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Assess Before You Fix: Using a Concept Inventory to Identify Improvement Opportunities in a Mass and Energy Balances Course

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Assess Before You Fix: Using a Concept Inventory to Identify Improvement Opportunities in a Mass and Energy Balances Course

Abstract

This paper discusses the use of an existing concept inventory to examine the effectiveness of pedagogical strategies and content in a Mass and Energy Balances (M&EB) course within a traditional Chemical Engineering undergraduate program at a large R1 university. M&EB is a foundational class for chemical engineering students, often regarded as the entry point to the major, and it serves as a prerequisite for many subsequent undergraduate courses in the discipline. Given its critical importance, the primary objective of this study was to assess whether the instructional methods and materials effectively promote the conceptual understanding necessary for success in the field.

The concept inventory was first administered to students toward the end of the Fall 2023 class. The results of this initial experience allowed the authors to make small adjustments to the instrument aimed at making the language clearer for the students and removing ambiguity. The adjusted instrument was then administered in a pre/post manner to students in Spring 2024 and Fall 2024.

Preliminary results across all these terms indicated that students entered the class with an intermediate understanding of the subject matter, as reflected in their initial scores. As expected, misconceptions were common for concepts that are counterintuitive or deviate from students' experiences in the physical world. Subsequent analysis of the 2024 data revealed statistically significant improvements in post-assessment scores, suggesting that students developed a more robust understanding of the concepts throughout the course.

The insights gained from administering the concept inventory can inform curricular development and instructional strategies. By identifying gaps in understanding and addressing them through evidence-based changes, educators can enhance the overall educational experience for students. Looking ahead, future work will focus on exploring further evidence-based changes to curriculum and pedagogy informed by the results of the concept inventory. This may involve investigating additional instructional methods, integrating active learning strategies, or enhancing collaborative learning opportunities within the classroom. By continuing to assess and refine the educational approach based on student performance and feedback, this research aims to contribute to the ongoing enhancement of chemical engineering education.

Introduction

Concept inventories are assessment tools designed to evaluate students' understanding of fundamental concepts in a specific subject area. They are widely used in educational settings, particularly in STEM fields, to identify misconceptions and measure conceptual understanding. This paper examines the use of an existing concept inventory (CI) to assess students' grasp of the core concepts in a Mass and Energy Balances (M&EB) course within a traditional Chemical Engineering (ChE) undergraduate program at a large R1 university. The use of the CI in this study was exploratory, with no efforts to identify or address misconceptions through instruction implemented at the time of writing.

Mass & Energy Balances, or Material & Energy Balances, is a foundational course for chemical engineering students, and serves as the entry point into the major at most institutions [1]. The course builds on fundamental concepts learned in introductory chemistry, physics, and math courses and generally serves as a prerequisite for subsequent undergraduate courses in the chemical engineering discipline. The course introduces key concepts in conservation of mass (mass balances) and conservation of energy (energy balances) both with and without chemical reactions, as well as an introduction to concepts in thermodynamics including equations of state, multi-phase systems, and liquid/vapor equilibrium. These concepts are foundational to later chemical engineering courses including Thermodynamics, Separations, and Reaction Engineering, as well as to the "transport sequence" of courses (Fluid Transport, Heat Transport, and Mass Transport). Thus, the failure of students to fully grasp the foundational concepts in Mass & Energy Balances can lead to challenges as they progress through the chemical engineering curriculum.

The Mass & Energy Balances course at Virginia Tech is typically taken in the Fall of the second-year and is the first Chemical Engineering course taken by students entering the major. The course is also offered in the spring semester for students that are off-sequence, and enrollment in the spring semester course is typically much smaller than in the fall semester course. One of the authors of this paper has been teaching the course since 2019, and teaches the course using a combination of traditional lectures, active learning, and flipped classroom techniques. Students are provided with "skeletal" lecture notes that they complete and annotate during in-person lectures or while watching online lecture videos. Participation in in-class learning activities is encouraged through the use of a classroom response system (Top Hat). Lecture videos for all topics are made available online to the students for their review. Weekly problem sets are assigned and students take three in-class exams and a final exam. Students also participate in a group project involving the completion and evaluation of a mass and energy balance for a student-selected industrial process (e.g. hydrogen production, polymer synthesis, carbon capture).

