Integrating Thermodynamics II Concepts into Heat Transfer Courses: A Curriculum Adaptation Strategy

Mohammadhosein Ghasemi Baboly, Kansas State University

Dr. Baboly received his Ph.D. in Mechanical Engineering from the University of New Mexico in July 2016, after which he joined Kansas State University as a postdoctoral fellow. His research in MEMS has centered on the simulation, fabrication, and characterization of acoustic metamaterials, commonly referred to as phononic crystals (PnCs). In August 2017, he began his academic career as an assistant professor at the University of Jamestown in North Dakota. With a background that bridges engineering, physics, and applied mathematics, his expertise spans machine design, mechanics of materials, manufacturing engineering, materials science, and dynamic systems. He returned to Kansas State University in August 2019, where he currently serves as a teaching faculty member.

Manar Younis, Rafik Hariri University

Dr. Manar Younis is a lecturer in the Mechanical and Mechatronics Engineering Department at Rafik Hariri University, where she teaches courses on Thermodynamics, Heat Transfer, HVAC, Fluid Mechanics, and Thermal Fluid Sciences. She holds a PhD degree in Mechanical Engineering from the American University of Beirut, a ME in Mechanical Engineering (Applied Energy) degree from the same institution, and a BE in Mechanical Engineering from Beirut Arab University. Her research primarily focuses on the thermofluid track, specifically enhancing the performance of solar stills to increase water yields. Additionally, she has worked extensively on improving thermal comfort for occupants through passive integrated systems. Dr. Younis has made significant contributions to the field with several publications, including experimental and optimization studies on solar stills and renewable biofuel production. Before joining RHU, Dr. Younis taught at Phoenicia University, where she was involved in teaching courses such as HVAC, Mechanical Design, Manufacturing Processes, Instrumentation and Measurements, Thermodynamics, AutoCAD, CAD CAM, and more. She also supervised several final-year projects, providing students with invaluable guidance in their academic and professional development.

Kamel Ghali Dr. , Phoenicia University

Dr. Kamel Ghali earned his Ph.D. in Mechanical Engineering from Kansas State University in August 1992, after completing both his M.Sc. (May 1988) and B.Sc. (December 1986) in the same field at the same institution. He also holds a B.Sc. in Chemistry from the American University of Beirut, obtained in February 1983. Over the years, Dr. Ghali has built a distinguished academic and professional career, serving as a Visiting Professor and Research Scholar in Mechanical and Nuclear Engineering at Kansas State University and later as a Tenured Full Professor at the American University of Beirut from 2019 to 2024. Between 2012 and 2019, he held the position of Professor and Chairman of the Mechanical Engineering Department at AUB, where he led major curriculum developments and successfully secured ABET reaccreditation. In addition to his academic leadership, Dr. Ghali gained industry experience as a Senior Mechanical Engineer at Dar Al-Handasah Consultants from 1994 to 1997. His early research career included postdoctoral appointments as a Research Associate in Biomedical Engineering at Case Western Reserve University (1993–1994), where he focused on human body modeling, and at Kansas State University (1992–1993), where he conducted research on air quality and indoor air velocity measurement. He also worked as a research assistant at the Institute for Environmental Research at Kansas State University from 1990 to 1992. Dr. Ghali's expertise encompasses air quality, indoor air velocity measurement, human body modeling, energy conservation in buildings, poultry housing, and human well-being in both indoor and outdoor environments. With more than 300 publications in international journals and conferences, he has been recognized among the top 2% of global scholars in a study conducted by Stanford University.

