Educación Química

Comunicación

Determination of chemical composition in Tri-Metal Alloys: a three variable linear equation system approach

Determinación no destructiva de composición química en aleaciones de tres metales: aproximación de sistema de ecuaciones lineales en tres variables

Ariel Van-Sertima[1], Sandra Simmons[1], Raul Zablah-Vasquez[1] y Adrian Villalta-Cerdas[1]

Resumen

Para mejorar el puente entre las representaciones macroscópica y simbólica utilizadas en química, diseñamos un módulo de laboratorio centrado en un sistema de tres ecuaciones para el análisis de la composición química. Los estudiantes evalúan la composición de aleaciones de cobre, estaño y aluminio midiendo dos propiedades: densidad y capacidad calorífica. Estos procedimientos no destructivos se ajustan a las duraciones estándar de las sesiones de laboratorio. Tras recopilar datos, los estudiantes abordan tres ecuaciones lineales que vinculan el porcentaje en masa del elemento con la composición de la aleación, la densidad y la capacidad calorífica. Al agrupar datos de diversas muestras, la clase logra una comprensión integral. Este método se alinea con objetivos para la educación en laboratorios, enfatizando el razonamiento científico, habilidades prácticas y dominio del tema. Los resultados de los estudiantes se desviaron en un +/-10% de las composiciones reales de las aleaciones. La discusión sobre los datos recopilados por los estudiantes y los resultados respalda la viabilidad de la experiencia de laboratorio para su implementación en laboratorios introductorios de química.

Palabras clave

Densidad, capacidad calórica, calorimetría, aleaciones, composición química, ecuaciones lineales

Abstract

To enhance the bridge between macroscopic and symbolic representations in chemistry, we crafted a laboratory module focusing on a three-equation system for chemical composition analysis. Students assess the composition of copper, tin, and aluminum alloys by measuring two properties: density and heat capacity. These non-destructive procedures fit within standard laboratory session durations. After gathering data, students tackle three linear equations linking element mass ratio to alloy composition, density, and heat capacity. By pooling data from various samples, the class achieves a comprehensive understanding. This method aligns with objectives for laboratory education, emphasizing scientific reasoning, practical skills, and subject mastery. Students' results deviated by +/-10% from actual alloy compositions. The discussion of student-gathered data and results supports the feasibility of the laboratory experience for its implementation in introductory chemistry laboratories.

Keywords

Density, heat capacity, calorimetry, alloys, chemical composition, linear equations.

[1] Universidad Sam Houston State.

Cómo citar: Van-Sertima, A., Simmons, S., Zablah-Vasquez, R., y Villalta-Cerdas, A. (2024, enero-marzo). Determination of chemical composition in Tri-Metal Alloys: a three variable linear equation system approach. *Educación Química*, *35*(1). https://doi.org/10.22201/fq.18708404e.2024.1.86324

Introduction

The world of chemistry unfolds across various representational domains, each offering unique perspectives to elucidate the vast phenomena of the discipline (Chamizo, 2009). As learners embark on the journey through chemical knowledge, they are confronted with the task of navigating between these domains – the macroscopic views highlighting tangible laboratory techniques and experimental procedures; the microscopic giving insight into atomic and molecular dynamics; and the symbolic realm that encapsulates chemical equations and mathematical modeling (Robinson, 2000; Taber, 2001; Talanquer, 2010).

Research has underscored the pivotal role of technological visualizations and representations in fostering enhanced comprehension and retention in chemistry education, particularly in unraveling the intricate atomic-level workings of chemical processes (Kelly & Akaygun, 2019). Studies by Kelly et al. have explored how students interpret, critique, and align macroscopic observations with submicroscopic representations by employing varied methodologies such as resource-based frameworks, eye-tracking, and qualitative analysis (Kelly et al., 2017; Hansen et al., 2019; Kelly et al., 2021). The discernment of accurate atomic models and mechanisms in reactions, facilitated by contrasting animations and visual feedback, emerged as crucial in honing students' conceptual understanding and critical evaluation skills. By engaging with structured animations and scrutinizing varying accuracy in representations, students were guided to bridge the gap between macroscopic phenomena and symbolic or submicroscopic representations, fostering a more holistic and critical grasp of chemical processes (Kelly et al., 2017). This underpins the essential endeavor in chemistry education to seamlessly integrate visualizations and representations, ensuring they are not merely perceived as novel tools but as instrumental aids that empower students to be critical, purposeful, visual consumers and to more profoundly grasp and link the macroscopic, symbolic, and submicroscopic realms of chemistry (Hansen et al., 2019).

However, introductory chemistry laboratory programs often fall short of seamlessly integrating these layers. A common observation is that students grapple with compartmentalized laboratory experiments while exposed to diverse chemistry content knowledge and practical skills (Galloway & Bretz, 2015). These weekly distinct experiments, devoid of an explicit interrelation, inadvertently lead students into a fragmented understanding, rendering them unable to discern the intricate interconnections between chemistry concepts, laboratory techniques, and the holistic curriculum design (Bretz et al., 2013).

Recognizing the pivotal role that an interconnected laboratory experience can play in deepening conceptual understanding (Millán, 2012), we designed an innovative learning experience. The core of this experience pivots around fostering a robust bridge between the macroscopic and symbolic levels of chemistry, achieved by guiding students into a layered chemical composition analysis of metal alloys. Emphasizing real-world relevance, these metal alloy samples were chosen for their varied chemical compositions, and their properties—density and specific heat capacity—were used as the key investigative parameters.