Given its critical role within the ChE program, the primary objective of this study was to evaluate whether the instructional methods and materials at the study institution effectively promote the conceptual understanding of M&EB concepts essential for success in the field.

Conceptual Framework

The notion of concept inventories as a tool to assess formal knowledge in a specific discipline was first crystallized in the *Force Concept Inventory* published three decades ago by Hestens, Well, and Swackhamer [2]. This seminal work not only laid the foundation for the development of concept inventories in other fields but also revolutionized the way educators assess and address students' misconceptions in STEM education. Drawing from the work of Hestenes and colleagues, the Foundation Coalition, a decade later, extended the concept of CIs to other STEM disciplines, including Chemistry, Thermodynamics, Fluid Mechanics, and Transport Processes, among others [3]. This work prompted the widespread adoption of CIs as valuable tools for education and educational research, particularly in engineering and science.

The straightforward premises underlying concept inventories, coupled with variations in specific content and concepts emphasized across different contexts, have led to an open-ended development of various instruments. Consequently, the validity of CIs has been both examined and occasionally questioned. Nevertheless, overall findings continue to support their application [4]. Moreover, Jorion and colleagues have proposed a structured framework for assessing the validity of CIs, which also includes recommendations for their development [4], [5]. These recommendations involve collaboration among multiple subject-matter experts to identify the core concepts of a discipline, the identification of common student misconceptions or counterintuitive ideas, and the psychometric validation of the instrument using pilot data collected from students.

Several of the disciplines covered by the first CIs developed during the early 2000's are relevant to Chemical Engineering, but none was specifically tailored to the content of a particular course within this program. In 2010, Shallcross released a CI for Material and Energy Balances (MEBCI) [6]. This inventory later served as a major input for the Chemical Engineering Fundamentals Concept Inventory (CEFCI), published in 2012 by Ngothai and Davis [7]. Since this study focuses specifically on a M&EB course, the MEBCI was deemed a more appropriate assessment tool.

The MEBCI is a 22-question multiple-choice validated assessment designed to evaluate students' understanding of fundamental concepts in a basic Material and Energy Balances course. Its primary purpose is to identify pre-existing misconceptions that may hinder learning if left unaddressed. Results from administering the MEBCI to 170 students in a pre/post format demonstrated its utility in highlighting significant reductions in some misconceptions, while revealing others that remain more deeply ingrained [6].

Methods

Students across three sections of the M&EB course (Fall 2023, Spring 2024, and Fall 2024) at the study institution were invited to respond to the MEBCI as an extra-credit class activity. All sections were taught by the same instructor, who is a coauthor of this study and has ample experience teaching this course. The instrument was adapted for administration via Canvas as a quiz. The Human Research Protection Program at the study institution determined this study is not research involving human subjects as defined by HHS and FDA regulations, therefore not requiring further review and approval by the institution's IRB.

For the Fall 2023 section, the original instrument was administered at the end of the semester, without any modifications. In Spring and Fall 2024, students received a slightly adapted version of the original instrument, which was administered in a pre/post format at the beginning and end of each semester, respectively. Minor adjustments were made to the instrument after the first application to improve question clarity. However, no adjustments to course instruction were made based on these preliminary analyses.

Descriptive statistics were calculated for all five data sets to assess the consistency of results, both for the baseline captured before the course and the outcomes of the CI administration at the end of the course. To evaluate the significance of changes between the pre- and post-administration of the CI, parametric tests (t-tests) were conducted.

Results and Discussion

Table 1 summarizes the descriptive statistics for the administration of the CI across the three sections included in this study, two of which included pre/post administration. Grayed columns indicate the administration of the CI at the end of the course. Each correct response was assigned a value of one for a maximum possible score of 22.

Table 1. Descriptive Statistics.

