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Student-centered design: A capstone design project of a batch vacuum evaporator for food science students by a multidisciplinary team of engineering seniors

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Abstract

A multi-disciplinary team of engineering students taking a non-conventional senior capstone course designed, built, and tested a professional-grade vacuum evaporator for university students studying food science and human nutrition. In lieu of a traditional senior capstone design course, students from the various engineering disciplines have the option of enrolling in an integrated design experience where they are placed in collaborative teams to solve real-world projects sponsored by external stakeholders. The program comprises four parties: (1) the design team of senior engineering students who are responsible for all design decisions, analysis, and manufacturing; (2) a faculty coach to mentor and guide the team in best practices; (3) the sponsor, who provides the scope of the design need and funding, (4) and program administration who coordinate course matter, grades, and events.

In this project, students were hired by researchers in the field of food science to build a vacuum evaporator for a pilot plant that can also be used as a learning platform for students. Vacuum evaporators are used in the food industry to produce concentrated products of liquid foods that are free of volatile contents, such as tomato paste, condensed milk, or concentrated fruit juice. The apparatus was to be fully operational, up to the standards of the food industry and have extra features to fully measure internal conditions. In addition, a transparent condenser was designed to provide visual access to its internal operation.

Using the principles of human-centered design, every facet of the project was completed with the needs of food science students as paramount. Senior-level food science students were involved during testing to provide feedback and evaluate the effectiveness of the design to produce desired food products and to teach fundamental principles. The case is made that such projects provide a real-world experience as an effective capstone design challenge to senior engineers as well as provide services and innovations tailored to the specific needs of engineering and non-engineering students alike.

Introduction

Human-centered design is a flavor of engineering design taught in several academic institutions where, in addition to common traits found in all design such as problem scoping, ideation, etc., it is emphasized that the needs of human users form the basis for all design decisions. This is especially important today and in the future as we become more aware of the similarities and differences of the individuals that make up society. As our knowledge of ourselves and our neighbors increases so does our ability to design more pointedly to solve the problems and fulfill the needs of individual user groups.

Just as the identity characteristics and needs of user groups form chief design constraints so too does the identity of the engineers attempting to solve those problems affect the outcomes. In short, a design group with identity A that is building solutions for a user group with identity B produces a fascinating interrelationship of perspectives that is not only worthy of study but is imperative. But what if the group identity of the designer and the user are the same? What if Group A designs for other members of Group A? The designers then, more so than any other group are empathetic to the particular nuanced needs of the users and may find solutions, perspectives, motivations, and inspirations that are more difficult for other groups to find. In the search for engineering designers to empathize with the needs of a particular user group, employing finely trained designers in that user group themselves warrants careful study.

In this work, researchers study the unique needs, perspectives, and approaches of students in the technical sciences as they design for other students in the technical sciences. Here a team of interdisciplinary undergraduate engineers working on a senior capstones design project are designing a laboratory system that will be used by senior undergraduate food science majors. While the designers and the end users are not from the exact same discipline, the subject matter of both groups is in the field of thermodynamics and heat transfer.

A group of three undergraduate senior engineers, two mechanical engineers and one chemical engineer, participate in a design program in lieu of a traditional capstone design course. The design program groups engineering seniors into multi-disciplinary teams to work on a real-world, industry sponsored project through its entire life cycle from concept to prototype to testing and deployment. In this project, however, instead of an industry sponsor coming from a private company, the sponsor is another department at the academic institution. The department of food sciences has sponsored a project to build a vacuum evaporator to be used as a laboratory platform in their on-campus pilot plant. The sponsor requires a fully functional completed apparatus ready for use by senior food science students in practical laboratory courses for the following year.

Description of the Program

The Integrated Product and Process Design (IPPD) program at the University of Florida is a two-semester, year-long optional course track that engineering students may elect instead of their curriculum's traditional senior capstone design courses. The program lasts during the fall and spring semesters of an academic year and allows students to follow the complete life cycle of an engineering design project from problem need and concept generation through prototype building, testing, and marketing. The IPPD program differs from traditional capstone design courses in several ways.

First, students are placed in interdisciplinary teams across the college of engineering based on the need of the project as determined by faculty and industry stakeholders. For example, a team may consist of two mechanical engineering students, two electrical engineering students, and a computer science engineering student. This gives students the opportunity to work with a wider range of expertise and to complete a more complicated project than would be allowed by a single discipline's capstone experience.

Second, each student project is sponsored by an industry liaison. Companies, research laboratories, even other academic institutions fulfill the role of industry liaison, or customer, to each student team providing prototyping funds, project needs, and a preliminary problem scope. Each student team receives monetary support and often equipment, tools, and test platforms from liaisons as well as regular communication and guidance.

