

EDUCATIONAL INNOVATION IN BUILDING ENGINEERING THROUGH EXPERIENTIAL LEARNING OF FLUID THERMODYNAMICS

RAÚL BRIONES LLORENTE
Universidad de Burgos, Spain

MOHAMED LIFI
Universidad de Burgos, Spain

NATALIA MUÑOZ-RUJAS
Universidad de Burgos, Spain

JESÚS ÁNGEL MARTIN-GONZÁLEZ
Universidad de Burgos, Spain

FERNANDO AGUILAR ROMERO
Universidad de Burgos, Spain

EDUARDO A. MONTERO
Universidad de Burgos, Spain

ABSTRACT

In the face of climate change and the 2030 Agenda's Sustainable Development Goals, the building sector is critical, accounting for 36% of CO₂ emissions in the European Union. To transform this model, higher education must equip future engineers and architects with robust skills in energy efficiency and thermodynamics.

In this context, the Teaching Innovation Group of the Universidad de Burgos has developed a multilingual (Spanish, English, and French) open educational resource focused on active learning of the thermal equation of state of fluids. Through laboratory experimentation, students analyse pressure-volume-temperature (PVT) relationships and fluid behaviour across various thermodynamic regions. This methodology, successfully implemented in

Spanish and Moroccan universities, strengthens the conceptual understanding required to optimize energy performance in residential and industrial thermal systems, promoting more sustainable engineering practices.

KEYWORDS

Thermal equation of state, energy efficiency, active learning, sustainability.

INTRODUCTION

One of the greatest challenges facing contemporary society is climate change and its associated consequences, such as an increase in extreme weather events, the advancement of desertification, and the rise in diseases related to air quality (Diaz, Md, Mph-Tm, Drph, J. H., 2007). They all also have high economic costs due to the need to replace damaged infrastructure, reinforce existing infrastructure, and on the other hand, higher medical expenses due to the pathologies generated (Desmet, K., Rossi-Hansberg, E., 2024).

These issues are closely linked to greenhouse gas emissions, which have driven the development of policies and strategies aimed at both mitigation and adaptation across different productive sectors (Bilgili, M., Tumse, S., Nar, S., 2024). In this context, the 17 Sustainable Development Goals of the 2030 Agenda (United Nations. Department of Economic and Social Affairs, 2015) constitute a key reference framework for promoting more sustainable development models.

The building sector plays a particularly significant role in this challenge, as it is responsible for approximately 36 % of CO₂ emissions and 40 % of primary energy consumption in the European Union (European Council. Council of the European Union, 2023). This highlights the need to improve building design, management, and energy efficiency, both in terms of the thermal

envelope and active systems for heating, cooling, and energy production. All of this is aligned with one or more of the 17 SDGs, such as: (Goal 7) Ensure access to affordable, reliable, sustainable and modern energy for all, (Goal 11) Make cities and human settlements inclusive, safe, resilient and sustainable, and (Goal 13) Take urgent action to combat climate change and its impacts.

In this scenario, higher education emerges as a fundamental tool for advancing a more sustainable building sector. It is essential that future Building Engineers, Architects, and Industry Engineers acquire a solid background in sustainability principles, energy efficiency, and the thermal behaviour of systems, with particular emphasis on understanding the thermodynamic properties of the fluids used in building services (Lange Salvia, A., Londero Brandli, L., Leal Filho, W., Gasparetto Rebelatto, B., Reginatto, G., 2020).

In this framework, this work presents the contribution developed by the Teaching Innovation Group of the Universidad de Burgos on Active Learning and e-Learning in Engineering, materialized in an experimental open educational resource for learning the thermal equation of state of fluids. The resource consists on a website, entitled “From the laboratory to the open digital resources in energy engineering” (<https://www.ubu.es/laboratory-open-digital-resources-energy-engineering>, 2021), and also in an electronic book (Montero García, E., Muñoz Rujas, N., Rubio Pérez, G., Lifi, M., M’hamdi Alaoui, F. E., 2021). and available in Spanish, English, and French, proposes an active learning methodology based on experimentation using laboratory equipment to obtain pressure-volume-temperature (PVT) relationships. Through this approach, students analyse fluid behaviour in different thermodynamic regions, such as superheated vapor, liquid–vapor equilibrium,

saturated liquid, and compressed liquid, as well as the identification of saturation lines and the critical point.

