EPJ Web of Conferences **377**, 06011 (2026) https://doi.org/10.1051/epjconf/202637706011
IPS 2026

EXPERIMENTAL INVESTIGATION OF IDEAL GAS BEHAVIOR USING REAL-TIME DATA LOGGER SYSTEM

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Abstract. Understanding ideal gas macroscopic behavior is often constrained by conventional laboratory instruments with low temporal resolution and parallax errors. This study evaluates the reliability of a real-time data logger system in verifying the thermodynamic characteristics of gases under isothermal (Boyle's Law) and isochoric (Gay-Lussac's Law) conditions. The apparatus integrates a data logger station with a digital barometer and a thermocouple probe. Quantitative analysis employed linear regression and uncertainty evaluation based on the Guide to the Expression of Uncertainty in Measurement (GUM) framework. For Boyle's Law verification, the experimental data yielded an average PV constant of 20286 hPa·mL with a relative uncertainty (RU) of 0.355%. Linear regression between pressure and reciprocal volume (P versus $1/V$) produced a coefficient of determination approaching unity, indicating excellent agreement with the theoretical prediction. Meanwhile, Gay-Lussac's Law testing yielded an average P/T constant of 3.30128 hPa/K with an RU of 1.541% and a coefficient of determination of 0.99. The low uncertainty values and high linearity obtained under both experimental conditions indicate that the developed instrumentation provides stable and reliable real-time measurements of thermodynamic variables. These findings demonstrate the suitability of the data logger system for quantitative investigations of gas behavior under controlled laboratory conditions.

1 Introduction

Understanding the thermodynamic behavior of an ideal gas represents a fundamental pillar in statistical physics and fluid mechanics. From a physical perspective, the ideal gas laws provide a macroscopic description of the interactions among pressure (P), volume (V), and temperature (T). Theoretically, the macroscopic behavior of an ideal gas is formulated through the ideal gas equation of state:

$$PV = nRT \tag{1}$$

where P is the pressure, V is the volume, n is the number of moles, R is the universal gas constant, and T is the absolute temperature. This equation constitutes a synthesis of

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fundamental empirical laws. One such principle is Boyle's Law, which dictates that under isothermal conditions ($T = constant$), the gas pressure is inversely proportional to its volume:

$$PV = constant \quad (2)$$

Additionally, the relationship between pressure and temperature at a constant volume ($V = constant$) is described by Gay-Lussac's Law, which asserts that the gas pressure is directly proportional to its absolute temperature:

$$\frac{P}{T} = constant \quad (3)$$

Although these relationships appear straightforward in theory, empirical verification within a laboratory environment often encounters technical challenges regarding measurement precision. Traditional instruments, such as analog manometers, exhibit limitations in terms of temporal resolution and are susceptible to parallax errors. Previous studies have emphasized that the design of specifically developed laboratory apparatus is highly crucial for accurately observing the comparison of physical variables [1]. The inability of conventional instruments to record data automatically implies that rapid transitions of physical variables are frequently not captured with sufficient precision [2].

The integration of digital technology and real-time sensor systems in physics experiments has been shown to produce representative visualizations of physical phenomena with high measurement stability and reliability [3, 4, 5]. Utilizing a data acquisition system enables the transformation of abstract data into concrete graphical representations in real time. This aligns with the development of sensor-based instruments designed to capture the dynamics of physical variables simultaneously, which has been proven to significantly enhance the accuracy of experimental data interpretation [3]. Furthermore, the application of digital sensors in physics experiments is effective in validating physical laws with a high degree of accuracy while minimizing human error [5, 6]. Recent developments in pressure sensing technology also demonstrate significant improvements in sensitivity, linearity range, and signal stability for scientific measurement systems [7, 8].

In this study, a physical investigation was conducted by integrating the data logger system with a digital barometric pressure sensor and a K-type thermocouple. The deployment of the thermocouple is critical due to its low thermal mass, which enables a rapid response time to temperature fluctuations of the gas within a closed system [9]. This methodology allows for a deeper analysis through data logging techniques to minimize experimental uncertainty [10, 11].

The primary objective of this research is to evaluate the reliability of a real-time data logger system in verifying ideal gas behavior with a high level of precision. The analysis focuses on the stability of the electronic signals and the system's capacity to maintain the linearity of the $P - 1/V$ and $P - T$ relationships in accordance with the theoretical parameters stated in Equation (2) and Equation (3) [12]. Through this methodology, it is expected to yield highly accurate experimental data, while simultaneously contributing to the development of modern, actual-data-driven physics laboratory instrumentation [14, 15].

