Introductory Concepts in Chemical Engineering – A Textbook with a Simplified Approach to Mass and Energy Balance Calculations

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Abstract. Mass and energy balance is fundamental in chemical engineering and other fields. The first course comprises basic principles emphasizing mass and energy balance calculations. This paper aims to teach computations in a simplified manner using algebra and arithmetic. The strategy applied is to regard problems in mass and energy balance calculations under steady-state situations as verbal problems in algebra or arithmetic. Students are familiar with similar problems on mixing, compounding, separation, etc., in their high school algebra. The book is structured such that each chapter has only a few new relationships, thus avoiding overloading the students. Towards the end of the book, the students are confident in solving mass and energy balance problems. The following are the chapters: 1. Introduction, 2. Essential Basic Principles, 3. Mass Balance I: No Chemical Reactions Involved, 4, Mass Balance II: Chemical Reactions Involved, 5. Heat Balance, 6. Graphical Solution 7. Equilibrium and Mass & Heat Balances, and 8. Energy Balance. The textbook has been used at the University of the Philippines for several years and would suit other schools.

1. Introduction

Mass and energy balance calculations (MEBC) are essential to chemical engineering. Based initially on stoichiometry, it has transformed into its present form since the introduction of unit operations in 1915. How can we improve the teaching of such a course? This task is difficult, considering the course structure is established and satisfactory. A non-traditional approach may be required to introduce a change. While the principles are simple, MEBC is essential in higher chemical engineering, such as modeling and simulation. Using advanced mathematics and computers allows us to automate calculations. This development tempts us to extend the use of computers to MEBC for beginning chemical engineering students. As these students lack most of the necessary background in chemical engineering, using the technique becomes less effective. The logical approach is to teach them the fundamentals and tools that match their background level. Instead of computer-aided computation, we should employ the traditional manual calculation method. Students have taken up arithmetic and algebra before. Some verbal problems they have encountered, such as mixing, separation, and compounding, are simple mass balance problems. This paper discusses a proposed teaching strategy that regards MEBC under steady-state situations as an extension of arithmetic and algebra subjects.

2. Development of Techniques in Mass and Energy Balance Calculation The first paragraph

Other The teaching of mass and energy balance calculations is an integral part of the history of chemical engineering. It has become the starting point of many activities in this discipline. One of the first books on MEBC was "Metallurgical Calculations" by Richards (1906), which mainly dealt with stoichiometry for the metallurgical industry and was also used for industrial chemistry. The calculations were arithmetical. MEBC for systems not involving chemical reactions became necessary with the introduction of unit operations in 1915 and the subsequent publication of the book, "Principles of Chemical Engineering" (Walker et al., 1923). Lewis and Radasch (1926) extended stoichiometry to mass balance without chemical reaction with the publication of "Industrial Stoichiometry," which dealt mainly with applications in some process industries. The computations involved simple arithmetic and algebraic solutions using ratios and fractions very prominent. Relationships derived from physical and chemical principles were evident.

Hougen and Watson (1931) published the book "Industrial Chemical Calculations" and presented MEBC with a more elementary and fundamental approach. The two books became the basis of the modern MEBC. The book "Chemical Process Principles" (Hougen et al., 1947) placed MEBC on a higher level as a significant subject in chemical engineering. The methods of calculation were still algebraic and arithmetical. Since then, the role of MEBC in process, equipment, plant design, and related activities has become more critical. With the start of the engineering science movement in the 1960s, MEBC became a part of mathematical modeling in chemical engineering. Steady-state mass balance calculations are fundamental in finding alternatives in plant design and the economics of chemical processes. The general mass balance problem involves solving a large set of non-linear equations or a problem in non-linear programming using computers. Rosen (1962) proposed a particular mathematical formulation of the problem and solution algorithm. This dual application of MEBC – in an introductory course and an application in higher chemical engineering – has affected how we teach mass and energy balances. We should take a fresh look at the situation to adopt an appropriate strategy. The approach offered by this paper follows.

3. Basis and Conception of the Strategy

The MEBC subject had a profound effect on me during my undergraduate education. The textbook used in MEBC influenced me to develop my chemical engineering skills. Later, as a chemical engineering instructor, I taught mass and energy balance calculations. I prepared my lecture notes with a course syllabus based on the textbooks I used during my undergraduate education. I arranged the topics based on what I believed was the logical way of teaching: start with the simplest theories and gradually add the necessary relationships so the students are not overwhelmed. My students did not perceive the change in the degree of difficulty of the topics as the course progressed. I used algebra and arithmetic.

