Online-Journals.org

iJEP International Journal of Engineering Pedagogy

iJEP | eISSN: 2192-4880 | Vol. 16 No. 3 (2026) | OPEN ACCESS

https://doi.org/10.3991/ijep.v16i3.60829

PAPER

Democratising Engineering Education: Fabrication and Experimental Validation of a Low-Cost FDM 3D-Printed Metal-Composite Plate Heat Exchanger

Héctor de Paz Carmona (✉),
Rubén Díaz López,
Óscar García-Afonso

Universidad de La Laguna (ULL), La Laguna (Tenerife), Spain

hpazcarm@ull.edu.es

ABSTRACT

Heat exchange is a key part of the current chemical and mechanical engineering curriculums at the university. However, students often see it as abstract because of the 'black box' nature of commercial heat exchangers in industry and the high cost of laboratory pilot plants for learning. This manuscript introduces an innovative educational project focused on the design, 3D-printing, and experimental testing of a plate heat exchanger (PHE). To overcome the low thermal conductivity of standard PLA for FDM printing, a high-metal-composite filament (>60% bronze-filled) was used, which allowed for much more efficient heat exchange. The project, conducted by a chemical engineering undergraduate student, consisted of an initial screening of open-source 3D models of heat exchangers, followed by fused deposition modelling 3D printing using different filaments and technical validation. The experimental testing was performed using tap water at 60ºC and 20ºC to determine the overall heat transfer coefficient. Our results indicate that 3D-printed PHEs show a significant thermal performance, providing a low-cost alternative to commercial units or expensive learning units. To the best of authors' knowledge, this approach goes beyond technology. This offers a practical way to update and democratize engineering laboratories while increasing student engagement through hands-on challenges.

KEYWORDS

chemical engineering education, additive manufacturing, active learning, metal-polymer filaments, low-cost laboratories

1 INTRODUCTION

Heat transfer, together with momentum and mass transfer, [1], [2], is one of the fundamental pillars of knowledge of the current Chemical and Mechanical Engineering (ChE/ME) curriculum. Understanding heat exchange principles is a core

de Paz Carmona, H., Díaz López, R., García-Afonso, O. (2026). Democratising Engineering Education: Fabrication and Experimental Validation of a Low-Cost FDM 3D-Printed Metal-Composite Plate Heat Exchanger. *International Journal of Engineering Pedagogy (iJEP)*, 16(3), pp. 53–66. https://doi.org/10.3991/ijep.v16i3.60829

Article submitted 2026-01-03. Revision uploaded 2026-02-12. Final acceptance 2026-02-17.

engineering competency for future engineers. It is not just a theoretical requirement. This competency is straightforwardly related to design, process safety, energy efficiency, and modernizing industry, among other critical points [2], [3].

As with other engineering subjects, teaching and learning heat transfer pose significant pedagogical challenges. In this context, students often struggle to bridge the gap between mathematical models (usually abstract) and the reality of industrial equipment [4]. Generally, heat exchangers are considered ‘black boxes’ in which students have only information about inlet and outlet parameters, with internal fluid dynamics and the influence of geometry on transfer coefficients treated as theoretical concepts [5]. This serious deficiency is often addressed through practical laboratory experiments, which provide only a superficial understanding of heat transfer phenomena.

The hands-on laboratory sessions are mandatory for consolidating engineering knowledge. However, several barriers limit their effectiveness in current engineering departments. The most significant problem is the economic cost. In this sense, specialized laboratory-scale pilot plants for heat transfer studies are expensive to acquire, with prices ranging from thousands of euros to tens of thousands of euros [6]. In most cases, this excessively high cost results in a low equipment-to-student ratio, forcing students to work in large groups and playing more the role of spectators than active participants in the laboratory experience [7], [8].

Aside from the fact that a large laboratory-scale pilot plant is practically unaffordable, commercial units often lack pedagogical flexibility [9]. These units are normally ‘closed’ models designed only for durability and safety, offering very limited opportunities for students to explore internal geometries or how different materials affect heat transfer phenomena [10], [11]. Moreover, if a malfunction occurs or maintenance is required, specialized technical support is needed, resulting in lengthy maintenance shutdowns. This fact is not feasible for teaching purposes, where the time schedule plays a key role in the proper development of the subjects [12]. In view of this situation, there is a need to identify or develop a robust, low-cost, and flexible solution that complements traditional laboratories, promoting a more inclusive and interactive learning environment [13], [14].

Additive manufacturing (AM) by fused deposition modelling (FDM), also known as FDM 3D printing, has transitioned from a rapid prototyping tool to a robust manufacturing method with direct implications for engineering education [15]–[19]. Undoubtedly, the rapid development of this technology is not only due to its great practical usefulness but also to the support of some of its main developers, who have released their designs as open source. This democratization of AM has resulted in a technology capable of manufacturing complex geometries beyond our imagination while maintaining low cost [20]. A key point of this shift is the continuous proliferation of open-source 3D design repositories, which allow educators worldwide to ‘curate’ engineering models for pedagogical purposes [21], [22].

In the context of ChE/ME [23], one of the main challenges of using AM for developing heat transfer equipment is the significantly low thermal conductivity (k) of standard polylactic acid (PLA) filaments used for FDM printing, which range from 0.10 to 0.25 W/m·K [24], [25]. Moreover, many open-source models for shell-and-tube or spiral heat exchangers available online are often designed for illustrative purposes rather than as functional thermal exchangers. In addition, the complex internal structure seems to require the use of soluble supports, which would increase costs and post-processing requirements, making them less suitable for implementation in undergraduate laboratories. Despite the enormous potential of AM in engineering education [26]–[29], most of the existing literature is focused on illustrative models of high-end industrial applications that are far beyond the reach of a typical teaching budget for laboratory infrastructure [30]–[34].

