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Article

Data Acquisition System for Exothermic and Endothermic Reaction: A Novel Laboratory Approach in Chemistry Learning

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Abstract. The determination of exothermic and endothermic reactions using conventional thermometers is often constrained by limitations in visualization and objectivity during practical activities. This study aims to investigate the performance of a DAS as an alternative for classroom practical work. The method involved characterizing thermal dynamics through a Design Science Research (DSR) approach using the MEDS evaluation framework. To record real-time temperature profiles, a thermistor sensor was integrated into the Mixer Mini and MGA as the DAS. Calcium carbide reaction and urea dissolution were utilized as the thermochemical systems. The analysis results show that the DAS: (1) is capable of detecting phenomena that go undetected using conventional methods; (2) exhibited strong baseline stability during the pre-reaction phase with a slope approaching zero and high reliability under homogeneous conditions, indicated by RSD values of 0.45% and 3.44% for urea dissolution and the calcium carbide-water reaction, respectively; and (3) showed stable internal consistency despite deviations from literature values caused by external factors. The novelty of this research lies in the operational efficiency of a self-contained measurement system that operates without the need for coding procedures. Consequently, the DAS provides a practical, objective, and scientifically valid solution to enhance data integrity in thermochemical analyses.

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1. Introduction

Every chemical reaction and physical process involves an exchange of energy with the surroundings. Based on the direction of heat flow, these processes are classified as exothermic reactions, in which heat flows from the system to its surroundings, and endothermic reactions, in which heat flows from the surroundings into the system [1-2]. In an experiment, temperature changes are considered the most fundamental factor determining this energy exchange process [3]. Temperature measurements must be accurate and sensitive because temperature variations in reaction processes occur continuously and dynamically [4-5]. This means that temperature measurement methods should comprehensive thermodynamic data collection.

At the Senior High School level, in phase F, the concept of energy transfer is taught on the topic of thermochemistry. This topic includes the definitions of system and surroundings, exothermic and endothermic reactions, thermochemical equations, and calculating the enthalpy changes. A deeper conceptual grasp is best achieved when students actively explore exothermic and endothermic processes through hands-on laboratory work [6]. Through observation experiments, it is hoped that students will relate theoretical concepts in thermodynamics to practical applications seen through observation. However, temperature measurements in high school laboratory activities still rely on conventional or analog thermometers. These instruments have several limitations, such as a dependence on subjective visual observations, the inability to record data continuously, and delayed response times (time lags). Such limitations make it difficult to capture temperature fluctuations in real time, which may affect students' understanding of reactions [7-9]. Thus, students find it difficult to completely comprehend the real essence of energy change dynamics in chemical reactions. In order to overcome the shortcomings of analog instruments, the use of a Data Acquisition System (DAS) is one approach to support the digitalization of chemistry education.

To resolve these limitations in instrumentation techniques, the integration of DAS has becomes essential in digital chemistry education. In this study, the DAS setup includes the a-Mixer mini hardware to convert analog signals into digital data and the Meter Graph Analysis (MGA) software for analyzing the acquired data. Using DAS allows data acquisition and computation to be performed simultaneously [10]. The use of computerized processes in the transformation of information into graphs and tables increases efficiency and minimizes chances of human error, thus helping students focus more on interpretation than on technical challenges.

Despite advances in digital measurement technology, previous DAS designs have relied heavily on stand-alone microcontrollers, which require complex hardware assembly and programming, as demonstrated by Potabuga et al. [11] and Baeyens et al. [12]. This poses a practical barrier in classroom settings where time is limited. In contrast, the proposed system combines A-Mixer mini hardware and MGA software to enable real-time thermal monitoring through a more accessible and operationally efficient platform for school laboratory environments.

Based on this urgency, the present study aims to evaluate the performance of the DAS in exothermic and endothermic reaction experiments. The primary focus of this study is the system's effectiveness in recording real-time temperature changes. This study is limited to the technical validation of the DAS as a preliminary step toward its potential implementation in chemistry learning environments, particularly for activities involving graph interpretation and thermochemical data analysis.

2. Experimental Section

2.1 Materials

The materials used in this study included distilled water (H_2O), technical-grade calcium carbide (CaC_2) (PT Emdeki Utama Tbk), and technical-grade urea ($CO(NH_2)_2$) (Farmalab). All chemical reagents were used directly without further purification. These three materials were selected as model systems to investigate the thermal dynamics of exothermic and endothermic reactions.