In 1988, the National Research Council Committee on "Chemical Engineering Research Frontiers: Needs and Opportunities" reported on a study on the future of chemical engineering. It examined the potential impact of chemical engineering on other fields alongside the relevant definition of the profession. The report expounded on the changing paradigm of chemical engineering and its implication. The paradigm of chemical engineering refers to the characteristic set of problems and systematic methods for obtaining solutions. Initially, the profession did not have any paradigm. The significant change was the introduction of the concept of unit operations in 1915, which was the start of the first paradigm of chemical engineering. The other branches were mass balance calculations, thermodynamics, unit process, reaction kinetics, and process control. The start of the second paradigm was the introduction of transport phenomena alongside chemical reaction engineering, process dynamics and control, instrumentation, process design, and interdisciplinary technology. (Hougen, 1977; Judson King, 1976) The paradigm of chemical engineering is progressing today toward the 5th phase.

Kuhn (1962) and Covey (1989) fuelled my interest in paradigms. I began probing the paradigm of chemical engineering. By tracing and examining the history of chemical engineering, we can delineate the development of its paradigm. We should try to recognize minor or significant shifts in the paradigm. We critically note the developments and examine the practices within the profession. The evolution and metamorphosis of curriculum, published books and textbooks, journal articles, proceedings of conferences and seminars, stories, and anecdotes are significant sources of information necessary for the probing activity. Probing paradigms involves not merely reading and noting history. It is much more than analyzing and investigating. It deals with going into the internals and getting the "feel" of the paradigm. It is somewhat equivalent to finding insights, perspectives, points of view, orientation, or critical evaluation. (Jose, 1998) The term "paradigm" is complex since an exact definition is difficult to phrase. In the Structure of Scientific Revolutions, Kuhn used 21 different contexts in his essay (Mastermann, 1976). Probing paradigms is equally complicated and intimidating.

One of the probing activity results is the following: We can observe that chemical engineering knowledge is increasingly growing because of the inclusion of new developments in the paradigm. Topics are added, but virtually none is discarded. Chemical engineers must adapt to the changes, making them flexible or versatile. Chemical engineers have also adapted the paradigm of chemistry, a subject that is difficult to integrate with engineering. By probing the paradigm of chemical engineering, we can reason out that full-pledged chemical engineers have complete knowledge of the paradigm of chemical engineering while beginning students have a hazy idea of the subject. A logical teaching technique would be one that gradually gives the fundamentals, much like fitting them carefully to a developing paradigm in the students' minds. In this manner, the paradigm is progressively reinforced. (Jose, 2003) I have applied the technique in teaching the introductory course in chemical engineering. By providing concepts or parts of the paradigm sequentially, I avoided giving an overload of ideas. I let the students "feel" the formation of the chemical engineering paradigm in their minds. The course presents the basic principles of mathematics, physics, and chemistry in a chemical engineering orientation. The concepts gradually become part of the chemical engineering paradigm.

4. Developing a Textbook

Probing the paradigm of chemical engineering enabled me to write a book to support my activities in formulating teaching strategies. (Jose, 2009) Writing on mass and energy balance calculations requires an author to have the ability to introduce the chemical engineering paradigm to the students systematically. For this objective, he must remember that his audience is beginning chemical engineering students, not professionals. Since he knows the entire paradigm of chemical engineering, he might make his discussion appeal to chemical engineering graduates who want to review mass and energy balance calculations. He must avoid this as the book will be less effective. Undergraduate students would not be able to comprehend some of the discussion.

Many introductory textbooks introduce the paradigm. Felder and Rousseau (2000) articulate this as

> "An introductory stoichiometry course … prepares the student to formulate and solve material and energy balances on chemical process systems and lays the foundation for subsequent courses in thermodynamics, unit operations, kinetics, and process dynamics … it introduces the engineering approach to solving process-related problems ... to solve for the unknowns using a combination of experimentation, empiricism, and the application of natural laws."

The book of Luyben and Wenzel (1986) has the objective of

> "introducing beginning students to the field of chemical engineering and teaching the principles of mass and energy balances in the context of designing and operating a chemical process most profitably and safely."

The early books (Lewis et al., 1954; Williams and Johnson, 1958) and the widely used ones today (Felder and Rousseau, 2000; Himmelblau, 1996) have similar objectives. With the elementary treatment of mass balances, a different perception arises. According to Mansfield (1993),

> "the most underrated activity in project work for process plants … is the mass balance … because … it is humdrum with a tinge of being tedious (It lacks glamour.) and … it is so plain and self-evident; it must not be important."

An advanced book on mass balance might not have an audience. However, it could be part of a book on design (Wells and Rose, 1986) where mass and energy balance is needed. For example, Sinnott (1999) included material and energy balance fundamentals chapters in his design book. A beginning student will have difficulty understanding those chapters. Usually, to apply the mass balance in process design, an understanding of the equipment and the process and relevant chemical engineering knowledge (thermodynamics, kinetics, rate, transport process, etc.) is required. Mass balances can be straightforward if we know all the details and the function of each piece of equipment. In other words, we need a knowledge of the chemical engineering paradigm. A beginning textbook should start with the basic principles to gradually build the chemical engineering paradigm's foundation and framework. It should present ideas in a structured manner to slowly form a robust framework. This mode avoids the pitfall of the author being ahead of the reader in terms of the paradigm.