This teaching material is used in engineering-related degree programs at both Spanish and Moroccan Universities within the framework of an international cooperation project aimed at creating open educational resources and is expected to be implemented in building engineering and civil engineering degrees at the same Universities. Given that these university degrees fall within the STEAM field (Science, Technology, Engineering and Mathematics), and in many cases, with a low presence of women studying them, this work is a useful tool to meet some of the 17 SDGs in this regard: (Goal 4) Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all, (Goal 5) Achieve gender equality and empower all women and girls, and (Goal 17) Strengthen the means of implementation and revitalize the global partnership for sustainable development.

The experience shows that the use of experimental and multilingual methodologies enhances the understanding of fundamental thermodynamic concepts and their subsequent application to the analysis and improvement of the energy performance of thermal systems in residential, tertiary, and industrial buildings.

1. METHODOLOGY

The e-book referenced in this work gathers the implementation of a laboratory practice in which the interdependence between the properties pressure, volume, and temperature in fluids is studied. The processes studied in the practice are of utmost interest to any engineering and building degree, since they underlie the thermodynamic behaviour of gases and liquids, that are often used in machines and industry processes. One of the

most interesting applications of fluids to which the knowledge acquired in this practice is important is the use of cooling (or heating) fluids in air conditioning and aerothermal. These fluids undergo phase change from liquid to gas and vice-versa during the working cycle, being this phase change a result of the changes in pressure, volume and temperature experienced by the fluid, in order to achieve the desired result: to heat or to cool the building. Then, the main knowledge acquired by the students with this practice is:

1. The mutual dependence in the state variables, pressure, volume and temperature (P-V-T) for a fluid contained in a variable volume when pressure and temperature are modified.
2. The distinction of the fluid properties in the different operating regions.
3. The obtention of the vaporization curve (P-T), as well as the (P-V) diagram for a fluid.

The practice apparatus consists of a graduated tube that contains a fluid (initially in gas state), with which the experiment will be conducted. The experimental set up can be seen in Figure 1.

The volume of the gas contained in the tube can be controlled by moving upwards the mercury column operating on a rotating wheel. Thus, the volume (V) can be measured in the graduated column. The maximum volume value reaches 4 cubic centimetres. Pressure (P) is obtained by means of a manometer. When the volume of the fluid in the graduated tube is changed, the pressure value changes. Finally, temperature (T) is measured indirectly by a thermometer located in a thermostatic bath. The water contained in the bath is heated, and it is pumped to a concentric tube that contains the graduated tube with the fluid. Applying the temperature equilibrium criterion, the temperature

of the gas contained in the graduated tube is assumed to be the same of that of the heated water.

Maintaining the temperature constant and changing the volume of the fluid inside the graduated tube, a value of pressure is obtained. To obtain an isotherm, this process should be repeated by changing the volume several times. Increasing the temperature of the water, another set of P-V values is obtained. These P-V-T sets, when plotted in a P-V diagram, allow to obtain the saturation curve of the fluid, with the saturated liquid and saturated gas lines, superheated gas region, subcooled liquid region, and also the critical point. A representation of the P-V diagram with the different regions is shown in Figure 2.

