Master's thesis and Internship : Framework for Evaluating the Design Requirements of ATEX-Certified Psychrometric Chambers

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Framework for Evaluating the Design Requirements of ATEX-Certified Psychrometric Chambers

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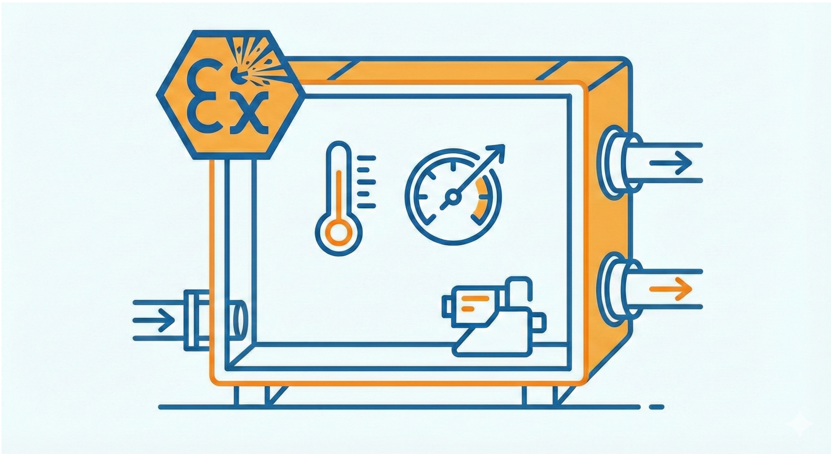

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Abstract

Driven by increasingly stringent environmental and safety regulations, as well as emerging restrictions on per- and polyfluoroalkyl substances (PFAS), the HVAC/R industry is rapidly transitioning toward natural refrigerants like highly flammable propane ($R290$). The use of such fluids in HVAC/R applications requires special testing facilities to safely evaluate their thermal performance.

This thesis addresses these risks by implementing a zone-avoidance engineering strategy. By combining safety ventilation that ensures sufficient dilution, with automated fail-safe shutdown sequences, potential refrigerant leaks are properly managed. This guarantees both personnel and installation safety. This approach enables the establishment of a *Zone of Negligible Extent* (Zone 2 NE), thereby eliminating the need for explosion-proof instrumentation within the experimental volume.

To operationalize this framework, a comprehensive engineering design tool was developed as a Python-based Streamlit web application. The application integrates a three-tier computational engine comprising a transient 1D thermal RC network wall model for multi-layer heat transfer, a dynamic energy balance module to evaluate real-time HVAC thermal load compensation, and a tree-based decision solver to map EN 378 compliance pathways and compute mandatory volumetric safety ventilation flow rates.

Finally, a techno-economic analysis was performed on a baseline twin-chamber configuration (32.19 m^3 individual volume, 30 kW dynamic thermal load compensation). A budget offer from Aralab indicates a capital investment of € 600,000 without accounting for installation costs, whereas a bottom-up cost estimation for a self-assembled alternative ranges from € 58,587 and € 100,453. While the in-house solution offers significant cost savings, it shifts a substantial engineering workload, safety validation and full legal liability onto the university.

Résumé

Sous l'impulsion de réglementations environnementales et de sécurité de plus en plus strictes, ainsi que des restrictions émergentes sur les substances per- et polyfluoroalkylées (PFAS), l'industrie du CVC/R migre rapidement vers des réfrigérants naturels parfois hautement inflammable comme le propane ($R290$). L'utilisation de ces fluides dans les applications de CVC/R impose de recourir à des installations de test spécifiques afin d'évaluer leurs performances thermiques en toute sécurité.

Ce travail aborde ces risques en mettant en œuvre une stratégie d'évitement de zone. En combinant une ventilation de sécurité garantissant une dilution suffisante avec des procédures d'arrêt automatique, les fuites potentielles de réfrigérant sont gérées de manière à ne jamais devenir un risque. Cela garantit à la fois la sécurité du personnel et celle de l'installation. Cette approche permet d'établir une zone d'étendue négligeable (Zone 2 NE), éliminant ainsi la nécessité d'utiliser de l'équipement certifié ATEX au sein du volume expérimental.

Pour mettre en place ce cadre méthodologique, un outil de conception global a été développé sous la forme d'une application web Streamlit en Python. L'application intègre un moteur de calcul à trois niveaux comprenant un modèle de paroi unidimensionnel en régime transitoire sous forme de réseau RC pour le transfert de chaleur à travers les murs, un module de bilan énergétique dynamique pour évaluer la compensation de la charge thermique en temps réel par le système de CVC interne à la chambre de test, et un solveur décisionnel pour cartographier les voies de conformité à la norme EN 378 et calculer les débits volumiques obligatoires de ventilation de sécurité.

