Using Design Thinking and Technological Domains to Assess Knowledge Transfer in Engineering Design

John J. Krupczak, Jr.
Department of Engineering
Hope College
Holland, Michigan USA
krupczak@hope.edu

Mani Mina
Industrial Design & Electrical and Computer Engineering
Iowa State University
Ames, Iowa USA
mmina@iastate.edu

Melissa Rands, Ph.D.
Accreditation and Assessment
Minneapolis College of Art and Designn
Minneapolis, Minnesota USA
mrands@mcad.edu

***Abstract*—This innovative practice work-in-progress paper examines the application of design thinking in engineering literacy courses and argues that, for engineering and technological literacy applications, design thinking exercises benefit from situating design activities within technological domains. This approach also facilitates assessment of the student design abilities. Design thinking is a well-known process for problem solving. However, when used in engineering literacy courses for non-engineering majors, the outcomes of the ideation stage are severely constrained by the student's internal technological knowledge base. Student design thinking exercises can result in technologically vague concepts. Liberal arts students from non-technical disciplines become frustrated and see the design process as suspect and fail to embrace a multidimensional perspective on design. Non-engineering students lack critical engineering science knowledge relevant to the problem but the nature of engineering literacy courses for non-engineers precludes in-depth mathematics-based engineering science prerequisites. We have found that the platform of technological domains effective in supporting students between the innovation of design thinking and the empowerment of engineering science. Technological systems form clusters or domains of related systems around a set of shared components based on similar underlying physical principles, for example, vapor-compression refrigeration systems. We have found that students benefit if design exercises are conducted in the context of a technological domain. In the work reported here, students studied the familiar domestic refrigerator as typifying the technology enabled by the engineering science underlying the vapor-compression cycle. Students were then presented with a design challenge involving a cooling application but different from the function of a domestic kitchen refrigerator. Non-engineering students were able to develop potentially feasible system design concepts at the component level that were novel to them. This approach made it possible to assess knowledge transfer and design ability of liberal arts students in a general education engineering literacy course.**

Keywords*—*design thinking, design assessment, engineering design, liberal arts engineering, general education.

I. Background

This paper describes an effort to improve the technological and engineering literacy of non-engineers and to develop a means to assess an aspect of this literacy through the design process. There is a need for non-engineers to have a basic understanding of the nature of technological systems and the products of the engineering disciplines. The National Academy of Engineering has emphasized greater technological and engineering literacy [1] and the National Science Foundation includes promoting the STEM-literacy of all Americans as part of its strategic plan [2]. A familiarity with the engineering design process at some level is widely seen as a central element of technological and engineering literacy [3]. During the time that engineering and technological literacy developed as an important component of the education of all students, the concept of design thinking has also emerged as a broadly applicable process for problem solving [4,5]. Elements of design thinking include a customer-centered perspective, enumeration of goals, emphasis on low-stakes testing and embracing iteration. Also involved is an ideation stage employing classical brainstorming to develop potential solutions. Design thinking is widely promoted as applicable to a range of disciplines and problems and advocated as an appropriate aspect of a liberal education [6-10].

Efforts have been made to promote the engineering literacy of non-engineering liberal arts students through undergraduate general-education engineering courses that include design activities [11-14]. At the same time, the promotion of design thinking has resulted in a desire for these courses to combine design thinking and engineering design activities. When used with non-engineering students to address technological problems, we have found that outcomes of the ideation stage are severely constrained by the student's internal technological knowledge base. Brainstorming is only as successful as the depth and richness of the available catalog of potential solution elements. We find these student design thinking exercises result in technologically naïve and vague concepts. Students then become frustrated at their poor results and view design methods as irrelevant to solving "real" problems. Students lacked critical engineering science knowledge relevant to the problem that would empower them to envision more sophisticated solutions. Simultaneously it is difficult to meaningfully assess the level of engineering literacy acquired and the extent to which the non-engineers have been successful in carrying out a version of an engineering design process appropriately scaled to their background and experience.

Technological Domains

We have found that the framework of technological domains can serve a catalytic or bridging role for students between the open-ended methods of design thinking and the empowerment of engineering science. Technological systems form groups or domains of related systems around a set of shared components based on similar physical principles [16]. For example vapor-compression refrigeration systems form a domain or technological family. We have found that students benefit if design exercises are conducted in the context of a technological domain. We have also found that working within a domain makes it possible to determine if students have been successful in transferring knowledge from one context to another and utilizing new knowledge to inform their design activities.