2 Research Method

This physical investigation examines the thermodynamic characteristics of an ideal gas under isothermal and isochoric conditions utilizing an integrated digital data acquisition system to ensure stability and minimize measurement uncertainty. The experimental hardware configuration was constructed by connecting high-resolution sensors directly to the central station of a standalone data logger, operating at a data recording sampling frequency of 1 Hz.

The digital data flow architecture was governed directly by the internal processing unit of the data logger station. A digital pressure transducer sensor was employed to detect the absolute gas pressure (P). Meanwhile, the temperature parameter (T) was measured using a digital thermocouple probe with a thermal operating range of -200°C to +1200°C. The deployment of this low-thermal-mass thermocouple is critical for providing a rapid response to gas temperature fluctuations. Each signal transmission from the sensors to the main data interface was regulated via a single-cable interface configuration to reduce electronic wave interference (noise) and maintain the consistency of real-time physical data readings.

The dynamics of the enclosed gas variables, with a constant number of moles (n), were characterized through two distinct and separate physical measurement scenarios. In the isothermal testing to verify Boyle's Law, the gas system was confined within a 20 mL volumetric syringe connected airtightly to the digital pressure sensor, as illustrated in Figure 1. The gas volume (V) was decreased from 20 mL to 12 mL in steps of 2 mL. To maintain a strictly isothermal process ($T = constant$) and prevent data distortion arising from instantaneous adiabatic compression effects, the piston displacement was executed slowly, allowing sufficient thermal stabilization lag time before the data was automatically archived by the data logger system.

Fig. 1. Experimental setup configuration for the verification of Boyle's Law.

Meanwhile, the isochoric testing to verify Gay-Lussac's Law was conducted using a gas system confined inside an airtight test tube. The test tube was placed inside an Erlenmeyer flask filled with water, which served as a water bath medium supported by a retort stand, as depicted in Figure 2. This indirect heating method was applied to ensure that heat propagation from the burner to the gas compartment remained homogeneous, thereby preventing local thermal fluctuations. The thermocouple probe was positioned hanging precisely in the center of the test tube cavity without touching the glass walls to avoid direct thermal conduction bias from the container. The gas within the closed system was heated incrementally from an initial temperature of 35° to an upper limit of 60°C. Data capturing the pressure fluctuations (P) and the absolute temperature increase (T, in Kelvin) were recorded simultaneously without lag time.

The complete set of obtained physical correlation data was extracted to a computer for quantitative analysis. For Boyle's Law verification, the regression analysis was performed between pressure (P) and the reciprocal of volume ($1/V$), since the theoretical relationship predicts a direct proportionality between these variables under isothermal conditions ($P \propto 1/V$). For Gay-Lussac's Law verification, linear regression was applied directly to pressure (P) versus absolute temperature (T), consistent with the theoretical relationship $P \propto T$ under constant-volume conditions. The precision and reliability of this data acquisition system were quantitatively evaluated by calculating the percentage of relative uncertainty (RU) based on the Guide to the Expression of Uncertainty in Measurement (GUM) methodology [12]. The mean value of the measurement data ($\bar{C}$) was calculated using Equation (4):

Fig. 2. Instrumental arrangement for gas heating in Gay-Lussac's Law testing

$$\bar{C} = \frac{\sum C}{n} \tag{4}$$

Subsequently, the data deviation (ΔC), representing the dispersion of values, was calculated using the standard formulation in Equation (5):

$$\Delta C = \sqrt{\frac{n\sum C^2 - (\sum C)^2}{n(n-1)}} \tag{5}$$

The precision level of the experimental results was determined through the percentage calculation of the relative uncertainty (RU) in Equation (6):

$$RU = \frac{\Delta C}{\bar{C}} \times 100\% \tag{6}$$

The digital measurement system is considered highly reliable when the coefficient of determination (R^2) approaches unity and the resulting relative uncertainty remains well below the general laboratory tolerance threshold of 5%.