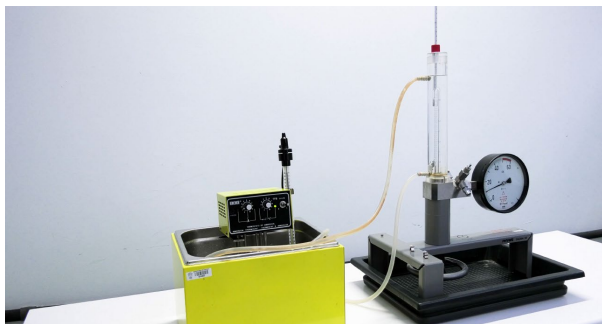


Figure 1: Experimental set-up

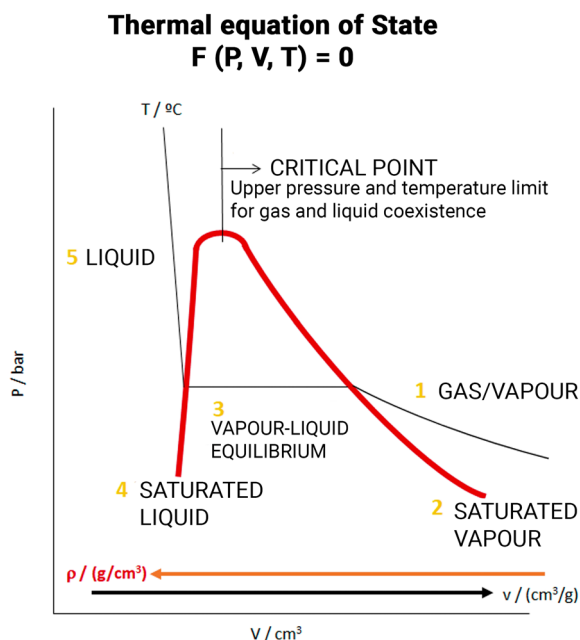


Figure 2: Representation of the P-V diagram with the different regions

The gas confined in the graduated tube is, in the case of the practice, Sulphur hexafluoride (SF_6). One of the applications of this fluid was as insulation in electric distribution systems, and as to lesser extent as cooling fluid. Nevertheless, its high Greenhouse Warning Potential (GWP) of 23500, drove it to be removed to its use in the industry several years ago, at expense of the (Montreal Protocol (1987)) and (Kyoto Protocol (1997)). It has to be noted that the fluid contained in the graduated tube can be removed and replaced, then it is possible to change this high GWP fluid by another one with better environmental properties. What has to be considered is that, when changing the fluid, the phase change will take place at different pressures, temperatures and volumes. This is of interest because it allows to obtain different P-V-T diagrams in order to compare them, and to better understand the behaviour of fluids.

Focusing in the possible environmentally friendly options of fluids that can be used as refrigerants in cooling machines and in aerothermal, and that can be considered as a replacement in the practice for the SF₆, some hydrofluorocarbons (HFCs) and hydrocarbons (HCs) could be the best options. Some that can serve as an example are shown in Table I.

Table 1. Different refrigerants that can be used in the practice, according to its GWP

TYPE OF REFRIGERANT	REFRIGERANT	GWP
HFC	R-32	675
	RS-90	2481
Hydrocarbons	R-717	0
	R-290	0
	R-600	0
	R-744	0

As gathered in the (Regulation (EU) 2024/573 of the European Parliament and of the Council of 7 February 2024 on fluorinated greenhouse gases), the options that can be seen in Table I. have a GWP that meet the current European regulations. Moreover, taking into account the Spanish regulations, the Royal Decree Law 20/2018, of 7 September, of urgent actions for the impulse of the economic competitiveness in the industry and in the trade sector in Spain (Real Decreto-Ley 20/2018, de 7 de septiembre, sobre medidas urgentes para el impulso de la competitividad económica en el sector de la industria y el comercio en España), urges to use the abovementioned refrigerants in new installations, as well as a replacement for those refrigerants that doesn't meet the current environmental requirements in older installations.

Considering the working pressures of the apparatus (from 0.1 to 50 bar), the selected option for the replacement is R-744 (carbon

dioxide), with a GWP = 0. This fluid also allows to visualize the critical point during the practice, as happens with SF₆.