II. Example application

In the work-in-progress reported here, students studied the familiar domestic refrigerator as typifying the technology enabled by the engineering science underlying the vapor-compression cycle. This was carried out with students at in a general education engineering literacy course [15]. As a pretest, students were asked to explain how a refrigerator works and include a diagram in their explanation. Figure 1 shows representative samples of typical pre-test explanations. As might be expected the pretest showed little understanding of how a familiar domestic kitchen refrigerator works. Many student attempts included components that they thought might be in a refrigerator such as motors, pipes, and fans, but none could depict a complete functioning system.

Course material then included both the design thinking process and engineering science content relevant to vapor compression refrigeration systems. These topics were not the entirety of the course content but are the sections most relevant to the work reported here. Typical design methodology topics include problem definition, ideation, prototyping, and testing.

In addressing engineering science content, the framework of a technological domain is employed. Domains are groups or families of technological systems that are developed around a core set of underlying physical principles [16]. The systems tend to share some common components and subsystems which may vary in scale in different systems within the domain. In this work vapor-compression refrigeration systems was the domain of interest. This domain includes systems such as domestic refrigerators, air conditioners, heat pumps, and dehumidifiers.

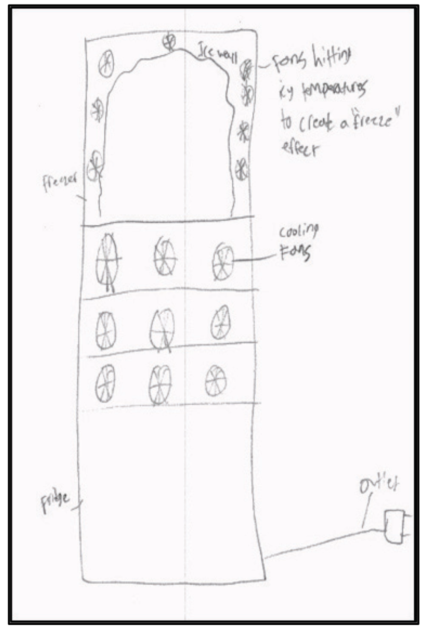


Figure 1: Typical Examples of Non-Engineers Response to the Initial Pre-Test Question of "How Does a Refrigerator Work?"

In this approach, a representative system is selected as the primary system to be studied. In this case the domestic kitchen refrigerator was used because of its familiarity and because the domain is well-characterized by the components and system architecture of the domestic refrigerator.

Course materials then address form, function, and underlying engineering principles of the main components, how the component's form and function meet the design requirements, the interconnection of components and modes of operation.

III. Summary of Treatment of Refrigeration Domain

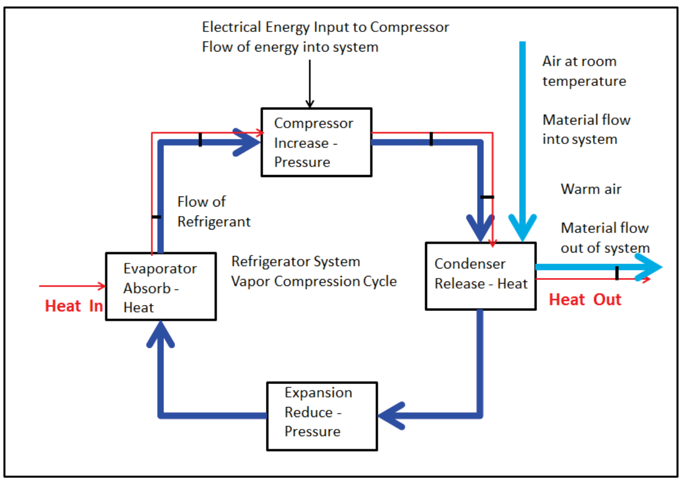
Vapor-compression refrigeration systems have a number of characteristics that are well-suited to being included in an engineering literacy course for non-engineers. The domestic refrigerator is common, used by nearly everyone, and readily recognized as an indispensable device critical in everyday life. As the pre-test results demonstrate, few students have any meaningful idea of how it works. The underlying principles of operation are not simplistic nor obvious but are accessible with appropriate instructions. The refrigeration system itself is based on only a few key components so it is possible to describe the system operation in a short amount of time with a limited amount of detail. As primarily a mechanical system, the components and their operations are visually accessible. That is, it is possible to see most of the components when looking at refrigerator and it is possible to describe the underlying principles using visual images, photographs, and drawings. Simple but informative quantitative analysis can be carried out from basic equations using algebra if desired.