Measurements of thermal changes during chemical reactions were performed using a simple coffee-cup calorimeter. The calorimeter components consisted of an inner glass vessel and an outer plastic insulating layer, equipped with a tight-fitting lid to minimize heat loss to the surroundings. Temperature fluctuations were monitored using a Negative Temperature Coefficient (NTC) thermistor sensor with an accuracy of ±1 °C, positioned vertically inside the calorimeter to ensure complete immersion in the solution. This sensor was a factory pre-calibrated component that did not require additional calibration [13]. The temperature sensor was integrated with a DAS device via a connecting cable, and the thermal data were transmitted in real time to the MGA software on a computer for data visualization and storage. The schematic diagram of the experimental setup is illustrated in Figure 1.

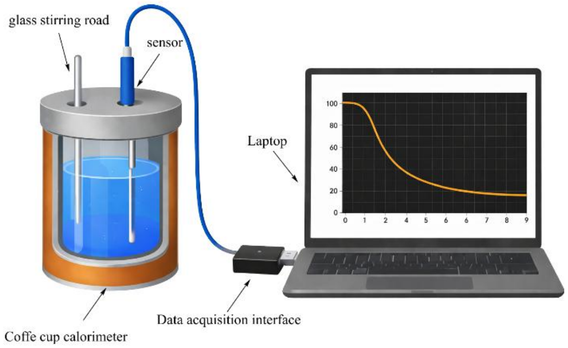
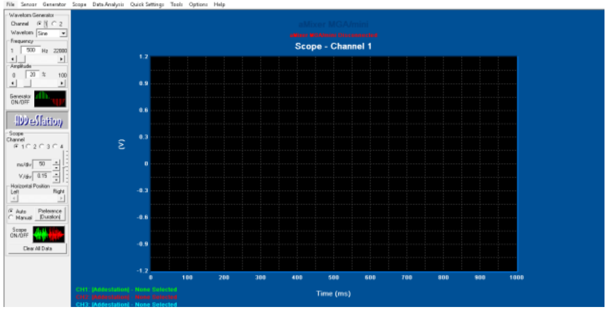


Figure 1. Schematic diagram of the experimental setup

The DAS software was configured at the beginning of the experiment to ensure the accuracy of data reading and recordings. The instrumentation parameters were set at a sampling rate of 1 Hz with a continuous monitoring duration of 20 minutes. The software interface was specifically adjusted to capture micro temperature fluctuations in order to generate a precise temperature versus time thermal curve. Figure 2 shows the MGA software interface, which displays real-time data visualization. The main graph illustrates the relationship between temperature and time, while the control panel on the left is used to configure parameters to ensure precise data acquisition during the experimental process. Figure 3 illustrates the control panel and the auto cope preference window. This interface allows the user to specify the sampling rate and the duration of the data monitoring.



Channel ● 1 ○ 2
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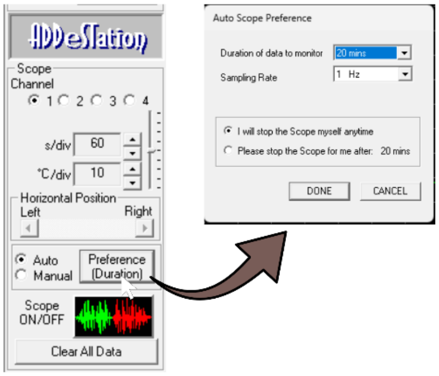
ms/div 50
V/div 0.15
● Auto ○ Manual
CH1: [Addestation] - None Selected
CH2: [Addestation] - None Selected
CH3: [Addestation] - None Selected

Figure 2. Interface of the MGA software



Channel: ● 1 ○ 2 ○ 3 ○ 4
s/div: 60
°C/div: 10
Horizontal Position: Left – Right
● Auto ○ Manual
Duration of data to monitor: 20 mins
Sampling Rate: 1 Hz
● I will stop the Scope myself anytime
○ Please stop the Scope for me after: 20 mins

Figure 3. Software configuration for data acquisition parameters.