Third, faculty provide the student teams with more than typical design instruction. Permanent program faculty provide student teams with traditional instruction in engineering design techniques, project management, branding, marketing, and planning; all generic design instruction that all teams will value. Program staff provide logistic support such as facilitating travel to and from industry sponsor sites, purchasing, and fulfilling manufacturing needs. In addition, each team is guided by a faculty coach. The coach is an engineering faculty with particular expertise in the primary project area for each time to provide specific guidance, and indeed sometimes instruction, to achieve project success.

Program Structure

The class structure of the two-semester program follows typical patterns seen in traditional capstone design courses, laboratory courses, and seminar courses. Class time consists of a single weekly three-hour seminar-style session that starts at the beginning of the fall semester (semester 1 of the program) through to the end of the spring semester (semester 2 of the program). The three-hour weekly class is effectively a traditional instruction experience for the first several weeks of the first semester as students become acclimated to their teams, coach, and project. The weekly class eventually fulfills more of a seminar function as teams begin retreating into the specifics of the life cycle of their project. Seminar topics include several broad engineering design skills such as entrepreneurship, branding, managing mental health in team-based work, effective communication, and more. Guest speakers that lead each seminar are faculty from a variety of engineering disciplines speaking to their own expertise.

The remainder of the students' course time, apart from the single three-hour lecture/seminar experience, is spent in some fashion working on the specifics of their project. Teams are meant to schedule a single, weekly, often one-hour, meeting with their liaison engineers from their industry sponsor, a single, weekly, often one-hour, meeting with their faculty coach, and as much additional time as necessary to work as a team completing project objectives. Project milestones, from concept generation, periodic design reviews, and semester prototype reviews are scheduled by the program faculty on a week-to-week basis. Figure 1 shows the typical semester weekly milestones for the first semester of the course. The first semester of the course focuses on all aspects of project design planning. Teams are meant to have completed a conceptual design of their project prototypes by the end of the fall semester. Of note are the Preliminary Design Review (PDR), the Prototype Inspection Day (PID) and System-Level Design Review (SLDR) which function effectively as a preliminary, mid-way, and end-of-semester assessment of their progress, respectively. Judgement of team progress is carried out by a panel of four program faculty coaches based on well-defined rubrics.

Week 1:	IPPD intro, IPPD Staff presentations, Project Pitch presentations, Door Code Assignments Team Building Workshop on first Saturday after first class meeting
Week 2:	Scope of Work, Deliverables, Team Name and Logos, Stakeholders
Week 3:	Concept Design, Generation, Selection and Scoring
Week 4:	Preliminary Design Review (PDR) intro, Concept Selection & Concept Testing, House of Quality
Week 5:	Elevator Pitch, System Architecture
Week 6:	Concept Scoring, Product Architecture, Project Management and Roadmap, Project Business Case
Week 7:	Peer Review of the Preliminary Design Review (PR-PDR)
Week 8:	Professional Development Workshops (PDW)
Week 9:	Prototyping, Advanced Project Management, Test Planning, Design Report
Week 10:	Prototyping, Design of Experiments, Preparing for Prototype Evaluation
Week 11:	Ethics, Development Plans, Preparing for PID
Week 12:	Prototype Inspection Day (PID)
Week 13:	Preparing for PR-SLDR & SLDR events
Week 14:	Peer Review of the System Level Design Review (PR-SLDR) & SLDR draft due
Week 15:	System Level Design Review (SLDR)
Finals period:	Signed SLDR Report submission deadline one week after SLDR

Figure 1: A week-by-week breakdown of project milestones during the first semester (fall semester) of the course.

The second semester of the course follows a similar structure of weekly project milestones with three major project reviews conducted by faculty coaches. Where the first semester focuses on design planning, by the beginning of the second semester teams are meant to begin purchasing materials and equipment and conducting prototype building, testing, refining, and documentation.

The Sponsor Role

There are three primary roles taken by faculty or professional engineers who guide the students through the program: (1) program administrators who conduct the lectures and seminars outlined in the previous section, (2) liaison engineers employed by industry sponsors, and (3) the faculty coach. The liaison engineers fulfill the role of customer, manager, or boss to the student design team. The liaisons are a team of engineers at the sponsor company with backgrounds similar to the students who have been chosen for the project. Liaisons have typically built a pre-existing relationship with program administrators or faculty coaches and have been approached to collaborate with the university to fulfill common industry-academia partnerships. Sponsors donate a monetary sum to the program to fund a prototype budget for their team. As such sponsors retain all intellectual property rights to the finished works.

The Coach Role

The faculty coach is perhaps the most vital guide to the design team. Faculty coaches are just that, coaches, whose job is to facilitate the success of the team in a myriad of ways. Effective coaches may sometimes fulfill the role of an instructor to the team in those areas of expertise that require each member to learn new skills. For example, coaches may be called upon to teach particular project-specific skills such as finite-element analysis, dynamic modelling, virtual reality programming, and the like. More often, however, the faculty coach is a mentor to the team leading them to effective project management strategies, conflict resolution, meeting management, morale management, soft skills, and communication strategies with other engineers such as technicians, manufacturers, and sales engineers.

