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Clear Writing Promotes Clear Thinking: Implementation and Effectiveness of a Homework Writing Guide for Chemical Engineering and Materials Science Undergraduates

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Abstract

Clear communication is essential for engineering students to improve their conceptual understanding of core material and to communicate their ideas and research in professional settings effectively. However, curricular efforts to improve writing in engineering often emphasize lab reports, technical memos, or other professional genres. Homework problem sets are often overlooked as a form of written communication, yet these assignments offer a critical opportunity for skill development early in students' training. Addressing errors in homework problems related to organization and process can help reveal conceptual misunderstandings and allow instructors to better support student learning.

This paper describes the development and launch of a homework guide for undergraduate students in Chemical Engineering and Materials Science. Faculty and instructors in a combined Chemical Engineering and Materials Science department collaborated with staff in the Writing Enriched Curriculum (WEC) program to establish graduation-level writing expectations for the two undergraduate programs offered by the department. As part of the initial implementation effort in this multiyear collaboration, department instructors, teaching assistants, and WEC staff explored the elements of effective homework responses (e.g., defining assumptions, writing key mathematical formulas, commenting code, and annotating figures). These elements were incorporated into a single homework guide and implemented in undergraduate engineering courses, including sophomore-level chemical engineering and mixed-level material science and engineering courses. The guide was briefly presented to students in class and modeled through example problems, but no additional in-class instruction or changes to homework practices were instituted. The quality and clarity of students' written responses were considered as a component of students' scores. Students were surveyed three times during the semester about their use of the guide and its value.

Following the initial implementation in chemical engineering, student responses were largely positive, with more than half reporting that the use of the guide helped organize and clarify their thinking, improved their learning and exam performance, and increased their confidence. The feedback from the materials science and engineering course identified a need to further emphasize the guidelines as a strategy for organization that should be adapted to meet diverse problem requirements. Overall, this work provides an example implementation of a low time-demand educational tool that can be introduced early and incorporated throughout the engineering curriculum to support student communication and conceptual understanding of course material.

Introduction

Strong problem-solving and communication skills are both paramount to engineering education as precursors to the demands in the profession. Homework sets are commonly used to strengthen problem-solving skills and yet are often overlooked as a potential communication skill-building tool. Developing competency in technical writing as a professional skill is emphasized in laboratory and capstone courses, but learning to reliably produce a clear homework solution presents an opportunity to build communication skills earlier in engineering education. Even creating visual representations, a step seen in almost all complex engineering homework solutions, is a key communication tool that students must learn to construct and interpret.

Improving effective problem-solving instruction has been a goal for instructors from grade schools to universities. Several problem-solving theories have emerged including those based on behaviorism, cognitive psychology, and information processing [1]. Most strategies share basic steps such as reading the problem, determining what is asked and what is given, drawing a schematic, selecting relevant equations, solving the problem, and evaluating the solution [2], [3], [4], [5], [6], [7], [8]. How and to what extent these steps are explained, practiced, or achieved varies greatly from study to study.

Different approaches have been attempted and assessed, typically with a treatment and a control group, and often with a pre- and post-treatment assessment, frequently in the fields of mathematics, physics, chemistry, and engineering (particularly statics). Some strategies are based on replicating how experts in a field tend to solve problems, while others are based simply on assisting novices to more reliably solve the problem of interest, regardless of how that compares to expert solvers [1], [3], [4]. Defining the problem or developing an initial problem representation is often noted as a key step deserving individual study [9], [10] and for which students showed marked improvement with explicit strategy instruction [3], [6]. Sometimes the treatment includes not only instruction on problem solving methods or steps but also talking through problems or working with a partner or group [3], [8], [11]. Metacognition or reasoning activities have also been shown to aid student problem solving abilities and/or conceptual understanding if generated by the student [11], [12], [13], [14], [15], [16] but not if provided for the student [17]. Further, the use of conceptual problem-solving strategies with emphasis on explanations of principles and justifications has been shown to increase students' conceptual learning and problem-solving ability [14], [18]. The goal of these interventions is typically to increase the accuracy of the solution or conceptual understanding. However, self-efficacy [5] as well as organization, clarity, and communication have also been of interest [19].

Results varied, with many studies noting significant improvement following more deliberate instruction [3], [8], [13], [14], [18], while others saw no significant difference [7], [15], [20]. Challenges with strategy instruction include the effort and time required to teach and for students to implement and follow through with the strategy, as well as issues with limited flexibility and creativity [7], [20]. Additionally, most educational problem-solving strategies and instruction have been aimed at single semester general introductory science or math courses rather than as an organized curriculum-wide intervention.

Incorporating writing into homework assignments to assess or aid student understanding and recall has been often investigated, while emphasis on learning to communicate clearly within one's future profession via homework is often neglected. This work investigates a homework guide intervention that shows students the key elements needed to communicate increasingly complex solutions to chemical engineering and materials science problems, thereby building strong technical communication skills. The first stage of implementation is reported here for courses early in the major, during sophomore year, with the intent to consistently reinforce and model the method throughout all courses within the respective curricula.

The guide also aims to promote transparency, growth mindset, and inclusive teaching, which have been shown to reduce achievement gaps between students [21], [22], [23]. By clearly illustrating what elements are needed in a good homework solution, students are shown that communicating their problem-solving strategy is a skill that can be learned and improved. Regardless of prior instruction, they are all shown the elements that are expected, which may help reduce the impact of differences in prior problem-solving experience or training.

Methods

Context for the Study

The study was conducted at a large public flagship research institution (approximately 42,000 undergraduates). The Chemical Engineering and Materials Science department of this institution enrolls more than 400 undergraduate students in its two majors: chemical engineering and materials science. Admission to the College of Science and Engineering and the majors is competitive, and selected students are enrolled in their major in the second semester of their sophomore year.

Homework guide development

The idea for a homework guide was inspired by colleagues in the Mechanical Engineering department, who developed their own writing resource guides through the Writing Across the Curriculum Program. Faculty in the Chemical Engineering and Materials Science and Engineering department resonated with viewing homework writing as a form of written communication that could be more consistently taught. At the same time, the homework guide used in this study was developed from scratch and did not reference the prior example directly.

To develop a set of guidelines for communication instruction, a working session was held with eight faculty members from the departments of Chemical Engineering and Materials Science and Engineering. Prior to the meeting, faculty completed a pre-session survey on (1) the general steps used to model homework problems in their lectures, (2) essential aesthetic elements of homework solutions, (3) essential content for students to include in their solutions, and (4) what types of problems the homework guide should address (e.g., mathematical solutions, conceptual responses, compare and contrast, code, plotting, etc.). Responses were compiled and discussed in an in-person workshop. Feedback was used to design an initial set of writing guidelines for homework problems in both majors. An initial draft of the homework guidelines underwent a series of revisions based on feedback from a subset of five faculty members from the initial larger working group. The final version of the guide was reviewed by nine faculty members from both departments prior to the guide's implementation.

The final version of the homework guide contained general steps for solving problems commonly encountered in Chemical Engineering and Materials Science and Engineering courses, with additional sections elaborating on problems involving code, graph formatting, and tips for submitting electronic work (Figure 1, Appendix A). An example problem from an undergraduate Chemical Engineering material and energy balances course and an example from an introductory course to materials science and engineering were annotated to demonstrate key features of well-communicated solutions.