The practice was carried out with industry engineering students of two different degrees (Electronics and Automation Engineering and Organization Engineering) for several academic years using SF₆ as working fluid. Two different approaches, on site (before and after COVID-19 pandemic) and out of laboratory (during COVID-19 pandemic). The two methodologies were explained in (Muñoz-Rujas, N., Rubio-Pérez, G., Briones-Llorente, R., Lifi, M., Aguilar, F., Montero, E. A., (2022))

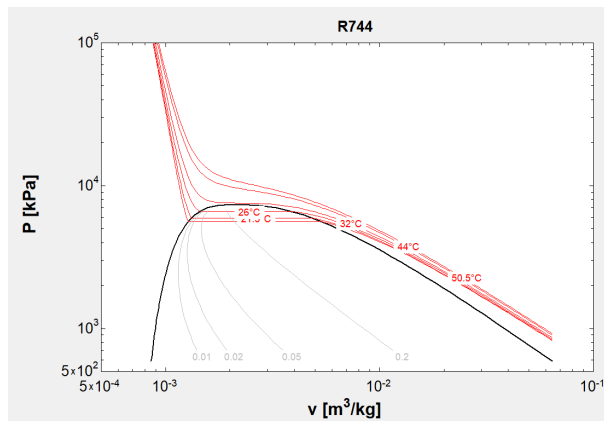


Figure 3: Obtained P-V diagram for CO₂

Since 2021, and as support of the practice, the students have available a website entitled “From the laboratory to the open digital resources in energy engineering”. This educational resource has embedded the aforementioned e-book, as well as access to the videos of the practice in Spanish, English, French and Arabic. The website completes the information with questionnaires to self-evaluate the knowledge acquired with the practice.

With the used fluids, SF_6 and CO_2 , students visualize how pressure varies when changing volume, at a stated temperature. To show the example of one academic course, Figs. 3 and 4 present the different P-V diagrams obtained for the two fluids. The isotherms measured in the case of SF_6 correspond to 19, 22, 30, 45.5, 48 and 55 °C. For CO_2 , the isotherms are 21.5, 26, 32, 44 and 50.5 °C. When drawing the obtained diagrams using the P-V-T data, the different regions (superheated vapor, subcooled liquid, liquid-vapor, and saturated liquid and vapor lines) can be easily differentiated.

By comparing the diagrams of the two fluids, it can be seen that the working pressures of SF_6 and CO_2 are similar, which justifies the replacement of the first fluid instead of the second. This replacement can be carried out both in the used equipment, and in cooling or aerothermal machines. Is for this reason that CO_2 is included in the group of natural refrigerants, considered as an ecological substance. The environmentally friendly behaviour of this substance makes it a great choice even in industry applications, such as trans-critical CO_2 refrigeration for medium and low temperatures.

The realization of this laboratory practice, supported by the aforementioned materials (e-book and website), helps the students to easily understand these concepts, that otherwise should be taught theoretically, with the difficulties that it implies.

In the case of Engineering students at the Universidad de Burgos, the practice is carried out within the course “Engineering Thermodynamics”, a second-year subject. At Chouaib Doukkali University (Morocco), similar contents are taught in the course “Thermodynamics – Fluid Statics” for second-year students. With regard to its possible implementation in the Building Engineering Degree at the Universidad de Burgos, the subject that best aligns with the explained contents is “Physics II”.