To give teams the best chance of success, coaches and liaisons are required to meet before the start of the semester to discuss a preliminary project problem statement and project scope. Broad strokes are used define an open-ended problem that student teams then scope to completion based on the communicated needs of the liaisons. Prior to the start of the semester each faculty coach, assigned to an industry liaison, will briefly pitch their project to the whole of the program's student population in search of a particular team makeup. Students are then asked to weigh their preferences of the project in which they would like to participate and program administrators match students to projects as equitably as possible. Figure 2 shows the project pitch information that was used to entice students to the project that is the subject of this study.

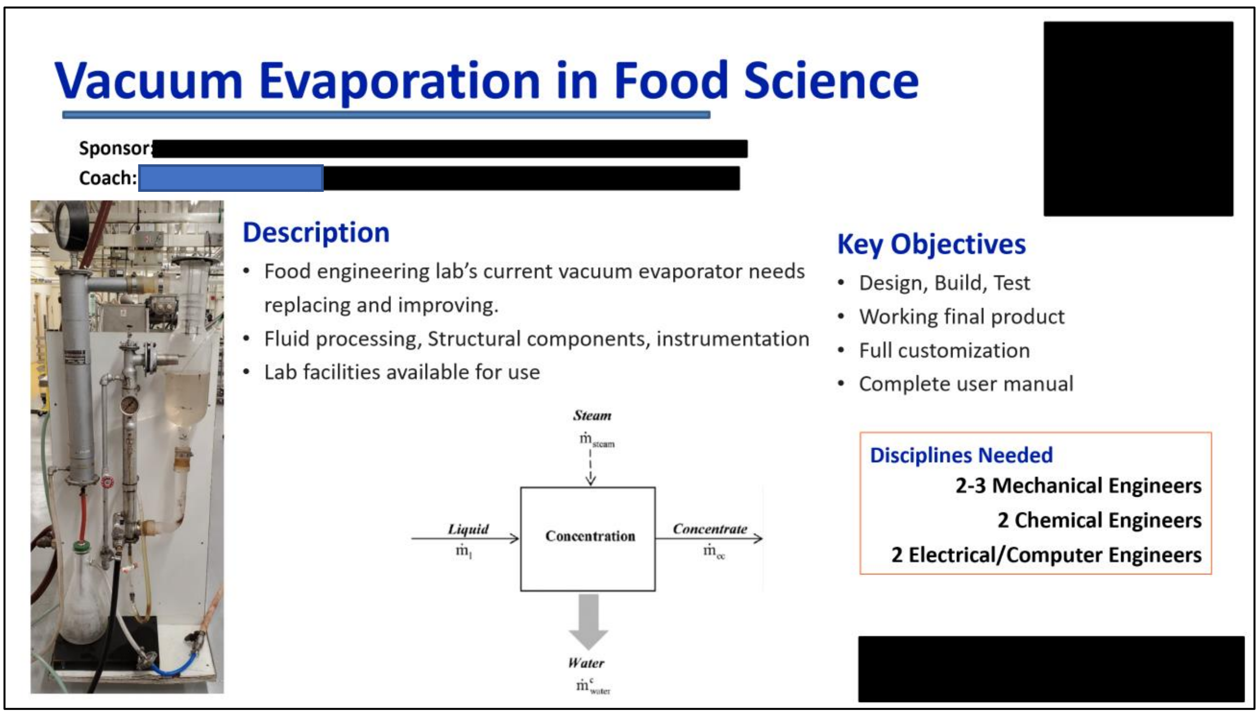

Figure 2: Project pitch slide presented to all program students prior to student selection.

Faculty coaches provide guidance to best ensure that design teams will ultimately be successful while also yielding design decisions and freedom to the student teams. The students complete all the work, have the final say on all design decisions, and are considered solely responsible for the finished product.

The Vacuum Evaporator Design Project

This project describes the one design team's response to the University of Florida's Food Science Department regarding their need for a new food vacuum evaporator system. Based on this need, the department has commissioned an IPPD team to design, build, and test a functional prototype for teaching students in their lab. This project deviates from typical program structure in that the sponsor company is a non-engineering department at the same academic institution rather than a true industry sponsor. Functionally the roles remain the same with the added component that engineering students are now designing for an end-user they share traits with: undergraduate students.

The University of Florida's Food Science Department boasts an impressive laboratory where students and professors explore the complexities of food science. Since many machines and systems in the pilot plant are highly technical and modern, the department decided it was time to replace their vacuum evaporation system, whose year of origin is unknown. Since the system currently used in labs is dated, has ill-fitting parts, and contains components that can no longer be replaced, the design team (adopting the name, "EvapoGators") has been tasked with designing a custom food vacuum evaporator for use in the pilot plant.