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Abstract

In this theory work- progress paper, a new curriculum adaptation strategy is proposed and tested. Recently, engineering programs have witnessed an obvious evolution in terms of the decreased number of credits and courses required, while there is a clear shift in introducing new courses related to industry like smart materials, renewable energy and control systems, etc. This has allowed students to select elective courses that line up with the ongoing industrial advances, but previous major courses like Thermodynamics II have become elective courses due to the credit's reduction strategy. However, the fundamental concepts covered in Thermodynamics II course, specifically entropy and irreversibility should not be excluded from the basic concepts of engineering. This scenario has imposed two main challenges. On one hand, the basic concepts of Thermodynamics II should be covered, and on the other hand, finding ways to deliver integrated thermal sciences content in a curriculum, where such a course cannot always be assigned.

One method to overcome these challenges is to integrate the Thermodynamics II principles within other courses, such as Heat Transfer, which represents a strong candidate for this scenario, since it requires the Fluid Mechanics course as a prerequisite and it comes after the Thermodynamics I course. Therefore, concepts like irreversibility, entropy generation and exergy destruction can be easily integrated within the course. This approach can be accomplished through two methods, either project based or lecture-based approach. In the project-based approach, a course project was given under the topic of heat exchangers assigned to 80 senior students enrolled in the Heat Transfer course. This work was followed by a questionnaire to assess individual understanding of the students, which required additional work from the instructor. Therefore, the lecture-based approach may offer a more dependable method to delivering this content, especially when discussing topics like heat exchangers that requires deep knowledge of both the first and second laws of thermodynamics, fluid mechanics, and heat transfer. This lecture-based method was successfully applied and tested, where a structured lecture was dedicated to integrating Thermodynamics II principles within the heat exchanger module. Students were then assessed individually through related questions, where results showed an accuracy of 93% in students' answers, which is higher than the accuracy of the project-based approach previously tested that resulted in an accuracy of 86%.

Keywords: Curriculum adaptation, thermodynamics principles, heat transfer, heat exchangers

Nomenclature

Symbol	**Definition**
$\dot{Q}$	Heat transfer rate (kW)
$\dot{m}$	Mass flow rate (kg/s)
C_p	Specific heat at constant pressure (kJ/kg K)
T	Temperature (K)
s	Specific entropy (kJ/kg. K)
$\dot{S}_{gen}$	Entropy generation rate (kW/K)
$\dot{S}_{gen,HT}$	Entropy generation due heat transfer (kW/K)
Δ_s	Change in specific entropy (kJ/kg·K)
ΔP	Pressure drop (Pa)
f	Darcy friction factor (-)
L	Pipe length (m)
D	Pipe diameter (m)
ρ	Fluid density (kg/m³)
V	Average flow velocity (m/s)
$\dot{X}_{dest}$	Exergy destruction rate (kW)

T_0	Ambient (dead-state) temperature (K)
Subscript	
h	Hot stream
c	Cold stream
in	Inlet
out	Outlet

Introduction

Engineering curricula have undergone noticeable changes, especially in the number of credits and courses, which has decreased. This is mainly due to the outcome- based accreditation frameworks that focused on delivering lifelong learning skills to students, and encouraging the inclusion of more elective courses [1,2,3]. Also, the continuous growth in industry and technology has imposed a strong need to introduce new electives that are related to industry and technology, such as renewable energy and advanced manufacturing, without increasing the total number of credits [4,5,6]. While this approach provides many benefits in terms of the variety of the courses offered and their direct link with the ongoing advancements, many studies showed that this has resulted in the elimination of some fundamental courses in engineering, in order to meet the credit reduction strategy [7,8]. In the Mechanical Engineering programs for example, this scenario has resulted in the shifting of the Thermodynamics II course from a mandatory to an elective one, risking by that the exposure of students to second law of thermodynamics concepts including irreversibility, entropy generation, and exergy destruction, that enable students to understand why systems deviate from their ideal performance, rather than simple energy conservation principles [9,10].