The uncertainty analysis in this study was primarily based on repeated measurements and evaluated using the GUM framework. Therefore, the reported uncertainty values represent Type A uncertainty derived from the statistical dispersion of the measurement data. In assessing measurement reliability, the specifications provided by the sensor manufacturers were also considered. The pressure sensor used in this study has a resolution of 0.632 hPa over a measurement range of 0 – 2068 hPa, while the K-type thermocouple has a resolution of ± 0.6°C and a linearity of ± 3°C within the temperature range relevant to this experiment. These instrumental characteristics indicate that the sensor-related uncertainty contribution is small relative to the measured variations in pressure and temperature, supporting the reliability of the acquired data.

3 Result and Discussion

The physical characterization of ideal gas behavior was quantitatively evaluated through the digital data acquisition system using two distinct thermodynamic scenarios: an isothermal condition to test Boyle's Law and an isochoric condition for Gay-Lussac's Law. The raw physical data recorded by the sensors were analyzed progressively using a statistical uncertainty evaluation approach based on the GUM methodology [12] to review the instrument's reliability, which was further validated through linear regression modeling to map the consistency of data trends against the macroscopic theory of gases.

In the investigation of the first scenario, which operated under constant temperature conditions, the air volume compression was performed manually over a volume range of 20 mL to 12 mL with a reduction interval of 2 mL. This reduction of the gas space triggered a monotonic increase in absolute pressure from 1018 hPa to an upper limit of 1683 hPa, as presented in detail in Table 1.

Table 1. Experimental Data of Gas Isothermal Characteristics (Boyle's Law)

P(hPa)	V(mL)	PV = constant (hPa·mL)
1018	20	20360
1131	18	20358
1267	16	20272
1446	14	20244
1683	12	20196

This inverse physical correlation between pressure and volume is visually mapped through the characteristic curve in Figure 3, where the continuous product of both variables ($PV = C$) exhibits a consistent value at each observation point with an average constant value of 20286 hPa·mL.

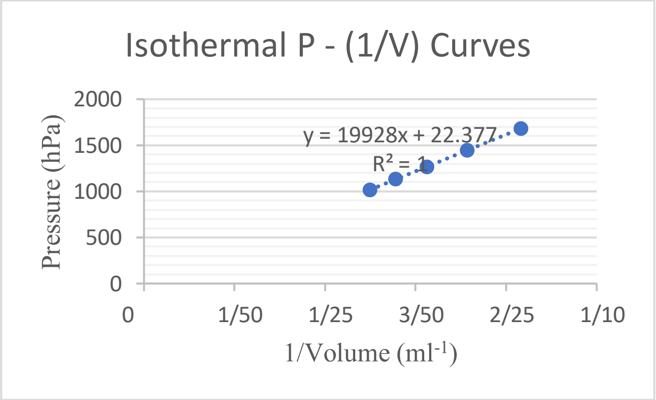

Fig. 3. Linear relationship between pressure (P) and reciprocal volume (1/V) under isothermal conditions.

The measurement reliability of the digital data acquisition system during the isothermal process is supported by the statistical analysis, which yielded an absolute uncertainty value of ΔC = 71.97 hPa·mL. This corresponds to a relative uncertainty (RU) of only 0.355%, which is substantially below the commonly accepted laboratory tolerance threshold. Such a low uncertainty value indicates excellent measurement precision and demonstrates the capability of the pressure transducer and data logger system to acquire stable data with minimal electronic noise interference.

The linear regression analysis of pressure as a function of reciprocal volume (P versus $1/V$), presented in Figure 3, produced the equation y = 19928x + 22.377 with a coefficient of determination (R^2) approaching unity. This result confirms excellent agreement between the experimental observations and the theoretical prediction of Boyle's Law, indicating that the inverse relationship between pressure and volume was successfully captured by the real-time data logger system. The small positive intercept may be attributed to experimental limitations such as sensor offset, environmental fluctuations, and measurement system characteristics. Although real gases may exhibit deviations from ideal behavior due to intermolecular interactions and finite molecular volume effects, particularly at smaller volumes [4,13], such effects were not significant within the experimental range investigated in this study. Therefore, the obtained results demonstrate that the developed instrumentation provides highly reliable measurements for verifying the thermodynamic behavior of gases under isothermal conditions.

The transition of the macroscopic physical behavior of the gas exhibits a different dynamic when the experimental system is switched to the second scenario, which maintains a constant spatial volume (isochoric). Through an indirect heating method using a water bath, the absolute temperature of the air inside the test tube was incrementally raised from an initial temperature of 308 K to an experimental upper limit of 333 K. This increase in the kinetic temperature of the gas is directly proportional to the simultaneous rise in absolute gas pressure recorded from 1039 hPa to 1076 hPa, as summarized in Table 2.