These labs help the students better understand the relationship between boiling point and pressure and the process of evaporation using steam input and vacuum pressure. The system is used in courses on unit operations and basic and advanced food processing. This apparatus has been used by both graduate and undergraduate students in the department's pilot plant for at least 20 years, but it is now out-of-date and due to be replaced. The current system in the pilot plant is shown in Figure 3.

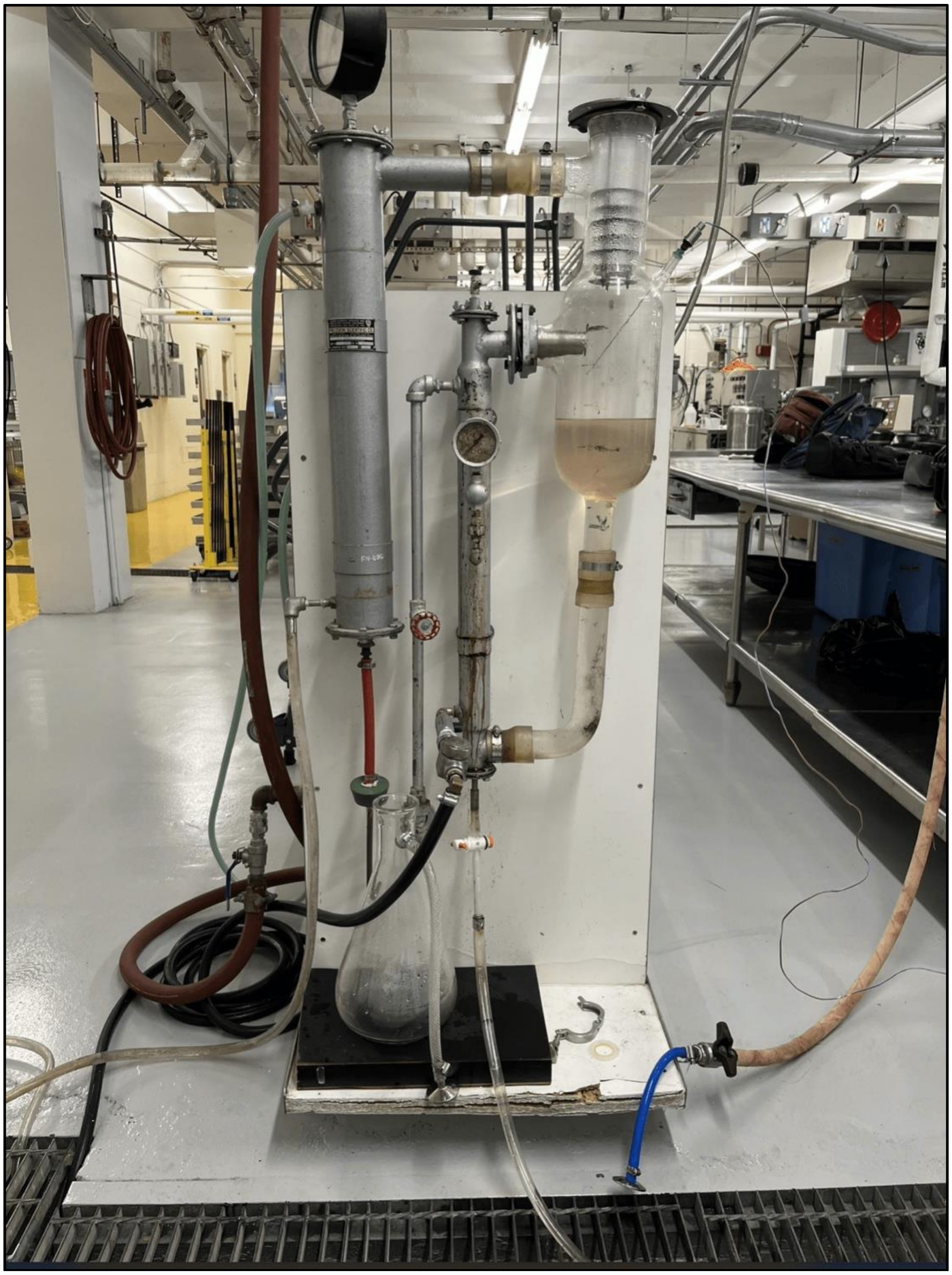

Figure 3. Original food vacuum evaporator apparatus.

The Problem Statement and Objectives

As previously mentioned, the year of origin of the current vacuum evaporation system is unknown. The system is composed of outdated technology that allows fluid leaks, uncertainties, and difficulty obtaining readings. Additionally, the vacuum evaporation system in the pilot plant contains parts that are not available for purchase, which makes the machine nearly impossible to update should those parts fail. At this point, however, the department would rather buy new than update the current system due to its old, corroding parts and its unpleasant aesthetic in a state-of-the-art food science lab full of shiny, stainless-steel machines. Because of these difficulties, the department of Food Science has allotted a budget of $10,000 for a completely new vacuum evaporator. This project requires a process of researching, brainstorming, designing, calculating, manufacturing, and validation testing to obtain an acceptable modern replacement of the original custom-built system.