Also, many studies have shown that without proper instruction, students struggle to understand the concept of the Second Law of Thermodynamics [11,12]. Therefore, by reducing the number of credits and shifting some mandatory courses to elective ones, students will only be able to apply energy balances and heat transfer rates without identifying irreversibility, entropy generation and interpret exergy destruction, which are key concepts in engineering analysis and optimization in thermal system analysis. Therefore, in order to overcome this challenge, a new approach has been proposed to include Thermodynamics II principles in other courses. Heat transfer course represents a strong candidate for this approach, since it includes topics like heat exchangers that can be directly linked to irreversibility, entropy generation and exergy destruction. For this, a study was conducted to include these concepts through a course project in the Heat transfer course that included 80 students. The project included the design of a comprehensive heat exchanger to assess students' ability to design and mathematically model a heat exchanger while reinforcing Thermodynamic II principles such as entropy generation, irreversibility, and frictional losses. However, students worked in groups, so not all of them achieved the same level of understanding, thus a structured questionnaire was used to evaluate students' comprehension of Thermodynamic II principles, which requires an additional work from the instructor. Despite the fact that this approach has reported an accuracy of 86% in students' answers, however it does not really emphasize the deep and equal understanding of the students to the topics of Thermodynamics II. Group-based learning environments may allow some students to rely on their peers, leading to uneven knowledge acquisition and masking individual theoretical shortages. Thus, students may superficially understand the required fundamental topics. Therefore, in this work, a new approach is proposed, where lecture notes are used to explain the basic principles of Thermodynamics II in the Heat Exchanger chapter in the Heat Transfer course. Students will be then tested in an examination question, to investigate the understanding of students at the individual level. This offers a more reliable method to delivering this content, especially when discussing topics like heat exchangers, a topic that requires deep knowledge of both the first and second laws of thermodynamics, fluid mechanics, and heat transfer as well. So rather than relying on indirect understanding attainment through group projects, this approach highlights direct instructor-guided explanation of second-law principles, supported by continuous interaction and in-class discussions. The lecture was designed to be highly interactive, encouraging students to actively engage through questioning and discussions which allows misconceptions related to entropy, irreversibility, and exergy to be identified and fixed in real time, thereby endorsing deeper understanding. Most importantly, students were individually examined, enabling a direct evaluation of each student's understanding and application of Thermodynamics II principles, supporting the success of lecture-based integration approach in reduced-credit engineering curricula.

Methodology

To address the gaps caused by displacing the Thermodynamics II course, students were introduced to irreversibility, entropy generation and exergy destruction through a tailored lecture integrated within the Heat Transfer course under the topic of Heat Exchangers. The lecture focused deeply on that irreversibility in heat exchangers arises primarily from two mechanisms: first, thermal energy that is transferred between two fluids without allowing them to mix, so fluids must flow inside pipes, tubes, or channels that isolate one stream from the other. However, forcing fluids to flow through confined passages imposes flow resistance, resulting in pressure drops, and the system experiences frictional (viscous) losses that represent an additional source of irreversibility. Therefore, the session opened by reviewing heat exchangers heat duty equation to show the equality of heat gain by the cold fluid and heat loss of the other one as follows:

$$\dot{Q} = \dot{m}_h C_{p,h}\left(T_{h,in} - T_{h,out}\right) = \dot{m}_c C_{p,c}\left(T_{c,out} - T_{c,in}\right) \qquad (1)$$

Where: $\dot{Q}$ is the heat transfer rate (kW), $\dot{m}$ is the mass flow rate (kg/s), C_p is the specific heat at constant pressure (kJ/kg. K) and T is the temperature (K). This imposed the introduction of the Second Law and the entropy balance for an adiabatic heat exchanger control volume:

$$\dot{S}_{gen,HT} = \dot{m}_h\left(s_{h,out} - s_{h,in}\right) + \dot{m}_c\left(s_{c,out} - s_{c,in}\right) \qquad (2)$$

Where: $\dot{S}_{gen,HT}$ is the entropy generation rate (kW/K), and s is the specific entropy (kJ/kg. K). Entropy change for compressible flow is calculated as follows:

$$\Delta_{s,steam} = m_s(s_f - s_g) \qquad (3)$$

Students were shown that a large temperature difference between the hot and cold streams leads to a higher rate of heat transfer and, thus, greater thermodynamic irreversibility, even though smaller heat exchanger sizes may be convenient. In contrast, operating with small temperature differences reduces heat transfer rates and thermal irreversibility, but requires larger heat exchangers, which in turn increases pressure losses and entropy generation due to fluid friction.