It is posited that the relationships between these experimental variables and the chemical composition can be deduced through content knowledge acquired in most introductory chemistry courses (Villalta-Cerdas & McCleary, 2019). Moreover, we ensured a sustained exploration and immersion by allowing students to engage with the same analytes across multiple laboratory sessions. This pedagogical approach, inspired by the natural learning trajectory of a scientist, endeavors to let students intuitively draw connections among measurements, laboratory techniques, and underlying chemistry concepts. This work aims to illuminate how a carefully curated laboratory experience rooted in macroscopic observations and symbolic representations can greatly enhance students' proficiency and appreciation of chemical phenomena (Figure 1).

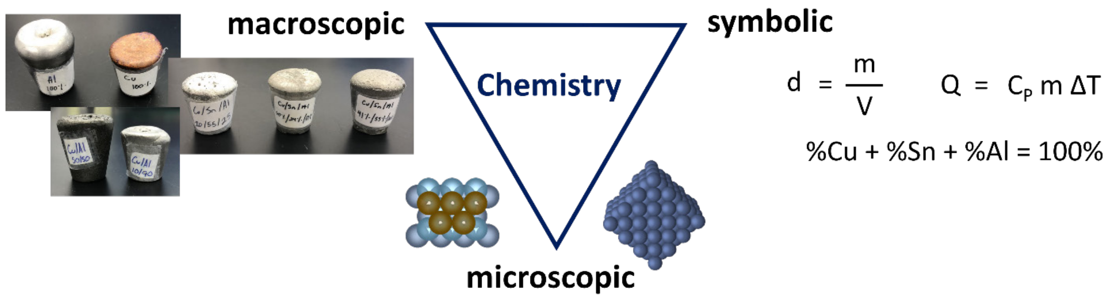

Figure 1. Macroscopic, microscopic, and symbolic representations in the laboratory experience.

Background

This study builds upon previously published work on metal alloy analyses by Villalta-Cerdas & McCleary (2019) in this journal.. Metal alloys, ubiquitous in tools, coins, and cookware, offer a comprehensive exploration into their chemistry. The selected laboratory approach can foster an interest in material science and the chemical modulations influencing material properties for specific applications. Designed as a trio of interlinked sessions, the previously published approach emphasized density determination and calorimetry as standalone experiments or a comprehensive unit to enhance student comprehension of the intricate relationship between chemical concepts and lab techniques.

In the preceding work, the emphasis was on three binary alloy systems. However, a proposition from a reader introduced the concept of amalgamating two binary alloy systems to formulate a tri-metal alloy system. This innovative approach aims to determine whether chemical composition can be deduced using a system comprising three linear equations with three corresponding variables. The theoretical associations delineated in equations 1, 3, and 5 were empirically evaluated by students through data acquisition on tri-metal alloy specimens composed of copper, aluminum, and tin. This evaluation aimed to validate their feasibility and subsequently gauge the laboratory exercise's potential to enhance students' understanding of macroscopic and symbolic representations in chemistry.

Relationship between chemical composition, density, and heat capacity in a tri-metal alloy

For this learning experience, we selected solid-state solutions as our analytes because their composition could be determined by carefully measuring the mass of each metal used during the alloy production. Thus, the first experimental assumption for the chemical analysis is that the alloys comprise three metals (Cu, Sn, and Al). The following equation is obtained considering the mass ratios of the components in the mixture:

Educación Química
Vol. 35, Núm. 1, enero-marzo 2024
https://doi.org/10.22201/fq.18708404e.2024.1.86324

$$m/m_{Cu} + m/m_{Sn} + m/m_{Al} = 1 \qquad \text{(eq. 1, assumption 1)}$$

From prior studies using binary metal alloys, we determined that the relationship between the density and chemical composition of alloys can be described assuming a linear addition of the volumes of each metal in the alloy mixture. Therefore:

$$V_{alloy} = V_{Cu} + V_{Sn} + V_{Al} \qquad \text{(eq. 2, assumption 2)}$$

Using the definition of density, d = m/V, and equations 1 and 2, it can be derived that:

$$1/d_{alloy} = m/m_{Cu} / d_{Cu} + m/m_{Sn} /d_{Sn} + m/m_{Al} /d_{Al} \qquad \text{(eq. 3)}$$

Lastly, if the absorbed heat (Q_{alloy}) by an alloy can be estimated by the linear addition of the heat required by each metal in the mixture, then:

$$Q_{alloy} = Q_{Cu} + Q_{Sn} + Q_{Sn} \qquad \text{(eq. 4, assumption 3)}$$

Using the definition of heat capacity, $C_p = Q / m\Delta T$, it can be derived that:

$$C_{p,alloy} = m/m_{Cu} \times C_{p,Cu} + m/m_{Sn} \times C_{p,Sn} + m/m_{Al} \times C_{p,Al} \qquad \text{(eq. 5)}$$

Equations 1, 3, and 5 collectively constitute a system of three linear equations with three variables: the chemical composition of each constituent metal in the alloy (i.e., m/m_{Cu}, m/m_{Sn}, m/m_{Al}). It is imperative to obtain empirical measurements of both density and specific heat capacity for the pure metals and alloy samples to elucidate this system. These experimentally determined values will subsequently serve as coefficients within the equations. Within the scope of this work, we sought to ascertain whether the tri-metal alloy composed of Cu-Sn-Al would result in a system of equations with a singular solution. Specifically, each equation within this system symbolizes a plane in a three-dimensional space. A solution to the system corresponds to a point concurrent on all three planes. Hence, the solution is deemed unique if a singular point is identified as concurrent on all three planes. Within the context of this experiment, this unique solution embodies the chemical composition of the tri-metal alloy.

