ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #45314

Incorporating Advanced Industry Practices into the Undergraduate Thermal System Design Course

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Incorporating Modern Heat Transfer Surfaces into a Senior-Level Thermal System Design Course

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Abstract

In the face of advanced computational demands in data centers [1] and high-performance requirements in automotive [2] and aviation [3] industries, traditional undergraduate thermal system design courses, which are focused primarily on fundamental theories and classical problems, fail to bridge the gap between academic instruction and practical industry needs. Modern thermal management technologies, such as those utilized in aviation, leverage additive manufacturing to achieve complex geometric surfaces that give high heat transfer rates and surface area-to-volume ratios, yet these are absent from current curricula. To address these deficiencies, we propose a course redesign at the senior level, by introducing a new module that integrates cutting-edge thermal management technologies like triply periodic minimal surfaces (TPMS) [4], topologically optimized surfaces [5], helical heat exchangers [6], and manifold-microchannel heat exchangers [7]. The redesign also incorporates design experience via the use of INSTED [8], a user-friendly, cloud-based software package developed by TTC Technologies, Inc. [9]. This tool allows us to tackle realistic thermal design challenges, thus enhancing the readiness of students for professional careers in the thermal management industry.

Introduction

The rapid advancement in computing power in today's data centers is creating an urgent need for highly efficient heat removal technologies, as traditional thermal management strategies are unable to cope. Similarly, high-performance components in industries like automotive and aviation, such as the supersonic jet engines developed by Reaction Engines [10], generate a large amount of heat. These engines use cutting-edge cooling technologies with complex heat transfer systems that dissipate an imaginable amount of heat microseconds. Conventional heat transfer devices like plate-fin and shell-and-tubes heat exchangers are becoming less effective, and new heat transfer surfaces emerge. The latter include triply periodic minimal surfaces (TPMS) (Fig, 1a), topologically optimized surfaces, foam heat transfer devices (Fig. 1b), manifold-microchannel heat exchangers, and helical heat exchangers (Fig. 1c), all of which are made possible by advances in additive manufacturing. This technology allows for the creation of intricate designs that significantly enhance heat transfer, with improved surface area-to-volume ratios and the coefficient of performance (COP).

Despite these technological breakthroughs, many undergraduate thermal system design courses still focus primarily on basic heat transfer and classical benchmark problems. This mismatch between what is taught, and the emerging technologies, highlights the need for curriculum updates. In addition, students often lack hands-on design experience and accessibility to commercial-grade thermal design software tools that enable them to tackle complex, real-world problems. These skills are vital as students transition into their professional careers.

This paper proposes an improvement to an existing thermal system design course taught in the department of mechanical engineering at Stony Brook University, MEC 422: Thermal System Design, by incorporating a new two-week module designed to address the foregoing deficiencies. The module is structured to enhance both theoretical knowledge and practical experience. The lecture component will introduce students to emerging thermal management technologies: the challenges they present, and modern design methods. The laboratory component will ask students to use INSTED on the cloud. By bridging the gap between theory and practice, the proposed approach aims to better prepare students for the challenges they will face in the industry.

In the following sections, the paper will detail the structure and content of this module, discuss the expected educational outcomes, and conclude with the broader implications of these curricular enhancements for thermal system design education.

The Current Curriculum

The MEC 422 Thermal System Design course is a senior-level undergraduate course designed to provide students with applied skills in thermal system design and performance analysis. We spend the first four weeks discussing practical performance analysis and the design of fluid-hydraulic systems consisting of series piping, parallel piping, and combined series-parallel arbitrary complex piping components. Optimization and economic considerations in piping system design are treated in the next two weeks, where system cost is based on an The Least Annual Cost method. Here, the pipe diameter is used as the basis for the capital cost, cost of fittings, maintenance cost, and annuity. Pump manufacturers' curves and the engineer's system curves are then covered in the subsequent week. Thereafter, for the next six weeks, we cover thermal management and various heat exchangers in data centers and the aviation, automotive, data center, and HVAC industries. We also cover the analysis of heat removal in selected aero-propulsion components and subsystems, such as the engine of the space shuttle. The outline of the original course is shown in Fig. 2.

While the course provides a solid foundation in these traditional areas, it primarily relies on the classical devices for system designs. The textbook, *Design of Fluid Thermal Systems* by William S. Janna [11], is well-written and serves as a reliable resource. However, it does not cover many of the recent innovations that are becoming increasingly important in the field. For instance, it lacks discussions on modern advancements in heat transfer surfaces, like TPMS, topologically optimized surfaces, helical heat exchangers, and manifold-microchannel heat exchangers, which are critical for today's high-performance thermal management systems.

Additionally, the reliance on manual problem setups prior to using MATLAB in the original course, limits students' ability to tackle complex and realistic thermal management systems. Without access to commercial thermal system design software packages such as INSTED, students miss out on valuable hands-on experience that's crucial for solving real-world problems in a professional setting.

To address these gaps and enhance the current curriculum, we propose adding a two-week module at the end of the semester with two key improvements:

1. Introduction to Latest Industry Advances: This component will introduce students to cutting-edge thermal management technologies, including advanced heat transfer surfaces such as TPMS, topologically optimized surfaces, and the latest innovative heat exchanger designs, like helical and manifold-microchannel heat exchangers. Their applications in areas such as automotive, aircraft, and rocket combustors will also be explored. These advancements, driven by innovations in additive manufacturing, will broaden students' understanding of modern thermal system design beyond traditional methods.

2. Practical Design Experience with INSTED Software: To complement the theoretical learning, this module will include practical design exercises using INSTED, a user-friendly, cloud-based thermal system design software developed by TTC Technologies, Inc. This hands-on tool will give students the chance to apply their knowledge in designing realistic thermal systems, helping them solve actual design challenges and better prepare for careers in engineering.

