2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #38164

Graduate Ph.D. Chemical Engineering Curriculum: Progress in Twenty Years

Mrs. Emily Nichole Ingram, University of Kentucky

2nd Year Ph.D. Graduate Candidate

Dr. Malgorzata Chwatko, University of Kentucky

Malgorzata (Gosia) Chwatko is an assistant professor in chemical engineering. She has gotten her Ph.D. at the University of Texas at Austin.

Graduate Ph.D. Chemical Engineering Curriculum: Progress in 20 years

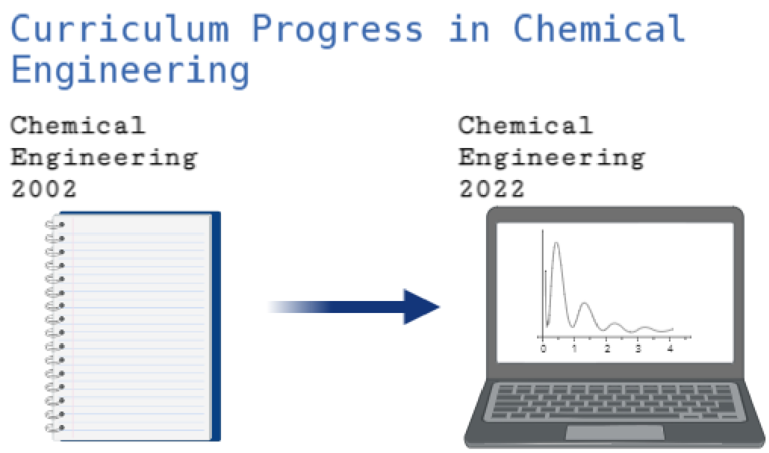
Emily Ingram, Malgorzata Chwatko

Chemical and Materials Engineering Department, University of Kentucky, Lexington, Kentucky

ABSTRACT

The chemical engineering field is constantly evolving to encompass new ideas such as genetic engineering and synthetic biology, green chemistry and sustainable materials, and engineering education. This evolution has been seen throughout the undergraduate curriculum with the development of new courses or certificate programs, as reported in the literature. The progress reported in the undergraduate programs has influenced us to investigate if there are any similar shifts in graduate program curricula. In this work, we studied the 2021-2022 chemical engineering Ph.D. curriculum at 100 US universities to gain insights into the courses that students take, as well as other degree requirements to obtain a terminal degree in chemical engineering. The institutions were chosen from the best chemical engineering programs, US News & World Report 2022. The data for the study was collected from the institutions' websites, as well as personal knowledge of the programs. We found that the majority of the core required courses remained the same, as reported by David Kauffman in 2002, and included transport phenomena, thermodynamics, and reaction engineering. There was, however, an increase in the diversity of elective courses which are offered by the departments. The study also investigated other program requirements, such as participation in seminars and teaching assistantship positions. We found a high percentage of schools had required teaching assistantships and seminar attendance as part of the program. Through these findings, we hope to identify future evolution in the graduate chemical engineering curriculum.

GRAPHICAL ABSTRACT



INTRODUCTION

In the late 1800s, chemical engineering emerged as a separate field of discipline. Quickly the core content of what all chemical engineers need to know has been set at the undergraduate and graduate levels of education. These core courses include thermodynamics, kinetics/reactor design, transport, and applied mathematics; which are at the heart of what it means to be a chemical engineer. [1,2] While this knowledge is essential to the traditional engineer, the definition of chemical engineering has been expanding in recent years. Involvement in fields traditionally labeled as “other” such as biology, chemistry, business, computer science, safety, and communication, among others, has led to the evolving definition of chemical engineers. The boundaries of this discipline have become grayer and allow for more interdisciplinary collaborations and broader research interests, leading to impactful discoveries.

The need for periodic review of processes is needed in all fields of endeavor, and chemical engineering education is no different. Curricula must change and evolve as the world changes and evolves to match the variety of applications and jobs/careers the students will undertake after completing their degree. These changes to the scope of chemical engineering can be seen in the undergraduate education curriculum.[1-4] Proposed changes include discussion of new technology such as computer science or green chemistry or soft skills like professionalism which were not part of the curriculum 20 years ago. However, the same level of action is not seen in the articles regarding the graduate curriculum. There are limited papers on the integration of new ideas into the graduate curriculum, and only one paper describing the course curriculum across the US.[1, 5-7] The study by David Kauffman attempts to capture the number of schools in the US which require/suggest the core chemical engineering classes at the graduate level in 2002.[7] In the nearly 20 years since this paper was published, the research on graduate studies curriculum in engineering has been lacking. This work investigates what the chemical engineering curriculum is and if significant changes occurred in the 20 years since Kauffman's work on describing the course program.