In this sense, to the best of authors' knowledge, there is a lack of references documenting the development of functional, modular heat-transfer equipment using open-source models and integrating high-metal-composite filaments. To fill this knowledge gap, this paper presents a comprehensive student-led project focused on the fabrication and experimental validation of an open-source and low-cost modular plate heat exchanger (PHE). Fabrication was performed by FDM 3D-printing using 60–80% bronze-filled filaments for plates and flexible TPU for gaskets. An experimental validation process was carried out by testing heat exchange between tap water at 60ºC and 20ºC and analyzing the overall heat transfer coefficient. Our results allow us to validate the 3D-printed PHE as a reliable and interactive tool for democratizing engineering laboratory practices worldwide.

2 MATERIALS AND METHODS

2.1 Selection and curation of 3D models

The first step of this student-led project consisted of the 'digital curation' of available open-source models of heat exchangers. For this purpose, a systematic search was conducted in the most significant open-source repositories currently available online, i.e., Thingiverse, Printables, and Cults3D [35]–[37]. These repositories are the most active and have significant amounts of free-to-use technical documentation, supported by an active engineering community. The keywords for searching were: 'Heat Exchanger,' 'Chemical Engineering,' and 'Industrial Equipment.'

Digital curation revealed a significant lack of functional models. Most of them were only for illustrative purposes, without internal fluid-tightness or functional inlet/outlet ports. Moreover, limitations of AM by FDM were not considered during design, which was especially critical in the need for internal supports in complex cavities. The four main archetypes were evaluated according to three screening criteria: 1) Technical Functionality (high relevance), Printability (medium relevance), and Open-source accessibility (low relevance):

- Option 1: Rectangular Baffled Exchanger [38]: designed for educational purposes as a model, not as a functional prototype. Its monolithic design makes it hard to print due to the need for internal supports from the flow channels (which are impossible to remove) and a long manufacturing time.
- Option 2: Concentric Cylindrical Exchanger [26]: an educationally validated design, easy to print without supports. It represents a direct and simplified transition from theory to practice. It works more as a basic laboratory experiment than as a representation of industrial heat transfer equipment.
- Option 3: Spiral Heat Exchanger [39]: similar to the first option [38] but offering a superior theoretical heat transfer coefficient due to its complex helical internal channels. However, its monolithic design offers the same manufacturing challenges as the rectangular baffled exchanger. The model is available online upon payment.
- Option 4: Modular Plate Heat Exchanger (PHE) [40]: This model was found to be the most optimal candidate for several reasons. Its modularity allows plates to be printed horizontally, eliminating internal supports and maximizing surface quality. Moreover, it allows a multi-material approach. Thus, plates can be manufactured from conductive materials (metal-composite filaments), and gaskets from flexible filaments. This is an essential fact for experimental validation. Finally, the model is available free of charge, ensuring full availability for everyone with internet access.

2.2 Materials and printing parameters

PHE manufacturing was carried out using a commercial Bambu Lab P1S (Bambu Lab, China) FDM printer. This 3D printer combines high reliability, easy operation (automatic calibration), and versatility to handle technical filaments. The printer was equipped with a 0.6 mm hardened-steel nozzle (model: FAH005-N-1) to handle abrasive metal-filled filaments and prevent clogging. The nozzle diameter also improves the structural integrity of the plate during printing, reducing the number of potential weld lines between layers. This is a critical fact to ensure watertightness.

The slicing process (converting a 3D design into layer-by-layer instructions, i.e., ‘G-code’) was managed using the open-source software Bambu Studio. This software allows the user to control the main printing parameters, such as wall thickness and infill density. This is a very important point for a functional heat transfer unit. To the best of our knowledge, the use of this commercial AM equipment and free software significantly enhances and reinforces the replicability of this student-led project in any engineering laboratory with a modest budget.

Three different commercial filaments were used to fabricate the PHE model and validate its suitability as a functional heat exchanger unit: Bronze-filled Heat-Treatable Polylactic Acid (Bronze-filled HTPLA), Standard Polylactic Acid (Standard PLA), and Flexible Thermoplastic Polyurethane (TPU). Table 1 shows the main characteristics of the commercial filaments.

Table 1. Main characteristics of the commercial filaments for printing plate heat exchanger

Filament	Standard PLA	Bronze-Filled HTPLA	TPU
Supplier	Bambu Lab	Proto pasta	Foamy
Melting temperature, ºC	163	155	183
Softening temperature, ºC	55	55	115
Density, g/cm^3	1.31	2.50	1.20
Thermal conductivity, W/m·ºC	0.13–0.16	5.70	–
Thermal capacity, kJ/kg·ºC	1.18–1.21	0.71	–

The bronze-filled HTPLA filament (Proto-pasta, USA) was used for the heat-conducting plates. According to specifications, this filament contains 60–80% bronze by weight, which significantly increases the printed plate’s density compared to common filaments. Standard PLA (Bambu Lab, China) was mainly used for screws and nuts, as well as for plates. The plates printed with standard PLA ensure the replicability of PHE, providing a low-cost alternative if metal-composite filaments are unavailable. TPU filament (Foamy, Spain) was used for the gaskets, ensuring a leak-proof assembly under mechanical compression.

Printing parameters were adjusted according to the manufacturer’s specifications for each material. This point usually means only a correct material selection in the Bambu Studio software, displayed in a standard printer profile of 0.2 mm. This layer height was preferred to balance surface finish and printing time. Bronze-filled HTPLA filament requires some very specific printing settings. They need a flow rate (extrusion multiplier) of 2.5 g/cm^3 and a recommended printing speed of 20–80 mm/s. All the PHE components were printed with 100% infill to ensure structural integrity during experimental runs.