By implementing these enhancements, the course will not only retain its strong theoretical foundation but also equip students with practical, industry-relevant skills that are essential for the evolving field of thermal system design.

Proposed Improvements to the Curriculum

A) Advancements in Thermal Management Technologies

The latest advancements in thermal management technologies will be discussed through lectures in this two-week module. The following topics will be covered:

- Introduction to Modern Thermal Management Solutions: This session will provide an overview of current thermal management technologies and their importance across various industries, such as automotive, aerospace, electronics, and energy systems. It will also highlight how technological advancements and thermal management needs are interconnected in these sectors.

- Additive Manufacturing for Thermal Systems: We'll discuss how recent breakthroughs in additive manufacturing (AM) are transforming the design of thermal systems, allowing for the creation of complex surfaces that were previously impossible.

- Triply Periodic Minimal Surfaces (TPMS): This topic will cover the basics of TPMS, including their geometric properties and the various forms. We'll explore how TPMS is applied to enhance heat transfer in modern heat exchanger devices, with a focus on the coefficient of performance (COP) and AM-related performance issues.

- Topologically Optimized Surfaces: We will discuss topological optimization as it applies to thermal system design. This topic involves a heat-transfer related figure of merit with the flow and energy equations serving as constraints. Although we will not be solving partial differential equations in this topic, we will take advantage of publicly available results for thermal management in energy applications.

- Helical and Spiral Heat Exchangers: This session will explore the design advantages of helical and spiral heat exchangers over traditional models, particularly in challenging environments like those involving viscous fluids or limited space. Turbulence created by rotational forces in this kind of device are explored to obtain improved heat transfer.

- Case Studies in Advanced Thermal Management: In this session, detailed case studies will showcase how advanced thermal management techniques have been successfully applied in different industries, giving students a practical understanding of these technologies.

- Future Trends and Challenges: The final lecture will address emerging trends and challenges in thermal management, helping students prepare to leverage future developments and contribute to advancements in the field.

These topics are designed to engage students with the latest technologies in thermal management, connecting theoretical frameworks with real-world thermal system design challenges. By the end of this module, students will have a well-rounded understanding of both the concepts and the practical applications of recent advancements.

B) Practical Design Integration Using INSTED

INSTED, developed by TTC Technologies, Inc., is a comprehensive commercial engineering software tailored for thermal analysis. This tool facilitates the design, performance evaluation, sizing, and optimization of various types of heat exchanger configurations, including plate-fin, plate-frame, concentric-tubes, shell & tubes, cross flow, manifold-microchannel, and cold plate. Notably, INSTED recently incorporated helical heat exchangers, and TPMS is currently being tested. Also note that from inception, INSTED supports the analysis of piping systems, tube banks, fin arrays, and multi-layer conduction analysis.

INSTED comes with an extensive built-in database that gives users easy access to single-phase and two-phase thermophysical properties, fin j/f data for different fin types, Moody charts, and fouling factors. The software package also has several built-in engineering tools that make it more user-friendly, like automatic unit conversions, advanced mathematical calculations with customizable functions. These include an integrated Excel tool for generating industry-grade reports directly from the simulation results.

INSTED's simulation engine uses a one-dimensional, low-order, finite-volume-type numerical integration approach to solve the flow and heat transfer equations. This method allows for fast computations while still handling complex geometries and physical phenomena, like two-phase problems. It is perfect for industrial applications and instructional purposes alike, producing quick results that will keep students engaged. Thus, INSTED allows users to experiment with different thermal system designs in a classroom setting.

Moreover, INSTED offers a cloud version, allowing the platform to run on cloud servers with its user interface accessible via any Internet browser. This feature solves a common problem in educational settings by removing the need for powerful local hardware. Since all calculations are done in the cloud, students don't need high-performance computers to run complex simulations, making INSTED an ideal tool for thermal engineering education. This ensures that all students, no matter their personal hardware preference, can engage in advanced engineering simulations.

In the proposed module, students will first need to get familiar with INSTED's basic features by working through sample problems provided within the software. These exercises will introduce students to analyzing different types of heat exchangers, like plate-fin and shell-and-tubes configurations. Through guided examples, students will learn how to set up simulations, evaluate performance, and optimize designs using INSTED's built-in features. The user interface of INSTED is shown in Fig. 3.

After the foregoing exercises, students will proceed to carry out design assignments. Three samples of these are described in this paper. In the first assignment, students are asked to design a cold plate device to remove a certain amount of heat from a computer chip on PCBs with known Thermal Design Power (TDP). The students will need to consider key design factors such as geometry, material selection, fin configurations, flow passes, partitions, and coolant flow rates, to ensure effective heat dissipation. Detailed guidelines for this task are provided in the sample assignment handout shown in Fig. 4.

For the second design assignment, students optimize an existing plate-fin heat exchanger device. The goal here is to re-design the system to minimize both the overall weight and flow pressure drop while maintaining a consistent heat transfer rate. Students will adjust variables like the number of flow passages and fin types to achieve this optimization. This task focuses on the trade-offs and decisions that engineers face in thermal system design, especially when it comes to balancing efficiency, size, and operational constraints. Specific instructions for this assignment are outlined in the handout displayed in Fig. 5.

Students are introduced to the cutting-edge field of manifold-microchannel heat exchanger design in the third assignment, wherein they are required to develop a manifold-microchannel heat exchanger and compare its performance against a traditional cold plate system under similar size and operational conditions. This task aims to demonstrate the effectiveness of modern heat transfer surfaces that utilize complex channel geometries and advanced manufacturing techniques to enhance thermal efficiency. Detailed instructions and the expected outcomes for this advanced project are provided in the sample assignment handout displayed in Fig. 6.