The objectives for this project include the generation of a functioning prototype of a new vacuum evaporator. EvapoGators will reach that main goal through the following objectives:

- Designing conceptual ideas and choosing the most appropriate design.
- Deciding which components should be fabricated versus bought.
- Building new design with both bought and manufactured components.
- Completing validation testing to ensure proper functionality of the system.
- Producing a complete lab manual that documents design, parts, and instrumentation of the device.

As this is a hardware-based project, there are specific expectations surrounding the design and prototype. The critical design expectation is a complete CAD design with part sourcing for when the components need to be replaced in the future. Also expected to accompany the functioning design and prototype is an operator's manual. The expected contribution of the prototype is that it will allow manual control of pressure, energy input, and temperature. With easy manipulation and readings of these, students can better understand the process and calculations.

Customer needs for the new vacuum evaporator include visibility for educational purposes, mobility to easily move through the laboratory, and the ability to control temperature, flow rate, and pressure. Additionally, the system must be a batch operator that could function without the use of electricity or technology. Finally, the customer specified the need for a cumulative lab manual for the system with CAD drawings and components documented for reordering off-the-shelf parts for replacement.

Table 1 illustrates the customer's needs and important wants as prioritized for the vacuum evaporator. Importance ratings range from 5 (most important) to 1 (least important). The most important need (requirement) is the visibility of the apparatus for demonstration (R01), in which there will be multiple measurable gauges for laboratory data collection (R03/R04).

Table 1. Customer needs and corresponding importance.

Category	**Customer Need**		**Importance**
Features	R01	Visibility for demonstration	5
	R02	Mobility of frame/structure	5
	R03	Include gauges to measure temp, pressure, and flow	5
Performance	R04	Ability to control temp, pressure, and flow rate	4
	R05	Ease of draining/removing concentrate	4
	R06	Data syncs with computer	2
	R07	Creation of batch type vacuum evaporator	5
	R08	No leakages	4
	R09	Ability to run without electricity	5
Reliability	R10	Ability to clean between usages	1

	R11	Outsourced parts (replaceable)	3
Safety	R12	Follow pan evaporator and food safety standards	5
	R13	Create lab manual with drawings/parts	5

Design Architecture

After breaking down the customer needs and design specifications, the group could reverse engineer the existing system. They were able to analyze the current machine and assess which parts were necessary to keep and how others could be improved. By performing the undergraduate evaporation lab under the liaison's guidance, the team learned every component of the system and how each one interacted with others. After performing the evaporation lab, the team constructed multiple diagrams to aid in the reverse engineering of the system. The first diagram created includes a flowchart schematic of the system's physical elements as seen in Figure 4.