2.3 Fabrication and assembly process

PHE fabrication was carried out without printing supports. This point means that heat-conducting plates, flexible gaskets, and the structural screws and nuts were oriented flat on the 3D printer bed. This approach minimises material waste and ensures maximum surface smoothness at the heat-exchange interfaces, without the need for any post-processing. The dimensions and internal geometry of the plates are detailed in Figure 1. The modular design of the PHE allowed the assembly of three different experimental configurations for experimental validation. Table 2 shows the unit configurations for each printed PHE.

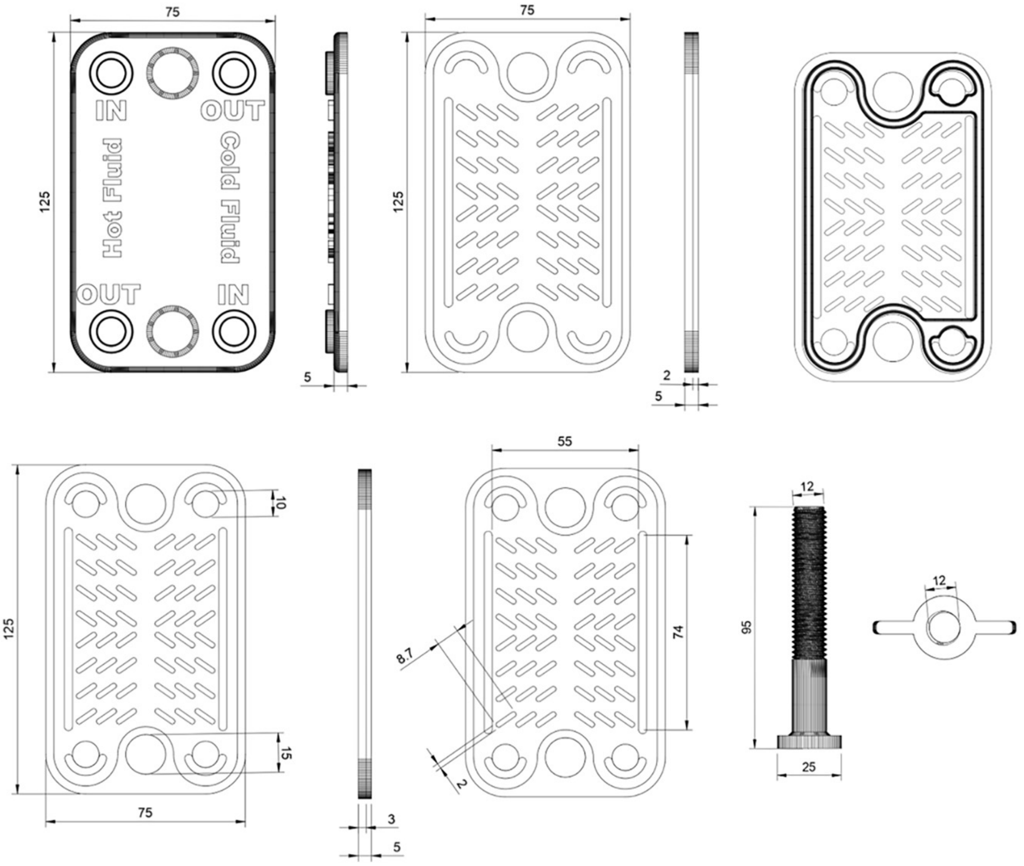

Fig. 1. Dimensions and internal geometry of the plates, gasket, screws, and nuts of the plate heat exchanger [40]

Notes: Original work in Fusion 360 software. Scales in millimetres (mm).

Table 2. Plate heat exchanger configuration based on the used materials for fabrication

PHE Component	1. Standard PLA	2. Bronze-Composite	3. Thin-Plates PLA
Front Plate	PLA	PLA	PLA
End Plate	PLA	PLA	PLA
Internal plates	PLA	Bronze-filled HTPLA	PLA
Gaskets	TPU	TPU	TPU
Screws	PLA	PLA	PLA
Nuts	PLA	PLA	PLA

Notes: PLA: Polylactic Acid; TPU: Flexible Thermoplastic Polyurethane; HTPLA: Heat-Treatable polylactic acid.

The difference between Standard PLA (1) and Bronze-composite (2) PHE consisted in the use of different materials for the internal plates, with the aim of improving heat transfer. Regarding the thin-plates PLA (3) PHE, the main difference from the other PHEs is geometric optimisation testing with six plates of half thickness (1.5 mm instead of 3.0 mm), aimed at reducing the thermal resistance of PLA by thinning the walls.

The assembly was analogous to an industrial PHE, following a sequential 'sandwich' structure: Front plate; Gasket; Internal plate; Gasket; (repeat internal structure twice); End Plate. Internal plates and the End plate had baffles (2 mm deep) to promote turbulence and increase fluid residence time (see Figure 1). The structural integrity and fluid-tightness of the stack were achieved by mechanical compression provided by two screws bolts and wing nuts (see Figure 1). Nuts were designed for manual tightening, allowing the user to adjust sealing pressure without external tools. Finally, connections to the external fluid circuit (hot and cold water) were made via the ports on the front plate using common silicone tubing sized to the port diameter. Figure 2 shows three PHEs assembled.