Enfin, une analyse technico-économique a été réalisée sur une configuration de référence à double chambre (volume individuel de 32.19 m^3, compensation de charge thermique dynamique de 30 kW). Une offre budgétaire d'Aralab indique un investissement en capital de € 600 000 sans tenir compte des coûts d'installation, tandis qu'une estimation des coûts par composants pour une alternative contruite par soi-même varie entre € 58 587 et € 100 453. Bien que la solution interne offre des économies financières significatives, elle transfère une charge de travail d'ingénierie substantielle, la validation de la sécurité et l'entière responsabilité juridique vers l'université.

Contents

Part I

Theoretical Context

1 Introduction

From the early 1900s to present day, the HVAC/R (Heating, Ventilation and Air Conditioning / Refrigeration) industry has undergone many changes in the name of efficiency, sustainability and safety. The evolution of refrigerants plays a big role in the transition of the industry. From ammonia and propane in the beginning, to the discovery of synthetic refrigerants such as CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons). The latter slowly being discarded due to its harmful nature that was depleting the ozone layer (Montreal Protocol 1987 [1]). This lead to the emergence of HFCs (hydrofluorocarbons) as alternative which also became a hot topic as their GWP (Global Warming Potential) was too important. This has led to the adoption of HFOs (hydrofluoroolefins) and other low-GWP blends. With the current PFAS (Perfluoroalkyl and Polyfluoroalkyl Substances) problematic, we see a resurgence of *natural* refrigerants like propane, carbon dioxide and ammonia [2, 3].

In the context of resurgence of *old* refrigerants that are sometimes highly flammable and/or toxic, testing facilities for HVAC/R devices must be able to accommodate the risk linked to the use of these refrigerants. These installations thus need to be designed with appropriate safety procedures in mind. Accident prevention is further reinforced by the EU (European Union) through regulations and directives (e.g. ATEX[1] directives) that are imposed on the producers and users of such facilities. These regulations drive industrials and academics toward harmonized technical standards, which serve as the standard blueprint for demonstrating compliance with safety laws.

The aim of the ULiege laboratory is to have a testing facility for HVAC/R applications where the environment can be temperature and humidity controlled at defined levels. This facility should accommodate flammable refrigerants and comply with ATEX regulations.

The aim of this thesis is to establish a framework that facilitates the identification of the design requirements for such an ATEX-certified psychrometric chamber.

2 Definition of psychrometric chamber

Defining a psychrometric chamber is a rather difficult challenge as there is no global consensus or definition adopted by the whole industrial or academic community. This is why the terms like environmental, calorimetric, psychrometric and climatic chambers are used interchangeably often without a precise meaning. Given the variability in terminology, the following working definitions are adopted for the scope of this thesis:

- **Environmental & climatic chamber:** essentially synonymous terms that define passive enclosure designed to simulate specific ambient conditions (temperature, humidity, solar radiation...) to observe how a product behaves under certain controlled conditions (e.g. variation of mechanical properties or ageing). The main purpose is to control the stability and homogeneity of the air volume to perform vulnerability tests on materials or devices.

[1] ATEX is derived from the French "ATmosphères EXplosibles"

- **Psychrometric chamber:** active testing facility used to measure the heating or cooling capacity of HVAC/R equipment. Relies on the control of temperature and humidity of air inside the chamber to create a stable environment adequate for performance tests.
- **Calorimetric chambers** active testing facility used to determine the thermal capacity of a HVAC/R equipment. Relies on a global energy balance on the room to compute the performance of the device.

Some precise testing methods are developed in standards like ISO 5151 [4] or ASHRAE 37 [5] but are not always specifically assigned to one type of room. Each type of chamber is not mutually exclusive and most of the testing chambers in the HVAC/R industry are often psychrometric and calorimetric (both the air and the heat fluxes are monitored).

3 Industrial and academic applications

To familiarise ourselves with the theoretical definitions and safety strategies of this framework within current industrial and academic practices, three technical site visits were conducted at facilities operating under explicit safety protocols for flammable fluids and/or gases.

The first visit took place at the Copeland factory in Welkenraedt, focusing on an industrial laboratory room where a formal risk assessment had been executed and an explosion protection document (EPD) was implemented. This facility contained multiple specialized test stands dedicated to compressor performance evaluation. While various refrigerants were utilized across these benches, several configurations actively operated with propane ($R290$), demonstrating the practical integration of hydrocarbon testing within a controlled industrial environment. Each individual stand was constantly ventilated to avoid the formation of an explosive atmosphere and gas detectors were installed everywhere to monitor refrigerant leakages. If a leak was detected, the power would be immediately and automatically shut down to avoid ignition hazards.