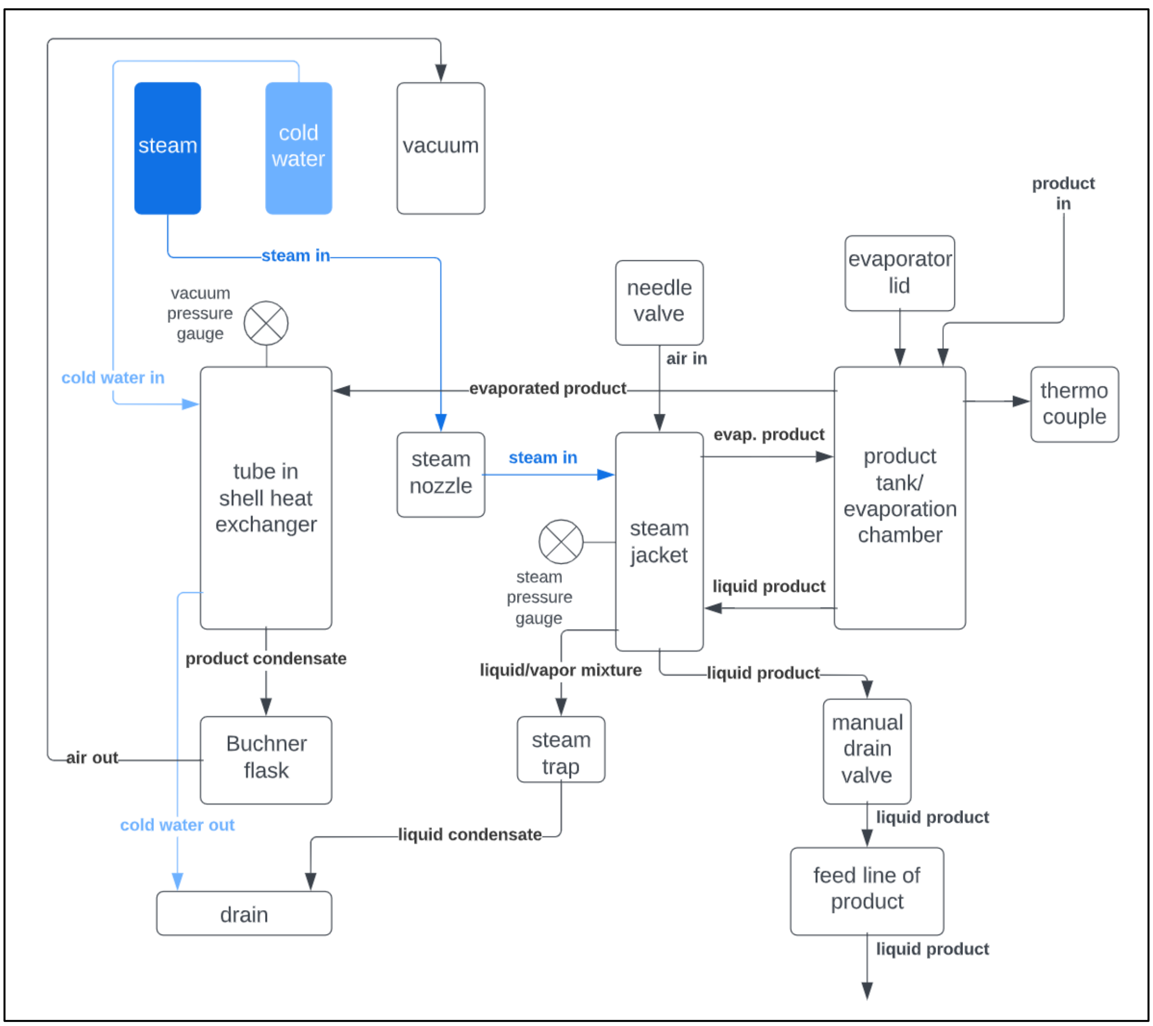

Figure 4. Flowchart schematic of all physical elements in current vacuum evaporation system.

The current vacuum evaporator system was decomposed into three process units, three utility lines, and a collection tank, as seen in Figure 5. The process units included the phase separator, evaporator, and condenser; these were the major components of the system. Additionally, the fourth cluster represented the utility lines with inputs of steam, cold water, and a vacuum to be used during the laboratory process. Finally, the Buchner flask acted as a collection tank to hold the final product condensate to be measured and studied.