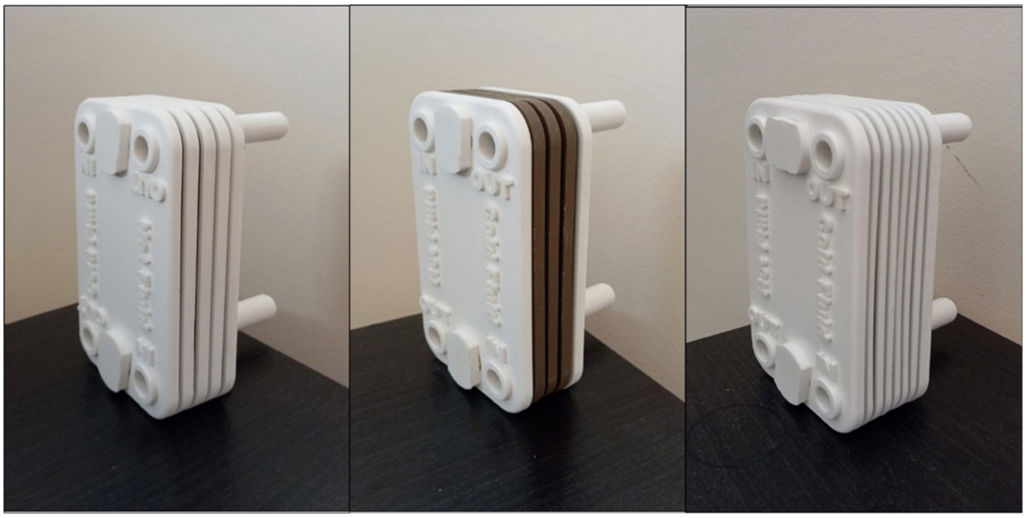

Fig. 2. Final assembly of the three experimental plate heat exchanger configurations

Note: From left to right: (1) Standard PLA, (2) Bronze composite, and (3) Thin-plate PLA.

2.4 Experimental setup and validation

For the experimental validation of PHE, it is not necessary to have a specific setup; only a supply of hot and cold water is required. In this sense, the experimental setup we used was a resourceful adaptation of a legacy industrial-scale shell-and-tube heat exchanger pilot plant. Thus, our setup was designed with a low-cost philosophy, leveraging and adapting the existing infrastructure in the University of La Laguna's Chemical Engineering experimental facilities.

The hot fluid (water at 60ºC) was heated using a commercial propane-heated unit integrated into the main laboratory facility. The cold fluid (water at room temperature ~20ºC) was supplied from a storage tank and driven by a centrifugal pump. The experimental setup was configured so that hot and cold water were discarded after passing through the 3D-printed PHE. Before each experiment, a leak test was carried out using water at room temperature. Elastic deformation of TPU gaskets provided sealing under manual torque, validating the 'all-3D-printed' PHE fabrication.

After the leak test, fluids were changed to hot (60ºC) and cold water (20ºC) and run for 70 minutes. The experiment's runtime was sufficient to reach thermal steady-state. During the experiment, process variables (i.e., outlet and inlet temperatures and flow rates) were monitored manually to enhance student engagement and emphasize the pedagogical strategy of the setup. The temperature of each water stream was monitored by sampling every 10 minutes and using the temperature sensor of a portable DMA 35 Basic (Anton Paar, Austria) densimeter. A traditional analog thermometer is also valid for this purpose. Flow rates were monitored at three different times (10, 30, and 55 minutes). They were measured with a graduated cylinder and a stopwatch to ensure steady-state conditions during the experimental run.

To evaluate the thermal performance, the heat duty (Q), logarithmic mean temperature difference (ΔT_{LMTD}), and the global heat transfer coefficient (U) were determined for each PHE configuration (Table 2). The Q (W) was calculated for both fluids according to the following energy balance equation [Eq. 1]:

$$Q = \dot{m} \cdot C_p \cdot (T_{outlet} - T_{inlet}) \quad [1]$$

where $\dot{m}$ is the mass flow rate (kg/s), C_p is the specific heat capacity of water at the average bulk temperature (J/Kg·ºC) and $T_{inlet/outlet}$ is the temperature (ºC) of the inlet/outlet of cold water. From the steady-state temperature of both fluids, it is possible to calculate ΔT_{LMTD} [Eq. 2], which represents the effective driving force for heat transfer in the unit:

$$\Delta T_{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \quad [2]$$

where T_h and T_c mean the temperature (ºC) of hot and cold water in the inlet or outlet of the unit, as appropriate. Finally, U (W/m^2·ºC) was calculated by rearranging the general heat transfer equation [Eq. 3]:

$$U = \frac{Q}{A \cdot \Delta T_{LMTD}} \quad [3]$$

where A (m^2) means the total effective heat transfer area. The area per plate was determined by Fusion 360, resulting in $3.235 \cdot 10^{-3}$ m^2. The total area was adjusted to account for the use of three (1 and 2) or six internal plates (3).

3 RESULTS AND DISCUSSION

This section presents the results of the technical validation, an economic analysis of the unit, and a description of the main educational competencies implied in this learning process.

3.1 Technical validation and thermal performance

The experimental data collected during technical validation are shown in Figure 3, where the transition from the transient heating phase to the steady state is clearly visible for all the configurations.