Experiment description

Alloy production

Ten alloy samples with varied copper, tin, and aluminum compositions were synthesized. An aggregate mass of 100 g, derived from individual pure metals, was introduced into a one-liter graphite crucible. Subsequently, the crucible was situated within a furnace pre-conditioned to 500 ˚C. The furnace's temperature was incrementally elevated to 1100 ˚C over 10 minutes. Following a 20-minute interval, the liquefied amalgamation was decanted into a pre-warmed graphite mold. Upon the alloy's temperature descending to approximately 700 ˚C, it underwent a quenching process in ambient temperature water. Post-quenching, the specimen was primed for experimental evaluation. The chemical composition of the alloy samples was determined relative to the mass proportions of the pure metals present in the initial mixture. See Appendix A for a detailed experimental procedure.

Density and specific heat capacity determination

Building upon prior work (Villalta-Cerdas and McCleary, 2019), the samples' density and specific heat capacity were ascertained. Density was meticulously evaluated using hydrostatic weighing, referencing established density values for deionized water at the experimental temperature (Figure 2). See Appendix A for a detailed experimental procedure.

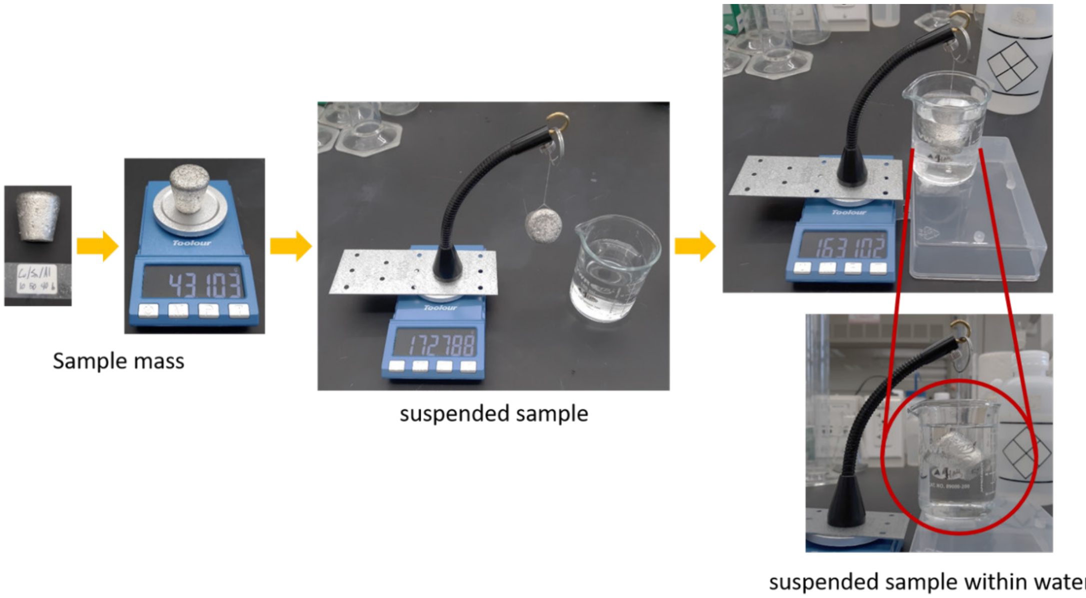

Figure 2. Hydrostatic weighing of alloy samples.

The specific heat capacity was determined by employing calorimeters traditionally utilized in foundational science curricula. The alloy sample was subjected to a thermal range of 90-100 °C within a hot-water bath before its introduction into the calorimeter. It contained 90 g of deionized water maintained at ambient conditions. Continuous agitation of the calorimeter was sustained until thermal equilibrium was reached (Figure 3). See Appendix A for a detailed experimental procedure.

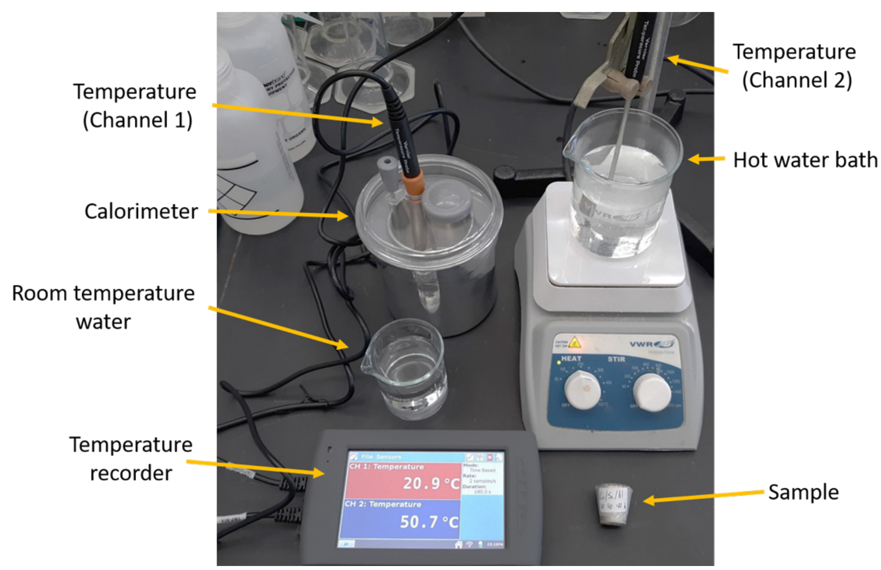

Figure 3. A calorimeter and other equipment are used to determine specific heat capacity.