For the heat transfer contribution, entropy generation is determined from inlet and outlet temperature changes of each stream using the following equation:

$$\dot{S}_{gen,HT} = \dot{m}_h C_{p,h}\, ln\left(\frac{T_{h,out}}{T_{h,in}}\right) + \dot{m}_c C_{p,c}\, ln\left(\frac{T_{c,out}}{T_{c,in}}\right) \qquad (4)$$

While frictional irreversibilities were related to pressure drop as follows:

$$\Delta P = f\,\frac{L}{D}\,\frac{\rho V^2}{2} \qquad (5)$$

Where ΔP is the pressure drop (Pa), f is the Darcy friction factor (dimensionless), L and D are the tube length (m) and diameter (m) respectively, ρ is the fluid density (kg/m³), and V is the average velocity (m/s). Therefore, entropy generation due to friction in pipes was calculated as follows:

$$\dot{S}_{gen,friction} = \frac{\Delta P \dot{m}}{\rho T_{avg}} \qquad (6)$$

Where T_{avg} is the average temperature between inlet and outlet (K).

Once entropy generation was clearly explained, the lecture then presented exergy destruction as the thermodynamic cost of irreversibility, using the following equation:

$$\dot{X}_{dest} = T_0\dot{S}_{gen} \quad (7)$$

Where $\dot{X}_{dest}$ is the exergy destruction rate (kW) and T_0 is the ambient (dead state) temperature (K). This represents the mathematical link between entropy generation and lost useful work potential, which shows that greater entropy generation means more exergy destruction, meaning that although energy is conserved, its usefulness is ruined.

Finally, the lecture concluded with reflection comparing project-based integration and lecture-based integration. Students were told that while project-based learning is important for engagement and application, it does not ensure individual theoretical understanding. In contrast, a structured lecture ensures every student is exposed to the same theoretical principles and full mathematical development, and is individually assessed. Unlike the project-based approach that included a questionnaire to asses students' understanding, only one lecture was required to deliver the required concepts.

Results and Discussion

Thermal Analysis of the Heat Exchanger

The proposed strategy was tested through an examination question given to 25 students. It started by considering a closed feed water heater shown in Figure (1), where steam flows on the shell side and water flows inside the tubes. The steam condenses on the outer surface of the tubes, maintaining a constant surface temperature corresponding to the condensation of the steam. Water enters the tubes at a temperature of 20 °C with a mass flow rate of 0.5 kg/s and C_p=4.18 kJ/kg. K, and it is required to be heated to 50°C at the outlet.

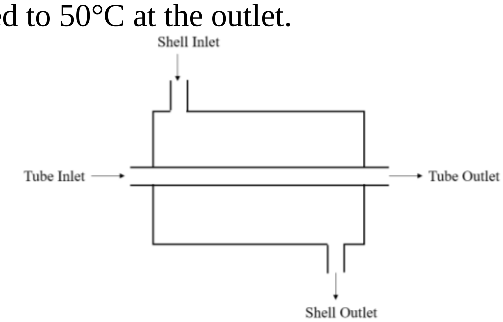

Figure 1: Closed Feedwater Heater

- **Determination of Steam Condensation Pressure and Mass Flow Rate**

Students were first asked to determine the pressure of the steam corresponding to a condensation temperature of 200 °C, and the required mass flow rate of the steam to achieve the desired heating effect. Students were then asked to repeat the problem using a condensation temperature of 100 °C. This part required the recognition that steam condenses at saturation temperature, so steam pressure corresponds to saturation pressure at a given condensation temperature, and steam tables should be used to read the corresponding saturation pressures. Regarding the mass flow rate calculation, students were able to recognize that the mass flow rate required for a steam at 100 °C was less than that required at temperature of 200 °C. In this part, students answered with an accuracy of 100%.