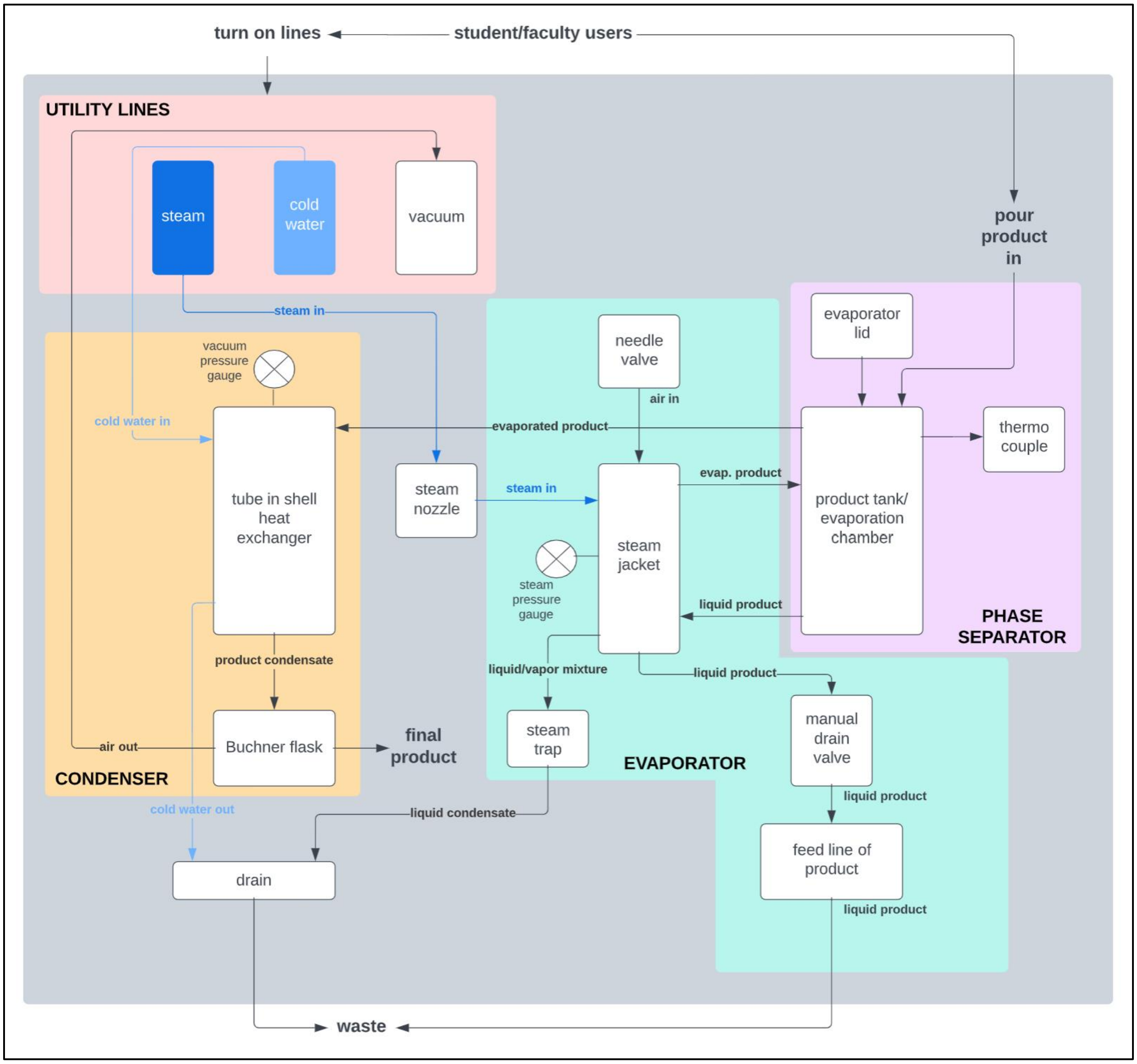

Figure 5. Diagram of entire physical architecture, broken into four clusters.

Accompanying the previous figure is Table 9 which details each cluster and its overall function in relation to the system's physical inputs and outputs when undergoing the vacuum evaporation process.

Table 2. Clustered components of vacuum evaporation system.

Cluster	**Description**	**Physical inputs/outputs**	**Function**
Condenser	Heat exchanger system uses cold water to cool evaporated product into liquid condensate.	Cold water in, Evaporated product in, Cold water out, Product condensate out, Air out	Convert product vapor into product liquid for easier measurement
Evaporator	System allows steam in to heat liquid product to its boiling point and turn it into a vapor.	Steam in, Liquid product in, Air in, Evaporated product out, Liquid product out, Liquid/vapor mix out	Convert liquid product into vapor
Phase separator	Tank allows product to be poured in as liquid and steam heats until turned into vapor.	Product in, Evaporated product in, Liquid product out, Evaporated product out	Chamber for phase separation
Utility lines	Connected to system to provide cold water, steam, and vacuum.	Air in, Steam out, Cold water out	Provide utility inputs

Throughout the design process, the team generated drawings of ideas for components, layouts, and the final product. This was done to help visualize the parts of the system and anticipate any changes that required attention As part of the team's preparation for program inspection of the prototype, CAD models of the different parts of the system were generated in SolidWorks. Two final assembly iterations including the frame, main process units, and other components can be seen below in Figure 6 and Figure 7.