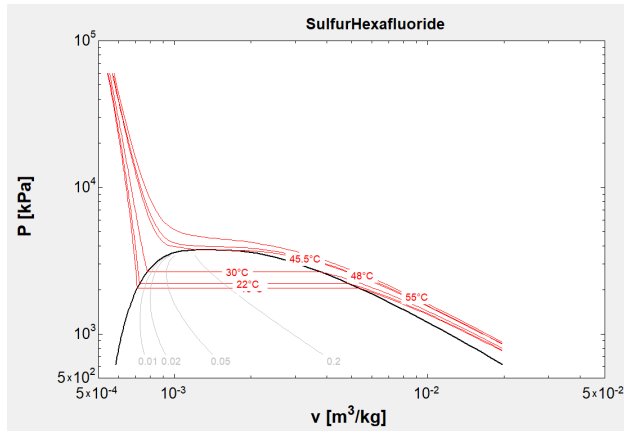


Figure 4: Obtained P-V diagram for CO₂

2. COURSE DEVELOPMENT: AN INTENSIVE WEEK

2.1. EXPERIMENTAL THERMODYNAMIC RESULTS

2.1.1. Isothermal P–V Behaviour

The experimental isotherms obtained with sulphur hexafluoride (SF₆) and carbon dioxide (CO₂) reproduce the expected thermodynamic behaviour of a pure substance below and near its critical point.

For temperatures below the critical temperature, three clearly differentiated regions are observed in the P–V diagrams:

- Superheated vapor región: Pressure increases smoothly as volume decreases at constant temperature. The relationship is continuous and monotonic, consistent with compressible gas behaviour.

- Liquid–vapor equilibrium región: At a given temperature, further reduction of volume does not increase pressure. Instead, a horizontal segment appears in the isotherm, indicating constant pressure during phase change. Experimentally, this corresponds to the appearance of a liquid phase within the gas and the progressive increase of the liquid fraction while pressure and temperature remain constant.
- Compressed liquid región: Once the last vapor bubble disappears, additional reduction in volume produces a sharp increase in pressure, characteristic of the low compressibility of liquids.
- These three regions coincide with the theoretical description of the thermal equation of state and phase transitions presented in the supporting e-book (Montero García, E., Muñoz Rujas, N., Rubio Pérez, G., Lifi, M., M’hamdi Alaoui, F. E., 2021). The experimental plateau directly visualizes the saturation phenomenon and provides empirical confirmation of phase equilibrium conditions.

2.1.2. Saturation Lines and Critical Point

By repeating the experiment at increasing temperatures, a family of isotherms was obtained. The saturation points corresponding to the first appearance of liquid (saturated vapor state) and the disappearance of the last vapor bubble (saturated liquid state) were identified for each temperature.

The graphical union of these points defines:

- The saturated vapor line
- The saturated liquid line

As temperature increases, the horizontal equilibrium segment shortens progressively. At approximately 45.5 °C in the case of

SF_6 , the equilibrium region collapses into a single inflection point with horizontal tangent, experimentally identifying the critical point (approximately 37.5 bar and 45.5 °C, as described in the e-book (Montero García, E., Muñoz Rujas, N., Rubio Pérez, G., Lifi, M., M'hamdi Alaoui, F. E., 2021).

Above this temperature, no phase coexistence is observed. The transition between low-density and high-density states becomes continuous, and the isotherm no longer exhibits a plateau. This behaviour confirms experimentally the disappearance of the liquid–vapor equilibrium region above the critical point.

2.1.3. Replacement of SF_6 by CO_2

The P–V diagrams obtained with CO_2 show the same qualitative thermodynamic structure:

- Smooth pressure increases in the vapor region
- Horizontal plateau during phase change
- Sharp pressure rise in the liquid region

Importantly, the working pressure range of CO_2 within the experimental setup (0.1–50 bar) remains compatible with the mechanical limits of the apparatus. Therefore, the substitution of SF_6 by CO_2 is technically feasible without modifying the experimental methodology.

From an environmental standpoint, this substitution is highly relevant. SF_6 has a Global Warming Potential (GWP) of 23500, while CO_2 (R-744) has a GWP of 0. The results confirm that equivalent thermodynamic learning outcomes can be achieved using an environmentally sustainable working fluid. This aligns the laboratory practice with current European regulations on fluorinated greenhouse gases and with sustainability objectives in engineering education.