Results and discussion

In the study, students initiated the process by determining pristine metal samples' density and specific heat capacity. The findings in Table 1 demonstrate a good agreement between experimental and literature-reported values for density and specific heat capacities

Educación Química

(Touloukian & Buyco, 1970; Haynes, 1984; Engineers Edge, LCC, 2021). Notably, deviations in specific heat capacity exceeded 10% for aluminum and tin. These disparities, however, cannot be attributed to sample impurities, as corroborated by the minimal error observed in the measured densities of these samples. Instead, these deviations can be traced back to the inherent limitations of the instrumentation deployed during the experiment. From an educational standpoint, this exercise remains invaluable, offering students an insight into the intricacies and inherent uncertainties of empirical work. For the objectives of the present study, solely the experimentally derived values were employed for the data analysis of the tri-metal alloys.

Table 1. Density values for pristine metals.

Measurement	Result	U(result)	Reported Value	%error
Density - 100% Cu	8.90 g/mL	0.02	8.940 g/mL	-0.4%
Density - 100% Sn	7.27 g/mL	0.01	7.280 g/mL	-0.2%
Density - 100% Al	2.711 g/mL	0.002	2.712 g/mL	-0.05%
Heat capacity - 100% Cu	0.367 J/g °C	0.007	0.377 J/g °C	-2%
Heat capacity - 100% Sn	0.19 J/g °C	0.01	0.218 J/g °C	-11%
Heat capacity - 100% Al	0.76 J/g °C	0.05	0.921 J/g °C	-18%

Subsequently, the students proceeded to analyze the tri-metal alloy samples. The composition of these samples was predetermined, as the alloys were synthesized in-lab by quantitatively assessing the mass of each metal before the melting process. The derived measurements for density and specific heat capacity are presented in Table 2. During this experimentation phase, students employed equations 3 and 5 to extrapolate the samples' anticipated density and specific heat capacity, referencing the chemical composition delineated as mass ratios. The computational outcomes demonstrate substantial concordance with the experimentally acquired values, bearing percent errors within the range of +/-10%. These findings reinforce the validity of the initial assumptions delineated during the derivation of equations 3 and 5 within the context of this work.

Table 2. Experimental and calculated density and heat capacity of tri-metal alloys.

Sample	Composition			Experimental Measurements				Calculated Properties			
	%Cu	%Sn	%Al	Density (g/mL)	U (density)	C_p (J/g °C)	U (C_p)	Density (g/mL)	% error density	C_p (J/g °C)	% error C_p
1	10%	50%	40%	4.55	0.01	0.423	0.008	4.39	-4%	0.437	3%
2	15%	59%	26%	5.18	0.01	0.374	0.010	5.13	-1%	0.368	-1%
3	20%	55%	25%	5.46	0.01	0.338	0.010	5.26	-4%	0.369	9%
4	23%	30%	47%	4.11	0.02	0.497	0.011	4.16	1%	0.498	0%
5	26%	26%	48%	4.21	0.01	0.501	0.009	4.14	-2%	0.508	1%
6	30%	10%	60%	4.02	0.01	0.553	0.015	3.73	-7%	0.582	5%
7	41%	33%	26%	5.18	0.01	0.416	0.002	5.32	3%	0.413	-1%
8	50%	33%	17%	6.41	0.01	0.340	0.014	6.09	-5%	0.376	10%
9	59%	24%	17%	6.35	0.01	0.368	0.021	6.18	-3%	0.393	7%
10	60%	30%	10%	6.32	0.03	0.377	0.004	6.85	8%	0.355	-6%
								average	-1%		3%
								SD	4%		5%

Educación Química
Vol. 35, Núm. 1, enero-marzo 2024
https://doi.org/10.22201/fq.18708404e.2024.1.86324

System of three linear equations with three variables

The experimentation's concluding phase involved evaluating the algebraic and geometric solutions of the system of equations. Initially, an algebraic resolution of the triad of equations was undertaken for each of the three variables: m/m_{Cu}, m/m_{Sn}, and m/m_{Al}. The resultant solution is delineated in Figure 4.

Variables	Equations	Solution	Terms A and B:
$^{m}/_{m}Cu$	$^{m}/_{m}Cu + {^{m}/_{m}Sn} + {^{m}/_{m}Al} = 1$	$^{m}/_{m}\mathbf{Cu} = 1 - {^{m}/_{m}Sn} - {^{m}/_{m}Al}$	$\boldsymbol{A} = \left(\frac{1/d_{Alloy} - 1/d_{Cu}}{1/d_{Sn} - 1/d_{Cu}}\right)$
$^{m}/_{m}Sn$	$\frac{1}{d_{Alloy}} = \frac{^{m}/_{m}Cu}{d_{Cu}} + \frac{^{m}/_{m}Sn}{d_{Sn}} + \frac{^{m}/_{m}Al}{d_{Al}}$	$^{m}/_{m}\mathbf{Sn} = \boldsymbol{A} + \boldsymbol{B}\,{^{m}/_{m}Al}$	$\boldsymbol{B} = \left(\frac{1/d_{Cu} - 1/d_{Al}}{1/d_{Sn} - 1/d_{Cu}}\right)$
$^{m}/_{m}Al$	$C_{p,\,alloy} = ({^{m}/_{m}Cu} \times C_{p,\,Cu}) + ({^{m}/_{m}Sn} \times C_{p,\,Sn}) + ({^{m}/_{m}Al} \times C_{p,\,Al})$	$^{m}/_{m}\mathbf{Al} = \frac{C_{p,\,alloy} - C_{p,\,Cu} + \boldsymbol{A}\,C_{p,\,Cu} - \boldsymbol{A}\,C_{p,\,Sn}}{\boldsymbol{B}\,C_{p,\,Sn} + C_{p,\,Al} - \boldsymbol{B}\,C_{p,\,Cu} - C_{p,\,Cu}}$	

Figure 4. Algebraic solution of three equation system.