These assignments, which are detailed above along with handouts, aim to provide students with the skills required to apply foundational knowledge in practical applications. By integrating INSTED into the curriculum, students gain hands-on experience in thermal system design and learn to solve real-world problems through simulations. This approach not only enhances learning outcomes but also prepare students for the technical challenges they invariably will encounter in their engineering career.

Expected Educational Outcomes

The assessment for this module is streamlined to focus on the key deliverables that demonstrate students' understanding and application of the concepts taught:

- Assignment Reports: Students are required to complete design assignments using INSTED. The students will document their design process, simulation results, and subsequent optimizations in comprehensive reports. These reports will test their ability to apply advanced thermal management theories to practical problems, demonstrating their proficiency in using modern engineering tools.

- Presentations: Following the completion of their assignments, students will present their projects to the class. The presentations will assess their ability to effectively communicate complex engineering concepts and their solutions. They will also allow students to demonstrate their analytical skills and the ability to apply their theoretical knowledge to solve real-world design challenges.

The anticipated learning outcomes from this module align with ABET's Student Outcomes (SOs) for mechanical engineering, as follows:

- SO1 - Ability to Apply Knowledge of Mathematics, Science, and Engineering: The module's focus on advanced thermal management technologies and use of simulation tools like INSTED enhances students' abilities to apply foundational sciences in complex engineering contexts.

- SO2 - Ability to Design and Conduct Experiments, as well as to Analyze and Interpret Data: By engaging with design projects and simulations, students learn to construct experiments and interpret data to make informed engineering decisions.

- SO3 - Ability to Design a System, Component, or Process to Meet Desired Needs within Realistic Constraints: Design assignments challenge students to consider various constraints, such as economic factors, environmental impact, and manufacturability.

- SO4 - Ability to Use the Techniques, Skills, and Modern Engineering Tools Necessary for Engineering Practice: Direct interaction with INSTED software equips students with modern tools and techniques essential for contemporary engineering practice.

- SO6 - Ability to Communicate Effectively: The requirement for written reports and oral presentations ensures that students can articulate complex ideas and technical results effectively.

These outcomes ensure that the educational activities of the module not only meet but exceed the standards set by ABET, preparing students for successful careers in mechanical engineering.

Conclusion

This paper highlights the critical need to close the gap between traditional classroom education and the practical skills required by the thermal systems industry. By introducing a comprehensive two-week module at the end of the semester, we aim to better align educational practices with the needs of modern industrial environments, helping students to become better prepared for professional engineering roles.

Our proposed applied learning strategy addresses the identified gaps in the existing curriculum by integrating cutting-edge thermal management technologies, such as TPMS, topologically optimized surfaces, and advanced manifold-microchannel heat exchangers, alongside practical design experiences using INSTED software. This approach not only deepens students' understanding of both fundamental and advanced thermal system concepts but also equips them with the practical skills to apply this knowledge effectively. By focusing on system design, optimization, and the application of innovative thermal analysis methods, the module prepares students to effectively tackle real-world engineering challenges. Emphasizing these modern technologies throughout the course ensures that students are well-prepared for the evolving demands of the thermal systems industry.

Given the alignment of this approach with industry needs and educational standards, this method holds potential for application in other senior-level design-related courses. Extending this model could enhance curricula across various engineering disciplines, better preparing students for the complexities of the modern workforce.

