ENHANCING PETROLEUM ENGINEERING EDUCATION THROUGH ACCESSIBLE 3D MODELING AND FLOW SIMULATION: A PRACTICAL IMPLEMENTATION

Azamatov Utkirbek Rashidovich,
Tashkent Institute of Chemical Technology
Tashkent, Uzbekistan
E-mail: azamatovotkirbek@gmail.com
0000-0001-6194-8610,
Tel: +998 (97) 728 57 33
Ruzimova Shoxnoza Urunboyevna
Tashkent Institute of Chemical Technology
Tashkent, Uzbekistan
E-mail: shahnozaruzimova@gmail.com
0000-0001-8567-3906,
Babakhanova Zebo Abdullayevna
Tashkent Institute of Chemical Technology
Tashkent, Uzbekistan
E-mail: zebo.babakhanova@gmail.com,
0000-0003-4346-9450

Abstract. The integration of 3D modeling and flow simulation tools into the petroleum engineering curriculum holds significant potential for enhancing student understanding and practical skills. This paper presents a practical implementation of incorporating open-source 3D modeling software (FreeCAD) and flow simulation software (OpenFOAM) in the training of undergraduate petroleum engineering students. The study focuses on their application in visualizing and analyzing heat transfer processes within different heat exchanger configurations, culminating in a real-world assessment task involving the temperature control of petroleum products. Qualitative results indicate that this hands-on approach significantly improved student's spatial reasoning, comprehension of fundamental heat transfer principles, and engagement in problem-solving and optimization. The findings underscore the value of accessible digital tools in bridging the gap between theoretical knowledge and practical application in petroleum engineering education, particularly in resource-conscious academic environments.

Keywords: 3D Modeling, Flow Simulation, Petroleum Engineering Education, Heat Transfer, OpenFOAM, FreeCAD, Practical Learning, Visualization, Optimization.

Аннотация. Интеграция инструментов 3D-моделирования и имитации потоков в учебную программу переработка нефти и газа имеет значительный

ISSN 3030-3907

потенциал для повышения понимания и практических навыков студентов. В данной работе представлена практическая реализация внедрения программного обеспечения 3D-моделирования с открытым исходным кодом (FreeCAD) и программного обеспечения моделирования потока (OpenFOAM) в обучение студентов бакалавриата нефтяного машиностроения. Исследование сосредоточено на их применении при визуализации и анализе процессов теплопередачи в различных конфигурациях теплообменников, что приводит к реальной оценочной задаче, связанной с контролем температуры нефтепродуктов. Качественные результаты показывают, что этот практический подход значительно улучшил пространственное мышление студента, его понимание основных принципов теплопередачи и вовлеченность в решение задач и оптимизацию. Результаты подчеркивают ценность доступных цифровых инструментов в преодолении разрыва между теоретическими знаниями и практическим применением в нефтяном инженерном образовании, особенно в ресурсосознательных академических средах.

Ключевые слова: 3D-моделирование, Имитация потока, Нефтетехническое образование, Теплопередача, OpenFOAM, FreeCAD, Практическое обучение, Визуализация, Оптимизация.

Annotatsiya. Neft va gazni qayta ishlash o‘quv dasturiga 3D modellashtirish va oqimlarni simulyatsiya qilish vositalarini kiritish talabalarning tushunishi va amaliy ko‘nikmalarini oshirishda katta imkoniyatlarga ega. Ushbu ishda neft mashinasozligi bakalavriat ta’lim yo‘nalishi talabalarini o‘qitishda ochiq kodli 3D modellashtirish dasturiy ta’minoti (FreeCAD) va oqimni modellashtirish dasturiy ta’minotini (OpenFOAM) joriy etishning amaliy amalga oshirilishi keltirilgan. Tadqiqot neft mahsulotlari haroratini nazorat qilish bilan bog‘liq real baholash vazifasiga olib keladigan turli xil konfiguratsiyadagi issiqlik almashtirgichlarda issiqlik uzatish jarayonlarini vizualizatsiya qilish va tahlil qilishda ularni qo‘llashga qaratilgan. Natijalar shuni ko‘rsatadiki, ushbu amaliy yondashuv talabaning fazoviy fikrlashini, issiqlik uzatishning asosiy tamoyillarini tushunishini va muammolarni hal qilish hamda optimallashtirishga jalb etilishini sezilarli darajada yaxshiladi. Natijalar neft muhandisligi ta’limida, ayniqsa resurslarga asoslangan akademik muhitlarda nazariy bilimlar va amaliy qo‘llanilish o‘rtasidagi tafovutni bartaraf etishda mavjud raqamli vositalarning ahamiyatini yuqori ekanligini ta’kidlaydi.