The calorimeter's heat capacity (calorimeter constant) was determined in the initial stage of the experiment to compensate for the heat absorbed by the device's calorimeter walls during the reaction [14-15]. The determination of this constant was carried out by mixing 50 mL of room-temperature water with 50 mL of hot distilled water at 40°C. The temperature of the cold water inside the calorimeter was recorded for the first 30 seconds as baseline data, followed by the addition of hot water with continuous stirring until the end of the monitoring duration. This standardization procedure was performed in five replicates to ensure instrumentation precision and reliability.

After the calorimeter heat capacity value was obtained, the experiment proceeded to the characterisation of exothermic and endothermic reactions. Optimization of the CaC_2 and $CO(NH_2)_2$ concentrations was performed first to ensure that the system's temperature response fell within the monitor's optimal detection range without requiring external data amplification. Thermal profile measurements were initiated by introducing 100 mL of distilled water into the calorimeter, followed by 30 seconds temperature recording to establish the system's initial temperature (T_0). Subsequently, the test substance CaC_2 or $CO(NH_2)_2$, was added to the calorimeter and stirred continuously until the entire thermal change data was completely recorded. The entire series of experiments for these exothermic and endothermic reactions was each repeated five times to ensure the consistency of the data obtained.

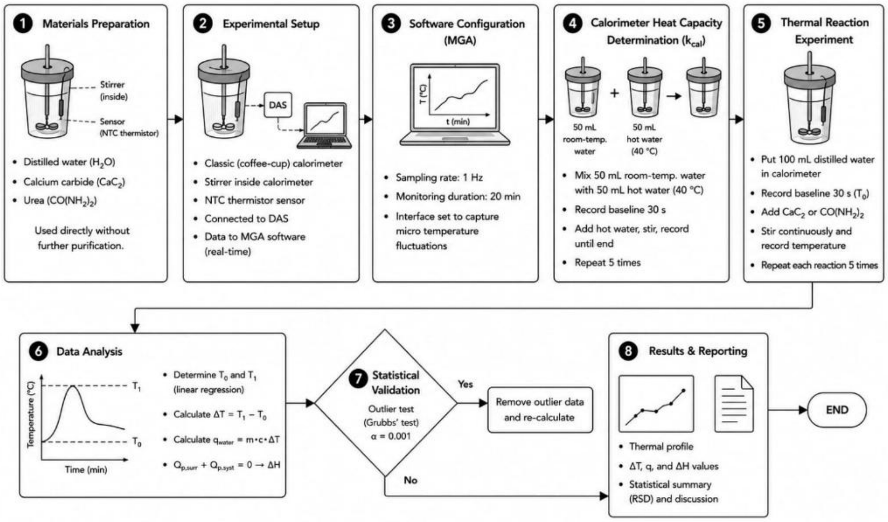


Figure 4. Eksperimental workflow for exothermic and endothermic reactions measurements using the developed DAS.

2.2 Methods

This study adopts the Design Science Research (DSR) paradigm, which focuses on the development and evaluation of an artifact in the form of a DAS to address the limitations of objectivity in conventional thermochemistry practicums [16-17]. The performance evaluation process of the apparatus was systematically designed based on the Methodology for Evaluation in Design Science (MEDS) framework. The evaluation was conducted through the Technical Risk and Efficacy trajectory within a controlled laboratory environment (artificial evaluation) to ensure the technical reliability of the device prior to its classroom implementation [16].

In accordance with the MEDS stages, the determination of the evaluated properties was prioritized using the MuSCoW (Must, Should, Could, Won't) technique, in which reliability, precision, and validity in detecting transient phenomena were established as the primary criteria (Must). The evaluation process involved two major stages: 1) baseline stability test were done to determine the reliability, and 2) using exothermic and endothermic reactions as functionality tests to confirm the system's ability to capture thermal dynamics in real-time. The evaluation employed a short-scoping approach that focused on sensor performance and data consistency to ensure resource efficiency without compromising scientific rigor.

The thermal data analysis was performed by analyzing the temperature versus time graph that was continuously recorded by the DAS and displayd through the MGA software at a sampling rate of 1 Hz. To minimize systematic errors due to heat transfer from the system to the surrounding, the initial temperature (T_o) and final temperature (T_1) were found using linear regression during the pre-reaction and post-reaction periods. The ΔT value was obtained by subtracting (T_1) and (T_o) values [18].