Summary of Problem Organization

Section	Content
Problem Summary	Define given values, constraints and boundaries
	Draw relevant diagrams
	State goal of the problem
Solution	Write relevant base equations in variable form
	Write any assumptions
	Show all necessary steps (include narration & units)
Answer	Box, circle, or highlight final answer
	Evaluate answer

Annotated Solution:

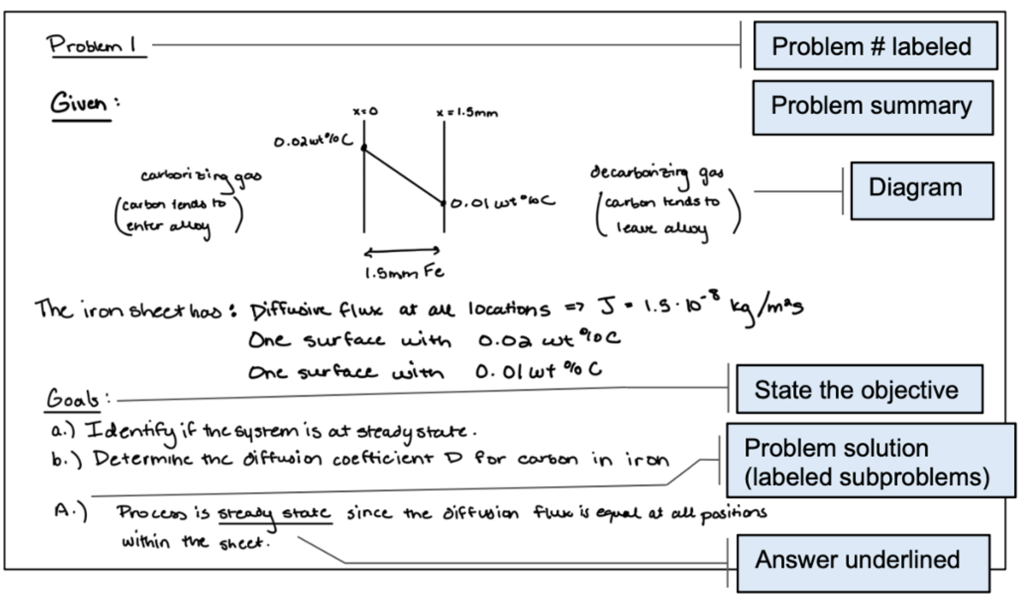

Figure 1: Excerpts from the homework guidelines. The guide described key steps commonly used across problems in the engineering majors, with the provided table summarizing the general steps for quick reference. Annotated example problems were also included to highlight features of well-communicated homework solutions.

Homework Guide Implementation

The two courses selected for the initial intervention both occurred in the spring semester of the same year. The larger course, a course in thermodynamics in chemical engineering (referred to as "ChEn Thermo" from here), had a total student enrollment number around 130. The smaller course, an introductory course in material science (referred to as "MatS" from here), had a population of just under 50 and, as a result of its place in the curriculum, had a slightly greater range of student experiences (with some students of more advanced standing). In the second semester of implementation, the guide was introduced in a materials and energy balance course in chemical engineering (referred to as "ChEn Balances" from here), which had 167 students enrolled. Students take this course as the first course in the major in the fall of their sophomore year. In both programs, the majority of students' lab work emerged in the junior year, and those lab courses were the typical sites for writing intervention. The goal in selecting these courses was to introduce principles of effective writing earlier in the curriculum to narrow gaps between the highest performing students and those with the least experience with technical writing.

The guide was briefly introduced in week three of each course, when the first major homework assignments were assigned. A research team representative attended the spring semester sessions of ChEn Thermo and MatS and the fall semester version of ChEn Balances to introduce the project and to explain the accompanying surveys that would be used to collect student data. The representative noted that the survey would be introduced at three different times in the semester, and encouraged students to fill out the surveys each time. In each course, a point incentive was provided for completing the survey, but even if a student completed the survey, they could select to have their data eliminated from the final aggregate via a final opt-out question. Thus, while students were encouraged to engage with the survey process, the small incentives for survey completion did not purchase students' consent to use their answers in this study's assessments.

In the first survey question, students were asked if they had heard of the assignment guide and where it may have been mentioned, knowing that all students who attended on the days of class visits would have heard about that the guide in their lectures, and that all students would see notes about the homework guide on their Canvas course pages. Teaching assistants in recitation sections knew about the guide, but their duties did not include providing additional explanation or support specifically for the homework guide. The surveys were designed to branch based upon students' use of the guide, but did not prescribe any particular pattern of usage.

Students were provided a link to a Google Form for each survey: one immediately after an early homework assignment and introduction to the guide, one at midterm, and one before final exams. The research team moved the final survey to before exams to not interfere with Student Response to Teaching surveys that are completed by all students at the end of the semester. A member of the research team, unaffiliated with the engineering departments, assigned each survey participant a unique identifier in order to redact identifying student information and to track which students completed all surveys. That team member also provided the teaching assistance with the list of student email addresses that corresponded to survey interaction, so whether students selected to have their data incorporated or not, all students could receive credit for completion. Completion rates were strongest early in the semester and slightly reduced toward the end, and refusal/opt-out rates were consistently between 10 and 20%.

Table 1: Coding terms with examples for open ended student survey responses

Theme/Code	Example
Problem Solving	
Organizing thoughts and essential information	"It allows me to organize my thoughts and start on the problem and neatly convey my answer and if needed why it makes sense."
Provides a problem solving framework	"I enjoyed using this homework format because it gave me a framework to think about how I solve problems."
Helps with understanding the problem statement	"The outline allows me to check that I've understood the question, especially when it comes to analyzing the scenario and conditions required to apply certain concepts."
Helps with understanding course concepts	"I think it's good to have a document that outlines steps and formats. It can benefit your understanding of the topic if you use the guide."
Helps with understanding own work	"It helps a lot when I want to review and study my homework problems, because I know where to find things and I can retrace my train of thoughts."
Helps with mistakes	"The guide made me see exactly where my mistakes and helped me improve my understanding."
Improves communication	"The guideline makes it so that the work I do is concise and understandable"
Problem solving process is rigid and restrictive	"If I'm being honest, the guide can restrict thinking. Thinking in a formulaic manner can be very helpful. But making such thinking required can restrict the ability to think freely. And only think within the bounds of a question."
Already have problem solving process prior to guide	"I always have clean homework that makes sense to anyone to looks at it, i can see how others might have messy homework but to those of us that are good about homework the guide doesnt help much"
Grading	
Improves grade	"it helps me get as many points as possible on homework and exams by helping me write as much information on the paper as possible."
Hurts grade	"It could be helpful, at the same time it makes the student lose marks"
Defines clear expectations	"The guide does a nice job laying out exactly what is desired on homework problems, which isn't always typical so it was helpful."
Time	
Improves problem solving efficiency	"I have gotten into the routine of formatting and organizing my homework this way, and it has helped me be more efficient in my homework."
Following guide requires too much time and work	"Adherence to the guide increased the amount of time I needed to spend on homework, not fun."
Critique of guide	
Not all parts of the guide are relevant	"I found it a little odd later in the semester, since a *lot* of it is not applicable to a lot of more abstract problems."
Guide has confusing sections	"I think the evaluating portion is helpful sometimes but also confusing because a large chunk of our problems have been deriving equations where we have no sense of whether our equation would be right or wrong"
Useful at the beginning of the semester but not later	"helpful at first, but feels redundant later on"

Analysis of survey results

Closed-ended questions (e.g., multiple choice) were analyzed using MATLAB. Percentages were calculated by dividing the number of times the option was selected by the total number of consenting respondents to that particular question, since students were not required to answer every question to complete the survey. An inductive content analysis approach [24] was used to analyze and summarize free response answers to the prompt "Please elaborate on your reasons for your answer. Full sentences are appreciated!" that was asked following the two questions:

1. If you could speak to future students in this course, how likely would you be to recommend using this guide for homework problems?
2. As you think about your future courses in the major, do you anticipate that a guide like this could be helpful for your learning?