- **Assessment of Entropy Generation and Irreversibility**

Then, students were asked to calculate the entropy generation for both cases, where water leaves the tube at a temperature of 50 °C. Students must know that entropy generation results from heat transfer and frictional losses. They should recall how to evaluate the change in entropy of water as it heats up, and to determine the entropy change of the condensing steam from the steam tables. In this part, students answered with an accuracy of 84%, showing that they are capable of linking the heat transfer concepts to the basics of Thermodynamics II principles.

- **Tube Length Sizing**

After that, students were asked to size the tube length for a given internal diameter, to achieve the required water temperature for the cases of 100 and 200 °C. A comparison was then required to decide which configuration requires a longer tube and why. To size the tube length, students should treat the water side as internal convection with a constant wall temperature. Thus, the condensing steam on the shell side maintains the tube wall at constant temperature equal to the steam saturation temperature. Thus, the following equation for internal flow with constant wall temperature should be used,

$$\frac{T_s - T_o}{T_s - T_i} = exp\left(-\frac{PLh_i}{\dot{m}C_p}\right) \tag{8}$$

Where: T_s is the (constant) steam/ wall temperature (K), h_i is the internal convection coefficient (W/m^2 K) and P is the inner perimeter of the tube (m). To determine h_i, students need to apply their internal convection knowledge to calculate the cross-sectional area of the tube from the given internal diameter, use the mass flow rate and water density to find the mean velocity in the tube, calculate Reynolds number and identify whether the flow is laminar or turbulent. Based on Reynold's number, students can use the appropriate Nusselt number correlation for internal flow and convert it to internal convection coefficient and finally solve explicitly for tube length L**.** In this part, students achieved an accuracy of 88%.

- Frictional Losses Comparison

Finally, students were asked to compare the frictional losses in both cases and draw out conclusions regarding the case that was expected to experience higher frictional losses and why. To address this part, students should recognize that longer tubes lead to higher pressure drops and therefore greater frictional losses. Using their understanding that the lower steam temperature case results in a smaller temperature driving force and thus requires a longer tube, students should conclude that this configuration will experience higher flow resistance. Students attained an accuracy of 100% in this part.

Discussion

As shown in Figure 2, students' responses showed a high level of understanding, indicating that the integrated lecture-based approach was an effective and successful tool in integrating Thermodynamics II concepts into Heat Transfer applications. Particularly, all students were able to determine the required steam pressure corresponding to a given condensation temperature, successfully calculate the required steam mass flow rate at each condensation temperature, and the required heat transfer energy required to raise the water temperature from 20 to 50 °C.

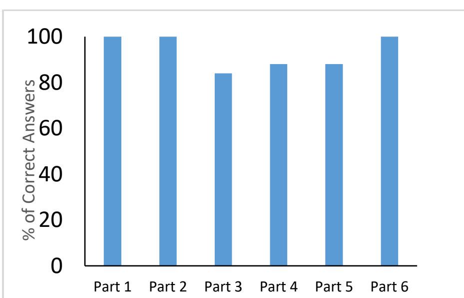

Figure 2:Percentage of Correct Answers for Each Part

In addition, noticeable results were observed in the sections related to applying second law of thermodynamics, which is a core objective in this proposed adaptation strategy. 84% of the students correctly calculated the entropy generation for the two condensation temperatures, and successfully recognized the relation between increasing the temperature difference between the heat source and the working fluid that leads to higher entropy generation and higher irreversibility. So, students were able to understand and consequently explain mathematically and conceptually why using a higher steam condensation temperature decreased the required steam mass flow rate but at the same time increased the entropy generation which is related to the large temperature gradients.