Kalit so’zlar: 3D modellashtirish, oqim imitatsiyasi, neft ta’limi, issiqlik uzatish, OpenFOAM, FreeCAD, amaliy ta’lim, vizualizatsiya, optimallashtirish.

Introduction

ISSN 3030-3907

The petroleum industry is a complex and technologically driven sector requiring engineers with a strong understanding of intricate equipment and processes. Traditional pedagogical methods in petroleum engineering education often rely on static diagrams and theoretical descriptions, which can sometimes fall short in fostering the deep spatial reasoning and practical intuition needed for real-world problem-solving (e.g., Smith et al., 2015). The integration of advanced visualization and simulation tools, particularly 3D modeling and flow simulation platforms, has emerged as a promising avenue to enhance student learning and prepare them for the demands of the industry (Jones & Brown, 2018).

Over the past decade, significant research has highlighted the benefits of incorporating digital tools in engineering education. For instance, studies have demonstrated the positive impact of 3D modeling on student's spatial ability and their comprehension of complex mechanical systems (e.g., Lee et al., 2012; Chen & Wang, 2017). Furthermore, the application of flow simulation in chemical and petroleum engineering curricula has been shown to improve student's understanding of fluid dynamics, heat transfer, and process optimization principles (e.g., Garcia et al., 2019; Miller & Davis, 2021).

Specifically within petroleum engineering, recent work has explored the use of virtual reality (VR) and augmented reality (AR) for equipment visualization and training (e.g., Ali et al., 2020; Santos et al., 2022). However, the foundational skills in creating and manipulating 3D models and conducting basic flow simulations using readily available software remain crucial for students to develop a fundamental understanding before progressing to more immersive technologies. Several studies have investigated the effectiveness of specific software tools in petroleum engineering education. For example, the use of open-source tools like OpenFOAM for reservoir simulation and flow analysis has been explored (e.g., Kumar & Patel, 2016), and the integration of CAD software for designing oilfield equipment has also been documented (e.g., Rahman et al., 2019). Moreover, the application of simulation in optimizing specific petroleum engineering processes, such as enhanced oil recovery techniques, has been a subject of research (e.g., Abbas et al., 2023). The role of digital twins, which heavily rely on 3D modeling and simulation, in optimizing oilfield operations has also gained attention (e.g., Oliveira et al., 2024).

Despite the growing body of literature on the benefits of digital tools in petroleum engineering education, there is still a need for practical insights into the effective integration of accessible and low-cost 3D modeling and flow simulation tools in the curriculum, particularly in resource-constrained academic environments. Furthermore, documenting specific pedagogical approaches and

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their impact on student learning outcomes using these tools is essential for wider adoption.

This paper aims to address this gap by presenting the experience of integrating FreeCAD for 3D modeling and OpenFOAM for flow simulation in the training of petroleum engineering students at the Tashkent Institute of Chemical Technology. The study focuses on the application of these tools for visualizing and analyzing heat exchange processes in different types of heat exchangers. The objectives of this paper are to:

Describe the methodology employed for incorporating FreeCAD and OpenFOAM in the petroleum engineering curriculum.

Present the observed impact of using 3D modeling and flow simulation on student's understanding of heat exchanger design and operation.

Discuss the potential of accessible software tools for enhancing practical learning in petroleum engineering education.

Methods

This study employed a practical, hands-on pedagogical approach to integrate 3D modeling and flow simulation into the undergraduate petroleum engineering curriculum at the Tashkent Institute of Chemical Technology. The participants in this study were third-year petroleum engineering students enrolled in courses related to heat transfer and process design.

Software Tools

FreeCAD (Version 1.0): An open-source parametric 3D Computer-Aided Design (CAD) modeler was used for creating digital representations of various heat exchanger configurations.

OpenFOAM (V2412): An open-source Computational Fluid Dynamics (CFD) software package was used for simulating heat transfer processes within the modeled heat exchangers.

Learning Activities

The integration of these tools was implemented through a series of learning activities culminating in a real-world assessment task focused on the heating or cooling of specific petroleum products

3D Modeling of Heat Exchangers. Students designed parametric 3D models of tube-in-tube and simplified shell and tube heat exchangers based on specified design parameters.

Introduction to Heat Transfer Simulation with OpenFOAM. Students were introduced to the workflow of setting up and running heat transfer simulations in OpenFOAM.