Required skillset for chemical engineers

The traditional definition of a Ph.D. program involves both continued education in fundamental principles of chemical engineering, as well as an intensive research experience. The courses in many institutions are structured to support the research content, and the quality of the experience depends heavily on the faculty advisor. In many groups, students gain a specific subset of skills and instruction in one research area such as membrane separation, where fundamental chemical engineering principles are applied. In chemical engineering, it is the advisor's responsibility to provide research funding and student funding when students are not supported by other scholarship/fellowship funding. The funding is therefore, a big driver for the work the students perform and learn about. While the structure has been in place for many years, any person who has obtained a degree in chemical engineering can tell you that outside of the classes, the quality of the experience varies. Every advisor stresses different skills or takes a different approach to teaching. However, when the degree is awarded, all students are expected to be able to lead projects, manage teams, have strong oral and written communication, teamwork, problem-solving skills, economic skills, and be aware of their professional and ethical responsibility. The required skills listed above come from a survey of alumni and employers by the New Jersey Institute of Technology.[8] As can be seen from this short list, specific expertise in a topic area is not the only major driver when hiring decisions are made, which, in contrast to the Ph.D. process that stresses the experience in your dissertation area. As such the question remains, are all these skills supposed to be taught in research settings, or is at least a portion taught in coursework required for the PhD?

METHODS

Using the US News and World Report Rankings in 2022, a list of the top 100 schools in graduate chemical engineering was fabricated to obtain data for each program. Each of the school's websites was used to compile core courses, electives, and other requirements such as seminars, qualifying examinations, and presentations. Some schools provided their graduate student handbook, which made obtaining information easier, while others provided little readily accessible information.

We tracked four main courses, reactor design, transport, thermodynamics, and applied mathematics. In the applied mathematics umbrella, we included courses such as numerical analysis but excluded courses about computational methods or statistics. Course data was split across three categories, core, cafeteria, and combination. The core courses are those listed as required for the completion of the degree program, such as reactor design, transport, thermodynamics, and applied mathematics. The cafeteria group of courses are those listed as an option to fulfill the graduate requirements. An example of this listing is asking students to complete three out of six courses. For cafeteria core, any three of these classes would suffice to complete the number of required classes.

RESULTS

Entrance requirements

Students aiming to receive a doctoral degree in chemical engineering need to meet certain requirements regarding their undergraduate degree. While most schools do not require an undergraduate degree in chemical engineering before applying, many require that students have degrees in related science fields such as biomedical engineering, chemistry, or physics. Students from related fields are commonly placed in the core undergraduate courses before taking the higher-level graduate courses to give them the best opportunity to succeed. During the application process, students must have their statement of purpose, transcripts, letters of recommendation, and resume and/or curriculum vitae (CV). Over the last few years, institutions have begun to move away from requiring a minimum Graduate Record Examination (GRE) score, as it can unfairly isolate those students who are not considered "good test takers" and does not accurately evaluate a student's knowledge.[9] On average, black students score about one standard deviation lower than White test takers.[10, 11] Many colleges and universities still require a minimum undergraduate GPA of 3.0 to apply to graduate school. Those student's seeking to apply from international schools also must provide a Test of English as a Foreign Language (TOEFL) score, as the vast majority US colleges require a minimum score of 100 out of 120. This is considered a "strong score," but some colleges will accept lower.[12] Many schools have also started to implement a holistic review to not fall victim to bias with greater success to include historically underrepresented minorities. [13]

Table 1. Required courses for students. Those that fall under the cafeteria criteria have the option to choose these as a part of their core courses.

Courses	2002[a]			2022		
	Required core (%)	"Cafeteria" Core (%)	Total (%)	Required core (%)	"Cafeteria" Core	Total (%)
Transport Phenomena	86	13	99	74	23	97
Thermodynamics	83	16	99	74	24	98
Kinetics/Reaction/ Reactor Engineering	78	17	95	69	26	95
Applied Mathematics	67	11	78	63	27	90

[a] Data from reference [9]

Courses

Of the schools analyzed in this survey, 94 out of 100 schools require students to take courses during their tenure in graduate school. These can include core courses, cafeteria courses, or a combination of both, however, it was observed that the majority of institutions still have a set of core courses for each student as seen in Table 1. Six of the schools did not specify the types of courses that they had available for students, but three of them required 500-level and above courses. Similar to the 2002 report from Kauffman, transport, thermodynamics, and reactor engineering are required or suggested at a high percentage of schools (>=95%). Applied mathematics courses such as numerical analysis had increased dramatically in their importance in the curriculum from 78 to 90%. The dramatic increase in the course offering may be due to the use of software such as MATLAB or Wolfram Mathematica in such courses. In addition, several schools offer advanced statistics rather than applied mathematics, which ensure students have a good understanding of data analysis and reporting statistically significant results. Statistics courses were not included under the applied mathematics category in this study but together showcased the push to develop mathematical models and data analysis within the curriculum.