5. Explanation of the Strategy

The efficient implementation of a teaching strategy depends on the structured textbook for that strategy. For that reason, I wrote the text with arithmetic and algebraic solutions to problems incorporated because of probing the paradigm of chemical engineering. It was already in the fourth year of writing that a name for the strategy crystallized: Regard MEBC in a steady-state situation as an extension of arithmetic and algebra subjects. The problems in MEBC are viewed as verbal problems in arithmetic and algebra. Since all engineering students have more than a sufficient background in these subjects, learning MEBC will be easier and teaching more efficient. Most relationships needed to solve the problems are principles from chemistry, physics, mathematics, chemical engineering, and other fields. The others are the usual conditions given in arithmetic or algebra. Students will soon realize that many of the principles presented are the same ones they have learned. In this manner, the perceived difficulty in studying a new subject dissipates. The textbook and the course structure are such that only a few principles (used as relationships) are in each chapter. In this manner, the students are not overloaded. By the time all the relationships are given (towards the end of the book), students are confident in solving MEBC problems. The topic arrangement is in the following manner: (1) Introduction, (2) Mathematical, chemical, and physical principles, (3) Mass balances without chemical reaction, (4) Mass balances with chemical reactions, (5) Heat balance, (6) Graphical solution, (7) Equilibrium, and (8) Energy balances.

Based on the problem's structure and the students' experience, they can easily decide whether to use algebra, arithmetic, or both. For arithmetical solutions, they apply the arithmetical operations of addition, subtraction, multiplication, and division, among others, to the given quantities and obtain the required items. In other problems, the calculation is not direct. They must apply algebra (implicitly, generalized arithmetic). Here, they consider the required quantities as unknowns. They set up the equations using the appropriate relationships and solve for the unknowns. A limitation of using algebra is that manual solution is tedious if the number of unknowns exceeds four. As much as possible, the number of unknowns is kept to no more than three. We usually achieve this by using a combination of arithmetic and algebraic methods. Some quantities are evident that we can solve them arithmetically, reducing the number of unknowns. I prepared most problems in my book so that the number of unknowns is not more than three. We remind the students that they can use computers to solve problems involving hundreds of unknowns when they know all the principles.

What do we gain in using the strategy? With the process, students become adequately equipped with calculation tools. They would attack MEBC problems as arithmetic or algebra problems more confidently. With the gradual introduction of principles and relationships, the students can cope with the problems getting more difficult as the number of available relationships increases.

6. Comments From The Students

I used and tested the strategy in my classes and obtained favorable comments and reactions. I also noticed improved performance by the students. The following are some of the remarks given:

"The change is not abrupt as students are already familiar with algebra and arithmetic. All the students must do is manipulate known concepts and apply them to problems at hand with new knowledge from higher chemical engineering subjects."

"This strategy would improve my performance in future engineering courses since this approach makes me understand better the concepts behind mass and energy balances."

"It's like enjoying mathematics and chemistry simultaneously in the chemical engineering way."

"This method is very effective, essentially because of its simplicity. It is advantageous for the students to start solving problems they are familiar with and with methods they know by heart. It also lessens the intimidation factor of the subject for the new student."

"an effective means of building the confidence of students … makes the subject easily understood."

"makes the calculations easier to comprehend."

"The strategy was excellent, and it helped me a lot … starting from basic operations on mass balance … slowly incorporating chemical reactions … was highly effective…."

"Sometimes, reading a mass and energy balance problem can be overwhelming, but when you realize that it can be solved by mere algebra and arithmetic, the 'problem-fright' goes away…"

"This is a good strategy since it starts with familiar principles from the math/science subjects … the level of difficulty increases only gradually … with enough practice … more complex problems tackled eventually."

7. Conclusion

Textbooks in MEBC stress that using fundamental principles, problem analysis, logical habits of problem attack, solution planning, and problem-solution presentation are good practices. However, the application is difficult if an efficient teaching strategy is absent. A teaching strategy should facilitate the learning process and make studying a different experience from the usual one. I formulated the teaching strategy presented by examining the history of chemical engineering (particularly MEBC) and probing its paradigm. It is apparent that the method for MEBC developed from 1925 to 1935 (Hougen, 1977) profoundly affected the education of chemical engineers and the chemical engineering paradigm. Hence, the strategy retains most of those methodologies. The arrangement of topics is a critical aspect of the process. The process can facilitate the transition of chemical engineering students from general engineering courses to chemical engineering subjects. For teaching elementary MEBC, methods in arithmetic and algebra are efficient; we should reserve computer-aided calculations for advanced MEBC as applied to modeling and other applications.

This activity answered a challenge, "How can we inject a fresh approach in teaching mass and energy balance calculations, a topic that is a century old?"

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