In the initial round of coding, student responses were labeled with specific codes to the extent possible. A single response could have multiple coded themes. From this initial round, codes with similar themes were grouped under broader thematic codes. For example, students described the homework guide as helping them receive "full credit", "better grade[s]," or "partial credit" which were grouped together under the theme "improves grade." Student free responses were then re-coded with the final theme categories (Table 1).

Results

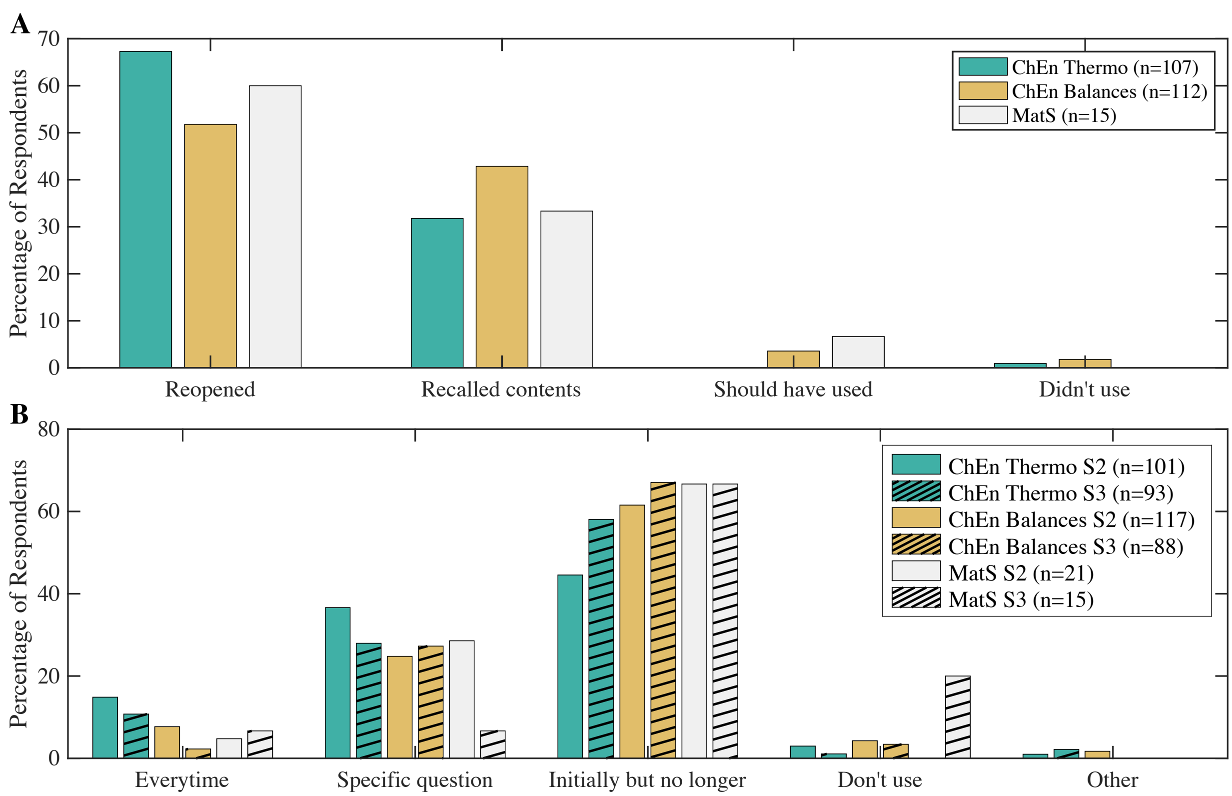

Figure 2: Student responses about guide usage. (A) Student responses to "Did you refer to the problem set guide when completing this problem set assignment" in the first survey of the semester. (B) Student responses to "Since you received the guide, how have you used it with your homework assignments" in the midterm (S2) and final (S3) survey for ChEn and MatS.

Student usage of the homework guidelines

In each of the three surveys, students were asked to report how they used the homework guide to assess changes in use throughout the semester-long courses. In the first survey submitted with an early homework assignment, at least half the students reported reopening the guide and about 30% of students recalled the contents of the guide to inform their homework submission (Figure 2A). Later in the semester, with the midterm (S2) survey and the final survey (S3), the direct usage of the guidelines declined, with more than half of the students in the midterm and final surveys saying they used the guide initially but no longer use the guide (Figure 2B). In a free response section later in the final survey for ChEn Thermo, one student reported that they "don't have to refer to the electronic document anymore because it has integrated itself into how I approach and solve problems now." This statement supports one possible explanation for the trend observed in all three courses, where direct usage of the guidelines decreases as students gain more competency in incorporating the guidelines into their problem-solving workflow.

Student perception of the homework guidelines

In the midterm survey, about half of ChEn Thermo students reported that the guide helped them perform better on the first exam, while about only 6% of students reported that it had a negative impact (Figure 3). For students in MatS, about a third of students reported that the guide had a positive effect, no effect, or that they did not know the effect, with no students reporting that the guide had a negative effect. In the free response allowing students to elaborate on their selection, ChEn Thermo students often reported that the guide helped them with organizing their work, understanding the problem, and receiving more partial credit. Examples of students' responses are included below:

- "[The guide] allowed me to stop and think about the problem first before diving into calculations and potentially getting lost"
- "How it helped me was I put my givens, assumptions, drawings, and system of the problem so I have a better understanding of the problem and where I could go from there."
- "I believe the guidelines helped me get better partial credit, by allowing me to show my work and thought process making it easier for my TA's to understand my work and reasoning."

Students in MatS also cited organization as a reason for the guide's positive impact, with one student writing that the guide was "specific and well guided enough for me to tackle problems in well-organized and thoughtful ways." Although students were not required to follow the homework guide format on the exam, students described increased time spent writing out exam answers as negatively impacting their exam performance. ChEn Balances was excluded from this analysis since there was a technical glitch in delivering this question to students in this course.