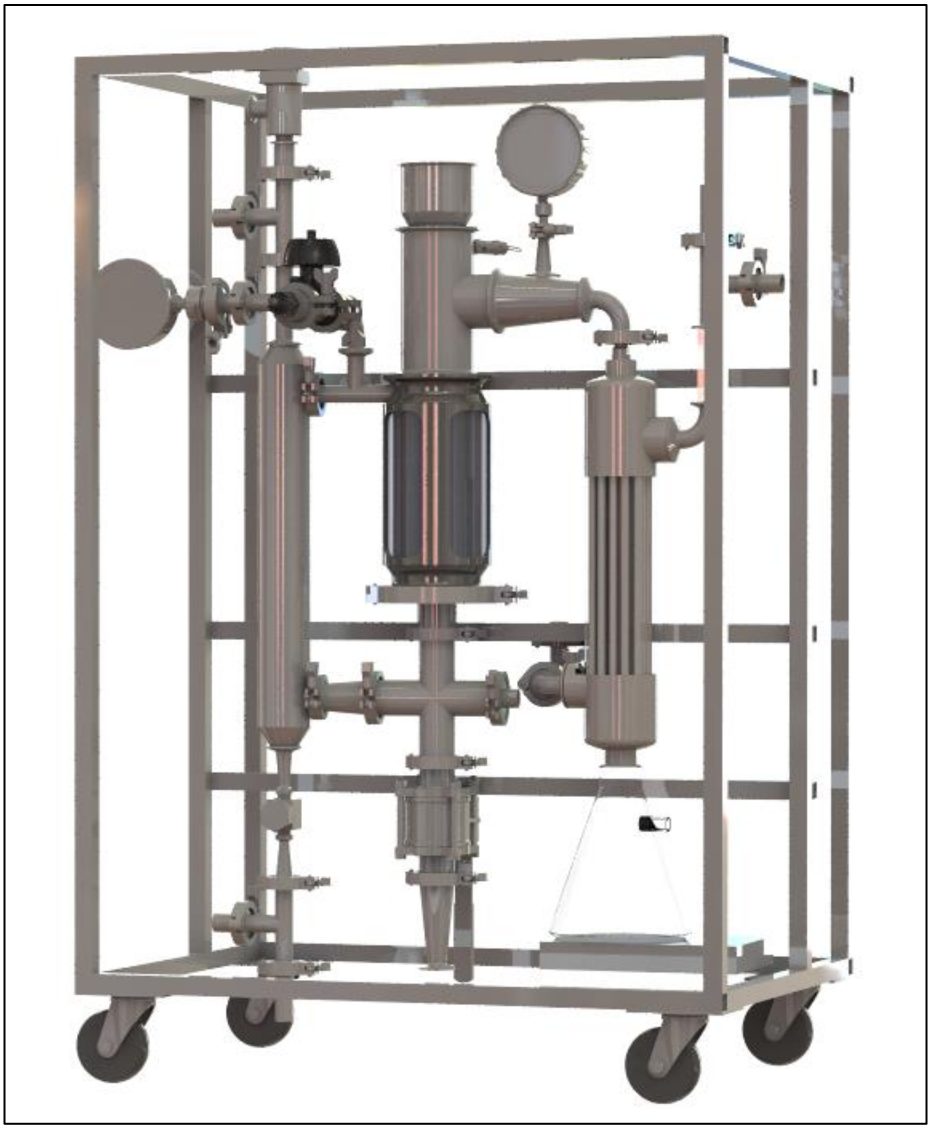

Figure 6. Final assembly design iteration 1 of vacuum evaporation system in SolidWorks.

Figure 7. Final assembly design iteration 2 of vacuum evaporation system in SolidWorks.

Iteration 2 is the product of several design iterations during the assembly of the welded stainless-steel frame, during off-the-shelf component purchasing, and preliminary assembly tests.

Educational Methodology and Pedagogy

The first task of the student design group was to investigate the vacuum evaporator laboratory platform as it has existed in the food science pilot plant for years. As the system was several decades old it had been used as a single week's experiment in food science laboratory classes. The design students performed the lab themselves as if they were food science students, recording temperatures and pressures and other operating conditions, performing the necessary heat and mass transfer calculations and formulating conclusions about the resulting heat transfer rates and food products.

Using their data, calculations, and results the design students reverse engineered the current system and ultimately developed the new, improved platform design as outlined in the previous sections. The final test of the efficacy of their design was to employ food science students as volunteers to conduct the same laboratory experiments on the new system. Their results and assessment of educational outcomes are compared to those from the old system from students in previous semesters to evaluate how student-centered design may have contributed negatively or positively to those outcomes.

The pedagogy surrounding the use of the vacuum evaporator laboratory for food science seniors is implemented over two courses: (1) a traditional lecture course where students are presented with theory and perform necessary theoretical calculations and (2) a laboratory course where students engage in experiential learning with the pilot plant's laboratory platforms of which the vacuum evaporator platform is just one. Through guided and individual learning experiences the students are expected to apply the theory from the first-semester course to acquire data and make conclusions in laboratory report submissions.

Educational data concerning the efficacy of student-centered design is taken in two ways. First, to compare the new vacuum evaporator system with the old students are asked to fully complete the laboratory exercise from data collection through lab report submission. The graded outcomes of the submitted lab reports are compared with a sample of those from previous semesters to determine any statistically significant variance between the fulfillment of learning objectives.

Second, to determine perceptions of the student-built nature of the apparatus, food science students complete surveys that provide self-reported reflections about their experience during the mock laboratory assignment. Students are asked to compare the effectiveness of the apparatus (ease-of-use, quality of measurement devices, etc.) to previous laboratory experiments they have performed. Students are also asked to qualify their experience based on the knowledge that the apparatus was built by peers rather than graduate students, faculty, or purchased from laboratory equipment manufacturers. The survey contains the following Likert scale questions:

1. How would you describe your current level of experience in the topics of thermodynamics, fluid mechanics, or heat transfer?
2. The lab instructions were well-organized and easy to understand.
3. You have a more thorough understanding of the vacuum evaporation process and what it is used for after performing the lab.
4. Undergraduate students designed this apparatus to have good visibility that allows for heat exchange properties to be seen.
5. The gauges, thermocouples, and flow meter were easy to read and collect data from.

6. The apparatus has more work that needs to be done.
7. You believe your experience with the lab equipment was improved because of your knowledge that this apparatus was designed and built by undergraduate students.

Undergraduate students are asked a series of standard demographic questions and are given the opportunity to supply any additional comments or opinions they wish.

Conclusions

Data analysis is hypothesized to show that student-centered design has a positive effect on the educational value and efficacy of experiential learning exercises as used in laboratory courses in technical fields. Student designers, while still in training as engineers, have unique perspectives that reflect in their completed products. Subtle logic of layout, simplicity in architecture, and creative license may all contribute to the perception that laboratory platforms create in student learners. Indeed, the simple knowledge that an experiential exercise is student designed, student tested, and student built may make the educational value of that exercise more available to student users. When students see the capabilities of their peers, they gain confidence in themselves that they might achieve such creative and effective results as well.

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