The second observation was carried out at the Copeland laboratory in Aachen, which features a psychrometric testing facility configured as a twin-chamber system (see Figure 1). This configuration is characterised by two rooms that can simulate two different environments at the same time, which is especially useful to test split heat pump systems[2] for example. This installation includes a movable partition wall separating the two environmental zones to accommodate diverse heating, ventilation, and air conditioning (HVAC) applications. Although the facility was initially designed for non-flammable fluids, it was subsequently retrofitted to safely handle flammable refrigerants. The safety concept of this chamber relies on continuous dilution ventilation to mitigate the formation of explosive atmospheres, coupled with automated shutdown sequences that isolate the system components in the event of an operational failure.

The final visit was conducted at the RWTH Aachen university, where several mono-chamber psychrometric rooms (see Figure 2) are used for academic and industrial HVAC research [6]. Among these testing rooms, only one specific chamber is equipped to accommodate flammable refrigerants, utilizing a distinct mitigation strategy. If a localized leak causes the refrigerant concentration to exceed a safety threshold, the system triggers the automatic opening of the building's adjacent garage doors to vent the gas to the exterior. Simultaneously, the main electrical power supply to the entire testing environment is isolated, ensuring that no electrical spark can act as an ignition source.

Other facilities also exist around the world like in Purdue University where a psychrometric chamber has been retrofitted to accommodate flammable refrigerants [8]. There are also some industrial companies that build such facilities of which some examples can be found below:

- Aralab is Portuguese company specialised in testing facilities for HVAC application [7].
- Weiss-Technik is a German company with a large catalogue of testing chambers for multiple fields of application [9].

[2] One part of the heat pump can be set in an *outdoor* environment while the other part is *indoor*.

Figure 1: Twin-chamber testing facility from Aralab [7].

Figure 2: Hardware-in-the-loop (HIL) climatic chamber at RWTH [6].

- ACS (Angelantoni Test Technologies) is an Italian company with an impressive amount of environmental testing chambers in its catalogue not specifically reserved to HVAC applications [10].

4 Safety certification

ATEX (which stand for *ATmosphère EXplosible*) is a certification issued for equipment and installations which work in environments where explosive atmospheres can occur. These atmospheres can be either dust clouds or flammable gas or even both. The purpose of this certification is to provide security to workers and infrastructure by ensuring that the equipment and installations are *explosion proof* either by preventing the explosion or by limiting the damage. It is especially important when working with flammable gases like the *natural* refrigerants used in thermodynamic cycles.

ATEX stems from two European directives namely the equipment directive [11] and the workplace directive [11]. The first one lays the rules for the manufacturers to certify that the equipment they built is explosion proof. The second directive looks at the certification of the entire installation to ensure the security of the workplace. Both directives have been directly transposed into Belgian law through the royal decree of 2016 [12] and the royal decree of 2003 [13]. The transposition into Belgium law added specifications regarding languages as well as the involvement of external parties which will be discussed in the following sections of this thesis.

4.1 ATEX directive for workplace safety

This directive from 1999 targets the employers, compelling them to take all *necessary* measures to ensure the safety of the workers. These prevention measures must follow a hierarchy of importance:

(1) Prevent the formation of an explosive atmosphere.

(2) Avoid the ignition of such atmosphere.

(3) Mitigate the detrimental effects if an explosion occurs.

The employer needs to conduct a risk assessment and document their safety measures in an **Explosion Protection Document** (EPD) which must be accessible at all times near the installation. This document also requires a classification of the hazardous areas in the workplace based on the type of atmosphere and the frequency of apparition. This classification is shown in Table 1:

Table 1: Classification of Hazardous Places into ATEX Zones

Atmosphere Type	Zone	Likelihood of Occurrence
Gas / Vapor	**Zone 0**	Present continuously, for long periods, or frequently.
	Zone 1	Likely to occur occasionally.
	Zone 2	Not likely to occur, or if so, for a short period only.
Combustible Dust	**Zone 20**	Present continuously, for long periods, or frequently.
	Zone 21	Likely to occur occasionally.
	Zone 22	Not likely to occur, or if so, for a short period only.

The transposition of the directive in Belgian law compels the involvement of prevention services to define the hazardous zones. The employer can thus not certify his own installation without the help of a prevention service (SIPPT or SEPPT).

4.2 ATEX directive for equipment

This directive from 2014 focuses on the production of equipment designed for explosive atmospheres. It sorts the equipment in different categories depending on their protection level and their location as shown in Table 2:

Table 2: ATEX Equipment Categories and Corresponding Zones [13, 12].

Category	Zones	Protection	Atmosphere Presence
Category 1	0, 1, 2 / 20, 21, 22	Very High	Permanent or long periods
Category 2	1, 2 / 21, 22	High	Occasional
Category 3	2 / 22	Normal	Rare or short-lived

This table only contains the categories relevant for equipment group II which is applicable for surface industries, equipment group I being relevant for mines (classification M1/M2).