In the final survey of the semester, students were provided a list of statements about the homework guide and asked to select all of the statements they agreed with. Across all three courses, 30-50% of students chose not to respond to statements related to performance confidence, learning, or grading, and a small number of students (less than 10%) selected two statements under the same theme (Figure 4A-C). Overall, the responses for ChEn Thermo were largely positive. 57% of respondents said that the homework guidelines had a positive impact on their performance, confidence, and learning, with less than 15% of respondents saying that the guide had no effect (Figure 4A-B). No students from ChEn Thermo said that the guide had a negative effect on their performance confidence, and only 2% of students said that it had a negative effect on their learning.

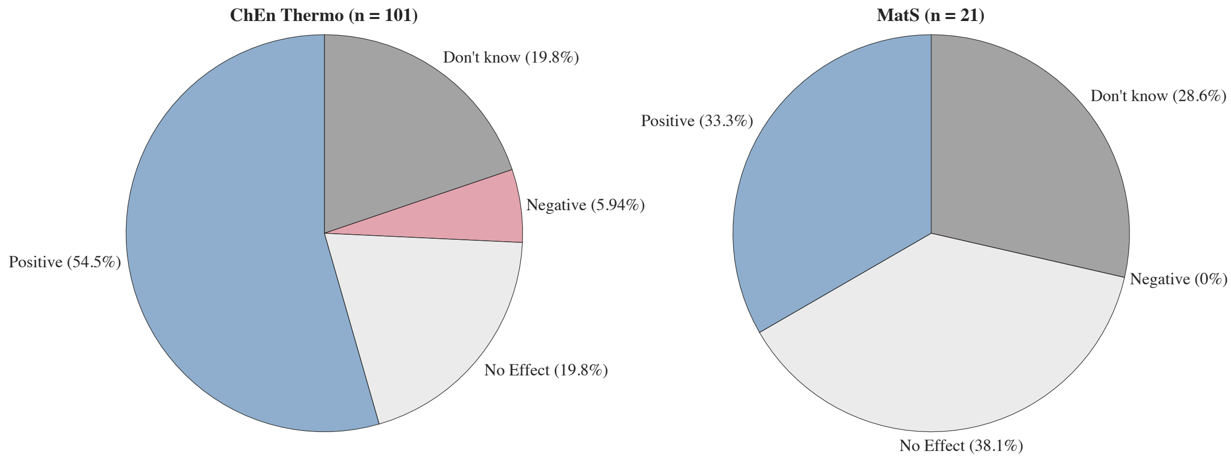

Figure 3: Student responses to how they perceived their exam performance being impacted by the homework guide. Students were asked if the homework guidelines helped them perform better (positive effect), had no effect, perform worse (negative effect), or if they did not know the effect on their exam performance.

While almost 30% of respondents in ChEn Balances still reported that the guide had a positive effect on their performance confidence and almost 40% reported a positive effect on their learning, there was a higher percentage of respondents from ChEn Balances and MatS who thought the homework guide had no effect on their performance confidence or learning. Since ChEn Balances is the first course students take in Chemical Engineering, students in this course do not have any course experience with chemical engineering prior to the introduction of the guidelines, unlike students in ChEn Thermo. This distinction could account for the differences in survey responses between the two courses. Students from all three courses responded similarly to how following the homework guidelines was incorporated into assignment grading (Figure 4C). Of the students that selected a response related to grading, roughly half of the students agreed with the statement that the "homework grading fairly accounted for the effort to follow the homework guide." Less than 10% of students thought that more credit should be given for following the guidelines, and one reason for this provided in the free response from ChEn balances was the increased time spent on completing homework assignments while following the guidelines.

About 15% of students said that the grading "should not account for following the homework guide," with students commonly citing increased stress about losing points for not following the guidelines exactly. One student from ChEn Thermo stated: "It is annoying to worry whether I will lose points because my solution does not strictly adhere to the letter to the solution formatting guide." It is important to note that in all three courses, students were not required to explicitly follow the guidelines in their homework solutions. The homework rubrics included a small category for clarity of communication or including applicable content consistent with the guide, and students were not required to follow the guide on exams. The first homework assignment in ChEn Thermo was an exception to this grading policy where students were required to explicitly follow the homework guidelines for the first assignment. Based on student feedback and to decrease confusion, this policy was changed in ChEn Balances to not require students to explicitly follow the guide to receive full credit on any of the homework assignments. This disconnect between course requirements and student beliefs about expectations highlights an area for improvement in how the guidelines are introduced to students to better clarify expectations for students and further emphasize that the guidelines are a learning and communication tool rather than a strict set of rules.

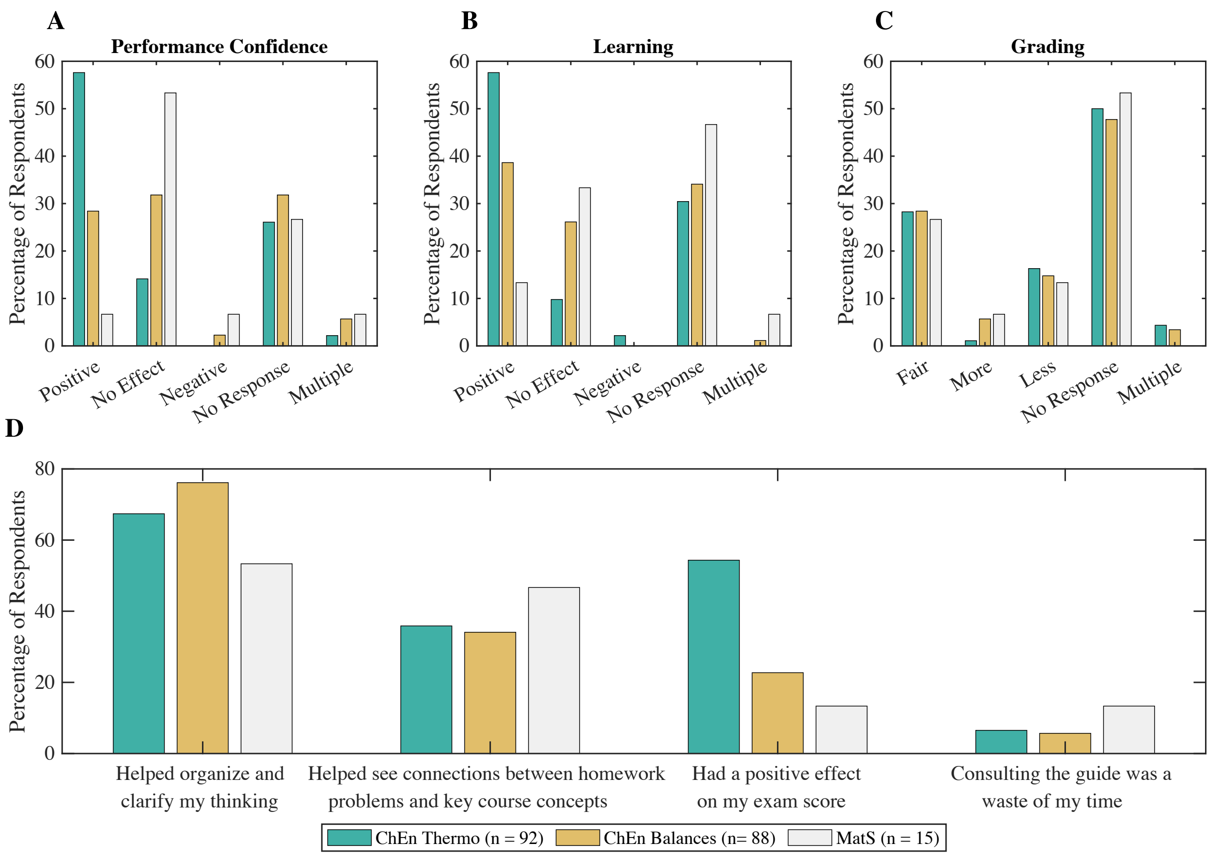

Figure 4: Student responses in the final survey to the question "Consider the following statements and check any with which you AGREE." (A) Students' perceptions on how the homework guide impacted their performance confidence. (B) Students' perceptions on how the homework guide impacted their learning. (C) Students' perceptions on if the homework grading fairly accounted for the effort to follow the homework guide (fair), if more credit should have been given for following the homework guide (more), or if the homework grading should not account for following the guide (less). (D) Students' agreement with the statements that the guide helped their organization, helped them see connections between homework and course concepts, had a positive effect on their exam scores, or was a waste of time.