The heat of reaction was calculated by considering the heat capacity of both the water and the calorimeter. The heat absorbed or released by the water was calculated using the equation $q_{water} = m.c.\Delta T$, where m represents the mass of water and c is the specific heat of water. The reaction heat was calculated based on the law of conservation of energy using the equation $Q_p surroundings + Q_p system = 0$. Since the experiment was conducted at constant pressure, this $Q_p sistem$ is referred to as the enthalpy change (ΔH) of the reaction [2]

The consistency of the calculated ΔT was subsequently validated statistically to ensure data integrity prior to further analysis. Outlier detection was performed iteratively using Grubbs' test at a significance level of $\propto = 0.001$. Mathematically, the G statistic was calculated based on the absolute deviation of the extreme value from the sample mean, as expressed in the following equation:

$$G = \frac{|X_{out} - \bar{x}|}{S}$$

Data were identified as outliers and subsequently eliminated if the G value exceeded the critical value (G_{crit}) [19-20]. The precision and repeatability were calculated using Relative Standard Deviation (RSD) [21-22]. All calculations for numerical data, statistical analysis, and graphing of the regression curves have been done by means of Microsoft Excel.

3. Results and Discussion

The evaluation of the DAS performance began with an analysis of the integrity of the raw data recorded in real-time. Unlike conventional thermometers, which are limited by visual parallax and observer subjectivity, this DAS system was capable of data acquisition at a sampling rate of 1 Hz, meaning temperature data is recorded every second. Although higher sampling rates such as 1 kHz, a sampling rate of 1 Hz was chosen to make the data clearly visible but still capture the phase transitions of heat transfer at the same time to ensure that the data could be interpreted directly without the use of additional data conversion.

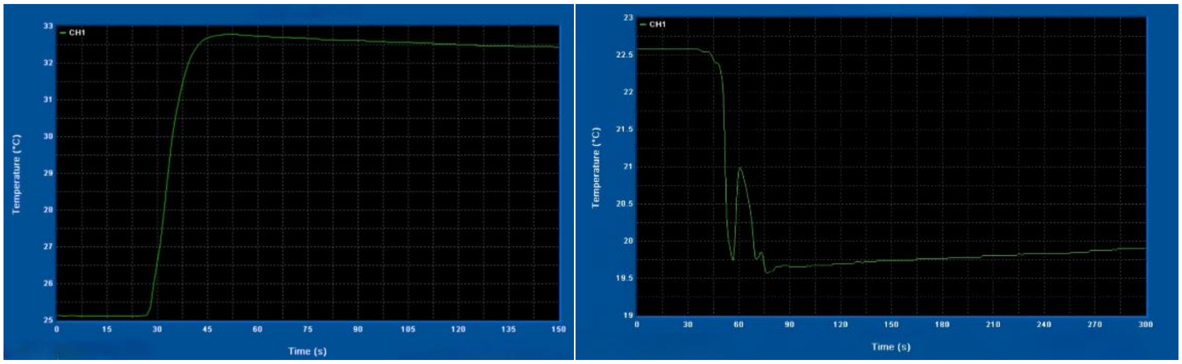


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Figure 5. Thermal profiles of (a) the reaction of CaC_2 (s) and H_2O (l), (b) the dissolution of $CO(NH_2)_2$ (s), recorded using a data acquisition system (DAS)

The thermal profiles provide an understanding of three distinctly defined observation zone: the pre-period phase, the main-period phase, and the post-period phase. In the pre-period phase, the DAS indicated an early temperatur stability of the liquid with verty few fluctuations. This indicates that the NTC thermistor sensor is sensitive [23-24]. Stability within this initial zone is crucial, as it serves as the baseline for determining the initial temperature value (T_0).

During the course of the main-period phase, temperature changes can be observed that are typical for the thermodynamic characteristics of the process. After the addition of calcium carbide (CaC_2), the graph shows the appearance of an increase in temperature, which proves the heat release of the reaction due to heat transfer from the system to its surroundings. On the contrary, when urea ($CO(NH_2)_2$) is added, the graph demonstrates a decrease in temperature, which means heat absorption from the surroundings into the system.

The temperature changes associated with endothermic processes are not necessarily monotonous since they usually contain oscillations that occur due to the uneven distribution of heat throughout the sensor during the experiment. The intense absorption of heat leads to the emergence of thermal heterogeneity, during which the temperature near the particles becomes considerably lower than the temperature of the solution as a whole. Since the initial temperature is stable, such oscillation cannot originate from sensor noise but rather represents the actual thermal dynamics successfully captured by the 1 Hz DAS.