Students determined the alloy samples' chemical composition using the solution equations derived from the algebraic approach. These results are tabulated in Table 3, expressed as percent mass. The deduced chemical compositions were observed to closely align with anticipated values, showcasing deviations within a range of +/-10% for all evaluated alloys. Such outcomes underscore the suitability of this learning module as an introductory avenue to material science topics and the implementation of mathematical models in real-world applications.

Table 3. Calculated percent mass composition of the alloys.

Sample	Experimental Measurements				Actual Composition			Calculated Composition			Deviations		
	Density (g/mL)	U (density)	C_p(J/g °C)	U (C_p)	%Cu	%Sn	%Al	%Cu	%Sn	%Al	$\Delta_{\%Cu}$	$\Delta_{\%Sn}$	$\Delta_{\%Al}$
1	4.55	0.01	0.423	0.008	10%	50%	40%	13%	50%	37%	3%	1%	-3%
2	5.18	0.01	0.374	0.010	15%	59%	26%	19%	55%	26%	5%	-4%	0%
3	5.46	0.01	0.338	0.010	20%	55%	25%	14%	65%	21%	-6%	10%	-4%
4	4.11	0.02	0.497	0.011	23%	30%	47%	20%	32%	48%	-4%	3%	1%
5	4.21	0.01	0.501	0.009	26%	26%	48%	27%	27%	46%	1%	0%	-1%
6	4.02	0.01	0.553	0.015	30%	10%	60%	37%	10%	52%	7%	0%	-7%
7	5.18	0.01	0.416	0.002	41%	33%	26%	37%	35%	28%	-4%	2%	2%
8	6.41	0.01	0.340	0.014	50%	33%	17%	43%	44%	13%	-7%	11%	-4%
9	6.35	0.01	0.368	0.021	59%	24%	17%	54%	32%	14%	-6%	8%	-3%
10	6.32	0.03	0.377	0.004	60%	30%	10%	57%	28%	15%	-3%	-1%	5%
										average	-1%	3%	-2%
										SD	5%	5%	4%

The minimal discrepancies observed in the chemical composition affirm that the system of three equations possesses a unique mathematical solution for the tri-metal system examined. Consequently, students endeavored to devise a strategy to geometrically ascertain the solution for this equation system. In pursuit of this objective, students adapted equations 1, 3, and 5 to evaluate them within a three-dimensional framework by transforming the original equations to versions where the variable m/mAl is deduced utilizing arbitrary value sets for the variables m/mSn and m/mCu (Figure 5). The coefficients of these equations remain the experimentally determined values for density and specific heat capacity of the pure metals. At the same time, the d_{alloy} and $C_{p,\,alloy}$ are contingent upon the specific tri-metal sample in question.

In the subsequent phase, three-dimensional point sets were derived for each linear equation. These sets were subsequently visualized in a tri-dimensional space employing computational software. For this work, visualizations were facilitated using the complimentary edition of Plotly Chart Studio (Plotly Technologies Inc., 2015). Figure 6 delineates a representative depiction wherein three distinct colored planes symbolize each linear equation in the three variables. The different perspectives show the single intersection point amongst the planes, representing the solution to the three-equation system.

Initial Equations

$$^{m}/_{m}Cu + {}^{m}/_{m}Sn + {}^{m}/_{m}Al = 1$$

$$\frac{1}{d_{Alloy}} = \frac{^{m}/_{m}Cu}{d_{Cu}} + \frac{^{m}/_{m}Sn}{d_{Sn}} + \frac{^{m}/_{m}Al}{d_{Al}}$$

$$C_{p,\,alloy} = (^{m}/_{m}Cu \times C_{p,\,Cu}) + (^{m}/_{m}Sn \times C_{p,\,Sn}) + (^{m}/_{m}Al \times C_{p,\,Al})$$

Modified Equations

$$^{m}/_{m}Al = 1 - (^{m}/_{m}Cu + {}^{m}/_{m}Sn)$$

$$^{m}/_{m}Al = d_{Al} \times \left(\frac{1}{d_{Alloy}} - \frac{^{m}/_{m}Cu}{d_{Cu}} + \frac{^{m}/_{m}Sn}{d_{Sn}} \right)$$

$$^{m}/_{m}Al = \frac{1}{C_{p,\,Al}} \left[C_{p,\,alloy} - \left[(^{m}/_{m}Cu \times C_{p,\,Cu}) + (^{m}/_{m}Sn \times C_{p,\,Sn}) \right] \right]$$

Figure 5. Modified equations to graph in a three-dimensional space.

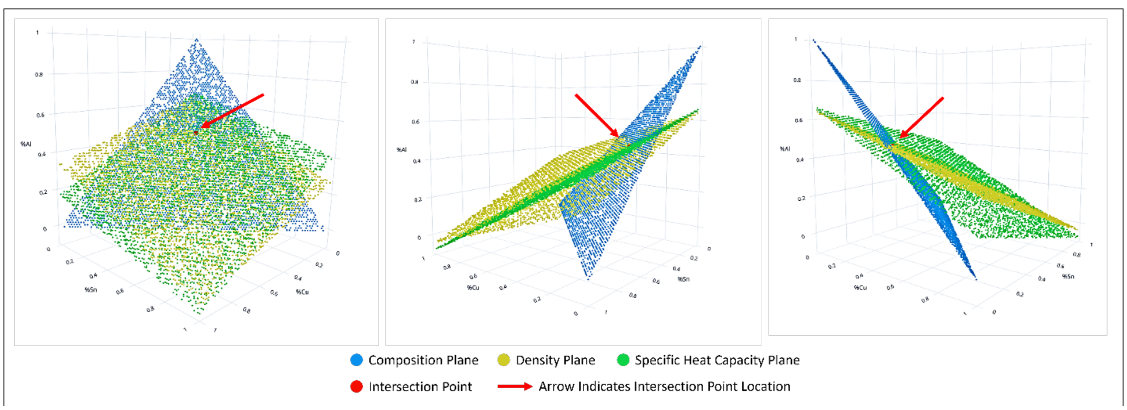

Figure 6. Geometrical method to solve the three equation system.