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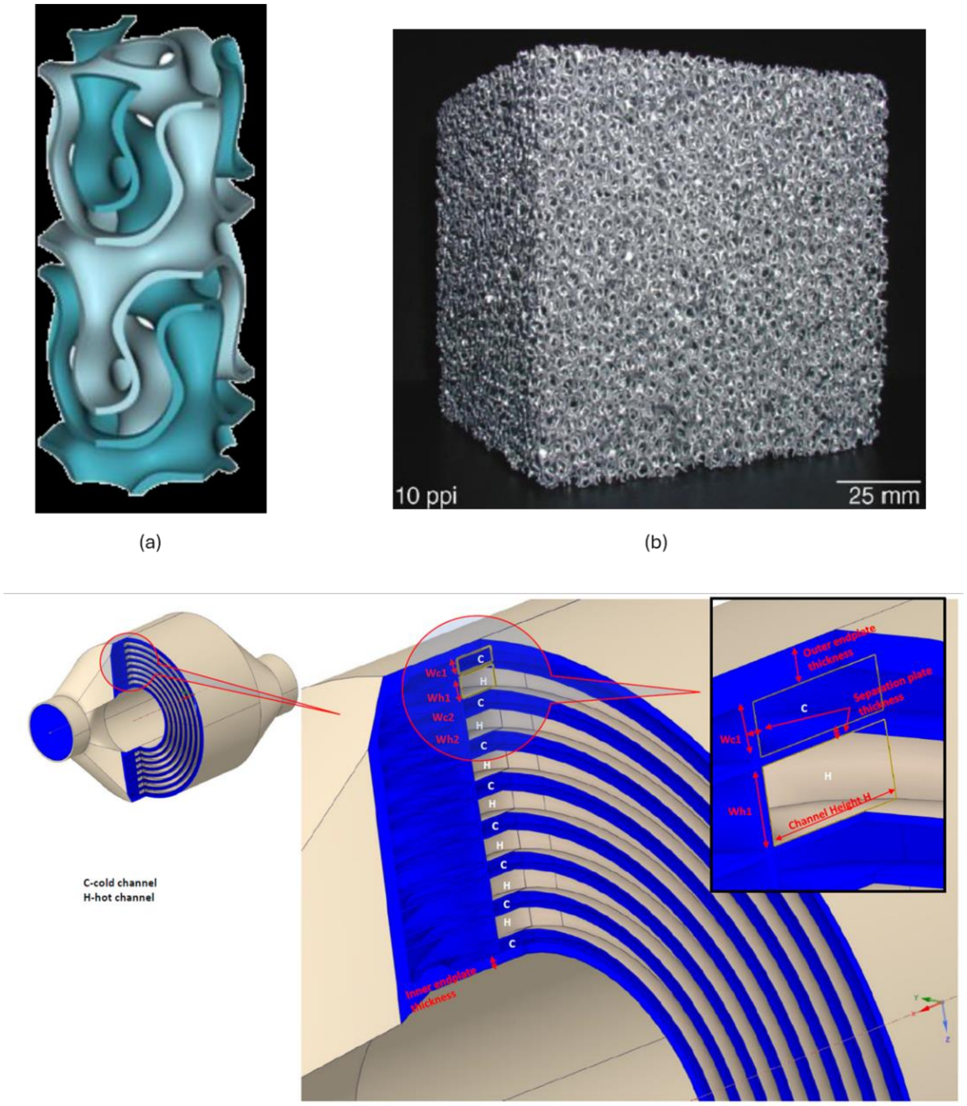
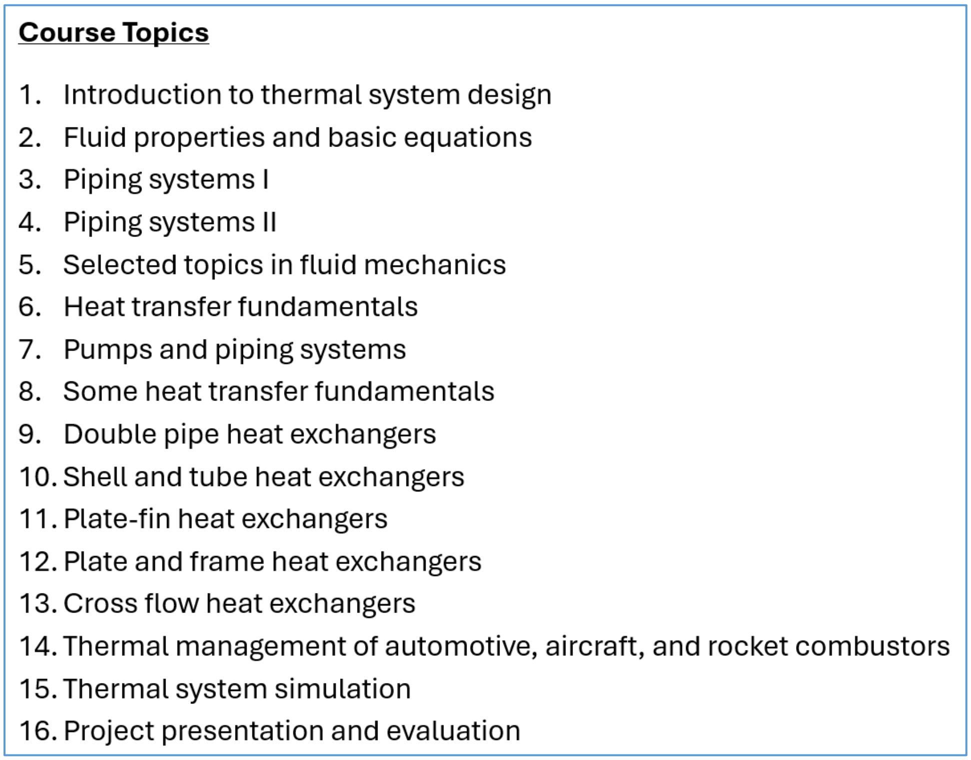


(a) (b)

(c)

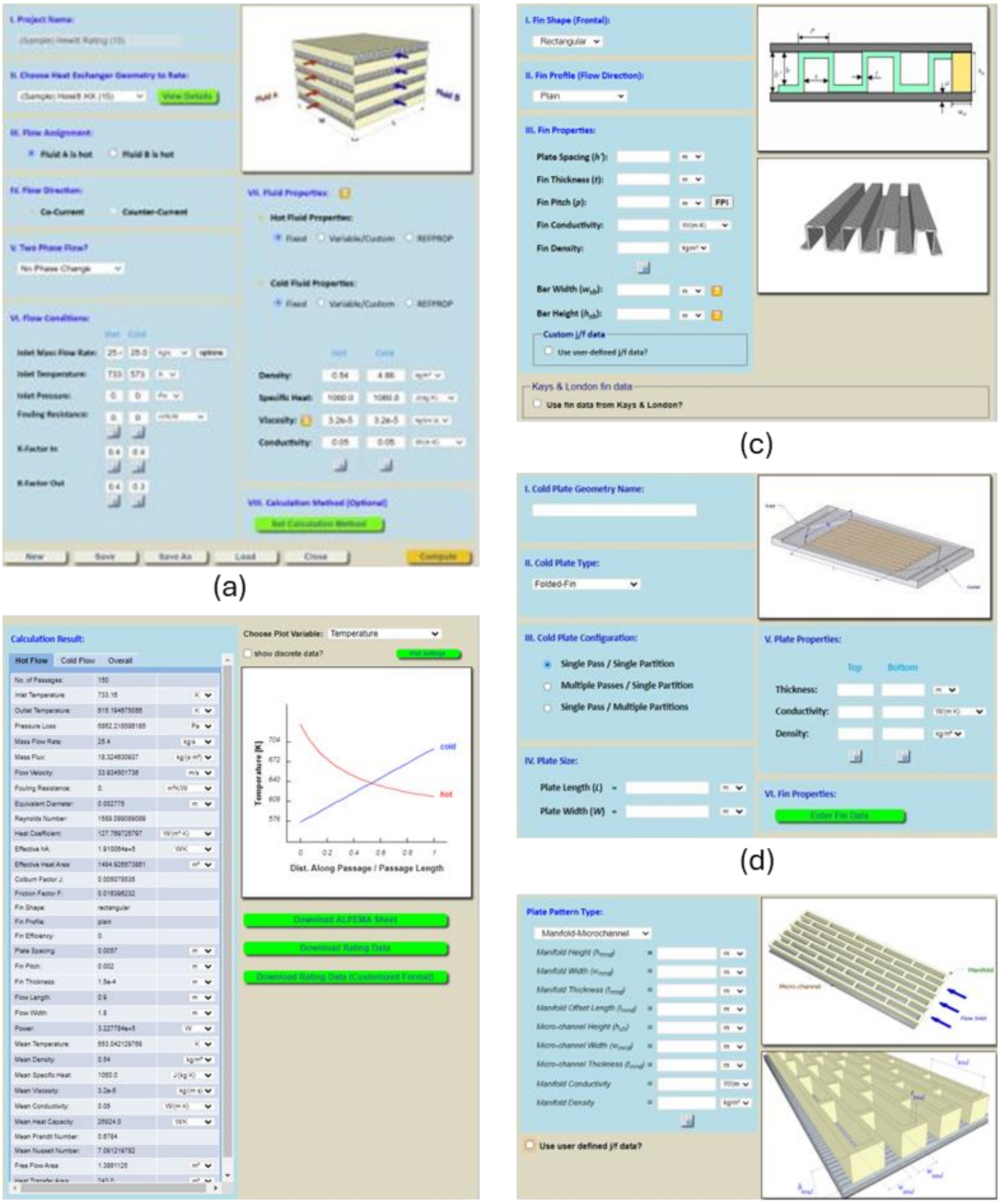
Fig. 1. Some Modern Heat Transfer Surfaces: (a) TPMS Heat Exchanger, (b) Foam Heat Exchanger, and (c) Helical Heat Exchanger.