	Fall '23	**Sp '24 Pre**	**Sp' 24 Post**	**Fall '24 Pre**	**Fall '24 Post**
N	55	20	20	43	38
Mean	12.33	9.75	13.05	9.67	12.63
SD	3.81	3.92	4.25	3.08	4.10
Min	5	2	5	3	2
Max	20	16	19	18	19

The mean scores and standard deviations of the pre-test scores are comparable, indicating a similar baseline of student conceptual understanding at the start of the course. Similarly, the post-test scores and their spread are comparable across sections, with mean scores higher than those of the pre-test administration, suggesting that the course had a positive impact on student understanding of M&EB concepts. To determine whether parametric tests were appropriate for further probing the significance of this difference, a histogram of the largest dataset (Fall ‘23) was created and is presented in Figure 1, approximating a normal distribution.

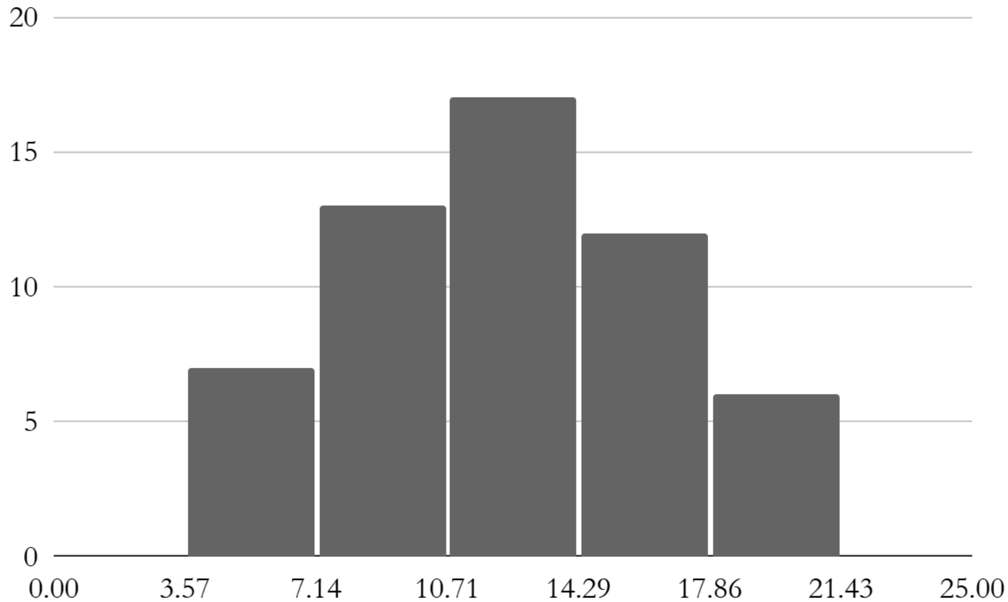


Figure 1. Histogram of student CI scores in Fall 2023.

In Fall 2023 the CI was administered for the first time to the students only at the end of the course, so we have no data on improvement during the course. However, this administration allowed us to get a sense of the difficulty of each individual item by looking at the percentage of correct responses, as presented in Table 2.

Table 2. Percentage of correct responses by question.

Question	Correct Responses	Incorrect Responses	% Correct Responses
1	30	25	54.5%
2	42	13	76.4%
3	33	22	60.0%
4	33	22	60.0%
5	37	18	67.3%
6	34	21	61.8%
7	24	31	43.6%
8	52	3	94.5%
9	37	18	67.3%
10	33	22	60.0%
11	27	28	49.1%
12	20	35	36.4%
13	13	42	23.6%
14	33	22	60.0%
15	37	18	67.3%
16	18	37	32.7%
17	28	27	50.9%
18	21	34	38.2%
19	39	16	70.9%
20	7	48	12.7%
21	44	11	80.0%
22	36	19	65.5%

The students generally performed well on the CI, but several questions showed notably low percentages of correct responses (i.e., questions 12, 13, 16, 18, and 20). We examined these questions to identify potential misconceptions or challenging concepts and compared our results with the findings of Shallcross.

For instance, only 32.7% of the students in our Fall '23 section responded correctly to Q16, which is moderately low and consistent with Shallcross's 26.7%. Incidentally, this is one of the questions that showed less improvement in the cited study, with a large proportion of students changing their correct answer on the pre-test to an incorrect answer on the post-test. The question focuses on enthalpies of mixing, a thermodynamics concept that is not emphasized in the current course.