In the post- reaction phase, the thermal profiles of both reactions do not show a constant horizontal line but exhibit a slope directed toward ambient temperature. This is because the classical calorimeter used is not perfectly adiabatic, allowing spontaneous heat exchange with the surroundings. Based on thermodynamic principles, heat naturally flows from a higher temperature to a lower one until thermal equilibrium is reached [25]. The instability observed during this post-reaction phase confirms the presence of a transient thermal gradient, which was successfully detected due to the high sensitivity of the sensor. Figures 6 and 7 show the plot for the linear extrapolation technique that was used in determining the initial temperature (T_0) and final temperature (T_1) using the temperature versus time plot of the exothermic and endothermic reactions.

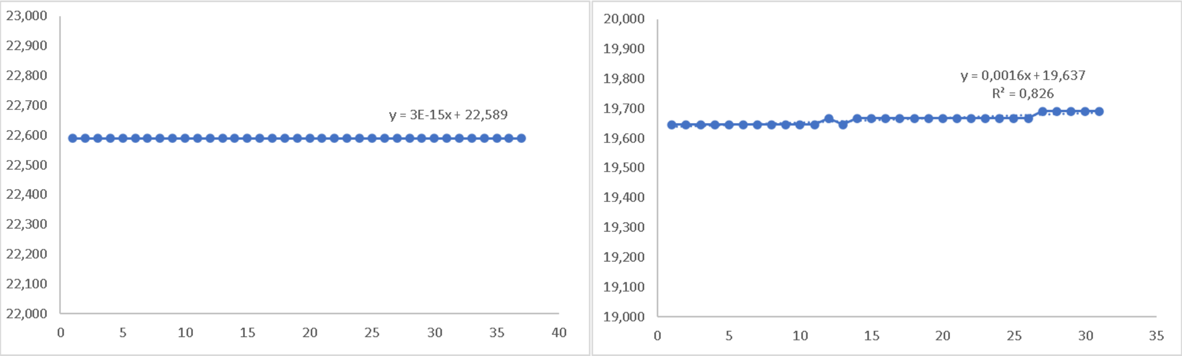

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Figure 6. Graphical representation of the linear extrapolation method for the temperature versus time curve in the dissolution of $CO(NH_2)_2$, (a) extrapolation determining T_0 (b) extrapolation determining T_1

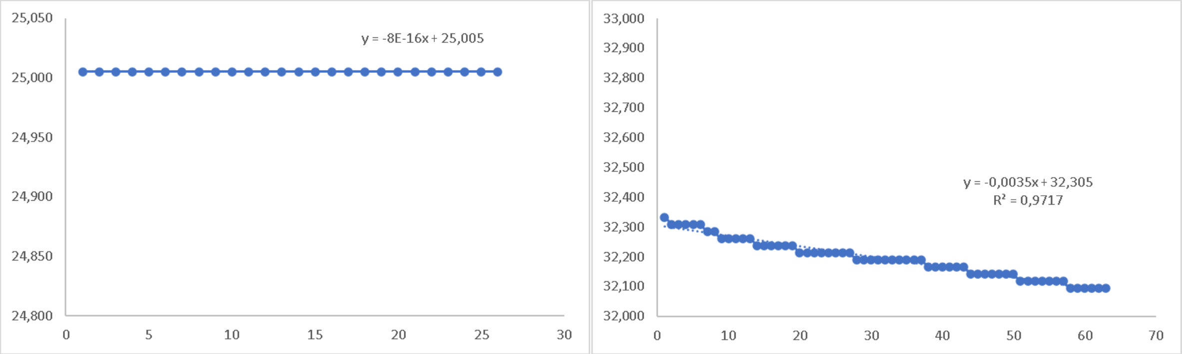

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Figure 7. Graphical representation of the linear extrapolation method for the temperature-versus-time curve in the CaC_2 and H_2O reaction, (a) extrapolation to determine T_0 (b) extrapolation to determine T_1

Based on the observation in Figure 6(a) and Figure 7(a), the initial pre-reaction phase exhibits constant temperature stability, represented by a horizontal line. In the post-reaction phase, the data show a trend of temperature change, with a high coefficient of determination ($R^2 > 0.8$), indicating that the post-reaction temperature shifts were accurately captured in real-time. The high R^2 value provides a high level of confidence in the linear extrapolation results for determining T_1, thereby minimizing systematic error in the enthalpy change calculations. Thus, the application of linear regression techniques to both phases serves as a compensation method to establish T_0 and T_1, effectively correcting temperature readings from a non-standardized device and compensating for calorimeter conditions that are not perfectly adiabatically isolated.