More than half of the students indicated that the guide helped with organizing and clarifying their thinking, and more than 30% of students indicated that the guide helped them connect homework problems to key course concepts (Figure 4D). More than half of the students in ChEn Thermo reported that the guide had a positive effect on their exam scores, with students noting that the guidelines helped them better identify the problem being asked, keep track of important variables, and identify next steps. One student wrote:

> I used to have a bit of a problem during exams where I would sometimes not read the entire problem and miss key concepts but the homework guide helped me create a systematic way of reading problem statements and helped me find a way to organize my thoughts quickly in a way to solve questions efficiently.

However, several respondents noted in the final survey that they spent too much time on the exam writing out their solutions according to the guidelines, and that they had to “rush through the end.”

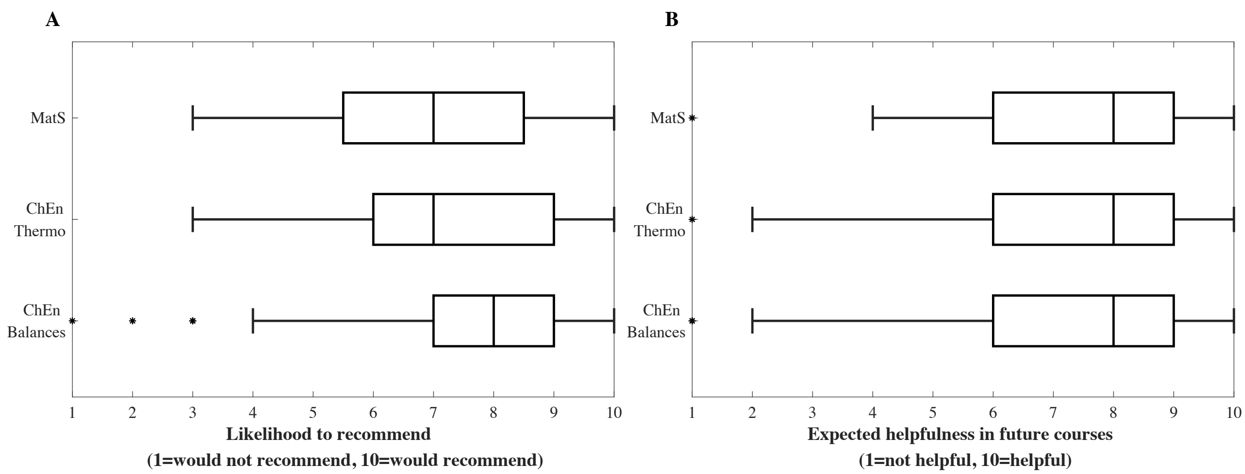

Figure 5: Student responses to (A) “If you could speak to future students in this course, how likely would you be to recommend using this guide for homework problems” and (B) “As you think about your future courses in the major, do you anticipate that a guide like this could be helpful for your learning?”. The number of respondents for each survey question equals 85 and 15 for ChEn Thermo and MatS, respectively. ChEn Balances had 92 and 91 respondents for (A) and (B), respectively.

Students also reported being likely to recommend the guide to future students and expected it to be helpful in future courses (Figure 5). In their free response explanations to these questions, feedback was largely positive, with many students writing that the guide helped with organizing complex problems, keeping track of information, and providing a general approach to problem solving to prevent getting lost (Table 2). Some students wrote that writing out the problem goals and given information helped them to better understand the problem goal, allowing them to maintain focus during their work. Students’ primary criticisms of the guide focus on the guide hurting their grade through inconsistent grading, or concerns that they would lose points if the guide wasn’t followed exactly. Other criticisms were that the guide increased the time to solve problems, that the process felt rigid and strict, and that not all parts of the guide were used for every problem, requiring discretion by the student.

Table 2: Student responses to "Please elaborate your reasons for your answer" for their selection on likelihood to recommend the homework guide to future students or the expected helpfulness of the guide in future classes.

	No. of responses/total responses		
Theme	ChEn Thermo (65/93)	ChEn Balances (59/88)	MatS (6/15)
Problem Solving			
Organizing thoughts and essential information	15/65	16/59	2/6
Provides a problem solving framework	20/65	17/59	5/6
Helps with understanding the problem statement and goal	6/65	4/59	0/6
Helps with understanding course concepts	2/65	4/59	0/6
Helps with understanding own work	2/65	2/59	0/6
Helps with mistakes	3/65	3/59	0/6
Improves communication	4/65	3/59	0/6
Problem solving process is rigid and restrictive	4/65	1/59	0/6
Already have problem solving process prior to guide	2/65	3/59	0/6
Grading			
Improves grade	9/65	4/59	1/6
Hurts grade	2/65	4/59	0/6
Defines clear expectations	10/65	10/59	1/6
Time			
Improves problem solving efficiency	0/65	2/59	0/6
Following guide requires too much time and work	7/65	10/59	1/6
Critique of guide			
Not all parts of the guide are relevant	5/65	2/59	1/6
Guide has confusing sections	1/65	0/59	0/6
Useful at the beginning of the semester but not later	5/65	1/59	0/6

Conclusions and Future Directions

Overall, this work has detailed the successful implementation of a low time-demand tool to support student communication in three full-scale undergraduate courses in Chemical Engineering and Materials Science and Engineering. Although it is challenging to isolate the effectiveness of a single instructional intervention outside a randomized experiment, students' self-reported data across the three courses indicate that many students view the guide positively for their problem-solving abilities, and open-ended responses provided examples of how students perceived the guide to be helpful or harmful to their learning or course performance. Student critiques of the guide provide concrete ways the implementation of the guide can be improved to increase student acceptance and better support learning.

One of the most common critiques of the guide throughout the semester was the increased time required to follow the problem-solving method detailed in the guide. The introduction of any new process, especially one that requires students to communicate more of their work, will likely increase the time they spend on the problems. While students were not graded on communication or following the guidelines on the exam, further emphasis on exam expectations could help reduce the timing problem experienced by these students. An additional section on time management could also be incorporated into the guide to provide advice for navigating the conflicting demands of time constraints versus providing thorough explanations.