2.2. EDUCATIONAL IMPLICATIONS OF THE EXPERIMENTAL RESULTS

2.2.1. Empirical Verification of the Equation of State

The experimental data confirm that only two thermodynamic variables can be independently fixed. For each isothermal process:

- Fixing temperature and volume uniquely determines pressure
- Fixing temperature and pressure determines volume
- Fixing pressure and volume determines temperature

This empirical observation reinforces the functional dependence expressed in the thermal equation of state, $F(P, V, T) = 0$.

Instead of introducing this dependence purely mathematically, students observe directly that a pure substance possesses two degrees of freedom. The laboratory results therefore support a deeper conceptual understanding of state-variable interdependence.

2.2.2. Visualization of Phase Transitions

The direct observation of:

- The first liquid droplet (saturated vapor),
- The liquid–vapor coexistence region,
- The disappearance of the last vapor bubble (saturated liquid),
- And the continuous transition at the critical point, reduces the level of abstraction typically associated with thermodynamics

The P–V diagrams constructed from real measurements provide a clear link between:

- Experimental data,
- Graphical thermodynamic representation,

- And practical applications in refrigeration and aerothermal systems

This is particularly relevant for building engineering degrees, where understanding the behaviour of refrigerants under varying pressure and temperature conditions is essential for energy efficiency analysis.

2.3. INTEGRATED DISCUSSION

The experimental results demonstrate that:

- The laboratory apparatus allows accurate qualitative identification of thermodynamic regions and phase transitions.
- The family of isotherms enables construction of saturation lines and experimental localization of the critical point.
- The substitution of SF_6 by CO_2 maintains the pedagogical objectives while improving environmental sustainability.
- The integration of the experimental practice with a multilingual open educational resource strengthens conceptual coherence between theoretical explanation and laboratory observation.

Overall, the results confirm that experiential learning of the thermal equation of state provides a rigorous and sustainable framework for teaching fundamental thermodynamics in engineering degrees, with direct applicability to energy systems in the building sector.

3. CONCLUSIONS

This work has presented an educational innovation experience in engineering thermodynamics based on the experimental determination of the thermal equation of state of fluids. Through laboratory practice supported by a multilingual open

educational resource, students analyse pressure–volume–temperature (P–V–T) relationships and directly observe the thermodynamic behaviour of pure substances across different regions, including superheated vapor, liquid–vapor equilibrium, saturated states, compressed liquid, and the critical point.

The experimental results confirm that the laboratory setup allows a clear qualitative identification of phase transitions, saturation lines, and the critical state. The family of isotherms obtained for both sulphur hexafluoride (SF_6) and carbon dioxide (CO_2) reproduces the theoretical behaviour of pure substances and enables students to empirically verify the functional dependence expressed by the thermal equation of state, $F(P, V, T) = 0$. This experiential approach reinforces the understanding of degrees of freedom and phase equilibrium beyond purely mathematical formulation.

The comparative analysis between SF_6 and CO_2 demonstrates that the replacement of a high Global Warming Potential (GWP) gas by a natural refrigerant (R-744) is technically feasible within the operational limits of the apparatus. This substitution maintains the pedagogical objectives of the practice while aligning the activity with current European environmental regulations and sustainability principles. In this way, the laboratory experience not only supports thermodynamic learning but also integrates environmental responsibility into engineering education.

From an educational perspective, the integration of experimentation, graphical analysis, and digital open resources contributes to reducing abstraction in thermodynamics and facilitates the transfer of knowledge to real applications, particularly in refrigeration and aerothermal systems used in the building sector. The methodology is adaptable to different

engineering degrees and institutional contexts, as demonstrated by its implementation in Spanish and Moroccan universities.

In the context of climate change and the Sustainable Development Goals, this proposal illustrates how higher education can connect fundamental scientific concepts with sustainable engineering practices. Experiential learning of the thermal equation of state thus becomes a strategic tool for training future building engineers capable of improving energy efficiency and contributing to more sustainable built environments.

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