Impact on student learning

The activity delineated in this work offers a robust platform for students to navigate the intricate relationship between macroscopic observations and symbolic representations in chemistry. It provides a tangible interface where theoretical constructs are melded with empirical explorations. Through the meticulous synthesis and analysis of alloy samples, students are ushered into a realm where the abstract nature of chemistry is decoded into discernible, tangible phenomena. This transition from the abstract to the tangible is a cardinal pedagogical stride; it morphs the obscure into the discernible, fostering a deeper comprehension and appreciation of chemical concepts (Talanquer, 2009; Kolb, D. A, 2014).

Central to this educational venture is the exploration of density and specific heat capacity. These fundamental concepts become the conduit through which students traverse between chemistry's macroscopic and symbolic realms. The activity beckons students to employ mathematical representations actively, notably in the formulation and solution of the system of linear equations. This engagement with mathematical models is not merely a mechanical exercise but an exploration of the symbiotic relationship between chemical composition and its attendant physical properties. It offers a narrative where numbers and symbols morph into substances with distinct identities and behaviors.

Moreover, the graphical representation of equations in a three-dimensional space imbues the students with a visual comprehension of the systemic relations inherent in the alloy system. This three-dimensional vista is a formidable tool for demystifying the often nebulous abstract relations underlining chemical phenomena. It fosters a spatial intuition of chemical relations, a crucial asset in the arsenal of developing scientists (Talanquer, V., 2010).

Conclusions

In experimental investigations, especially those situated within educational settings, the elucidation of results must be reconciled with anticipated deviations and instructional outcomes. Through our extensive analysis of the tri-metal (Cu-Sn-Al) alloy samples, several significant observations and inferences were made which can be extrapolated to broader pedagogical and scientific contexts.

- Accuracy and precision of determined values: the calculated densities and specific heat capacities of the Cu-Sn-Al alloys are noteworthy for their closeness to expected values. Notably, the observed errors lie within the acceptable margins for a pedagogical laboratory setting. Such data is imperative for students, as it instills confidence in experimental methodologies and offers a tangible correlation between theoretical predictions and practical outcomes.

- Chemical composition deviations: the evaluation of composition offered insightful results. While deviations from the anticipated values were indeed observed, they fluctuated both below and above the stipulated benchmarks. Such discrepancies might be attributed to random errors when determining specific heat capacities. It's imperative to understand that these variations do not necessarily indicate systemic inadequacies in the procedure, but could result from unforeseen variables or minor experimental oversights.

- Analysis assumptions and resulting variations: foundational assumptions guide any experimental undertaking. In the context of this analysis, the assumptions might not encapsulate all the complexities inherent to the real-world sample analysis. Consequently, deviations from these baseline assumptions can partly explain the recorded percentage errors and observed variations. Acknowledging and understanding these deviations is integral for both the students and instructors to ascertain the boundaries of the method employed and to refine future iterations of the experiment.

- Pedagogical merits: the sequential layout of experiments, encompassing varied methods and objectives, provides students with a holistic and integrative learning experience. The experiments leverage standard laboratory equipment, emphasizing the accessibility and reproducibility of the methodologies used. Such a comprehensive experience imparts crucial technical skills and reinforces foundational chemical concepts and their real-world applications.

- Impact on student learning: Central to this academic enterprise is the meticulous exploration of fundamental concepts such as density and specific heat capacity. These conduits usher students between the macroscopic and symbolic vistas of chemistry. The active engagement in mathematical representations transcends a mechanical exercise, unveiling a symbiotic narrative where numerical and symbolic elements metamorphose into substances with distinct identities and behaviors. Furthermore, the visual expedition into a three-dimensional representation of equations encourages students with a spatial comprehension of systemic relations within the alloy system, thereby demystifying abstract relations integral to chemical phenomena.

In summation, the experience stands poised to facilitate students in forging linkages between macroscopic observations and their corresponding symbolic representations in chemistry, embodied by the equations that elucidate such observations. While the empirical data and its deviations provide a foundation for scientific scrutiny and iterative refinement, the broader implications of this study reside in its pedagogical merit. It accentuates the importance of hands-on learning, critical analysis, and the iterative nature of scientific investigations within the educational domain.

Conflict of interests

The authors declare no conflict of interest.

Acknowledgments

The authors extend their gratitude to the Professional and Academic Center for Excellence (PACE) and the Engaging Classrooms Quality Enhancement Plan (QEP) for their unwavering support of active learning and the integration of evidence-based practices within the chemistry curriculum at Sam Houston State University (SHSU). This work was supported by the the Department of Chemistry at SHSU, the Welch Foundation (grant No. X-0011), and the National Science Foundation (grant No. 1725674). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Bretz, S. L., Fay, M., Bruck, L. B., & Towns, M. H. (2013). What faculty interviews reveal about meaningful learning in the undergraduate chemistry laboratory. *Journal of Chemical Education*, *90*(3), 281-288.