This directive places legal obligations on economic operators such as the manufacturers, authorized representatives, importers and distributors before selling or commissioning. The compliance is demonstrated through conformity assessment procedures after which products must display the CE marking and the specific Ex symbol (see Figure 3). Several procedures are accepted to assess the conformity of a product and are listed in Table 3.

The transposition of the directive imposes strict linguistic requirements depending on the region where the product is made available on the market. The technical documentation also has to follow this rule and must be supplied to the *Direction générale de l'énergie* and surveillance authorities.

Figure 3: Ex symbol

Table 3: ATEX Conformity Assessment Modules [12].

Module	Name	Prerequisites	Characteristics
A	Internal Production Control	Cat. 3 or Cat. 2 non-electric	Self-certification. Manufacturer assesses risk, compiles technical file, and signs Declaration of Conformity (DoC).
B	EU-Type Examination	Cat. 1 and 2 (Electrical/Engines)	Design phase check. A Notified Body (NoBo) examines prototype and design for Type Certificate.
C1	Conformity to Type (Supervised)	Cat. 2 (Follows Module B)	Production phase. Manufacturer tests products; NoBo performs random supervised safety tests.
D	Production Quality Assurance	Cat. 1 (Follows Module B)	NoBo audits and approves quality system for production, final inspection, and testing.
E	Product Quality Assurance	Cat. 2 (Follows Module B)	Focuses on quality systems for final product inspection and testing, audited by a NoBo.
F	Product Verification	Cat. 1 (Follows Module B)	NoBo verifies every individual product or a batch sample against the approved type.
G	Unit Verification	Custom Units (All Categories)	"All-in-one" for unique machines. NoBo inspects the specific unit and technical file.

4.3 Harmonized standards

The European directives and their transposition in Belgian law form the legal framework for ATEX installations and equipment. They however do not identify specific behaviours, thresholds or procedures to follow, to ensure the installation or equipment is *safe*. This is why manufacturers and industrials follow technical standards that offer a **presumption of conformity**: a project that strictly follows the technical standard is presumed to meet the legal requirements. This helps industrials to prove that their installation or equipment is *safe* according to the directive. This is also how NoBo's (Notified Bodies) verify the compliance. The technical foundation and guidance relevant for the ATEX certified psychrometric chamber is found in multiple standards like the EN 60079 series, ISO 817, EN 1127-1... These standards can sometimes appear to be redundant or conflicting depending on the application. They can be organized in a general to specific order to establish a clear architectural hierarchy, which helps explain why this perceived redundancy or conflict exists.

The standardization landscape is structured into three cascading layers: horizontal standards at the top define the global safety philosophy and master risk-assessment checklists applicable across all industries. Vertical standards in the middle translate this philosophy into concrete engineering toolkits, branching independently into separate tracks for electrical physics and mechanical machinery. Finally, product-specific standards at the base enforce design boundaries and threshold caps for individual components or commercial appliances.

Because of this top-down architecture, requirements often appear redundant at first glance. A single safety concept, such as preventing a spark, is intentionally repeated across the layers: it is introduced as a general hazard requirement at the horizontal level, calculated using specific engineering rules at the vertical level, and enforced via precise physical dimensions at the component level.

Understanding this hierarchy allows the engineer to navigate the standards sequentially, moving from broad system design down to specific hardware compliance. This structure governs the technical descriptions presented in the following sections.

4.3.1 ISO 817

The ISO 817 standard [14] establishes a universal, unambiguous alphanumeric designation system to classify the chemical composition and molecular structure of refrigerants. This standard assigns a unique identification number prefixed by the letter *R* (for refrigerant) to provide a snapshot of the underlying atom counts.

Reading this numerical code from right to left unlocks a systematic mathematical rule for organic compounds. The first digit from the right indicates the number of fluorine atoms, the second digit from the right denotes the number of hydrogen atoms plus one, and the third digit from the right signifies the number of carbon atoms minus one (which is omitted if the final value is zero). A fourth number accounting for carbon-carbon double bonds or other suffixes are sometimes appended depending on the composition (presence of Br, cyclic compounds...). This thesis will however not go through the entire system as the objective is to give an overview of the system while providing an origin to these designations.

To illustrate this logic, consider propane, designated as *R290* under this framework. Its chemical formula is C_3H_8. Applying the ISO 817 decoding rules reveals its structure directly from the ID:

- The first digit from the right is **0**, indicating zero fluorine atoms.
- The second digit from the right is **9**, indicating eight hydrogen atoms $(8 + 1 = 9)$.
- The third digit from the right is **2**, indicating three carbon atoms $(3 - 1 = 2)$.