Currently, data is only available for students who have used the homework guidelines for a single semester, but future work entails incorporating the homework guide across courses in both Chemical Engineering and Materials Science and Engineering. Within the single semester data, some students have already noted that following the guide made them more efficient problem solvers. As students gain more experience with the guide across multiple semesters, this fraction of students may increase as students have more experience with the homework guidelines. Future work will also address a current limitation where a control group was unavailable for the courses in this study. The courses only had one lecture section, so students could not be divided into different treatment groups, and most courses were being taught by the instructor for the first time, limiting comparisons to previous years. As the guide is implemented in more courses, it will be possible to compare student performance with the homework guide's introduction to previous years' data for courses taught by the same instructor. It will also be informative to see how students perform in writing intensive courses, such as upper division laboratory courses and capstone projects, and how the guide instruction translates to different forms of written communication.

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Appendix A: Chemical Engineering and Materials Science Homework Guidelines

Purpose

Clear, effective communication is essential to your success as an engineer. Many of the real-world problems that you will face will be complex and multi-staged, requiring documentation to be precise and understandable for team members, supervisory committees, and clients. Clear and transparent solutions improve your work with collaborators and increase the safety of the overall designs by minimizing any errors due to miscommunication.

In your engineering courses, well-explained and easy-to-follow solutions demonstrate your conceptual understanding of the material. Consider the following example:

> **Problem 1.** A 1.5 mm thick sheet of iron separates a chamber containing a carburizing gas (meaning carbon tends to enter the alloy) from one that contains a decarburizing environment (meaning that carbon tends to leave the alloy). After a period of time, the diffusion flux was measured to be 1.5×10^{-8} kg/(m^2s) at all locations through the thickness of the alloy. Under that condition, it is determined that one surface contains 0.02 wt% C and the other surface contains 0.01 wt% C.
>
> a) Indicate whether the problem is steady state.
> b) Determine the diffusion coefficient for C in Fe for the described system.
>
> A) Steady state B) $D = 2.87 \cdot 10^{-11}$ m^2/s

This homework answer would likely not receive full credit in your course, because instructors care about the process you take, not just the final answer. When you write solutions in a systematic and organized way, instructors are better able to:

- Provide feedback and support on areas that need improvement.
- Award more credit for work that shows your steps.

Communicating your work will also improve your understanding of the course material since it requires you to understand the process to reach a final answer. Developing these problem-solving techniques now will prepare you to be successful in your coursework and later in your professional career.

Problem Solution Formatting

The following format provides a framework for solving complex problems. This general template will provide a good starting point for many problems you'll see in your undergraduate studies, but some problems may require some modification of the given list.

1. **Problem summary:** Concisely summarize the problem scenario. This step helps ensure that you don't miss any important instructions and that you answer all problem components.
    a. List the problem statement's **given values, constraints, and boundaries**.
    b. **Draw relevant diagrams** to represent key aspects of the problem.
    c. **State the goal** of the problem. (What are you trying to calculate? What are the unknowns?)

2. **Solution:**
    a. Write **all relevant base equations** in variable form before any numbers are substituted.
    b. Write any **assumptions and constraints**.
    c. Show all necessary steps and mathematical calculations.
        i. Provide **narration** as you work through the problem solution. Including short descriptions between equations helps your reader understand your logic.
        ii. Write solutions in a linear, line under line format where each step is written underneath the previous.
        iii. Space out your work to increase legibility.
        iv. Make sure to include **units.** Show necessary conversions and check that the units are consistent across variables to avoid calculation errors.
    d. **Box or circle final answer**. Include the appropriate number of significant figures.

3. **Evaluate answer:**
    a. Check that your answer makes sense with the context of the problem. Some common conceptual checks are listed below:
        i. Do your units make sense? For example, if you are asked to find a flow rate, does your answer have "mol/s" or something comparable?
        ii. Does your order of magnitude make sense?
        iii. Do your mass fractions add to 1?
    b. You may be asked to provide a degree of confidence in your solution based on your answer evaluation. As an example, if your answer was order of magnitudes larger than the typical range expected for that type of value, you might report a lower degree of confidence. As an engineer, it will be extremely important for you to call out when answers are clearly not correct to prevent unsafe operations.

c. Even if the homework problem does not specifically ask you to perform this step, performing this step will help you catch any errors in your work and improve your conceptual understanding of the material.

Summary of Problem Organization

Section	Content
Problem Summary	Define given values, constraints and boundaries
	Draw relevant diagrams
	State goal of the problem
Solution	Write relevant base equations in variable form
	Write any assumptions
	Show all necessary steps (include narration & units)
Answer	Box, circle, or highlight final answer
	Evaluate answer

Exceptions

The problem organization listed here is a great tool to start many problems, but it's not possible to create a guide that anticipates all possible variations that you will see throughout your studies. Some problems may not require you to go through every step described here. For example, a conceptual question like in Problem 1A (see annotated example) requires a short answer response rather than a detailed mathematical solution. It is important to read the problem statements carefully to determine which components are necessary for your problem.

Tips for Writing and Submissions

Problems with Code

Like with mathematical problems, code should include **comments** to describe what is being done within the file. Figure 2 shows an example Jupyter notebook with comments that describe the function of the Python code and markdown cells that include the approach and rationale for the code implementation.

Numerically integrate using the trapezoid rule

The single-application trapezoid rule approximates the integral using the following expression:

$$\int_a^b f(x)dx \approx \frac{b-a}{2}[f(a) + f(b)]$$

Where $a = 0$ and $b = 1$ for this problem

In [4]:
```
def trap(x_l, x_r, f=f):
    """
    Numerically integrate y = f(x) over the domain [x_l, x_r]
        using the single-application trapezoid rule

    Args:
        x_l (float) : left domain boundary
        x_r (float) : right domain boundary
        f (function) : function to compute f(x)

    Returns:
        I (float) : numerical approximation to the integral of f(x) over [x_l, x_r]
    """
    return (x_r - x_l)/2 * (f(x_l) + f(x_r))

# apply trapezoid rule over [0,1]
I = trap(x_l=0, x_r=1)
print('The numerical approximation to the integral is %.2f' % I)
```

```
The numerical approximation to the integral is -3.70
```

Figure 2 | Python example code. Markdown cells describe the numerical integration approach, and comments describe the function's purpose, inputs, and outputs along with its execution. The executable file result is printed in the last cell.

If you have questions on getting started in Python, the department has a helpful guide, "Introduction to Scientific Python" found at this link: https://docs.cems.umn.edu/intro/intro.html.

Formatting Graphs

Some engineering problems will ask you to sketch or plot data to represent important conceptual trends as part of your solution. Whether you are making these graphs by hand or using a computer, all graphs should include the minimum components for accuracy and clarity:

- **Labeled axes**

- Defined variable symbols in legend or caption
- Legible and consistent text

Figure 1 shows an example of two types of graphs that you might be asked to generate in your courses. If you were asked to sketch how the concentrations of two compounds change over time, you might include a **sketch** like the one shown in Figure 1A.

If instead, you were given more information about the reaction conditions and were asked to **plot** the concentrations using software, you might provide a plot made in Excel like the one shown in Figure 1B. When plotting values using software, make sure to scale the x- and y-axes to allow for trends and differences to be observed.