Chamizo, J. A. (2009). Filosofía de la química: I. Sobre el método y los modelos. *Educación química*, *20*(1), 6-11.

Engineers Edge, LCC. Specific Heat Capacity of Metals. Visited on July 2023. https://www.engineersedge.com /materials/specific_heat_capacity_of_metals_13259.htm.

Galloway, K. R., & Bretz, S. L. (2015). Development of an assessment tool to measure students’ meaningful learning in the undergraduate chemistry laboratory. *Journal of Chemical Education*, *92*(7), 1149-1158.

Hansen, S. J. R., Hu, B., Riedlova, D., Kelly, R. M., Akaygun, S., & Villalta-Cerdas, A. (2019). Critical consumption of chemistry visuals: eye tracking structured variation and visual feedback of redox and precipitation reactions. *Chemistry Education Research and Practice*, *20*(4), 837-850.

Haynes, W. M. (1984). *CRC handbook of chemistry and physics*. CRC press.

Kelly, R., & Akaygun, S. (2019). Visualizations and representations in chemistry education. *Chemistry Education Research and Practice*, *20*(4), 657-658.

Kelly, R. M., Akaygun, S., Hansen, S. J., & Villalta-Cerdas, A. (2017). The effect that comparing molecular animations of varying accuracy has on students’ submicroscopic explanations. *Chemistry Education Research and Practice*, *18*(4), 582-600.

Kelly, R. M., Akaygun, S., Hansen, S. J., Villalta-Cerdas, A., & Adam, J. (2021). Examining learning of atomic level ideas about precipitation reactions with a resources framework. *Chemistry Education Research and Practice*, *22*(4), 886-904.

Kolb, D. A. (2014). *Experiential learning: Experience as the source of learning and development*. 2nd edition. Pearson FT Press.

Millán, G. H. (2012). Enseñanza experimental.¿Cómo y para qué? *Educación química*, *23*, 92-94. https://doi.org/10.1016/S0187-893X(17)30139-8.

Plotly Technologies Inc. (2015). Title: Collaborative data science Publisher: Plotly Technologies Inc. Place of publication: Montréal, QC.

Robinson, W. R. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use.

Taber, K. S. (2001). Building the structural concepts of chemistry: some considerations from educational research. *Chemistry education research and practice*, *2*(2), 123-158.

Talanquer, V. (2009). Química:¿Quién eres, a dónde vas y cómo te alcanzamos? *Educación química*, *20*, 220-226. https://doi.org/10.1016/S0187-893X(18)30056-9.

Talanquer, V. (2010). Construyendo puentes conceptuales entre las varias escalas y dimensiones de los modelos químicos. *Educació química*, 11-18. https://revistes.iec.cat/index.php/EduQ/article/view/61890.001

Touloukian, Y. S., & Buyco, E. H. (1971). Thermophysical properties of matter-the TPRC data series. Volume 4. Specific heat-metallic elements and alloys. *Thermophysical and electronic properties information analysis center Lafayette in*.

Villalta-Cerdas, A.; McCleary, C. (2019). Analysis of copper alloys as an introduction to data analysis and interpretation for General Chemistry courses. *Educación Química, 30*(2), 41-53. https://doi.org/10.22201/fq.18708404e.2019.2.67346.

Recepción: 07/08/2023. Aceptación: 19/10/2023.

Educación Química
Vol. 35, Núm. 1, enero-marzo 2024
https://doi.org/10.22201/fq.18708404e.2024.1.86324

Appendix A

Experimental Procedures

A) Synthesis of Cu-Sn-Al alloys

- Objective: to synthesize ten different alloy samples of copper, tin, and aluminum with varied compositions and evaluate their chemical compositions based on mass proportions of the constituent metals.

- Materials required:

1. Pure metals: copper (Cu), tin (Sn), and aluminum (Al)
2. One-liter graphite crucible
3. Furnace capable of reaching 1100 ˚C
4. Graphite mold
5. Calibrated weighing scale (two-decimal balance, with a maximum load of 300 g)
6. Protective gear: heat-resistant gloves, face shield, and apron

- Procedure:

Ensure that all safety protocols are adhered to before commencing the experiment. Put on protective gear, including heat-resistant gloves, a face shield, and an apron to prevent burns or injuries.

1. Weighing of metals:

- Accurately weigh the required amounts of copper, tin, and aluminum such that their total mass equals 100 g. Use Table 2 on the main manuscript to determine the percent composition of the mixture to be produced.

- Record the masses of Cu, Sn, and Al in grams to the second decimal. These values will be used for later determination of the actual chemical composition.

2. Crucible loading:

- Carefully place the weighed metals into a one-liter graphite crucible.

3. Melting:

- Position the loaded crucible in a furnace preheated to 500 ˚C.

- Gradually increase the furnace temperature to 1100 ˚C over 10 minutes.

4. Alloy formation:

- Maintain the temperature at 1100 ˚C for 20 minutes to ensure complete melting and mixing of the metals.

- Carefully remove the crucible from the furnace (ensure you are wearing heat-resistant gloves) and pour the molten metal into a pre-warmed graphite mold.

5. Cooling and quenching:

- Allow the molten alloy to cool to around 700 ˚C within the mold.

- Once the temperature reaches 700 ˚C, immerse the mold with the alloy in water at room temperature to quench it.

6. Sample preparation:

- Remove the cooled alloy from the mold and dry it thoroughly.

- The alloy sample is now ready for further experimental evaluation.

7. Chemical composition analysis:

- Determine the chemical composition of the alloy samples by evaluating the mass proportions of copper, tin, and aluminum based on the recorded masses from Step 1.