Similarly, Q20 had the lowest correct response rate in our study (12.7%). Comparably, Shallcross's students performed similarly poorly at the start (8.0%), with improved post-course performance (29.1%). We attribute the difficulty of this question to the nuanced distinctions between the concepts of *evaporation*, *vaporization*, and *boiling*. This serves as an excellent example of how a simple instructional adjustment in an M&EB class, informed by CI data, could address a fundamental misconception.

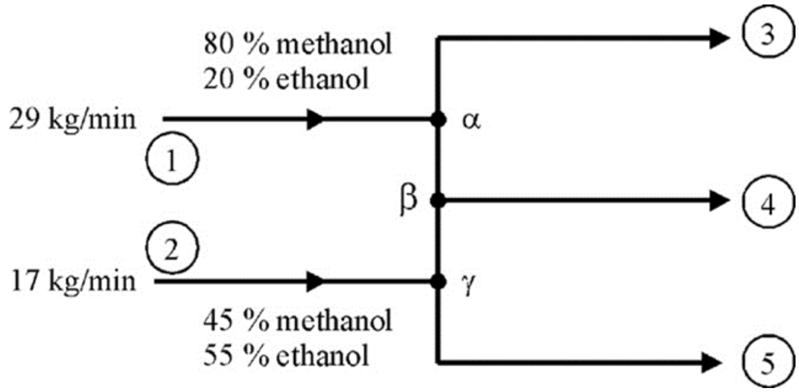
Before administering the CI to the Spring '24 and Fall '24 sections, we examined the results on a question-by-question basis and made several minor modifications aimed at improving question clarity. Questions 16 and 20 mentioned above are among the ones we deemed unclear. The modified questions are shown below with changes indicated by bold italics.

Question 7: Which one of the following statements is false?

a. Water boils at a temperature less than 100 °C at the top of a high mountain.
b. Water in the gas phase cannot exist in a room at temperatures less than 100 °C if the total pressure in the room is one standard atmosphere.
c. ***Liquid wate*r** can only exist at a temperature of 200 °C if the pressure is very much greater than one standard atmosphere.
d. The temperature at which water boils increases with increasing pressure.
e. The wisps of 'steam' seen coming off the surface of a hot mug of tea or coffee on a cold day are actually ***condensed*** water vapor.

Question 11: Which one of the following statements is correct?

a. The composition of stream (3) is the same as stream (1).
b. Stream (3) is between 45% and 80% methanol.
c. The composition of stream (4) is the same as stream (3).
d. The flow rate of stream (4) is between 17 and 29 kg/min.
e. The composition of stream (4) is ***37.5***% ethanol.



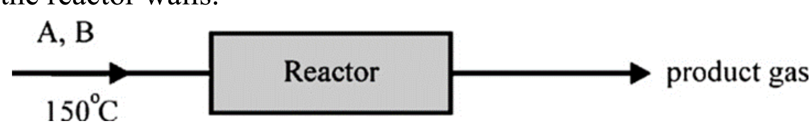
Question 16: An insulated vessel contains 200 ml of water at 60 °C. ***200 ml of a different liquid at 20 °C is poured into the vessel.*** The contents of the vessel are then well mixed. If no heat is lost or gained through the walls of the container while the liquids are being mixed what will be the temperature of the mixture? Assume no chemical reactions take place.

a. Less than 40 °C.
b. 40 °C.
c. Greater than 40 °C.
d. Less than or equal to 40 °C.
e. Impossible to say as the temperature will depend on the properties of the mixture.

Question 17: Two chemicals, A and B, react in the gas phase to produce a gas C, according to the reaction:

$$A(g) + B(g) \rightarrow 3C(g)$$

The reaction is exothermic meaning that heat is ***produced during*** the reaction. The reaction occurs within a perfectly insulated reactor so that no heat may enter or leave the reactor through the reactor walls.