An additional shift in the curriculum can be seen in the percentage change from required to cafeteria-style courses. This shift is present in all courses in this study. This shift is encouraging as it encourages student flexibility. As noted in the introduction, chemical engineering now encompasses such diversity as synthetic biology, educational research, and software development. By switching to cafeteria offerings, the curriculum is acknowledging that every student may benefit from a more individualized program.

There is minimal similarity between other core courses mentioned between universities. Only 14 of the 100 schools require core courses outside of the traditional four mentioned above. Eight schools require a form of research training labeled as “research methods” or “approaches to research.” Furthermore, five schools listed a biotechnology course as a core, with only four listing a required safety course. A few schools also allowed students to choose biomolecular or cellular engineering over the traditional reactor course, which supported the transition to biotechnology and data science/modeling.

An area that is still lacking in engineering is communication and professional development courses. Whether students strive to be in industry or academia, effective communication skills are highly sought after and often a requirement. As students transition from undergraduate courses to graduate courses, the amount of writing and conveyance of data shifts drastically; however, even after twenty years, there still lacks the requirement for formal instruction of these soft skills. Students have identified that writing is stressful and, therefore could benefit from more formal instruction in scientific writing.[10, 11]

Teaching Assistantship

While formal instruction of professional development and communication is not required in many institutions, 36 out of the 100 schools specified that students must serve as a teaching assistant. If taken advantage of properly, students can learn how to articulate and communicate scientific information. However, there was not any detailed information given for whether the assistantship was solely to grade assignments or if the students were given the opportunity to teach a lesson. We were unable to compare these requirements to the 2002 study, given that they did not track teaching opportunities at that time. Additionally, limited to no information was found regarding teaching assistantship training.

Communication Requirements

As aforementioned oral and written communication is vital to the success of an individual whether they choose to take an industry or academia path. During a Ph.D. program, these soft skills can be sharpened. 43% of schools required students to give an oral presentation and/or a symposium presentation of their work. Fifteen schools specified a formal or "written proposal" of their research, some requiring it by the end of the first year. This method gives students a more structured start to their residency in graduate school while building the necessary written communication skills. Students may also write journal publications with their advisors, but that is not a formal requirement in the curriculum. Lastly, students are expected to create a dissertation document of their work throughout the program. This final work is published and gives students an opportunity to summarize their work.

Students are also expected to participate in seminars to practice oral communication skills. Seminar attendance was noted as a mandatory activity for 41% of the schools. These seminars include presentations given by visiting faculty, which allows students to learn different presentation techniques that faculty use to convey information about their own research. Having formal presentations amongst peers can help students learn what methods of presenting work and do not work to advance their oral communication skills. Once again, the 2002 study did not examine such requirements, and thus, we cannot adequately compare the progression of this specific curriculum.

Exam Requirements

Written and/or oral examinations are a key requirement for all of the schools studied in this survey. The purpose of the qualifying exam is to test students' knowledge regarding their project. This type of exam can also help the student to understand where they lack in conveying their research project and what skills they need to work on. A student may be terminated or demoted to the master's program if they were to fail their qualifying exam. Such presentations are traditionally given in front of a committee of faculty who assess a student's weaknesses and strengths, while guiding them in the next steps of their research. Although the exam usually happens after year two or three, marking a good halfway point, twelve schools noted that they additionally required yearly reports to the committee. Yearly reports can be beneficial to the student to ensure they are on the right track and continue building skills.

Further investigation revealed that some schools still require a written exam pertaining to the core classes that students are required to take. Seventeen schools require an exam at the end of the first year of graduate candidacy that is designed to test students' knowledge in fundamental chemical engineering knowledge. Of the institutions that require these exams, many of them allow the exam to be taken up to three times if any weaknesses are identified. However, these examinations may be considered redundant as most students entering chemical engineering Ph.D. have the same undergraduate degree. Any students who hold alternative bachelor's degrees are typically required to take key undergraduate chemical engineering courses first.

Kauffman's study did not look at examination requirements and thus, we could not compare how it has changed over time. However, it can be hypothesized that a transition to more meetings with a students' committee could prove to be useful to students. More frequent meetings allow students to enhance their project management and communication skills. An increase in the frequency of committee meetings could prove to be beneficial to not only the student, but members of the committee as well, being that collaborations could begin, expanding a student's teamwork skills. Likewise, this committee-based approach is more representative of the environment students are entering outside of school.