Course Topics

1. Introduction to thermal system design
2. Fluid properties and basic equations
3. Piping systems I
4. Piping systems II
5. Selected topics in fluid mechanics
6. Heat transfer fundamentals
7. Pumps and piping systems
8. Some heat transfer fundamentals
9. Double pipe heat exchangers
10. Shell and tube heat exchangers
11. Plate-fin heat exchangers
12. Plate and frame heat exchangers
13. Cross flow heat exchangers
14. Thermal management of automotive, aircraft, and rocket combustors
15. Thermal system simulation
16. Project presentation and evaluation

Fig. 2. Original Course Topics for MEC422 - Thermal System Design.



(a)

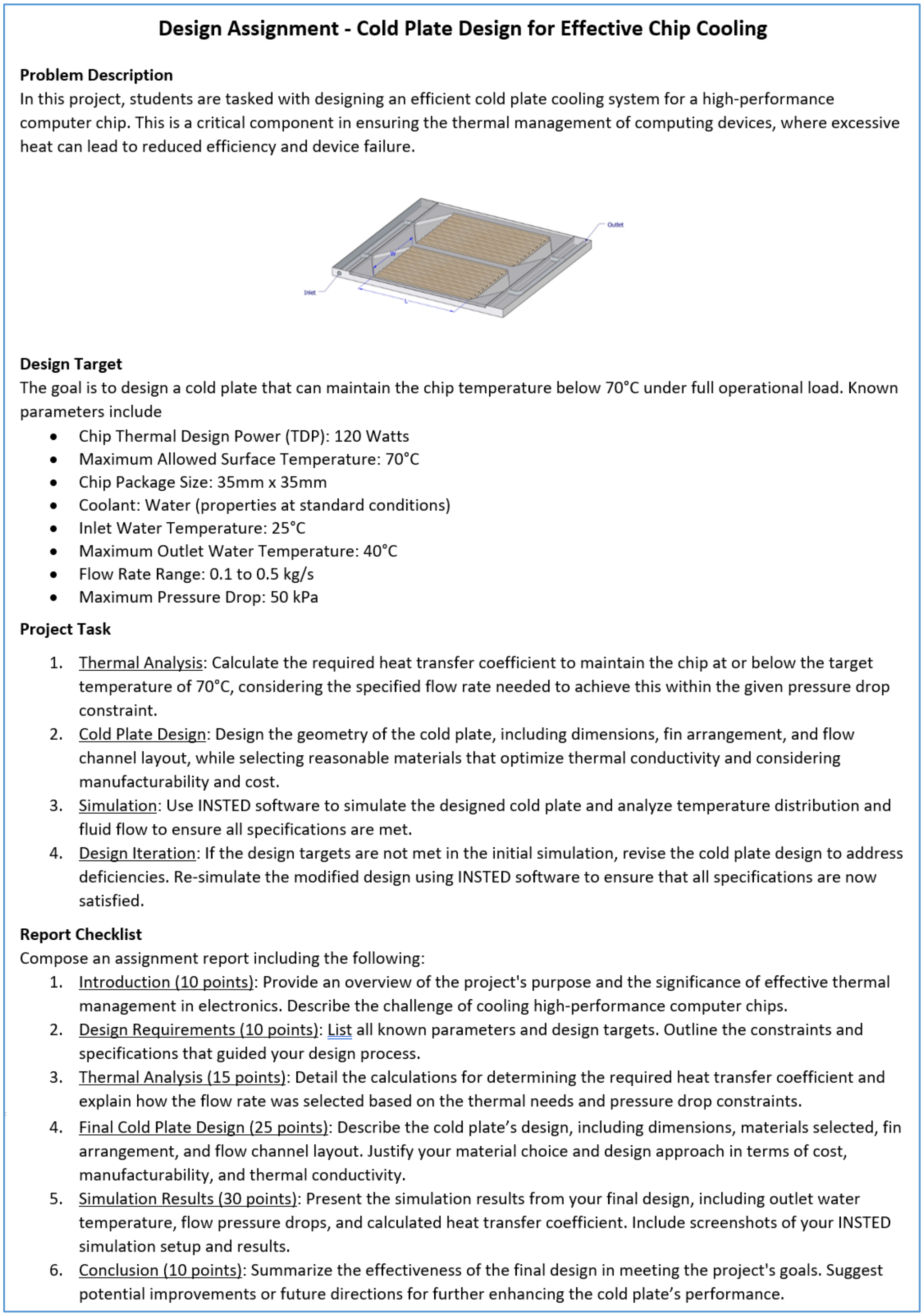
(b)

(c)

(d)

(e)

Fig. 3. Sample INSTED User Interface: (a) Plate-fin Heat Exchanger Rating, (b) Heat Exchanger Rating Results, (c) Fin Geometry Setup, (d) Cold Plate Design, (e) Manifold-Microchannel Heat Exchanger Design.