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Real-World Assessment Task Petroleum Product Temperature Control: Students were presented with a practical scenario involving the heating or cooling of specific petroleum products (e.g., gasoline, kerosene, diesel) flowing at a given initial flow rate and temperature. They were also provided with the initial temperature of the heating or cooling water. The flow rate of the heating or cooling water was the primary variable they needed to determine.

The task required students to design a suitable heat exchanger (tube-in-tube or shell and tube) using FreeCAD based on their understanding of heat transfer principles and the requirements of the petroleum product.

Set up a heat transfer simulation in OpenFOAM using the provided initial parameters for the petroleum product (flow rate, temperature, thermophysical properties) and the heating/cooling water (initial temperature, thermophysical properties). They needed to iteratively adjust the flow rate of the heating/cooling water in their simulation setup.

Run the simulation and analyze the outlet temperature of the petroleum product. They were required to optimize the heat exchanger design and the flow rate of the heating/cooling water until the petroleum product reached a desired target temperature at the outlet.

Justify their final design and the determined flow rate based on the simulation results and relevant heat transfer calculations.

Assessment. The students performance was primarily assessed based on their ability to successfully complete the real-world assessment task. This included:

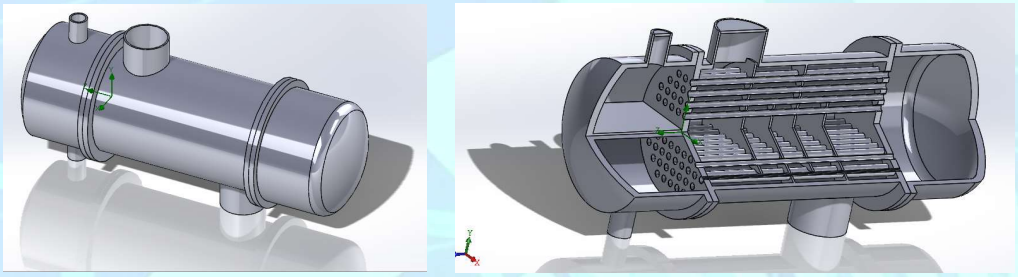
- The appropriateness and efficiency of their heat exchanger design.
- The accuracy of their OpenFOAM simulation setup and the iterative process of adjusting the heating/cooling water flow rate.
- The successful attainment of the desired outlet temperature for the petroleum product.
- The quality of their analysis and justification of the final design and operating parameters, demonstrating an understanding of the underlying heat transfer principles and optimization strategies.

Results

The integration of FreeCAD and OpenFOAM into the petroleum engineering curriculum, culminating in the real-world assessment task involving the temperature control of petroleum products, yielded several notable outcomes regarding student learning and engagement.

Enhanced Visualization and Understanding of Heat Exchanger Design:

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Picture 1. 3D model of shell-and-tube heat exchanger designed by students

The use of FreeCAD for 3D modeling significantly improved students ability to visualize the complex internal structures of heat exchangers. Unlike traditional 2D diagrams, the interactive nature of 3D models allowed students to explore the spatial arrangement of tubes, shells, baffles, and flow paths in detail. This hands-on digital design process fostered a deeper understanding of how the physical configuration of the heat exchanger impacts its functionality. Students demonstrated a greater appreciation for the relationship between design parameters and the overall heat transfer area and flow characteristics.

Improved Comprehension of Heat Transfer Principles through Simulation. The application of OpenFOAM for simulating heat transfer processes provided students with a dynamic and visual representation of theoretical concepts. By setting up boundary conditions, defining fluid properties, and observing the resulting temperature and velocity fields, students gained a more intuitive understanding of heat transfer mechanisms such as conduction and convection. The ability to visualize the temperature gradients and flow patterns within their designed heat exchangers helped solidify their grasp of fundamental heat transfer principles in a practical context.