This structured notation allows engineers to instantly recognize the basic molecular chain and hydrocarbon family of a refrigerant, avoiding long chemical names or formulas.

This standard also introduces the concept of refrigerant safety classes, grouping refrigerants into categories (A2L, B2...) based on their toxicological and flammability profiles.

The toxicity classification is denoted by a capital letter, where *Class A* signifies low toxicity fluids whereas *Class B* designates higher toxicity. Flammability is quantified numerically by classes 1, 2L, 2, and 3, determined by maximum burning velocity, the lower flammability limit (LFL), and the heat of combustion. *Class 1* indicates no flame propagation under specific conditions (60°C, 101.3 kPa). *Class 2* represents mildly flammable fluids to which an *L* can be added (*Class 2L*) when they are characterized by a low burning velocity (less than 10 cm/s). *Class 3* identifies highly flammable fluids.

Combining these two criteria (toxicity and flammability) yields a distinct safety group categorization. For instance, propane (R290) is classified as an *A3* refrigerant, indicating a fluid with lower toxicity but high flammability. This alphanumeric safety classification serves as an important parameter for engineers to determine limits on their facilities such as a refrigerant charge limit (see section 9).

ISO 817 standard is the foundation to characterise the refrigerants that will be used in the psychrometric chamber and is essential for safety computations. This norm contains tables [15] providing important parameters (LFL, safety class...) for many refrigerants which will be used to form a database integrated in the design procedure of the psychrometric chamber.

4.3.2 EN 378

EN 378 is a standard for refrigerants [16] providing safety rules for the design and installation of systems. EN 378-1 defines for example a procedure to identify the charge limit requirements for refrigerating systems that will be used in the design tool that is developed in Part II. It also develops some calculations for ventilation requirements that will also be addressed in Part II.

4.3.3 EN 1127-1

As a horizontal safety standard, EN 1127-1 [17] establishes the overarching framework for explosion prevention and protection across all industrial sectors. Unlike the specialized standards that follow it (EN 80079), this norm does not specify engineering criteria for individual components; instead, it defines the global risk-assessment protocol required to analyse an installation. The core of this standard is the classification of thirteen standardized industrial ignition sources, ranging from electrostatic discharges and hot surfaces to mechanical friction sparks, which must be systematically evaluated during the design phase of a facility.

Within this framework, EN 1127-1 acts as the master analytical checklist that feeds directly into downstream, vertical standards (EN 80079). While it establishes the basic principles to determine whether an ignition hazard exists, engineers must look to the EN IEC 60079 series to execute the specific fluid dynamic and electrical calculations, or to the EN ISO 80079 series to apply mechanical protection types. By defining the baseline chemistry and physics of ignition prevention, EN 1127-1 ensures that the structural risk-assessment methodology remains consistent before specific hardware mitigations are implemented.

4.3.4 EN 60079

The EN IEC 60079 series serves as the primary technical foundation for explosive atmosphere engineering, providing guidance about the physical behaviour of flammable gases and the safety design of electrical systems. It introduces the basic requirements for industrial installations, including the definition of gas groups, temperature groups, and environmental marking codes [18]. These form the basis for all risk assessments involving explosive atmospheres. A sub-part of the standard, EN IEC 60079-10-1 [19], provides the mathematical models and fluid dynamic equations required to execute ventilation calculations, evaluate dynamic gas dilution rates, and define the boundaries of hazardous areas (ATEX zoning).

Furthermore, the standard describes the electrical installation rules to safely integrate electrical subsystems, such as connecting a testing device inside an existing enclosure [20]. Protection modes are defined for equipment that is used inside explosive atmosphere depending on the method utilised. A comprehensive summary of these standardized electrical protection types (such as intrinsic safety **Ex i** or flameproof enclosures **Ex d**) is compiled for reference in Table 6 of Appendix A.

4.3.5 EN 80079

While the EN 60079 series governs the safety of electrical hardware and gas behaviour, the EN ISO 80079 series focuses strictly on the certification of non-electrical (mechanical) equipment and multi-component machinery assemblies, such as fans, gearboxes, or custom-built test benches. To avoid duplicating fundamental material science rules, the non-electrical standard series directly adopts the underlying physical test criteria (such as housing impact resistance and material thermal properties) defined in the electrical general requirements standard, EN 60079-0. However, for mechanical devices, the specific requirements of the EN ISO 80079 series take legal precedence wherever conflicts arise.

The core of this framework is EN ISO 80079-36 [21], which mandates a formal Ignition Hazard Assessment (IHA) to systematically evaluate mechanical risks like frictional heating or impact sparks. If an ignition risk is identified, sub-part EN ISO 80079-37 [22] establishes specific protection concepts unified under the single **Ex h** designation, as summarized in Table 7 from Appendix B.