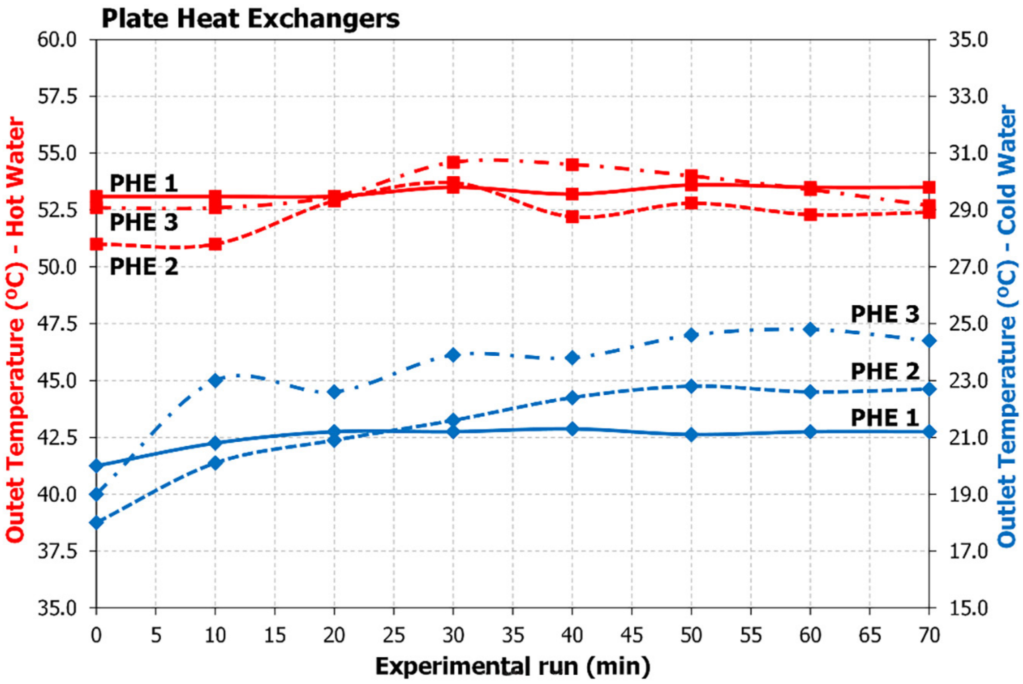

Fig. 3. Thermal evolution of the three units during the experimental run. PHE 1 (Standard PLA); PHE 2 (Bronze-composite); PHE 3 (Thin PLA)

As shown, all tested configurations consistently reached steady state within 20–30 minutes of running. In Experiment 1 (Standard PLA), the outlet temperatures got stabilised around 21.2ºC for the cold water and 53.4ºC for the hot water. Experiment 2 (Bronze composite plates) showed a similar behavioural pattern, although it reached a higher temperature (22.7ºC). Finally, Experiment 3 achieved the most significant heat exchange, with a cold-water temperature of 24.4 C. This fact confirms that 70-minute experimental runs are appropriate for experimental replicability in student lab practice planning. The mass flow rates of both fluids fluctuated slightly across all experiments, from 13.5 to 15.5 · 10^{-3} kg/s, with no significant changes. After steady state was reached in each experiment, Heat Duty (Q), Logarithmic Mean Temperature Difference (ΔT_{LMTD}), and Global Heat Transfer Coefficient (U) were calculated. Table 3 shows data on these parameters to evaluate the thermal performance.

Table 3. Heat duty, logarithmic mean temperature difference, and global heat transfer coefficient for all three PHE tested configurations

PHE Configuration	1. Standard PLA	2. Bronze-Composite	3. Thin-Plates PLA
Heat duty, W	65.3	320.7	302.9
Logarithmic Mean Temperature Difference, ºC	34.6	34.4	33.1
Global Heat Transfer Coefficient, W/m^{2}·ºC	194.3	962.0	470.9

A comparative analysis of the U coefficient and the total heat exchanged (Q) provides significant findings related to the tested different configurations (refer to Table 2). First, the Standard PLA configuration serves as a baseline (Experiment 1), with the lowest values for Q and U coefficients. However, when internal plates were replaced with the bronze-composite filament plates (Experiment 2), both parameters significantly increased, reaching a Q of 320.7 W and a U value of 962 W/m^{2}·ºC. This fact means a clear improvement (up to 400%) of heat exchange efficiency, highlighting the significant impact of metal-composite on the thermal conductivity of the polymer matrix. In addition, when standard PLA plates were replaced with 'Thin plates' (Experiment 3) as an alternative in case metal-composite filaments were unavailable, a significant change in thermal performance was also observed. Thus, by doubling the number of plates (from three to six) and halving their thickness to 1.5 mm, the PHE configuration showed a Q of 302.9 W and a U-value of 470.9 W/m^{2}·ºC. These results make sense because PLA filament has lower conductivity. Overall, these results suggest that these PHE 3D-printed models are technically valid and suitable for educational purposes.

3.2 The low-cost paradigm: economic viability vs. Experimental precision

The fabrication of these 3D-printed PHE models addresses the high cost of commercial educational units by offering a high cost-benefit ratio. Table 4 shows the approximate manufacturing cost and printing required time for each unit.

While commercial laboratory-scale PHE cost several hundred to thousands of euros, these functional prototypes cost less than 40 € each in the worst-case scenario. This means using the bronze composite, which is the most expensive filament (~ 130–140 €/kg). Other filaments (PLA and TPU) cost between 35 and 40 €/kg. The printing time is also plausible, ranging from 8 to 11 hours per unit. This printing time estimation was calculated assuming each unit is printed separately, component by component. Possible combinations of different PHE components can be combined to optimise printing time.