Table 2. Experimental Data of Gas Isochoric Characteristics (Gay-Lussac's Law)

P(hPa)	T (K)	P/T = constant (hPa/K)
1039	308	3.373376623
1045	313	3.338658147
1052	318	3.308176101
1063	323	3.291021672
1071	328	3.265243902
1076	333	3.231231231

This proportional relationship yields a constant pressure-to-absolute-temperature ratio ($P/T = C$) with an average value of 3.30128 hPa/K, whose linear correlation visualization is depicted in Figure 4.

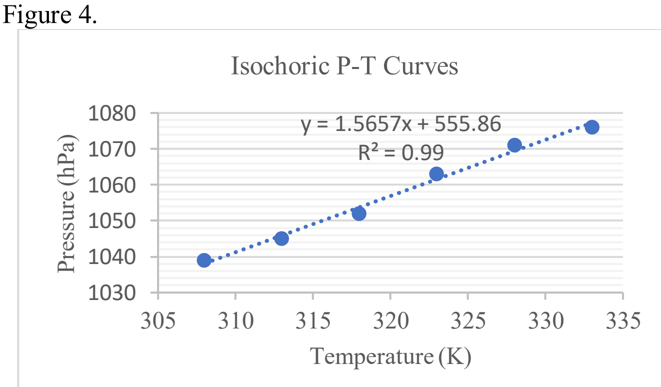

Fig. 4. Linear correlation plot of the gas pressure increase against absolute temperature ($P - T$) under isochoric *conditions*.

Based on the standard error of the mean calculation using the Guide to the Expression of Uncertainty in Measurement (GUM) methodology for the isochoric test data, the system's absolute uncertainty registers at ΔC = 0.05089 hPa/K with a relative uncertainty percentage of 1.541%. This uncertainty value is slightly higher than that of the isothermal condition due to the thermal lag barrier in heat energy transfer from the water to the glass wall of the test tube. However, this margin of error is still categorized as highly precise since it remains well below the general physical standard deviation limit of 5%. The stability of these thermal parameter readings is reinforced by the linear regression modeling in Figure 4, which yields a straight-line equation of $y = 1.5657x + 555.86$ with a coefficient of determination R^2 = 0.99. This determination value, nearly touching perfect unity, serves as robust evidence that the fluctuating variations in absolute gas pressure are linearly governed by the increase in absolute temperature. This finding aligns with previous studies stating that the use of a real-time digital data acquisition system enhances the quality of regression fitting and yields highly stable proportional relationships between thermodynamic variables [2, 10, 15]. This exceptionally high degree of linearity occurs because, within a low-to-moderate temperature range and at a relatively low gas pressure near the 1 atm threshold, the intermolecular interaction characteristics of the real gas inside the vessel still approximate the ideal behavior of an ideal gas. Consequently, positioning the K-type thermocouple probe hanging precisely in the center of the test tube cavity proves highly effective in reducing direct thermal conduction bias from the container walls, allowing the linear relationship between pressure and absolute temperature in Gay-Lussac's Law to be validly and accurately verified via the digital technology [15].

4 Conclusion

The real-time data logger system successfully recorded pressure, volume, and temperature data during isothermal and isochoric processes, allowing the behavior of the gas to be examined in accordance with Boyle's Law and Gay-Lussac's Law. The linear relationships obtained from the experimental data, together with the low uncertainty values, indicate that the system was able to provide consistent and reliable measurements throughout the experiments.

The results show that the integration of a digital pressure sensor and thermocouple probe can be used to monitor thermodynamic variables continuously and to characterize gas behavior with good accuracy. Minor departures from ideal behavior may arise from experimental limitations and the inherent properties of real gases; however, these effects did not significantly influence the overall agreement between the measurements and the theoretical models.

This work was limited to a relatively narrow range of pressures and temperatures using laboratory air as the test gas. Further investigation under different operating conditions and with additional sensor calibration procedures would provide a more comprehensive evaluation of system performance.

This publication was funded by the Indonesia Endowment Fund for Education (LPDP) on behalf of the Indonesian Ministry of Higher Education, Science and Technology, and managed under the EQUITY Program (Contract Number 4308/B3/DT.03.08/2025 and B/284/UN39/HK.07.00/2025).

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