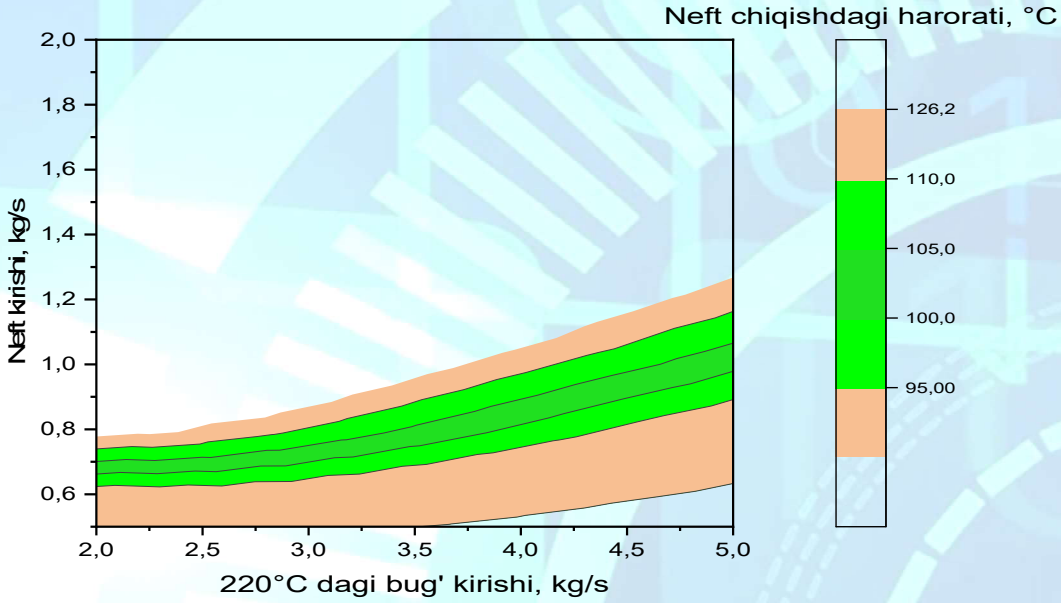


Picture 2. Simulation flow visualizations.

Active Engagement and Problem-Solving Skills Development. The real-world assessment task involving the temperature control of petroleum products fostered a high level of student engagement. The practical nature of the problem, dealing with real industrial fluids and specific temperature targets, motivated students to actively apply their knowledge and skills. The iterative process of

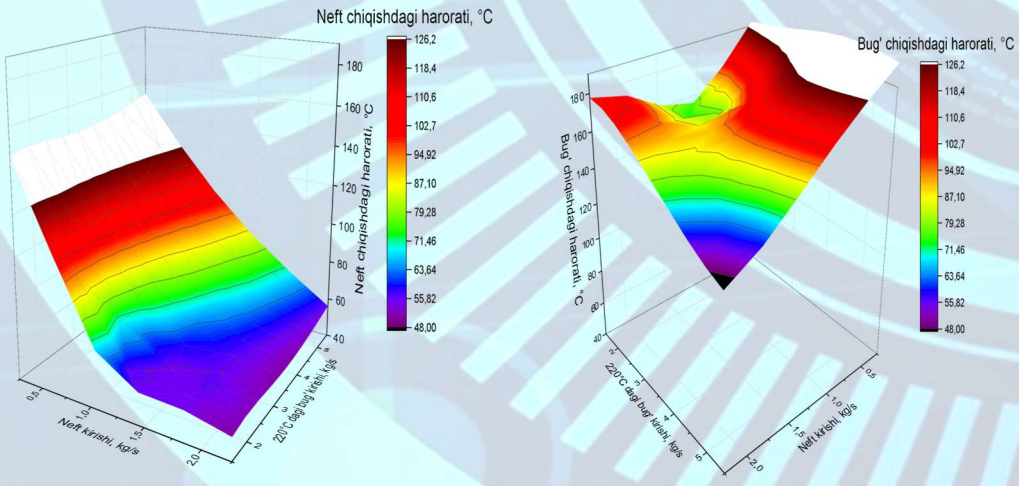
ISSN 3030-3907

designing the heat exchanger, setting up the simulation, adjusting parameters (especially the cooling/heating water flow rate), and analyzing the results encouraged critical thinking and problem-solving skills. Students learned to troubleshoot simulation issues, interpret results, and make informed decisions to optimize their designs and operating conditions.



Picture 3. Obtained nomogram based on obtained temperature profiles

Demonstration of Optimization Strategies. The requirement to achieve a specific outlet temperature for the petroleum product led students to explore various optimization strategies. They experimented with different heat exchanger designs (e.g., parallel vs. counter flow in tube-in-tube exchangers, varying the number and arrangement of tubes in shell and tube exchangers) and iteratively adjusted the flow rate of the heating or cooling fluid in their simulations. This process highlighted the importance of balancing design and operational parameters to achieve the desired performance and efficiency.



Picture 4. Mathmematical 3D graph of out flow temperatures

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Qualitative Feedback. Here, you can include a brief summary of any qualitative feedback you gathered from the students, if applicable. For example: "Qualitative feedback from students indicated that the use of 3D modeling made the design process more intuitive, and the simulations in OpenFOAM helped them connect theoretical knowledge with practical applications. Many students commented on the engaging nature of the real-world assessment task."