If reactants A and B enter the reactor at a temperature of 150 °C, at what temperature will the product gases leave the reactor?

a. Less than 150 °C.
b. 150 °C.
c. Greater than 150 °C.
d. Impossible to say as we do not know the molar ratio of A to B entering the reactor.
e. Impossible to say as we are not told if all the A and B are consumed.

Question 20: Which one of the following statements is true?

a. The vaporization process starts with boiling ~~***(i.e., a liquid has to be heated up to its boiling point before it will start boiling)***~~.

b. Vaporization only occurs at the surface of a liquid.
c. Vaporization requires a change in temperature to occur.
d. A liquid must be heated for a certain period of time in order for it to vaporize.
e. At one standard atmosphere water can vaporize at 5 °C.

The modified instrument was administered pre/post course completion to students in the Spring '24 and Fall '24 sections. Table 3 presents the results of one-tail, paired t-tests for this administration on the CI. Note that, due to some students not completing both the pre- and post-course assessments, the mean values reported for the paired tests may differ from those reported for each dataset individually.

Table 3. One-tail, paired t-test results.

	N	*Mean*	*SD*	*Min*	*Max*	t-test *p* value
Pre Sp '24	19	10.05	3.78	2	16	< 0.001
Post Sp '24		12.89	4.31	5	19	
Pre Fall '24	37	9.70	3.21	3	18	< 0.001
Post Fall '24		12.54	4.12	2	19	

In both cases, the average post-course scores are significantly higher than the pre-course scores at the 99% confidence level. The gains observed are similar to those discussed by the authors of the MEBCI in their own administration of the instrument, where the mean number of correct answers was 8.9 and 13.3 for the pre-test and post-test respectively [6].

Limitations

The results presented in this paper are exploratory and have several limitations. First, the sample size is relatively small, which limits the statistical power of the tools used for comparison. In addition, despite the statistical results being well beyond commonly accepted thresholds for significance, only a superficial inspection of the data's normality was conducted to determine the appropriateness of using parametric tools. Finally, all three sections of the course were taught by the same instructor, who is a co-author of this paper. While no intentional efforts were made to tailor instruction to the specificities of the MEBCI, in any study of this nature it is worth considering the potential for this situation to influence the results.

Conclusion

In summary, a modified version of the concept inventory developed by Shallcross was administered to students at the beginning and end of the second-year chemical engineering Mass & Energy Balances course in the spring and fall semesters of 2024. In both of these cases, we observed a statistically significant increase in the mean number of correct answers between the beginning and end of the course, indicating that students are improving their conceptual understanding.

The observed increase in the mean number of correct answers between the beginning and end of the course suggests that the current methods of instruction are having a positive effect on student understanding of important Mass & Energy Balance concepts. Moreover, the improvement we saw is comparable with the results observed by the MEBCI authors [6]. The consistency between the two course offerings subjected to pre/post administration of the CI, both taught by the same instructor, indicates that these mean values could serve as a baseline to evaluate the impact of instructional changes in future course iterations.

However, we argue that the average score on the MEBCI has limited utility for M&EB instructors, as it does not necessarily clarify what constitutes a "good" score or how variations in instructional approaches or individual instructors may influence the results. Moreover, aiming for a higher overall CI score might not be the aim of an instructor when redesigning their class. Focusing on concepts that align with the course learning outcomes and are crucial down the line may be more important. For instance, we could adjust teaching strategies around the concept of vaporization, because this is a key concept for chemical engineering students as they progress onto later coursework in thermodynamics and chemical separations. Therefore, greater insight may be gained through a more detailed analysis of student performance on specific CI questions tied to key course concepts. Additionally, administering the instrument repeatedly across multiple semesters can help instructors establish desirable performance benchmarks specific to their context.

Future work will focus on a detailed analysis of the Spring '24 and Fall '24 pre-test and post-test results for the different questions in the MEBCI. An initial examination of the results from the Fall '23 post-test indicated general agreement with the results reported by Shallcross in terms of the specific questions and concepts that were most challenging to the students. A full analysis of the Spring and Fall '24 data will help guide modifications to the future editions of the course aimed at helping students increase their understanding of these concepts.

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