4.3.6 Overview table

The technical standard landscape governing both the environment control loops and the explosion mitigation measures is synthesized in Table 4. This table serves as an overview of all the relevant standards that are linked to this project, albeit without detailed description when not actively used in this thesis. For example some standards such as EN 14986 [23] are only relevant when designing fans for explosive atmospheres. As the purpose of this thesis is to design a chamber and not fans, the standard in itself is not useful directly, but is still linked to the project as the fans installed in ATEX certified psychrometric chambers must follow this norm.

Table 4: Technical standards relevant to the subject of this thesis.

Standard code	Title	Role within the framework
Core process & safety infrastructure		
ISO 817	Refrigerants – Designation and safety classification	Provides a system for refrigerant designation (R+id number), assigning safety classes based on toxicity and flammability and concentration limits [14]. Tables listing the different characteristics are also part of this standard [15].
EN 378 series	Refrigerating systems and heat pumps – Safety and environmental requirements	Provides safety rules for system design and installation, defining charge limits based on occupancy categories, location classifications, and minimum ventilation rates [16].
EN 1127-1	Explosive atmospheres – Explosion prevention and protection – Part 1: Basic concepts	Provides a comprehensive list of thirteen standard industrial ignition sources and outlines a structured methodology to evaluate and eliminate explosion risks during equipment assembly [17].
EN IEC 60079 series	Explosive atmospheres (Focus on Parts 10-1 & 14)	Provides mathematical formulas for dynamic dilution calculations, specific rules for physical hazardous area classification, and engineering layout criteria for electrical installations [19, 20].
EN ISO 80079-36:2016	Explosive atmospheres – Part 36: Non-electrical equipment – Basic method	Provides the fundamental requirements and validation steps for executing an ignition hazard assessment on mechanical components, supporting conformity under national product decrees [21].
Adjacent & Subsystem Reference Standards		
ASHRAE 15	Safety standard for refrigeration systems	Provides alternative engineering criteria for mechanical room ventilation, structural piping safety limits, and open-loop exhaust air parameters used in North American practice [24].
EN IEC 60335-2-40	Safety of household and similar electrical appliances – Part 2-40	Provides product-specific charge mass limits (m_1, m_2, m_3), structural requirements for refrigerant-tight enclosures, and rules for active leak detection sensor integration for household appliances (may be relevant for the test bench).
EN ISO 80079-37	Explosive atmospheres – Part 37: Non-electrical equipment – Protection types	Provides specific technical design criteria for type **Ex h** non-electrical protection concepts, detailing constructional safety ('c') and control of ignition sources ('b') rules [22].
EN 14986	Design of fans working in potentially explosive atmospheres	Provides geometric limits for impeller clearances, requirements for anti-static material pairings, and manufacturing rules to prevent frictional sparks in circulation or extraction systems [23].

Continued on next page

Table 4 – Continued from previous page

Standard code	Title	Role within the framework
ASHRAE 37	Methods of testing for rating electrically driven air-conditioning equipment	Provides standard instrumentation layouts, aerodynamic tunnel geometries, and sensor balancing equations required to execute air-enthalpy performance tests [5].
ISO 5151:2021	Non-ducted air conditioners and heat pumps – Performance testing	Provides standard target psychrometric environmental profiles, cooling capacity verification methods, and steady-state thermal equilibrium tolerance margins [4].

5 Zone avoidance strategy

As shown in section 4, regulations and standards form a complex framework which is hard to navigate when trying to build a facility containing flammable refrigerants. This is why most of the time, the objective is to avoid most of the rules that are imposed in case of explosive atmosphere with two methods:

- Avoid the formation of an explosive atmosphere. Designing the installation with sufficient ventilation in such a way that the concentration of refrigerant can never be above a certain threshold ensuring a **zone of negligible extent**. This is classified as **Zone 2 (NE)** and signifies that the dangerous volume is functionally zero (due to dilution for example).
- In case of failure of a system, automatic shutdown procedures are triggered to ensure that an explosive atmosphere can never be ignited.

This set of two measures effectively enables to avoid a lot of complications like using ATEX-certified equipment.

This however does not mean the psychrometric chamber will be exempted of all regulations. Some computations will still be needed to ensure certain thresholds are not exceeded and that the dilution is sufficient.