Recommendations

From this study, there are several recommendations and questions that should be considered. First, the ability for graduate students to become familiar with working in a team and gaining broad insight from peers stresses the need for the development of an interdisciplinary workforce. In the last few years, there has been increased support for interdisciplinary programs such as the National Science Foundation's (NSF) Integrative Graduate Education and Research Traineeship (IGERT). This program provides institutions with funding and support to develop broad interdisciplinary training programs. The evolution of such interdisciplinary education occurs across many specialties and thus, chemical engineering programs could greatly benefit from participating in such programs as well. [12,13] Additionally, similar changes can be fostered by having broader requirements for core courses, or having instructors from different background co-teach certain courses, such as drug delivery, membranes, or biotechnology. A drug delivery course co-taught by professors in chemical engineering, biochemistry and pharmacy could help students understand the transport, chemical/biological composition, and bioavailability of drug delivery systems by professionals in these topics.

Another key discrepancy is that graduate students are often asked to become experts in "one manageable problem."[13] There could be a benefit to requiring students to work on at least one unrelated project to expand their knowledge base and comfort level of obtaining new information. Furthermore, having multiple projects instills project and time management skills to students over time. One potential option of achieving such a goal is by co-advising students or having active committees.

It is important to maintain the foresight that graduate education is supposed to prepare students for their future careers. While the choice of careers may be broad, many skills can be transferred across platforms. These include communication, leadership, creativity, and problem-solving. Being a researcher can help to develop many of these skills, however, sole reliance on this method can lead to gaps and inequalities in instruction and learning. Moreover, our chemical engineering graduate programs should consider if the curriculum and program structure is justifiable and supports the growth of the student alongside research productivity. Finally, a growing mental health crisis is evident in graduate education and should be taken seriously across all disciplines.[14,15] Thus the reliance on single PI model, and publication as the outcome of "successful" Ph.D. may need to be reconsidered to generate truly successful Ph.Ds.

Conclusion

Since the study done by Kauffman 20 years ago, we found that the core graduate chemical engineering courses had not changed much. We found that there had been an increase in the cafeteria style core and noncore courses, with more of a focus on biotechnology. This shift better aligns with the current job opportunities that are being offered to students. We also identified gaps in communication and professional development areas of the curriculum which could better match what employers and alumni identified as key skills required to perform job duties. We suggest a more formal peer and committee-based mentorship which could focus on improving skills as one potential solutions, or development of special courses designed to teach writing or communication skills.

References

1. Altarawneh, M.; Dlugogorski, B. Z., Introducing Quantum Chemistry in Chemical Engineering Curriculum. *Journal of Chemical Education* **2018,** *95* (9), 1562-1571.
2. Fogler, H. S.; Hirshfield, L. J., Process Safety Across the Chemical Engineering Curriculum. *ACS Chemical Health & Safety* **2021,** *28* (3), 183-189.
3. Glassey, J.; Haile, S., Sustainability in chemical engineering curriculum. *International Journal of Sustainability in Higher Education* **2012,** *13* (4), 354-364.
4. Hesketh, R. P.; Kathryn, A. H.; Deneb, B. J., Incorporating Green Engineering in the Chemical Engineering Curriculum. **2003**.
5. Binous, H.; Bellagi, A., Orthogonal collocation methods using Mathematica© in the graduate chemical engineering curriculum. *Computer Applications in Engineering Education* **2016,** *24* (1), 101-113.
6. Binous, H.; Kaddeche, S.; Abdennadher, A.; Bellagi, A., Numerical elucidation of three-dimensional problems in the chemical engineering graduate curriculum. *Computer Applications in Engineering Education* **2016,** *24* (6), 866-875.
7. Kauffman, D. In *The Core Graduate Chemical Engineering Program: Does It Exist?*, 2002 American Society for Engineering Education Annual Conference & Exposition, 2002.
8. Knox, D.; Barat, R., Updating The Chemical Engineering Curriculum For The 21 St Century. In *Association for Engineering Education*, American Society for Engineering Education: Salt Lake City, 2004.
9. Langin, K. A wave of graduate programs drops the GRE application requirement 2019.
10. Newman, D. A.; Tang, C.; Song, Q. C.; Wee, S., Dropping the GRE, keeping the GRE, or GRE-optional admissions? Considering tradeoffs and fairness. *International Journal of Testing* **2022,** *22* (1), 43-71.
11. Posselt, J., *Inside Gradaute Admissions: merit, diversity, and faculty gatekeeping*. Harvard Uniersity Press: 2016.
12. Wood, S. The complete guide to the TOEFL Test. (accessed 5/1/2023).
13. Wilson, M. A.; Odem, M. A.; Walters, T.; DePass, A. L.; Bean, A. J., A Model for Holistic Review in Graduate Admissions That Decouples the GRE from Race, Ethnicity, and Gender. *CBE Life Sci Educ* **2019,** *18* (1), ar7.