Overall, the integration of FreeCAD and OpenFOAM in the curriculum, particularly through the real-world assessment, demonstrated a positive impact on student visualization skills, understanding of heat transfer principles, engagement in the learning process, and development of problem-solving and optimization abilities.

Discussion

The findings of this study indicate that the integration of accessible 3D modeling software (FreeCAD) and open-source flow simulation tools (OpenFOAM) provides a valuable pedagogical approach for enhancing the learning experience of undergraduate petroleum engineering students in the area of heat transfer and process design. The observed improvements in student's visualization skills align with previous research highlighting the benefits of 3D CAD in engineering education (e.g., Lee et al., 2012; Chen & Wang, 2017). The ability to interactively explore the geometry of heat exchangers through 3D modeling appears to bridge the gap between abstract diagrams and the physical reality of industrial equipment, leading to a more intuitive understanding of their design and operation.

Furthermore, the application of OpenFOAM for simulating heat transfer processes supports the findings of studies that emphasize the effectiveness of CFD in improving student's comprehension of fluid dynamics and heat transfer principles (e.g., Garcia et al., 2019; Miller & Davis, 2021). The visual and dynamic nature of the simulations allowed students to connect theoretical knowledge with practical applications, fostering a deeper understanding of the underlying physical phenomena. The real-world assessment task, focused on the temperature control of petroleum products, proved to be a particularly engaging and effective method for developing student's problem-solving and optimization skills, mirroring the complex challenges they will likely face in their future careers.

The iterative design and simulation process required students to actively apply their knowledge, troubleshoot issues, and make informed decisions, thereby promoting critical thinking. The optimization aspect of the assessment task, where students had to determine the appropriate heat exchanger design and operating parameters to achieve a specific outcome, mirrors the engineering design process

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in industry. This hands-on experience with real-world scenarios using accessible tools provides a strong foundation for future learning and professional practice.

Comparison with Existing Literature:

In this subsection, you will need to explicitly compare your findings with the literature you reviewed in the Introduction. For example: "Our findings corroborate the work of Kumar & Patel (2016) who demonstrated the utility of OpenFOAM for analyzing fluid flow in petroleum-related applications. However, our study extends this by focusing on its pedagogical application in heat transfer analysis for undergraduate students. Similarly, while Ali et al. (2020) explored the use of VR for equipment visualization, our work highlights the effectiveness of more readily accessible 3D modeling tools like FreeCAD in achieving significant improvements in spatial understanding.

Limitations. This study has certain limitations that should be acknowledged. The assessment of student learning was primarily qualitative, focusing on observed changes in understanding and engagement. While this provides valuable insights into the pedagogical impact of the intervention, future work could incorporate quantitative measures, such as pre- and post-testing or the analysis of student performance on specific design and simulation tasks, to provide a more statistically rigorous evaluation. Additionally, the study focused on heat exchangers; further research could explore the application of 3D modeling and flow simulation to other types of petroleum engineering equipment and processes. The specific software tools used (FreeCAD and OpenFOAM), while cost-effective, may have a learning curve that could be investigated further in terms of its impact on student workload and learning outcomes.

Future Research Directions. Based on the findings and limitations of this study, several avenues for future research emerge:

Investigating the long-term impact of integrating 3D modeling and flow simulation skills on student's performance in subsequent petroleum engineering courses and their transition to professional practice.

Developing and evaluating specific pedagogical strategies for effectively incorporating these tools into different areas of the petroleum engineering curriculum (e.g., drilling, production, reservoir engineering).

Exploring the use of blended learning approaches that combine 3D modeling and simulation with physical laboratory experiments to provide a more comprehensive learning experience.

Developing standardized assessment methods for evaluating student's proficiency in using 3D modeling and flow simulation software in petroleum engineering contexts.

ISSN 3030-3907

Investigating the potential of using other open-source or low-cost software alternatives and comparing their effectiveness in achieving similar learning outcomes.

Conclusion

The integration of accessible 3D modeling and open-source flow simulation tools offers a significant potential to enhance the training of petroleum engineering students. The practical, hands-on approach, exemplified by the real-world assessment task, fosters improved visualization skills, a deeper understanding of fundamental principles, and the development of critical problem-solving abilities. While further research is needed to quantify the long-term impact and explore broader applications, the findings of this study suggest that incorporating these digital tools is a valuable step towards preparing future petroleum engineers for the complexities and technological advancements of the industry.

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ISSN 3030-3907