Regarding the parts related to calculating the length of the tube required at the two different condensation temperatures, the majority of the students correctly realized that the lower steam temperature required a longer tube length to get the same water exiting temperature, which is related to the lower temperature differences. Finally, the majority of the students were able to realize the relation between the increased frictional pressures losses associated with using longer tubes. This also emphasizes the success of the proposed approach, where students were able to link fluid mechanics concepts into heat transfer analysis.

In a prior project-based assignment, students designed a concentric-tube heat exchanger, analyzing parallel and counterflow flows, sizing heat transfer, and examining how flow rate and temperature affect entropy generation and irreversibility. A 20-question follow-up showed an average score of 86%, indicating good qualitative understanding, though mostly superficial rather than individually analytical. In contrast, the lecture-based integration achieved 93% average accuracy, ensuring consistent mathematical development of entropy generation and evaluating understanding through individual exams. Thus, it provided uniform exposure and effectively reinforced Second-Law principles, compensating for the removal of Thermodynamics II from the curriculum.

Conclusion

Credit-reduction strategies have unintentionally eliminated Thermodynamics II in many curricula, threatening students' exposure to Second-Law principles. This study shows that integrating irreversibility, entropy generation, and exergy destruction within the Heat Transfer course through a structured lecture-based approach is an effective tool. Unlike the earlier project-based strategy, the lecture-based approach ensures uniform exposure to Thermodynamics II principles to students. Examination results confirmed that students could not only recognize but also apply Second-Law analysis in heat exchanger applications. Therefore, this approach offers a practical and superior curriculum adaptation strategy for restoring essential thermodynamic knowledge without increasing program credits.

References

[1] R. M. Felder and R. Brent, “Designing and teaching courses to satisfy the ABET engineering criteria,” *Journal of Engineering Education*, vol. 92, no. 1, pp. 7–25, 2003.
[2] J. W. Prados, G. D. Peterson, and L. R. Lattuca, “Quality assurance of engineering education through accreditation: The impact of Engineering Criteria 2000 and its global influence,” *Journal of Engineering Education*, vol. 94, no. 1, pp. 165–184, 2005.
[3] L. R. Lattuca, P. T. Terenzini, and J. F. Volkwein, *Engineering Change: A Study of the Impact of EC2000*. Baltimore, MD: ABET, 2006.
[4] R. Graham, *The Global State of the Art in Engineering Education*. MIT Report, 2018.
[5] E. Crawley, J. Malmqvist, S. Östlund, and D. Brodeur, *Rethinking Engineering Education: The CDIO Approach*, 2nd ed. Springer, 2014.
[6] National Academy of Engineering, *Engineering Education for a Changing World*. Washington, DC: NAE, 2017.
[7] J. Froyd, P. Wankat, and K. Smith, “Five major shifts in 100 years of engineering education,” *Proceedings of the IEEE*, vol. 100, pp. 1344–1360, 2012.
[8] S. Williamson, “A survey of credit hour requirements in ABET-accredited engineering programs,” in *Proceedings of the ASEE Annual Conference*, 2017.
[9] S. Kotas, *The Exergy Method of Thermal Plant Analysis*. Oxford: Pergamon Press, 1985.
[10] A. Bejan, *Entropy Generation Minimization: The Method of Thermodynamic Optimization of Finite-Size Systems and Finite-Time Processes*. CRC Press, 1996.
[11] R. L. Streveler, T. A. Litzinger, R. Miller, and P. S. Steif, “Learning conceptual knowledge in the engineering sciences: Overview and future research directions,” *Journal of Engineering Education*, vol. 97, pp. 279–294, 2008.
[12] J. Hadgraft and R. Kolmos, “Transforming engineering education,” *European Journal of Engineering Education*, vol. 45, no. 4, pp. 475–490, 2020.