The limitations of the container's isothermal properties were precisely observed in the post-reaction phase through the linearity of the obtained data. In the $CO(NH_2)_2$ dissolution reaction, Figure 6(b), the graph exhibits an upward temperature trend ($m \approx 0.0016$) over time, representing the reabsorption of heat from the surroundings. Meanwhile, the reaction between CaC_2 (S) + H_2O (l), Figure 7(b) shows a downward temperature trend ($m \approx -0.0035$), indicating heat loss to the surroundings.

Table 1. Summary of Extrapolated Temperature

Parameter	CaC_2 (s) + H_2O (l) Reaction	$CO(NH_2)_2$ Dissolution
Mean T_0 (°C)	25.310	22.734
Mean T_1 (°C)	32.586	19.777
Mean ΔT (°C)	7.276	-2.956

A total of five ΔT values were obtained for each experiment; consequently, identification was performed using Grubbs'Test to ensure that no extreme or anomalous data points (outliers) were present. This step is important to ensure that each observation is consistent and there are not random error that could compromise the accuracy of the calculations. As a prerequisite for this test, data normality was verified using the Shapiro-Wilk Test, which was selected due to the small sample size ($n<50$). The results indicated that the data distributions for both the exothermic and endothermic experiments were normally distributed. Based on Grubbs'Test at a significance level of 0.01, all data points for both the CaC_2 and $CO(NH_2)_2$ dissolution were accepted ($G<g_{rit}$), thus maintaining data integrity for enthalpy calculations [19-20].

The determination of enthalpy change (ΔH) through calorimetric experiments requires precise data regarding the heat absorbed by the calorimeter (c_{all}) [26]. Therefore, a standardization phase was first conducted by characterizing the calorimeter's heat capacity (C_{cal}). The T_0 and T_1 data were analyzed using linear regression techniques, supplemented by outlier analysis to ensure data accuracy. Based on the calibration results, the calorimeter heat capacity (C_{cal}) was determined to be 63.98 J/°C. The average q_{cal} was 427.098 J, representing the mean heat absorbed by the calorimeter under the calibration conditions.

After determining the ΔT values and q_{cal}, values, the heat of reaction (q_{rxn}) was calculated for both the exothermic and endothermic processes. Based on the experimental results, the average q_{rxn} for the reaction CaC_2 and H_2O was -111499.7 J. Thermodynamically, the negative sign of this q value confirms that the reaction is exothermic, wherein heat is released from the system to the surroundings [1]. Conversely, the dissolution of $CO(NH_2)_2$ value was +8145.82 J. This positive value represents the characteristic of an endothermic reaction, indicating that the system absorbs heat from the surroundings to proceed [1].

Since the experiment was conducted at constant pressure, the q_{rxn} is equal to the enthalpy change [27]. Based on the experimental results and data processing, the average enthalpy change for the reaction CaC_2 and H_2O was -111.50 kJ/mol, while the dissolution of the $CO(NH_2)_2$ reaction was 8.145 kJ/mol. Statistical parameters, including the mean, Standard Deviation (SD), and Relative Standard Deviation (RSD), were calculated to evaluate the precision and reliability of the measurements [28-29]. A summary of the calculated data is presented as follows:

Table 2. Summary of ΔH, SD, RSD, and SE results

Reaction System	Mean ΔH (kJ/mol)	SD	RSD (%)	SE
CaC_2 (S) + H_2O (l)	-111.50	3.83	3.44	1.71
Dissolution $CO(NH_2)_2$	8.145	0.036	0.45	0.02

Based on the results of the statistical analysis presented above, there is a significant difference in precision profiles between the two reaction types. The $CO(NH_2)_2$ dissolution exhibited a highly precise and remarkably high degree of repeatability, as indicated by the average enthalpy change of 8.145 kJ/mol and the relatively low SD of 0.036. This is further confirmed by the RSD value of 0.45%.