Part II

Modelling & Design

As one of the objectives of this thesis is to look at the design of a psychrometric chamber, I developed a tool to help computing the needs in terms of power and safety for any installation. This tool takes the form of a web application [25] (accessible directly via the link in the reference) that will simulate the psychrometric chamber when a certain number of data entries are given. Its purpose is to have a rapid estimate of the power requirements for a given scenario while simultaneously looking at its feasibility in terms of safety. This tool was developed with Python using the streamlit library [26] and is presented in three distinct expanders. Expanders are a specific structure of streamlit which enlarge when clicked upon. Three expanders are found inside the application:

(1) Wall configuration

(2) Simulation parameters

(3) Safety parameters

Each expander tackles a specific aspect of psychrometric chamber design and requires different inputs.

All the expanders are also affected by a *master switch* that chooses between a *mono-chamber* or a *twin-chamber* configuration. This switch is especially important because most of the computations will depend on the configuration: either one zone, or two zones separated by a wall.

6 Global structure of the code

The code for this web application is structured as shown in Figure 4.

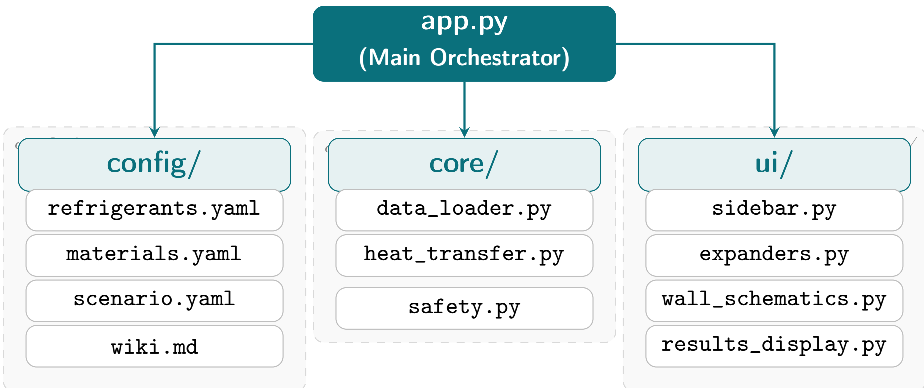


Figure 4: Architectural file and directory layout of the developed psychrometric simulator.

`app.py` main streamlit entry point orchestrating the ui skeleton and action routing.

`config/` Directory containing static data and reference material:

- `refrigerants.yaml:` refrigerant properties database storing information relevant to safety computations.
- `materials.yaml:` library of materials and their properties relevant for heat transfer simulation.
- `wiki.md:` en-378 reference documentation directly accessible in the web application.

`scenario.yaml`: configurations and input parameters that are stored via the scenario saving feature. This allow the user to save a configuration and reuse it later without having to reset all the parameters.

`core/` Directory containing core computational logic:

`data_loader.py`: functions to parse yaml (Yet Another Markup Language) files into python dictionaries.

`heat_transfer.py`: computations for the thermal part of the psychrometric chamber simulator.

`safety.py`: safety logic (EN 378, ATEX classifications, ventilation).

`ui/` Directory containing user interface definitions:

`sidebar.py`: streamlit functions for the sidebar elements.

`expanders.py`: core block rendering (walls, simulation, safety) and execution routing.

`wall_schematics.py`: function rendering the wall schematic.

`results_display.py`: functions to generate metric cards, charts, and warning banners displaying the results of the simulation.

7 Wall configuration

The purpose of this expander is to simulate the heat transfer that would occur through the walls of the psychrometric chamber. Therefore, the user can define the wall he wants in the panel by specifying the different layers that compose the wall. Each layer can be customized with a specific material (either present in the database or added by the user), thickness and characteristics (thermal conductivity λ, density ρ and specific heat capacity c_p). This allows the user to assemble any wall imaginable.

Furthermore, if the chamber is composed of different types of walls or if the user wants to estimate the heat losses through the ceiling or ground, the tool accommodates multiple configurable surfaces.

7.1 RC network

The transient heat transfer that is assumed to be one dimensional is then estimated through a resistor-capacitor (RC) network model. This model will allocate a capacity to each layer of the wall (in its center) which will be connected through resistances to other layers or the external boundaries. A scheme explaining the network modelling is shown in Figure 5.

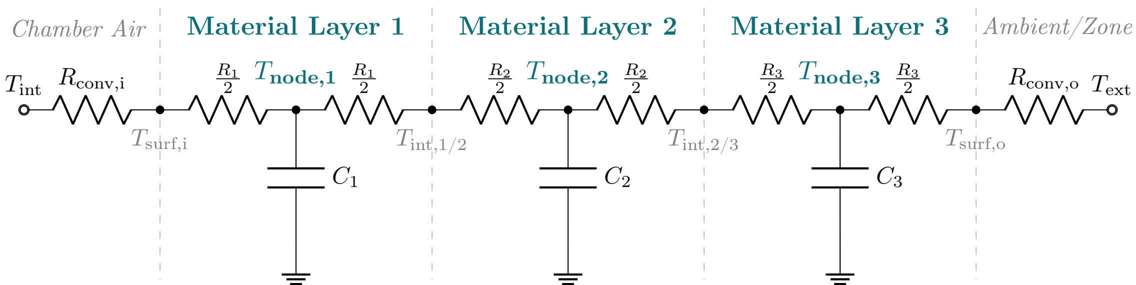


Figure 5: RC network modelling for a 3-layered wall.