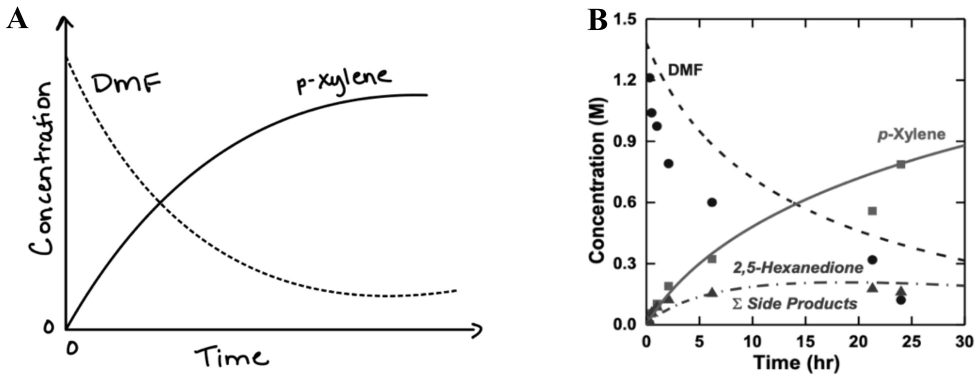


Figure 1 | Example graphs A. Sketch reactant dimethylfuran (DMF) and product p-xylene concentrations over time **B.** Plot of DMF (●), p-xylene (■), and side product 2,5-hexanedione (▲) concentrations over time. Data obtained from open source publication by Patet, et al.[1].

Electronic Submissions

Many classes now require homework to be scanned and submitted electronically. Here are some tips to make sure that your scans are easy to read so that you receive full credit.

- Double check the quality of your scans to ensure there is no blurring or smudging.
- Make sure that your images are scaled appropriately for the greatest legibility. Often, a standard Letter (8.5''x11'') size works well. Do not take extended screenshots since these are often generate small, blurry images for different computer operating systems. Converting your homework files to PDF will often solve problems associated with sizing.
- Light pencil markings or dark page colors make it difficult to read solutions. Make sure that there is sufficient contrast with your work and the page background. Using a "high contrast" setting on your scanner can also help improve legibility.
- If submitting on GradeScope, connect each problem with the problem statement in the submission portal.

Annotated Examples

Let's look back at Problem 1 that was introduced at the beginning of the guide. Here is how you might show your work. The problem statement is given again for reference and important values are underlined. Notice how these values show up at the beginning of the student's problem solution, so that the solution itself is a stand-alone document with all relevant information.

Part a is an example of an exception to the "Problem Solution Formatting" guide where not all the steps in writing out the solution are necessary. While you don't need to write out equations and show mathematical work for this sub-problem, this conceptual question still requires you to explain your decision-making rationale in a short answer response.

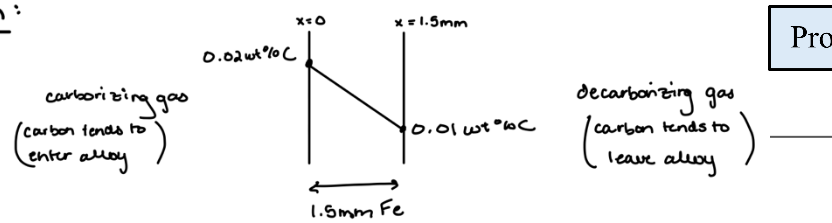
Part b is an example of a common multi-step problem that requires most of the steps in the "Problem Solution Formatting" section. Narration accompanies the mathematical steps of the solution, so it is clear what the student is doing and why.

> **Problem 1.** A <u>1.5 mm thick sheet of iron</u> separates a chamber containing a carburizing gas (meaning carbon tends to enter the alloy) from one that contains a decarburizing environment (meaning that carbon tends to leave the alloy). After a period of time, the <u>diffusion flux was measured to be 1.5×10^{-8} kg/(m^{2}s) at all locations</u> through the thickness of the alloy. Under that condition, it is determined that <u>one surface contains 0.02 wt% C</u> and the <u>other surface contains 0.01 wt% C</u>.
>
> a) Indicate whether the problem is steady state.
> b) Determine the diffusion coefficient for C in Fe for the described system.

Annotated Solution:

<u>Problem 1</u> — Problem # labeled

<u>Given</u>: — Problem summary



Diagram

The iron sheet has: Diffusive flux at all locations => $J = 1.5 \cdot 10^{-8}$ kg/m^{2}s
One surface with 0.02 wt% C
One surface with 0.01 wt% C

<u>Goals</u>: — State the objective
a.) Identify if the system is at steady state.
b.) Determine the diffusion coefficient D for carbon in iron

Problem solution (labeled subproblems)

A.) <u>Process is steady state</u> since the diffusion flux is equal at all pos
within the sheet.

Answer underlined

B.) Convert C concentration from wt % to kg/m³ to match the given units of flux

Narration

$$C_c'' = \frac{C_c}{\frac{C_c}{\rho_c} + \frac{C_{Fe}}{\rho_{Fe}}}$$ where ρ_c & ρ_{Fe} = densities of carbon & iron

Subproblem labeled

Write base equation

At $x = 0$, $C_c = 0.02$ wt % & $C_{Fe} = 99.98$ wt %

$$C_c''(x=0) = \frac{0.02}{\frac{0.02}{2.25\ g/cm^3} + \frac{99.98}{7.87\ g/cm^3}} \cdot \frac{1\ kg}{1000\ g} \cdot \left(\frac{100\ cm}{1m}\right)^3$$

Each step written underneath previous

$$C_c''(x=0) = 1.57\ kg/m^3$$

At $x = 1.5$, $C_c = 0.01$ wt % & $C_{Fe} = 99.99$ wt %

$$C_c''(x=1.5) = \frac{0.01}{\frac{0.01}{2.25\ g/cm^3} + \frac{99.99}{7.87\ g/cm^3}} \cdot \frac{1kg}{1000g} \cdot \left(\frac{100\ cm}{1m}\right)^3$$

$$C_c''(x=1.5) = 0.787\ kg/m^3$$

Write base equation

Using Fick's Law:

$$J = -D\frac{\Delta c}{\Delta x}$$

Numbers, with units, substituted at the last step

Solve for D:

$$D = \frac{-J\Delta x}{\Delta c}$$

$$D = -\frac{(1.5 \cdot 10^{-8}\ kg/m^2 s)(0.0015\,m - 0\,m)}{0.787\ kg/m^3 - 1.57\ kg/m^3}$$

Answer boxed with units and the correct number of significant

$$\boxed{D = 2.9 \cdot 10^{-11}\ m^2/s}$$

Evaluate answer:

Evaluate Answer

The final answer has units of m²/s which is consistent with the units of a diffusion coefficient. The order of magnitude ($\sim 10^{-11}$) is smaller than typical D is liquid or gases, which would be expected for diffusion in a solid.

The following is an example of a well-explain homework solution to a common chemical engineering homework prompt.