Design Assignment - Cold Plate Design for Effective Chip Cooling

Problem Description

In this project, students are tasked with designing an efficient cold plate cooling system for a high-performance computer chip. This is a critical component in ensuring the thermal management of computing devices, where excessive heat can lead to reduced efficiency and device failure.

Design Target

The goal is to design a cold plate that can maintain the chip temperature below 70°C under full operational load. Known parameters include

- Chip Thermal Design Power (TDP): 120 Watts
- Maximum Allowed Surface Temperature: 70°C
- Chip Package Size: 35mm x 35mm
- Coolant: Water (properties at standard conditions)
- Inlet Water Temperature: 25°C
- Maximum Outlet Water Temperature: 40°C
- Flow Rate Range: 0.1 to 0.5 kg/s
- Maximum Pressure Drop: 50 kPa

Project Task

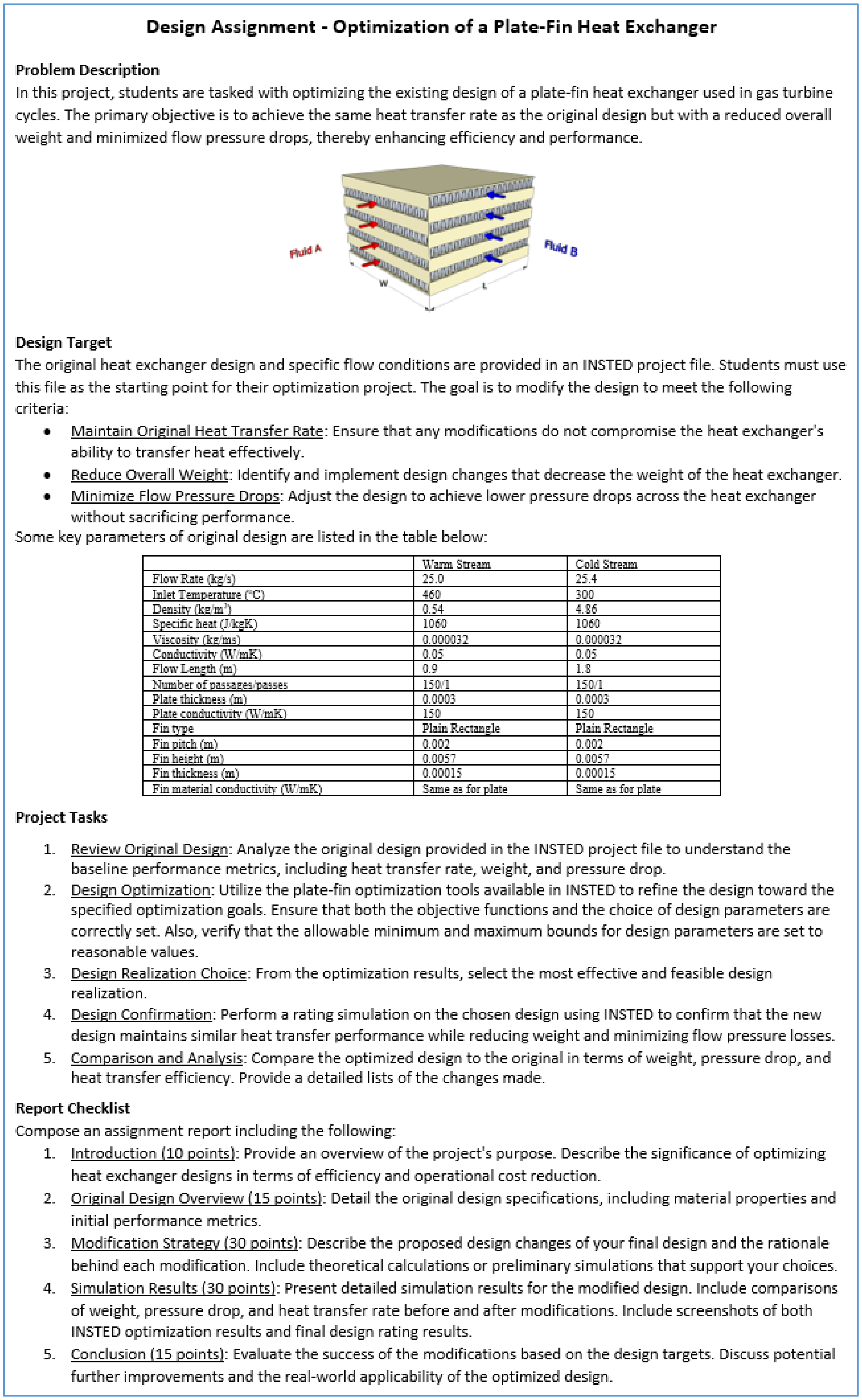
1. Thermal Analysis: Calculate the required heat transfer coefficient to maintain the chip at or below the target temperature of 70°C, considering the specified flow rate needed to achieve this within the given pressure drop constraint.
2. Cold Plate Design: Design the geometry of the cold plate, including dimensions, fin arrangement, and flow channel layout, while selecting reasonable materials that optimize thermal conductivity and considering manufacturability and cost.
3. Simulation: Use INSTED software to simulate the designed cold plate and analyze temperature distribution and fluid flow to ensure all specifications are met.
4. Design Iteration: If the design targets are not met in the initial simulation, revise the cold plate design to address deficiencies. Re-simulate the modified design using INSTED software to ensure that all specifications are now satisfied.