According to the AOAC International [30], repeatability can be evaluated through repeated measurements under constant conditions, and the extremely low variance observed in this study indicated excellent repeatability. The obtained precision profile aligns closely with the highly stable and uniform nature of homogeneous dissolution processes. This indicates that the DAS system functions effectively with a high degree of stability when dealing with a homogeneous dissolution process. In the case of the CaC_2 + H_2O reaction, a considerably higher degree of variability was observed, as indicated by the SD of 3.83 and RSD of 3.44%. In terms of the instrumentation aspect, the high observed value of RSD does not mean the poor quality or lower reliability of the DAS equipment instead, it accurately represents the intrinsic dynamics of the reaction itself.

The reaction of CaC_2 is very energetic, heterogeneous, and exothermic in nature, with the formation of gases at extremely fast rates and multiple phase interfaces, while also having random changes in the composition due to the impure nature of raw materials. In analytical instrumentation practice, RSD values below 5% are still commonly considered acceptable for complex heterogeneous systems, particularly those involving rapid transient thermal behavior. Therefore, the observed variability remains within a reasonable precision range for real-time thermal acquisition measurements.

The enthalpy values of dissolution of urea and reaction of calcium carbide obtained from various literature sources at a pressure of 1 atm and a temperature of 25°C, then corrected to the experimental conditions of 21.5°C and 0.991 atm for urea, and 25.5°C and 1 atm for calcium carbide The corrected enthalpy changes were 15.335 kJ/mol for dissolution of urea and -127.890 kJ/mol for reaction of calcium carbide [31]. In comparing the experimentally obtained data with literature values, a significant deviation was observed, particularly in the case of urea dissolution. This discrepancy may be attributed not only to the use of technical-grade samples without prior purification, but also to the inherent thermal characteristics of the process.

Urea dissolution is an endothermic reaction characterized by relatively small and gradual temperature changes, making the system more susceptible to surrounding heat exchange. In addition, the slow and proressive nature of the endothermic temperature change, as shown in Figure 5(b), indicates that the dissolution process occurs in a gradual manner over time. This slow thermal response further contributes to reduced sensitivity in capturing accurate temperature changes, where even minor heat gains from the surroundings or the calorimeter walls can significantly affect the measured temperature and thus the calculated enthalpy value. Furthermore, the calorimeter was not fully adiabatic, as indicated by gas leakage observed from the reaction flask during the calcium carbide reaction.

Overall, the design setup proves to be highly efficient in the characterization of the thermal properties of exothermic and endothermic reactions. This is demonstrated by the high precision levels obtained in multiple repetitions of experiments, as indicated by the low RSD, SD, and SE values achieved during all experiments. Despite slight increases in variability in heterogeneous reactions (such as the reaction of calcium carbide), the precision level of the experiments remains satisfactory for dynamic thermal processes.

Moreover, the DAS significantly improves the quality of thermal measurement parameters due to continuous real-time temperature monitoring. The system proves to be sensitive. Thus, slight temperature changes were easily registered using the developed DAS. Through the application of a 1 Hz sampling rate and linear extrapolation correction, thermal changes were accurately captured. Statistical analysis also enabled the recording of all thermal changes objectively. Therefore, the developed DAS demonstrates strong potential for real-time monitoring of thermal dynamics in various exothermic and endothermic reactions.

4. Conclusion

This study successfully evaluated the performance of a Data Acquisition System (DAS) in comprehensively characterizing thermal dynamics of the exothermic and endothermic reactions. According to the assessment results, the DAS, which operates at a 1 Hz sampling rate, accurately captures the objective change in thermal phases in real-time. One of the main advantages of the system is the high level of efficiency in its use, because the device can be used without requiring complex coding techniques. In terms of technical characteristics, the DAS successfully identifies distinctive thermal dynamics of both types of reactions.

Despite the presence of deviations from the accuracy values mentioned in literature due to external factors such as material quality and thermal insulation, the system demonstrates a high level of precision with an RSD value being equal to 0.45%. By combining the linear compensation technique and Grubbs' Test, the system provides accurate measurements of the thermal dynamics based on scientifically valid data. Overall, the DAS represents a reliable, practical, and efficient independent measurement solution for laboratory-scale analysis of exothermic and endothermic reactions in school laboratories. In order to increase the accuracy of measurements, it is expected that the DAS will use higher purity (pro-analysis grade) materials. Moreover, modifications in calorimeter design should help to achieve a better insulation system in order to prevent any heat losses to the surroundings.

5. Acknowledgement

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