A Modified Approach to Material & Energy Balances

D. C. Miller, M. H. Hariri, M. Misovich, M. Anklam, and R. Artigue
Department of Chemical Engineering
Rose-Hulman Institute of Technology

Introduction

The first course in chemical engineering (material and energy balances) has traditionally been a challenging course, which many students approach with fear and trepidation. Over the past several years, we have developed an approach, which we believe helps the students to better learn the concepts by reorganizing the material that more strongly emphasizes the fundamental concept of *conservation*. We accomplish this by broadly introducing the "balance" concept before delving into the complexity that can result with the more difficult types of problems. As such, our approach could be characterized as breadth-first, as opposed to the more widely used depth-first approach.

Looking at two of the most widely used texts[1,2] for M&E Balance courses reveals a remarkably similar organization. This is summarized in Table 1. In general, the books provide some introduction to chemical engineering and problem solving, followed a section on material balances, followed by a section on gasses and phase equilibrium, followed by a section on energy balances. In both texts, authors move completely through the concept of material balances before expanding balance principles to other areas, such as energy.

Table 1. Summary of material in two popular M&E Balance textbooks.

Topic	**Felder and Rousseau[1]**		**Himmelblau[2]**	
	Chapters	Pages	Chapters	Pages
Introductory material	1-3	80	1-2	140
Material balance	4	106	3	121
Gasses and phase equilibrium	5-6	124	4	126
Energy balances	7-9	193	5	155

The organization in these textbooks is closely followed by every single syllabi we were able to find posted on the web. We refer to this as the traditional organization and is the organization that we followed for many year. The hallmark of this approach is focusing on material balances in detail before moving on to energy balances. In some cases, this occurs in a single semester; in others, the material is covered in two quarters. In either case, the general organization of material is similar to that shown in the left column of Table 2. The first half consists essentially of mass balances; the second, energy balances. This material in the traditional approach rapidly increases in complexity with the addition of reactive systems, followed immediately by gasses and multiphase systems. The material then returns to a simpler level with the introduction of energy balances. This approach can be described as a "sequential linear approach," in which the students learn mass balances, starting with very simple applications, followed by more and more complicated applications of balances involving mass only. This approach is then repeated in the second half for energy balances.

The primary advantage of this approach is that it follows the format of the primary textbooks, and allows the class to proceed linearly through the book. This also makes the assignment of problems straightforward, since the problems in the text were written such that a student who had studied the prior chapters could complete them.

When we followed this approach, we found that there were significant negatives, however. First, the complexity of topics increases very rapidly from simple mass balance systems to systems with recycle, by-pass and chemical reaction. As a result students have little time to practice and digest the fundamental principle of conservation. Our reorganized approach postpones the additional complexity of reactive systems. Secondly, because the topics of mass and energy are considered separately, students may miss out on the importance of the idea that conservation is applicable to many types of properties (e.g., mass, energy, momentum, charge). Thus students tend to consider mass and energy conservation as two separate topics, and this approach inadvertently sends the wrong message to students. As a result of considering the topics separately, students have difficulty grasping the concept of coupled mass and energy balances that usually occurs in chemical engineering problems. Finally, although the traditional approach includes the concepts of input, output, generation, consumption, and accumulation, nearly all examples reduce to input equals output, thus making it more difficult for the students to transfer the concepts to other courses where they learn about the conservation of momentum (linear and angular) and the conservation of electrical charge. Thus, for example, the students miss the fact that Kirchhoff’s laws are just conservation principles applied to electrons.

Modified approach

In 1997 we undertook a process of revamping our curriculum. One aspect of that review concerned our two introductory material and energy balance courses. In conjunction with a number of initiatives at the Institute, we determined the that increasing the focus on conservation principles would better enable students to grasp these fundamental concepts that are so important for the remainder of the curriculum.

As a general principle, we teach conservation related to mass, energy, charge and linear momentum. Instead of taking each conserved quantity (mass, energy, etc.) separately and progressing from simple to complex applications, we follow a "coordinated parallel" approach as shown in Table 2. In this approach students first learn to apply the basic conservation law to simple situations involving mass, energy, momentum, and/or charge so that they could appreciate the commonality of application of a fundamental conservation law. In addition, the students more immediately become aware that mass and energy balances are closely coupled.

In solving problems related to these topics, the same solution approaches are required: development of process diagrams, determining degrees of freedom and writing the appropriate balance equations. By stressing the similarities between different types of conservation problems, we reinforce the basic concepts, which are so fundamental to engineering problem solving, yet are often so difficult to develop. Once these concepts are firmly established, we move on to single-phase systems and condensable systems in the first course and reactive systems, heat capacities, and transient systems in the second course.

In addition to developing greater proficiency in formulating and solving chemical engineering problems, students learn that the same fundamental approach applies as well to diverse fields. Thus, the students retain a better understanding of statics, dynamics, and elements of electrical engineering than was typical in the past.

Naturally, we still want our students ultimately to achieve a mastery level in mass and energy balances involving complex reactive systems. This is achieved later, in what is for us, the second course when they are better prepared for it, based on the solid foundation developed in the first course. (The same organization would work equally well in a semester-based course by reorganizing the material.) Thus, in the second course, we revisit mass and energy balance topics with the added complexity of reactive systems. Based upon a survey, 40% of the students felt that this change helped them learn more effectively. The other 60% were neutral.

Based on our experience, one of the difficulties of this approach lies in the fact that most textbooks do not follow this approach. Thus, students sometimes get frustrated at the seemingly random coverage from the book. However, based on a survey of students, 60% felt this was not a problem. In addition we need to be more careful in selecting problems since in many cases, book problems presuppose learning that our students will not get until later in the course.