Report Checklist

Compose an assignment report including the following:

1. Introduction (10 points): Provide an overview of the project's purpose and the significance of effective thermal management in electronics. Describe the challenge of cooling high-performance computer chips.
2. Design Requirements (10 points): List all known parameters and design targets. Outline the constraints and specifications that guided your design process.
3. Thermal Analysis (15 points): Detail the calculations for determining the required heat transfer coefficient and explain how the flow rate was selected based on the thermal needs and pressure drop constraints.
4. Final Cold Plate Design (25 points): Describe the cold plate's design, including dimensions, materials selected, fin arrangement, and flow channel layout. Justify your material choice and design approach in terms of cost, manufacturability, and thermal conductivity.
5. Simulation Results (30 points): Present the simulation results from your final design, including outlet water temperature, flow pressure drops, and calculated heat transfer coefficient. Include screenshots of your INSTED simulation setup and results.
6. Conclusion (10 points): Summarize the effectiveness of the final design in meeting the project's goals. Suggest potential improvements or future directions for further enhancing the cold plate's performance.

Fig. 4. Assignment Handout for Cold Plate Design



Design Assignment - Optimization of a Plate-Fin Heat Exchanger

Problem Description

In this project, students are tasked with optimizing the existing design of a plate-fin heat exchanger used in gas turbine cycles. The primary objective is to achieve the same heat transfer rate as the original design but with a reduced overall weight and minimized flow pressure drops, thereby enhancing efficiency and performance.

Design Target

The original heat exchanger design and specific flow conditions are provided in an INSTED project file. Students must use this file as the starting point for their optimization project. The goal is to modify the design to meet the following criteria:

- Maintain Original Heat Transfer Rate: Ensure that any modifications do not compromise the heat exchanger's ability to transfer heat effectively.
- Reduce Overall Weight: Identify and implement design changes that decrease the weight of the heat exchanger.
- Minimize Flow Pressure Drops: Adjust the design to achieve lower pressure drops across the heat exchanger without sacrificing performance.

Some key parameters of original design are listed in the table below:

	Warm Stream	Cold Stream
Flow Rate (kg/s)	25.0	25.4
Inlet Temperature (°C)	460	300
Density (kg/m^3)	0.54	4.86
Specific heat (J/kgK)	1060	1060
Viscosity (kg/ms)	0.000032	0.000032
Conductivity (W/mK)	0.05	0.05
Flow Length (m)	0.9	1.8
Number of passages/passes	150/1	150/1
Plate thickness (m)	0.0003	0.0003
Plate conductivity (W/mK)	150	150
Fin type	Plain Rectangle	Plain Rectangle
Fin pitch (m)	0.002	0.002
Fin height (m)	0.0057	0.0057
Fin thickness (m)	0.00015	0.00015
Fin material conductivity (W/mK)	Same as for plate	Same as for plate

Project Tasks

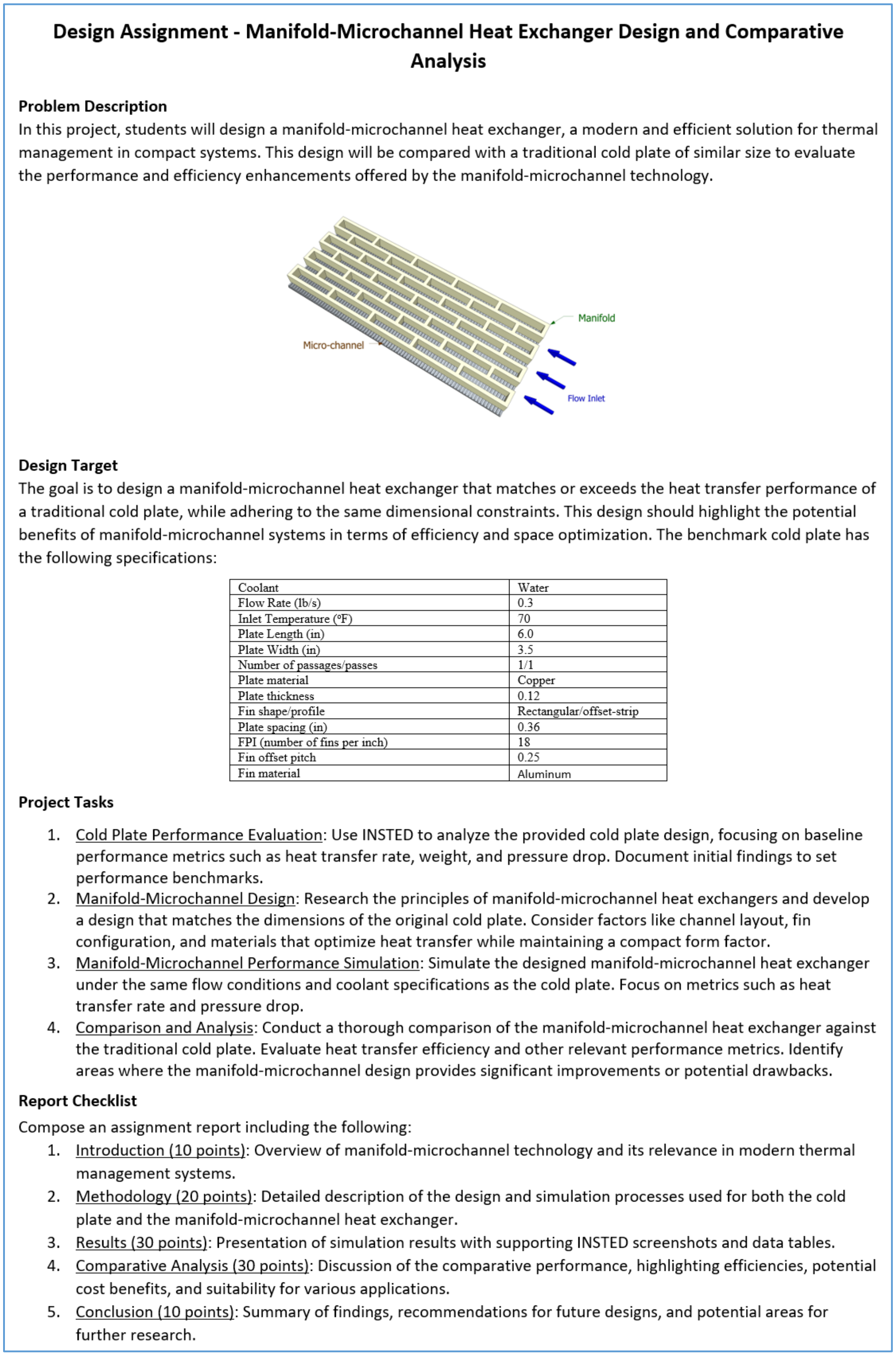
1. Review Original Design: Analyze the original design provided in the INSTED project file to understand the baseline performance metrics, including heat transfer rate, weight, and pressure drop.
2. Design Optimization: Utilize the plate-fin optimization tools available in INSTED to refine the design toward the specified optimization goals. Ensure that both the objective functions and the choice of design parameters are correctly set. Also, verify that the allowable minimum and maximum bounds for design parameters are set to reasonable values.
3. Design Realization Choice: From the optimization results, select the most effective and feasible design realization.
4. Design Confirmation: Perform a rating simulation on the chosen design using INSTED to confirm that the new design maintains similar heat transfer performance while reducing weight and minimizing flow pressure losses.
5. Comparison and Analysis: Compare the optimized design to the original in terms of weight, pressure drop, and heat transfer efficiency. Provide a detailed lists of the changes made.