The content of the refrigeration systems module used can be covered in about two class sessions and one laboratory session. The basic content is summarized here to provide an overview of the level of the material and how it is presented to the non-engineering students.

The essential function of the system is to transfer thermal energy from a low temperature to a higher temperature. This is opposite the normal direction of heat flow from hot to cold. A summary diagram of the system is used. This is included in Figure 2. The five major components of the system are the evaporator, compressor, condenser, expansion, and the circulating refrigerant fluid. Figure 3 shows a photograph of the main components as seen in a compact refrigerator. The components are similar in a full-sized refrigerator but are more easily observed by students directly in a compact model.

Figure 2: Basic System Diagram of a Domestic Refrigerator

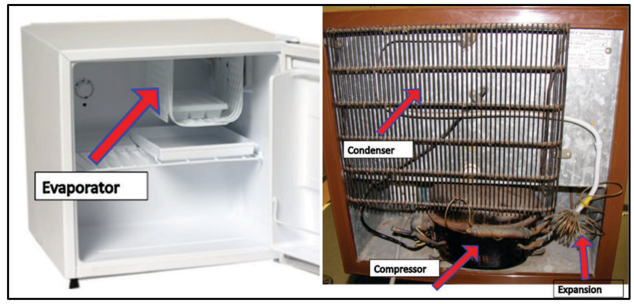
The circulating refrigerant is the only major component not immediately visible since it is contained within the tubing. The



refrigerant transports heat (thermal energy). It is a colorless liquid / gas with a boiling temperature of -14F at atmospheric pressure and relatively high heat of vaporization so it absorbs a significant amount of heat in the process of boiling at -14F. The evaporator is a series of tubes or pipes which contain the liquid refrigerant. The function of the evaporator is to facilitate transfer of heat from whatever is to be cooled to the refrigerant fluid. This is where heat is removed from whatever is being cooled. The next major component is the compressor that functions to compresses refrigerant vapor, increasing its pressure. The fourth major component is the condenser. Heat leaves the system in the condenser. In a domestic refrigerator, heat is transferred to the air in the room. The last major component is the expansion. A common form for an expansion is a very long and narrow tube often coiled to reduce its overall size. The input side has very high pressure from the condenser. Because of the narrow tube, the fluid is constricted from flowing through the tube and only a small amount of fluid is able to move through the passage resulting in a much lower pressure than the inlet.

As the fluid expands into the low pressure of the outlet its temperature decreases. The reduction in pressure results in a reduction in temperature. The cooled liquid is now cycled back at the inlet to the evaporator.

Figure 3: Evaporator, Compressor, Condenser, and Expansion



as Seen in a Compact Refrigerator.

The system nature of the refrigerator is emphasized in this material for non-engineering students. Overall system operation is described in terms of the contribution made by each component as they interact to accomplish the overall system function of transferring heat from a lower to a higher temperature. Refrigerant evaporates at a low temperature changing from liquid to gas in the evaporator. Heat has been removed from what the user wanted to cool. The gas is then compressed in the compressor. The compressed gas moves to the condenser where heat leaves as it is transferred to the room which is at a higher temperature than the interior of the refrigerator. The refrigerant condenses from gas back to liquid in the condenser. The refrigerant is still at a high pressure. The pressure decreases as the refrigerant traverses the expansion. The decease in pressure results in a lowering of the refrigerant temperature. The refrigerant arrives at the evaporator and the cycle continues.

At this point in the module various standard-type of assignments are conducted to address remembering and understanding of concepts and definitions.

The next phase addresses how the representative system in the domain is modified to carry out related but different functions. This is in fact what causes a technological domain to evolve around a set of core technologies. The room air conditioner and the dehumidifier are studied. Briefly, the room air conditioner is a refrigerator with the evaporator in the room and the condenser outside. Variations in the domain are not identical to the representative system. In the room air conditioner motor-driven fans are used to increase air flow.

The dehumidifier utilizes the cold surface of the evaporator to condense water from the humid air. However, so as to not also chill the room, the air is now dry air heated before leaving the system. Often the heating is accomplished by bringing the air in contact with the condenser which operates at a higher temperature.