Homework prompt:

Problem 2. A fuel (C_xH_yO) is burned in air according to the (unbalanced) chemical reactions shown below:
R1: $C_xH_yO + O_2 \rightarrow CO_2 + H_2O$
R2: $C_xH_yO + O_2 \rightarrow CO + H_2O$

After reaction, 80% of O_2 and all C_xH_yO in the feed are consumed. Chemical analysis shows that the product exiting the reactor contains 7.30 mol % CO_2, 3.70 mol% CO, 16.5 mol % H_2O, 940. moles of N_2, and residual O_2. The process operates at steady state. Air contains 21 mol % oxygen and 79 mol % nitrogen.

a) Calculate the flowrate of each compound in the product stream.
b) Determine the value of x and y using element balances.

Annotated Solution:

Problem 2

Problem # labeled

Given: a fuel (C_xH_yO) burned in air according to the unbalanced reactions:

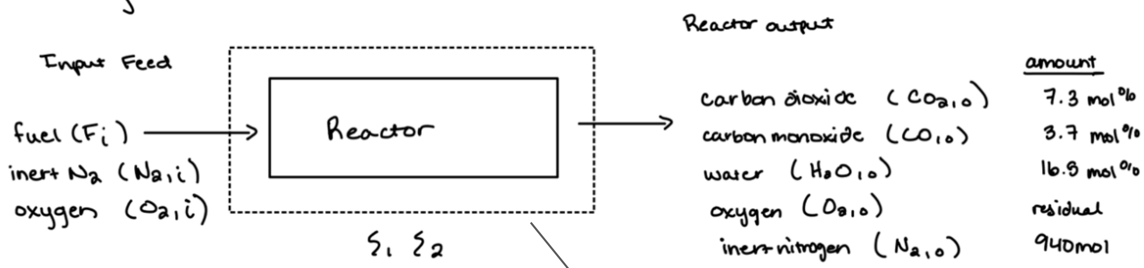
Problem summary

Extent of reaction

R_1: $C_xH_yO + \underline{a}O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O$ $\quad \xi_1$

R_2: $C_xH_yO + \underline{b}O_2 \rightarrow xCO + \frac{y}{2}H_2O$ $\quad \xi_2$

All C_xH_yO and 80% O_2 are consumed in the reaction.



Diagram

Air = 21 mol % O_2 & 79 mol % N_2

Goal: a.) Calculate moles of each compound in the exit feed
b.) Determine value of x & y

State the objective

<u>Part A</u> :

Subproblem labeled

Reactor molar balances : $0 = IN - OUT + GEN - CONS$

Write base equation

Balances for each species :

Narration

① F : $0 = F_i - \xi_1 - \xi_2$

② O_2 : $0 = O_{2,i} - O_{2,o} - a\xi_1 - b\xi_2$

③ N_2 : $0 = N_{2,i} - N_{2,o}$ since N_2 is inert in the reaction gen = cons = 0

④ CO_2 : $0 = -CO_{2,o} + x\xi_1$

⑤ CO : $0 = -CO_{,o} + x\xi_2$

⑥ H_2O : $0 = -H_2O_{,o} + \frac{y}{2}\xi_1 + \frac{y}{2}\xi_2$

Solve for molar output : N_2 : $N_{2,i} = N_{2,o} = 940 \text{ moles}$

Use the composition of air : $O_{2,i} = \frac{21}{79} N_{2,i}$

$= \frac{21}{79} \cdot 940 \text{ moles}$

$= 250 \text{ moles}$

80% of O_2 consumed : $O_{2,o} = (1-0.8)\, O_{2,i}$

$= 0.2\,(250 \text{ moles})$

$= 50 \text{ moles}$

Each step to solve written underneath the previous step

Exit stream molar balance : $1 = X_{CO_2} + X_{CO} + X_{H_2O} + X_{O_2} + X_{N_2}$

$1 = 0.073 + 0.037 + 0.165 + X_{O_2} + X_{N_2}$

$0.725 = X_{O_2} + X_{N_2}$

Calculate the total molar output :

$0.725\,(n_{T,o}) = n_{O_2,o} + n_{N_2,o}$

$n_{T,o} = \dfrac{940 \text{ mol} + 50 \text{ mol}}{0.725}$

$n_{T,o} = 1365.5 \text{ mol}$ = total molar output

Using the total molar output and the given molar percentages

$$CO_{2,o} = X_{CO_2}(n_{T,o})$$
$$= 0.073\,(1365.5\,mol)$$
$$= 99.7\,mol$$

$$CO_{,o} = X_{CO}\,(n_{T,o})$$
$$= 0.037\,(1365.5\,mol)$$
$$= 50.5\,mol$$

$$H_2O_{,o} = X_{H_2O}\,(n_{T,o})$$
$$= 0.165\,(1365.5\,mol)$$
$$= 225.3\,mol$$

The output molar amounts:

$$\boxed{\begin{aligned} O_2 &= 50.0\ mol \\ N_2 &= 940.\ mol \\ CO_2 &= 99.7\ mol \\ CO &= 50.5\ mol \\ H_2O &= 225\ mol \end{aligned}}$$

Answer boxed with units and the correct number of significant

Part b:

From the species balances: ④ $\xi_1 = \dfrac{CO_{2,o}}{x}$ ⑤ $\xi_2 = \dfrac{CO_{,o}}{x}$ ⑥ $\xi_1 + \xi_2 = {}^2/_y\, H_2O_{,o}$

Substituting ④ & ⑤ into ⑥: $\dfrac{CO_{2,o}}{x} + \dfrac{CO_{,o}}{x} = \dfrac{2}{y} H_2O_{,o}$

Substituting mol outputs from part a: $\dfrac{y}{x}\,(99.7\,mol + 50.5\,mol) = 2\,(225.3\,mol)$

$$\frac{y}{x} = 3$$
$$y = 3x$$

Atom balances: mol atom input = mol atom output

C: $xF_i = CO_{2,o} + CO_{,o}$

H: $yF_i = 2H_2O_{,o}$

O: $F_i + 2O_{2,i} = 2O_{2,o} + 2CO_{2,o} + CO_{,o} + H_2O_{,o}$

$$F_i = -2\cdot 250\,mol + 2\cdot 50\,mol + 2\cdot 99.7\,mol + 50.5\,mol + 225.3\,mol$$
$$= 75\,mol$$

Numbers substituted at last step and included

Using C & H balances:

$$x = \frac{CO_{2,o} + CO_{,o}}{F_i} = \frac{50\,mol + 99.7\,mol}{75\,mol} \qquad y = \frac{2\,H_2O_{,o}}{F_i} = \frac{2\cdot 225.3\,mol}{75\,mol}$$

$$\boxed{x = 2 \qquad y = 6}$$

Answer boxed

Evaluate Answer

Evaluate answer: Check balanced equations for C & H

Reaction 1				Reaction 2			
	$C_2H_6O + \underline{a}O_2 \rightarrow 2CO_2 + 3H_2O$				$C_2H_6O + \underline{b}O_2 \rightarrow 2CO + 3H_2O$		
#C:	2	=	2	#C	2	=	2
#H:	6	=	6	#H	6	=	6
#O:	7 (a=3)	=	7	#O	5 (b=2)	=	5

Atom balances match for both reactions ✓

References

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[2] Elements of this writing guide were drawn from: Ben Adams and Will Durfee, "Mechanical Engineering Student Writing Guide", University of Minnesota, Twin Cities.