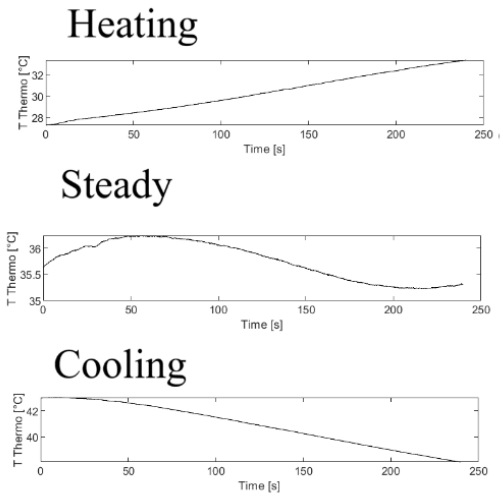


Figure 5. Comparison between the external NTC outlet temperature and the Type-K reference temperature. Source: Authors' elaboration.

D. Data Acquisition Performance

The implemented acquisition system was used throughout the 120 experimental runs while maintaining the same sensor arrangement and acquisition configuration. TempIn, TempOut, and WaterFlow were acquired through the STM32, while TempReal was acquired independently through the NI TC-01. LabVIEW provided simultaneous visualization and storage of the measurements. The resulting dataset contains 144,000 samples acquired at 5 Hz over approximately 8 h of experimentation. The measurements were organized by the thermal and water-flow conditions used in each test, providing a structured dataset for subsequent analysis.

The recorded signals enabled identification of the temperature and water-flow changes under different operating conditions. The temperature signals showed the water heater's heating and cooling behavior, while the flow signal distinguished the zero-, low-, and high-flow cases. The Type-K measurement also provided a reference for evaluating the outlet temperature obtained with the external NTC thermistor.

We further evaluated the relationship between TempOut and TempReal for the three thermal conditions. For each condition, we analyzed the temperature profiles and error over time, along with a scatter plot, to assess agreement between the two measurements. Figure 6 shows the results for the Heating condition.

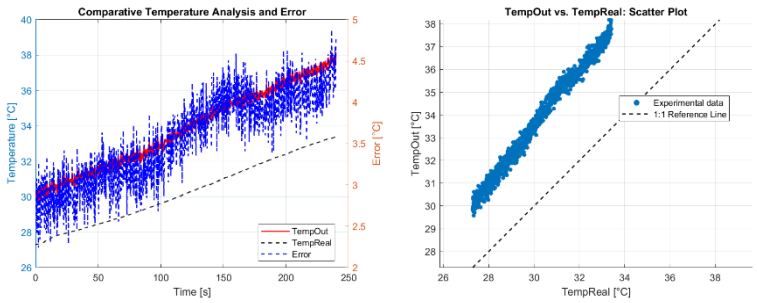


Figure 6. Comparative temperature analysis and scatter plot for the Heating condition.
Source: Authors' elaboration.

We performed the same analysis for the Steady condition. Figure 7 presents the corresponding temperature comparison, error behavior, and scatter relationship between TempOut and TempReal.

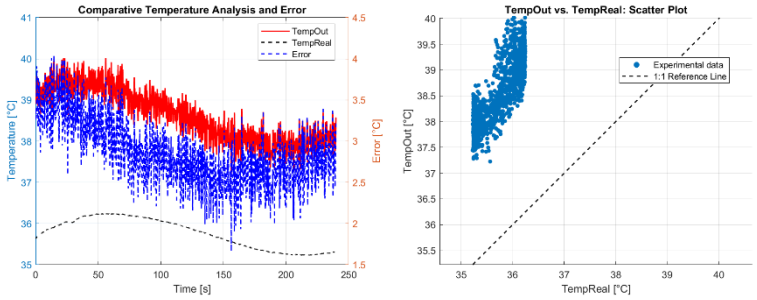


Figure 7. Comparative temperature analysis and scatter plot for the Steady condition.
Source: Authors' elaboration.

Finally, we analyzed the Cooling condition using the same approach. Figure 8 shows the temperature comparison, error, and scatter relationship obtained during the cooling stage.

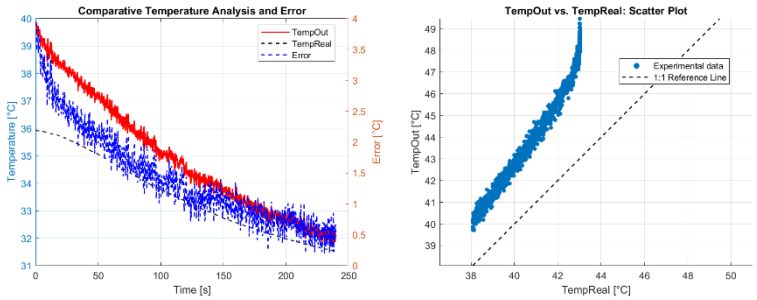


Figure 8. Comparative temperature analysis and scatter plot for the Cooling condition.
Source: Authors' elaboration.

The experimental results confirm that the proposed instrumentation operated under the tested conditions. The system continuously acquired temperature and flow variables and stored them, along with the reference temperature, for later analysis.

Conclusions

We implemented an instrumentation system to measure the main variables of a rapid-recovery water heater. The setup uses NTC thermistors on the inlet and outlet pipes, a Hall-effect sensor for water flow, and a Type-K thermocouple as the temperature reference. The STM32 acquired the NTC and flow signals, while the NI TC-01 handled the thermocouple. LabVIEW monitored and stored measurements from both paths.

The system was operated under heating, steady-state, and cooling conditions combined with zero-, low-, and high-flow levels. We acquired 120 experimental records, with 1200 samples collected at 5 Hz during each 240 s test, for a total of 144,000 samples. The same sensor arrangement and acquisition configuration were maintained throughout the experiments.

The temperature signals followed the changes caused by heater operation. TempOut increased during heating, remained within a limited range during steady-state operation, and decreased after the burner was turned off. The flow measurements also showed the expected difference between the three flow levels used in the tests.

The simultaneous recording of TempOut and TempReal showed similar temperature trends during the heating and cooling periods. The difference between the two measurements is due to their different installation locations and measurement configurations, since TempOut was obtained from the pipe's external surface and TempReal from an immersion thermocouple.

The implemented instrumentation system provided continuous acquisition and storage of the main thermal and hydraulic variables of the rapid-recovery water heater under the tested operating conditions. The resulting structured dataset provides an experimental basis for subsequent studies involving temperature characterization, control strategies, and indirect outlet-temperature estimation.

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