IV Design Problems

In terms of familiarizing students with a technological domain several key outcomes have been accomplished. The students know the main components and the basic operation of a representative system. It has also been demonstrated how the

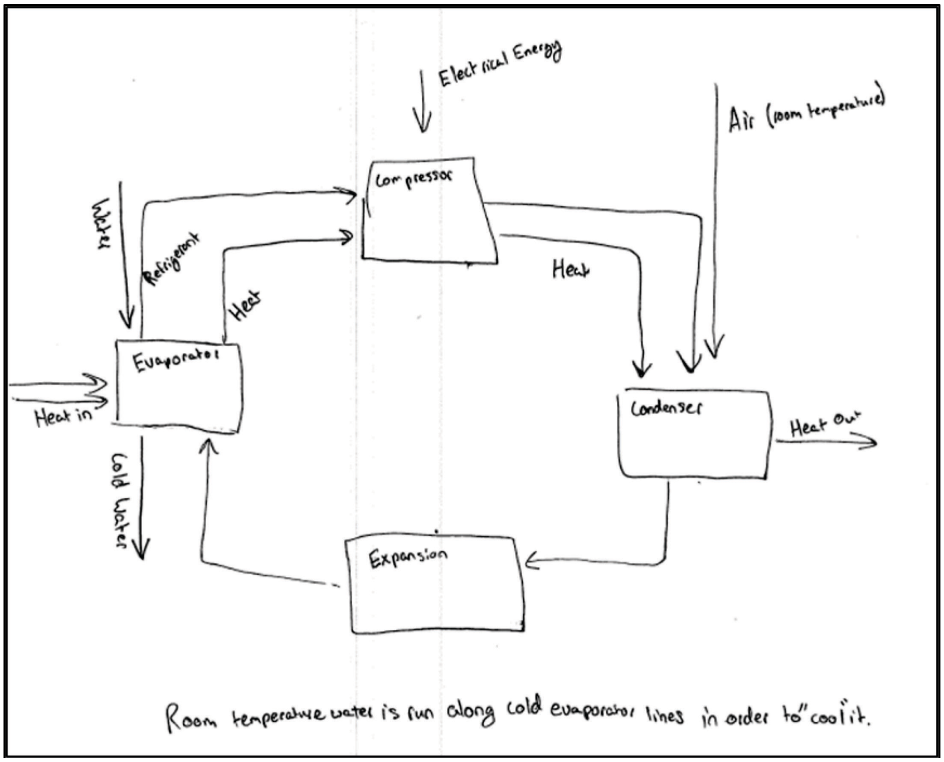


Figure 4: Design of a Water Cooler Developed by a Non-Engineer as an Examination Question.

core system can be modified to suit different but related requirements.

Critical component functions and the engineering science processes employed were studied along with the component interactions. Students were then presented with a design challenge involving a cooling application but different from the function of a domestic kitchen refrigerator. Students were asked to develop a design for a water cooler. This familiar device has an input of water at room or building temperature and outputs cooled water. This question was given as an examination question and students responded individually and could not consult any outside sources of information (such as conducting internet searches) during the examination.

Figure 4 shows an example student design. The student is able to create potentially feasible design for this application. Results show that non-engineers can carry out "real" engineering in using their knowledge to adapt an existing technological system to a new application. In the pre-test question asking how a refrigerator works non-engineering students showed almost no technological and engineering literacy. The average score for the group of 12 students was 17 percent for a 100 point scale. The average score was primarily based on including one or two components that happened to appear in a refrigerator. The post-test class averages for the group in the drinking fountain design problem demonstrated significant increases in engineering literacy. The average score for the non-engineering students was 60 percent, with 36 percent of the class scoring 90 or above. About a third of the non-engineers created very good designs.

The scoring rubric was based on five aspects of the system. These were: inclusion of appropriate components, correct interconnection of components, identification of inputs and outputs, adherence to conservation of energy, and adherence to conservation of material. The first two categories, inclusion of appropriate components and reasonable interconnection of components were given slightly higher weightings than the other categories.

Interestingly, a common misconception that emerged were designs with the cooled water taking the place of the refrigerant and circulating around the system rather than exchanging energy with the cold evaporator.

V. Conclusions and Future Work

In this work-in-progress encouraging results were seen in utilizing a technological domain-centric approach in linking principles of engineering science with specific implementation in actual components and systems. Non-engineering students were able to develop potentially feasible system design concepts at the component level that were novel to them. By working within an existing technological domain the catalytic and enabling role of engineering science knowledge was highlighted while simultaneously employing a design thinking format to encourage transfer of knowledge. While admittedly asking students to solve a cooling problem constrains the design space, the non-engineering students were empowered by the experience of developing a reasonably sophisticated and technologically feasible solution. Completion of a reasonable concept was readily assessed. Future work will expand the approach using other technological domains characterized by application of a well-defined set of engineering science principles. We will also assess the impact on the technological self-efficacy of undergraduate students.

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