8. Cleanup:

- Ensure the working area is cleaned, and all equipment is stored safely post-experiment.

B) Determination of alloy density

- Objective: to accurately determine the density of synthesized alloy samples using hydrostatic weighing.

- Materials required:

1. Alloy samples
2. Three-decimal balance (maximum load of 300 g)
3. Metal hook and support base
4. Fine cotton thread
5. Beaker (50 mL)
6. Deionized water
7. Thermometer

- Procedure: ensure all safety protocols are followed before commencing the experiment.

Set up a clean, level, and organized workspace to conduct the experiment.

1. Mass measurement of alloy sample:

- Using a three-decimal balance, accurately measure and record the mass of the alloy sample to the nearest thousandth of a gram.

2. Suspension setup:

- Carefully wrap a fine cotton thread around the alloy sample and attach it to a metal hook. See Figure 2 in the manuscript as a reference.
- Record the mass of the entire suspension system using the balance.

3. Water preparation:

- Fill a 50 mL beaker with deionized water and allow it to stabilize to the ambient temperature of the laboratory.
- Record the water temperature using a thermometer, as it is essential for referencing established water density values at this specific temperature.

4. Submersion and mass measurement:

- Gently submerge the suspended alloy sample into the water in the beaker, ensuring it does not touch the walls or base.
- Record the new mass measurement of the suspension system while submerging the alloy.

5. Calculations:

- Determine the difference in mass between the suspension system in air and submerged in water; this difference equals the mass of water displaced.
- Convert the mass of displaced water to volume using the density of water at the recorded temperature (referenced from established density values).
- The volume of displaced water equals the volume of the alloy sample.
- Calculate the density of the alloy sample using the formula:
- Density = Mass of Alloy / Volume of Displaced Water

6. Cleanup:

- Ensure the working area is cleaned, and all equipment is stored safely post-experiment.

Educación Química

C) Determination of the specific heat capacity of the alloys

- Objective: to determine the specific heat capacity of synthesized alloy samples using a calorimeter.

- Materials Required:

1. Alloy samples
2. Calorimeter
3. Hot-water bath
4. Thermometer
5. Stirrer
6. Deionized water
7. Balance (two-decimal balance with a maximum load of 300 g)

- Procedure: ensure adherence to all safety protocols before initiating the experiment. Establish a clean, level, and organized workspace for conducting the experiment.

1. Sample pre-heating:

- Pre-heat the hot-water bath to a temperature range of 90-100 ºC.

- Place the alloy sample in the hot-water bath until it reaches a stable temperature within the specified range, monitoring the temperature with a thermometer.

2. Calorimeter setup:

- Measure and pour 90 g of deionized water into the calorimeter.

- Record the initial temperature of the water in the calorimeter using a thermometer.

3. Calorimeter constant determination: Determine the calorimeter constant using deionized water at room temperature and at 100 ºC, as per established procedures or guidelines provided.

a) Measure and pour a known mass (e.g., 100 g) of deionized water at room temperature into the calorimeter.

b) Record the initial temperature of the water using a thermometer.

c) Heat a separate known mass of deionized water (e.g., 100 g) in a hot-water bath until it reaches 100 ºC.

d) Carefully transfer the heated water to the calorimeter containing the room-temperature water.

e) Immediately cover the calorimeter and stir the mixture continuously until a stable temperature is achieved.

f) Record this final temperature using a thermometer.

4. Specific heat capacity of the alloy sample:

a) Carefully transfer the heated alloy sample from the hot-water bath to the calorimeter, minimizing heat loss during the transfer.

b) Dry the sample quickly with a paper towel to avoid transferring hot water into the calorimeter.

c) Place the lid on the calorimeter and continuously stir the contents to ensure uniform heat distribution.

d) Monitor and record the temperature inside the calorimeter until thermal equilibrium is reached (i.e., the temperature remains constant).

e) Record the final temperature of the water and the alloy sample.

5. Calculations:

- The constant of the calorimeter, C_{cal}: use the following equation to determine the constant of the calorimeter:

$$C_{cal} = [\ -(m_{hot\text{-}water} \times c_{s,water} \times \Delta T_{hot\text{-}water}) - (m_{cold\text{-}water} \times c_{s,water} \times \Delta T_{cold\text{-}water})\ ] / \Delta T_{calorimeter}$$

Where $m_{hot\text{-}water}$ and $m_{cold\text{-}water}$ are the masses of hot and cold water, respectively; $c_{s,water}$ is the specific heat capacity of water reported in the literature (i.e., 4.1844 J/g °C); and $\Delta T_{hot\text{-}water}$, $\Delta T_{cold\text{-}water}$, and $\Delta T_{calorimeter}$ are the temperature differences for the hot water, cold water, and the calorimeter during the experiment.

- Heat capacity of the alloy sample: use the following equation to determine the heat capacity of the alloy, $c_{s,alloy}$:

$$c_{s,alloy} = [\ (m_{cold\text{-}water} \times c_{s,water} \times \Delta T_{cold\text{-}water}) + C_{cal} \times \Delta T_{calorimeter}\ ] / (\ m_{alloy} \times \Delta T_{alloy}\ )$$

Where, $m_{cold\text{-}water}$ and m_{alloy} are the masses of the cold water and alloy, respectively; $c_{s,water}$ is the specific heat capacity of water reported in the literature (i.e., 4.1844 J/g °C); and $\Delta T_{cold\text{-}water}$, $\Delta T_{calorimeter}$, ΔT_{alloy} are the temperature differences for the cold water, the calorimeter, and the alloy during the experiment.

6. Cleanup:

- Ensure the working area is cleaned, and all equipment is stored safely post-experiment.