Table 4. Cost and print-time estimation for PHE configurations

PHE Component	1.Standard PLA Print-Time (Min)/Cost (€)		2. Bronze-Composite Print-Time (Min)/Cost (€)		3. Thin-Plates PLA Print-Time (Min)/Cost (€)	
Front Plate (1 unit)	70	1.4	70	1.4	70	1.4
End Plate (1 unit)	59	1.0	59	1.0	59	1.0
Internal plates (total)	165	3.0	330	31.0	180	2.0
Gaskets (total)	70	1.2	70	1.2	123	2.1
Screws (2 units)	70	0.9	70	0.9	70	0.9
Nuts (2 units)	34	0.4	34	0.4	34	0.4
TOTAL (per unit)	**< 8.0 h**	**< 8.0 €**	**< 11.0 h**	**~ 36.0 €**	**< 9.0 h**	**< 8.0 €**

Note: Original work using Bambu Studio software.

From a strictly scientific point of view, this low-cost approach has to be accompanied with by a critical evaluation of experimental precision. In this sense, it is true that energy balances do not close perfectly, with an average deviation of up to 10–15% between the heat transfer from hot water and the heat gained by the cold water. These differences, although easily improved, may be attributed to a lack of thermal insulation on the plastic frames and the manual measurement techniques for temperature and flow rate. Nevertheless, to the best of our knowledge, these deviations offer valuable teaching opportunities by forcing students to understand the limitations of real-world instrumentation. Indeed, the Bronze-composite configuration showed a significant U global coefficient, validating these prototypes as suitable educational units for engineering students, which is the most important aim of this study.

3.3 Development of engineering competences

The implementation of this 3D-printed PHE student-led project, in the context of a bachelor's thesis or laboratory practices, has been validated as a robust bridge for the development and acquisition of specific and transversal competences. In this sense, this project addresses some core principles of heat transfer and applied thermodynamics. Moreover, it is necessary to consider the challenges students face when applying these concepts to solve engineering problems, achieving a level of versatility and adaptability similar to that in the industrial world. A thorough analysis of key competencies expected to be developed in the project is as follows:

1. Problem-Solving and Creativity: The students are not just following a laboratory manual. They need to make critical decisions regarding material selection during printing. Also, it is not necessary to have a specific experimental setup. It should be enough to adapt an existing hot water installation. This point demands a high level of initiative and creative reasoning.
2. Data Interpretation and Critical Thinking: Manual instrumentation (volumetric method and thermometers) supports the student's understanding of experimental uncertainty. The comparison of 'black box' models with real-world deviations observed during the experimental validation promotes professional judgement.
3. Engagement with Cutting-Edge Technology: Integrating AM into ChE education aligns with current professional trends. The students demonstrate the ability to link theoretical concepts with modern technology in their field by printing and testing complex heat-exchange surfaces in materials such as metal-composite filaments.
4. Autonomy and Communication: This project-led requires a high degree of learning autonomy. From the digital slicing of models to the final synthesis of experimental results. It serves as a simulation of a problem they might face in their professional careers. Thus, this learning process prepares students for professional environments where they must transmit complex solutions to both specialised and non-specialised audiences.

4 CONCLUSIONS

In this study, a low-cost 3D-printed Plate Heat Exchanger (PHE) for educational purposes was fabricated and validated. Additive manufacturing of the prototypes was carried out on a commercial FDM 3D printer, using polylactic acid (PLA) and metal-composite filaments (bronze) for rigid components and thermoplastic polyurethane (TPU) for flexible components. The experimental validation was performed in a simple heat-exchange experiment using water. Our results demonstrated the technical feasibility of the 3D-printed PHE, reaching steady state within 20–40 minutes, which is compatible with standard laboratory sessions (3–5 hours). The use of metal-composite filaments provides a remarkable global heat transfer coefficient of up to 962 W/m^2·°C. Moreover, optimizing PHE plates to a thinner thickness also yields a plausible PHE with a similar total heat duty (303 W). Beyond technical viability, the remarkably low cost per unit (10–40 €) supports the democratization of laboratory experience in engineering, promoting the acquisition of core engineering competencies such as critical data interpretation and creative problem-solving. In this regard, experimental teaching has always had to struggle with the high costs of prefabricated educational equipment. This study is an example of how new technologies have arrived to change this paradigm for the better, providing a way to transform students from passive observers into proactive engineers through affordable, high-performance, and custom-made experimental setups.

5 REFERENCES

[1] B. Lopez, Y. Shao, and V. M. Zavala, "A graph-theoretic framework for analyzing and designing chemical engineering curricula," *Computers & Chemical Engineering*, vol. 200, p. 109150, 2025. https://doi.org/10.1016/j.compchemeng.2025.109150

[2] R. S. Voronov, S. Basuray, G. Obuskovic, L. Simon, R. B. Barat, and E. Bilgili, "Statistical analysis of undergraduate chemical engineering curricula of United States of America universities: Trends and observations," *Education for Chemical Engineers*, vol. 20, pp. 1–10, 2017. https://doi.org/10.1016/j.ece.2017.04.002

[3] D. Gürdür Broo, O. Kaynak, and S. M. Sait, "Rethinking engineering education at the age of Industry 5.0," *Journal of Industrial Information Integration*, vol. 25, p. 100311, 2022. https://doi.org/10.1016/j.jii.2021.100311

[4] R. M. Felder, "Teaching engineering at a research university. Problems and possibilities," *Educación Química*, vol. 15, no. 1, p. 40, 2018. https://doi.org/10.22201/fq.18708404e.2004.1.66214

[5] M. Valero, "Challenges, difficulties and barriers for engineering higher education," *Journal of Technology and Science Education*, vol. 12, no. 3, pp. 551–566, 2022. https://doi.org/10.3926/jotse.1696

[6] K. Achuthan and S. S. Murali, "A comparative study of educational laboratories from cost & learning effectiveness perspective," in *Software Engineering in Intelligent Systems*, R. Silhavy, R. Senkerik, Z. K. Oplatkova, Z. Prokopova, and P. Silhavy, Eds., Cham: Springer International Publishing, 2015, pp. 143–153. https://doi.org/10.1007/978-3-319-18473-9_15