Report Checklist

Compose an assignment report including the following:

1. Introduction (10 points): Provide an overview of the project's purpose. Describe the significance of optimizing heat exchanger designs in terms of efficiency and operational cost reduction.
2. Original Design Overview (15 points): Detail the original design specifications, including material properties and initial performance metrics.
3. Modification Strategy (30 points): Describe the proposed design changes of your final design and the rationale behind each modification. Include theoretical calculations or preliminary simulations that support your choices.
4. Simulation Results (30 points): Present detailed simulation results for the modified design. Include comparisons of weight, pressure drop, and heat transfer rate before and after modifications. Include screenshots of both INSTED optimization results and final design rating results.
5. Conclusion (15 points): Evaluate the success of the modifications based on the design targets. Discuss potential further improvements and the real-world applicability of the optimized design.

Fig. 5. Assignment Handout for Plate-Fin Heat Exchanger Optimization



Design Assignment - Manifold-Microchannel Heat Exchanger Design and Comparative Analysis

Problem Description

In this project, students will design a manifold-microchannel heat exchanger, a modern and efficient solution for thermal management in compact systems. This design will be compared with a traditional cold plate of similar size to evaluate the performance and efficiency enhancements offered by the manifold-microchannel technology.

Design Target

The goal is to design a manifold-microchannel heat exchanger that matches or exceeds the heat transfer performance of a traditional cold plate, while adhering to the same dimensional constraints. This design should highlight the potential benefits of manifold-microchannel systems in terms of efficiency and space optimization. The benchmark cold plate has the following specifications:

Coolant	Water
Flow Rate (lb/s)	0.3
Inlet Temperature (°F)	70
Plate Length (in)	6.0
Plate Width (in)	3.5
Number of passages/passes	1/1
Plate material	Copper
Plate thickness	0.12
Fin shape/profile	Rectangular/offset-strip
Plate spacing (in)	0.36
FPI (number of fins per inch)	18
Fin offset pitch	0.25
Fin material	Aluminum

Project Tasks

1. Cold Plate Performance Evaluation: Use INSTED to analyze the provided cold plate design, focusing on baseline performance metrics such as heat transfer rate, weight, and pressure drop. Document initial findings to set performance benchmarks.
2. Manifold-Microchannel Design: Research the principles of manifold-microchannel heat exchangers and develop a design that matches the dimensions of the original cold plate. Consider factors like channel layout, fin configuration, and materials that optimize heat transfer while maintaining a compact form factor.
3. Manifold-Microchannel Performance Simulation: Simulate the designed manifold-microchannel heat exchanger under the same flow conditions and coolant specifications as the cold plate. Focus on metrics such as heat transfer rate and pressure drop.
4. Comparison and Analysis: Conduct a thorough comparison of the manifold-microchannel heat exchanger against the traditional cold plate. Evaluate heat transfer efficiency and other relevant performance metrics. Identify areas where the manifold-microchannel design provides significant improvements or potential drawbacks.

Report Checklist

Compose an assignment report including the following:

1. Introduction (10 points): Overview of manifold-microchannel technology and its relevance in modern thermal management systems.
2. Methodology (20 points): Detailed description of the design and simulation processes used for both the cold plate and the manifold-microchannel heat exchanger.
3. Results (30 points): Presentation of simulation results with supporting INSTED screenshots and data tables.
4. Comparative Analysis (30 points): Discussion of the comparative performance, highlighting efficiencies, potential cost benefits, and suitability for various applications.
5. Conclusion (10 points): Summary of findings, recommendations for future designs, and potential areas for further research.

Fig. 6. Assignment Handout for Manifold-Microchannel Heat Exchanger Design and Comparative Analysis