Conclusions

We believe our approach offers advantages over the more traditional depth-first approach such as that found in typical chemical engineering texts. Because our new approach allows more time for students to come to terms with engineering problem solving and to focus on the basic principles, we have found that our students are better prepared to proceed through the curriculum.

Table 2. Comparison of course organization between the traditional approach and our revised organization. Material in italics is differs between organizations.

Traditional Organization	New Organization
Introduction to chemical engineering	**Introduction to chemical engineering**
System and conversion of units, significant figures	System and conversion of units, significant figures
Introduction to engineering calculations	Introduction to engineering calculations
Dimensional consistency of equations	Dimensional consistency of equations
Regression, nonlinear axes	Regression, nonlinear axes
Processes and process variables	Processes and process variables
Density, flowrate, composition, pressure, temperature	Density, flowrate, composition, pressure, temperature
Conservation of mass	**Conservation of mass**
Intensive and extensive properties	Intensive and extensive properties
System and its boundary	System and its boundary
Process classification, batch, semibatch & continuous process, flowcharts	Process classification, batch, semibatch & continuous process, flowcharts
Conservation of mass as an extensive property	Conservation of mass as an extensive property
Application of conservation of mass to single and multiple units	Application of conservation of mass to single and multiple units
Mass balances in reactive systems	**Conservation of energy**
Stoichiometry, conversion, and equilibrium	Conservation of energy as an extensive property
Multiple reactions	First law of thermodynamics, shaft work, flow work
Degree of freedom analysis, atomic and molecular balance, extent of reaction.	Enthalpy and reference state
Reaction with separation, recycle and purge	Application of conservation of energy to open systems
Combustion reactions	Steam table, mechanical energy balance, Bernoulli equation
Single phase systems	***Conservation of charge and momentum***
Liquid and solid densities, ideal gas law, standard conditions for gases	***Conservation of charge and linear momentum as extensive properties***
Ideal gas mixtures, compressibility equations of state for real gases	**Single phase systems**
Multiphase systems	Liquid and solid densities, ideal gas law, standard conditions for gases
Phase change, vapor pressure, phase rule	Ideal gas mixtures, compressibility equations of state for real gases
One component gas-liquid systems	**Multiphase systems**
Multicomponent gas-liquid systems	Phase change, vapor pressure, phase rule
Solutions of solids in liquids	One component gas-liquid systems
Two liquid phases	Multicomponent gas-liquid systems
Vapor-liquid systems	Solutions of solids in liquids
Solid-liquid systems	Two liquid phases
Liquid-liquid systems	Vapor-liquid systems
Conservation of energy	Solid-liquid systems
Conservation of energy as an extensive property	Liquid-liquid systems
First law of thermodynamics, shaft work, flow work	***Transient systems***
Enthalpy and reference state	***Mass balances in reactive systems***
Application of conservation of energy to open systems	*Stoichiometry, conversion, and equilibrium*
Steam table, mechanical energy balance, Bernoulli equation	*Multiple reactions*
Energy balances – additional material	*Degree of freedom analysis, atomic and molecular balance, extent of reaction.*
Heat capacity	*Reaction with separation, recycle and purge*
Phase changes & latent heat	

Psychrometric charts Mixing Enthalpy-concentration diagrams **Balances on reactive systems** Heat of reaction and Hess's Law Heat of formation and heat of combustion Energy balances on reactive processes, heat of reaction and heat of formation methods Adiabatic reactors Simultaneous material and energy balances Solution thermochemistry, neutralization Fuels & combustion, heating value Adiabatic flame temperature ***Transient systems***	*Combustion reactions* **Energy balances – additional material** Heat capacity Phase changes & latent heat Psychrometric charts Mixing Enthalpy-concentration diagrams **Balances on reactive systems** Heat of reaction and Hess's Law Heat of formation and heat of combustion Energy balances on reactive processes, heat of reaction and heat of formation methods Adiabatic reactors Simultaneous material and energy balances Solution thermochemistry, neutralization Fuels & combustion, heating value Adiabatic flame temperature

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DAVID C. MILLER
David C. Miller is an Assistant Professor of Chemical Engineering at Rose-Hulman Institute of Technology. Dr. Miller has previously taught at Michigan Technological University and The Ohio State University. He received a B.S. degree from Rose-Hulman Institute of Technology, an M.S. from University of Illinois, Urbana-Champaign, and a Ph.D. from The Ohio State University.

M. HOSSEIN HARIRI
M. Hossein Hariri is a Professor and Head of the Chemical Engineering Department at Rose-Hulman Institute of Technology. He received a B.S. degree from Abadan Institute of Technolgy in Iran, an M.S. from Illinois Institute of Technology, and a Ph.D. from University of Manchester in England. .

M. MISOVICH
Michael Misovich is an associate professor in the chemical engineering department of Rose-Hulman Institute of Technology. He has taught a wide range of chemical engineering courses, although he is fondest of teaching thermodynamics, statistics, design, and mass & energy balances. His research interests include thermodynamic property predictions from equations of state, physical chemistry of polymer solutions, chemical engineering education, and assessment.

M. ANKLAM
M. Anklam is an Assistant Professor of Chemical Engineering at Rose-Hulman Institute of Technology. He received a B.S. degree from Stanford University and received M.A. and Ph.D. degrees from Princeton University.

R. ARTIGUE
R. Artigue is a Professor of Chemical Engineering at Rose-Hulman Institute of Technology. He received a B.S. and M.S. degree from Texas A&M University, and a D.Eng. from Tulane University.