[7] A. Hofstein and V. N. Lunetta, "The laboratory in science education: Foundations for the twenty-first century," *Science Education*, vol. 88, no. 1, pp. 28–54, 2004. https://doi.org/10.1002/sce.10106

[8] S. Freeman *et al.*, "Active learning increases student performance in science, engineering, and mathematics," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 111, no. 23, pp. 8410–8415, 2014. https://doi.org/10.1073/pnas.1319030111

[9] R. J. Giles, "The evolution of a campus chemical and laboratory equipment recycling program," *J. Chem. Health Saf.*, vol. 17, no. 6, pp. 20–28, 2010. https://doi.org/10.1016/j.jchas.2010.02.003

[10] N. N. Nassar and A. K. Mehrotra, "Design of a laboratory experiment on heat transfer in an agitated vessel," *Education for Chemical Engineers*, vol. 6, no. 3, pp. e83–e89, 2011. https://doi.org/10.1016/j.ece.2011.06.001

[11] A. K. Mehrotra, N. N. Nassar, and A. S. Kasumu, “A novel laboratory experiment for demonstrating boiling heat transfer,” *Education for Chemical Engineers*, vol. 7, no. 4, pp. e210–e218, 2012. https://doi.org/10.1016/j.ece.2012.09.003

[12] L. Kavanagh and C. Crosthwaite, “Triple-objective team mentoring: Achieving learning objectives with chemical engineering students,” *Education for Chemical Engineers*, vol. 2, no. 1, pp. 68–79, 2007. https://doi.org/10.1205/ece06027

[13] C. Schnittka, R. Bell, and L. Richards, “Save the Penguins: Teaching the science of heat transfer through engineering design,” *Science Scope*, vol. 34, no. 3, pp. 82–89, 1991.

[14] N. A. N. Mohamed Nazim, S. Y. Seah, M. Z. Jumat, Y. B. Low, B. J. R. Thio, and S. Y. Wong, “Design and implementation of a portable heat exchanger kit in an undergraduate engineering heat and mass transfer course,” *Education for Chemical Engineers*, vol. 45, pp. 130–140, 2023. https://doi.org/10.1016/j.ece.2023.09.002

[15] I. Fidan *et al.*, “Recent inventions in additive manufacturing: Holistic review,” *Inventions*, vol. 8, no. 4, p. 103, 2023. https://doi.org/10.3390/inventions8040103

[16] J. Pernaa and S. Wiedmer, “A systematic review of 3D printing in chemistry education – analysis of earlier research and educational use through technological pedagogical content knowledge framework,” *Chemistry Teacher International*, vol. 2, no. 2, 2020. https://doi.org/10.1515/cti-2019-0005

[17] L. A. Trujillo-Cayado, J. Santos, F. Cordobés, and M. Ramos-Payán, “Influence of the use of 3D printing technology for teaching chemistry in STEM disciplines,” *Computer Applications in Engineering Education*, vol. 32, no. 4, p. e22738, 2024. https://doi.org/10.1002/cae.22738

[18] M. Renner and A. Griesbeck, “Think and print: 3D printing of chemical experiments,” *J. Chem. Educ*., vol. 97, no. 10, pp. 3683–3689, 2020. https://doi.org/10.1021/acs.jchemed.0c00416

[19] S. Ford and T. Minshall, “Invited review article: Where and how 3D printing is used in teaching and education,” *Additive Manufacturing*, vol. 25, pp. 131–150, 2019. https://doi.org/10.1016/j.addma.2018.10.028

[20] I. D. Amores, J. González-Gutiérrez, I. M. García, J. M. Franco, and C. Gallegos, “3D printing – present and future – A chemical engineering perspective,” *Chemical Engineering Research and Design*, vol. 187, pp. 598–610, 2022. https://doi.org/10.1016/j.cherd.2022.08.049

[21] J. M. Pearce, “Building research equipment with free, open-source hardware,” *Science*, vol. 337, no. 6100, pp. 1303–1304, 2012. https://doi.org/10.1126/science.1228183

[22] S. Chong *et al.*, “Integration of 3D printing and Industry 4.0 into engineering teaching,” *Sustainability*, vol. 10, no. 11, p. 3960, 2018. https://doi.org/10.3390/su10113960

[23] C. Parra-Cabrera, C. Achille, S. Kuhn, and R. Ameloot, “3D printing in chemical engineering and catalytic technology: Structured catalysts, mixers and reactors,” *Chem. Soc. Rev*., vol. 47, no. 1, pp. 209–230, 2018. https://doi.org/10.1039/C7CS00631D

[24] Y. Ibrahim and R. Kempers, “Effective thermal conductivity of 3D-printed continuous wire polymer composites,” *Prog. Addit. Manuf.*, vol. 7, no. 4, pp. 699–712, 2022. https://doi.org/10.1007/s40964-021-00256-5

[25] M. Doshi, A. Mahale, S. Kumar Singh, and S. Deshmukh, “Printing parameters and materials affecting mechanical properties of FDM-3D printed parts: Perspective and prospects,” *Materials Today: Proceedings*, vol. 50, pp. 2269–2275, 2022. https://doi.org/10.1016/j.matpr.2021.10.003

[26] M. Larriba *et al.*, “Lab at home: 3D printed and low-cost experiments for thermal engineering and separation processes in COVID-19 time,” *Education for Chemical Engineers*, vol. 36, pp. 24–38, 2021. https://doi.org/10.1016/j.ece.2021.02.001

[27] M. T. Munir, P. K. Jamwal, B. Li, S. Carter, and S. Hussain, “Revolutionising engineering pedagogy: The role of 3D printing in modern engineering education,” *Innovations in Education and Teaching International*, vol. 62, no. 2, pp. 575–593, 2025. https://doi.org/10.1080/14703297.2024.2346554

[28] A. S. Ullah *et al.*, "Tutorials for integrating 3D printing in engineering curricula," *Education Sciences*, vol. 10, no. 8, p. 194, 2020. https://doi.org/10.3390/educsci10080194

[29] T. Tabassum *et al.*, "Development and application of 3D printed mesoreactors in chemical engineering education," *J. Chem. Educ.*, vol. 95, no. 5, pp. 783–790, 2018. https://doi.org/10.1021/acs.jchemed.7b00663

[30] J. Bi *et al.*, "Experimental study on thermal–hydraulic performance of a nature-inspired mini-channel heat exchanger manufactured by 3D printing," *Applied Thermal Engineering*, vol. 257, p. 124309, 2024. https://doi.org/10.1016/j.applthermaleng.2024.124309

[31] M. Strobel and M. V. V. Mortean, "Pressure drop and fluid maldistribution analysis of a compact heat exchanger manufactured by 3D printing," *International Journal of Thermal Sciences*, vol. 172, p. 107331, 2022. https://doi.org/10.1016/j.ijthermalsci.2021.107331

[32] T. Dixit, E. Al-Hajri, M. C. Paul, P. Nithiarasu, and S. Kumar, "High performance, micro-architected, compact heat exchanger enabled by 3D printing," *Applied Thermal Engineering*, vol. 210, p. 118339, 2022. https://doi.org/10.1016/j.applthermaleng.2022.118339

[33] B. Anwajler, "Potential of 3D printing for heat exchanger heat transfer optimization—sustainability perspective," *Inventions*, vol. 9, no. 3, p. 60, 2024. https://doi.org/10.3390/inventions9030060

[34] M. Kruzel, T. Bohdal, K. Dutkowski, M. Kruzel, T. Bohdal, and K. Dutkowski, "Heat transfer enhancement in a 3D-printed compact heat exchanger," *Energies*, vol. 17, no. 18, p. 4754, 2024. https://doi.org/10.3390/en17184754

[35] Thingiverse.com, "Thingiverse – digital designs for physical objects." Accessed: Jan. 14, 2026. [Online]. Available: https://www.thingiverse.com

[36] Printables.com, "Base de datos de modelos 3D." Accessed: Jan. 14, 2026. [Online]. Available: https://www.printables.com/

[37] Cults 3D, "Cults · Descarga gratis modelos de impresoras 3D · STL, OBJ, 3MF, CAD." Accessed: Jan. 14, 2026. [Online]. Available: https://cults3d.com/es

[38] Thingiverse.com, "heat exchanger V2 by akajes." Accessed: Jan. 14, 2026. [Online]. Available: https://www.thingiverse.com/thing:1917929

[39] Cults 3D, "Heat exchanger spiral for water or air high efficiency." Accessed: Jan. 14, 2026. [Online]. Available: https://cults3d.com/en/3d-model/tool/heat-exchanger-spiral

[40] Thingiverse.com, "Plate type heat exchanger by DukeONS." Accessed: Jan. 14, 2026. [Online]. Available: https://www.thingiverse.com/thing:3420480

6 AUTHORS

Héctor de Paz Carmona is an Assistant Professor in the Departamento de Ingeniería Química (Facultad de Ciencias, sección de Química) at the Universidad de La Laguna. He obtained his MSc (Chemical Engineering) in 2012 and his PhD in 2017 at the same university. His research interests are focused on developing new catalytic materials and biofuels. As a result of his research work over the past few years (2018–2022), he has published 32 research articles in high-impact factor journals, three patents, and six utility models. He has participated in numerous international/national conferences (>20) and is a regular reviewer for multiple journals in his field. In addition to his research activities, H. Carmona also teaches in the Chemical Engineering degree at Universidad de La Laguna, covering subjects related to the Chemical Industry, Food Engineering, and Thermodynamics (E-mail: hpazcarm@ull.edu.es).

Rubén Díaz López is a Chemical Engineer with specialised training through an international master's in technology and management for Circular Economy across institutions such as UCT Prague, the University of Oviedo, and Åbo Akademi University.

His academic and professional background includes international experience in Slovenia and the Czech Republic, as well as contributions to EU sustainability initiatives, such as the DeliSoil project. His research interests focus on integrating circular economy principles and advanced technologies, including 3D printing (E-mail: rubeniqpr@gmail.com).

Óscar García-Afonso is a Senior Lecturer in the Departamento de Ingeniería Industrial (Escuela Superior de Ingeniería y Tecnología – ESIT) at the Universidad de La Laguna. He obtained his MSc (Internal Combustion Engines) in 2011 and the PhD degree in 2013 from Universidad Politécnica de Valencia. After completing his PhD, he joined the powertrain department at Jaguar Land Rover Ltd in 2014, working until 2019. In that year, he joined the Industrial Engineering Department at Universidad de La Laguna as a lecturer in the area of applied thermodynamics and thermal engines. O. Garcia is co-author of 28 research papers published in top-quality journals. Also, he is co-inventor of one active patent, developed in the industry environment and related to waste heat recovery in internal combustion engines. O. Garcia has also collaborated as a researcher in several research projects, contracts and collaborations in the topic of after-treatment systems for internal combustion engines, energy planning and energy consumption in transportation (E-mail: ogarciaa@ull.edu.es).