Each surface configured will thus be defined by an RC network as follows:

$$R_j = \frac{e_j}{\lambda_j} \tag{1}$$

$$C_j = \rho_j c_{p,j} e_j \tag{2}$$

Where:

R_j is the specific thermal conductive resistance of material layer j ($\mathrm{K\,m^2\,W^{-1}}$).

e_j is the physical thickness of layer j (m).

λ_j is the thermal conductivity of the material in layer j (W/(m · K)).

C_j is the specific thermal capacitance of material layer j (J/(m^2·K)).

ρ_j is the mass density of the material in layer j (kg m^{-3}).

$c_{p,j}$ is the specific heat capacity at constant pressure of the material in layer j (J/(kg · K)).

Once all the resistances and thermal capacities are computed for each material in the specific wall, they will be assembled to form the network as following:

$$R_{\text{int}} = R_{\text{conv,i}} + \frac{R_1}{2} \quad | \quad R_k = \frac{R_j}{2} + \frac{R_{j+1}}{2} \quad | \quad R_{\text{ext}} = R_{\text{conv,o}} + \frac{R_n}{2} \tag{3}$$

Where:

$\mathbf{R_{int}}, \mathbf{R_{ext}}$ are the total internal and external surface resistances (K m^2 W^{-1}).

$\mathbf{R_{conv,i}}, \mathbf{R_{conv,o}}$ are the internal and external convective boundary layer resistances (K m^2 W^{-1}).

R_k is the combined equivalent series resistance between adjacent internal nodes j and $j+1$ (K m^2 W^{-1}).

R_1, R_n are the specific thermal resistances of the first (innermost) and n-th (outermost) material layers (K m^2 W^{-1}).

To ensure the numerical stability of the finite-difference solver, the model evaluates the thermal time constant of each layer rather than applying a static capacity threshold. The time constant τ_j characterizes the thermal response rate of a material layer and is computed as the product of its thermal resistance and capacity:

$$\tau_j = R_j C_j \tag{4}$$

Layers with very low thermal mass or high conductivity such as thin air gaps or metallic sheets possess a minute time constant. In an explicit Euler integration scheme, these dynamically "fast" nodes forces small simulation time steps to maintain mathematical stability.

To bypass this limitation without sacrificing global accuracy, a minimum threshold $\tau_{\text{threshold}} = 360$ seconds is implemented. If $\tau_j \leq \tau_{\text{threshold}}$, the transient capacitive behaviour of the layer is neglected. The layer is instead treated as a pure steady-state thermal resistance, and its value is directly aggregated with the adjacent resistances. This effectively collapses the unstable node while preserving the overall heat transfer coefficient (U-value) of the wall assembly. This effectively forms an array of the conductive resistance between each temperature node. The overall heat transfer coefficient AU (W/K) can also be computed once the network is established:

$$AU = \frac{A}{R_{int} + \sum R_k + R_{ext}} \tag{5}$$

Where:

AU is the overall global heat transfer coefficient of the specified wall assembly (W K^{-1}).

A is the total surface area of the specific wall section (m^2).

8 Psychrometric chamber simulator

The goal of this expander is to determine the power required from the psychrometric chamber to maintain a stable environment. It uses a global energy balance on the entire chamber to compute the heating or cooling power necessary to have a balance. The goal of this expander is to determine the thermal power required from the psychrometric chamber to maintain a stable environment. It uses a global energy balance on the entire chamber to compute the heating or cooling power necessary to reach equilibrium:

$$\dot{Q}_{\text{HVAC}} = -(\dot{Q}_{\text{testbench}} + \dot{Q}_{\text{appliances}} + \dot{Q}_{\text{wall}} + \dot{Q}_{\text{fan}}) \tag{6}$$

Where:

$\dot{Q}_{\textbf{HVAC}}$ is the required heating (positive) or cooling (negative) thermal power from the chamber's air-handling unit (W).

$\dot{Q}_{\textbf{testbench}}$ is the sensible heat dissipation from the active unit under test (W).

$\dot{Q}_{\textbf{appliances}}$ is the total sensible heat generated by auxiliary measurement appliances inside the chamber (W).

$\dot{Q}_{\textbf{wall}}$ is the dynamic heat transfer rate through the chamber envelope, representing transmission gains or losses (W).

$\dot{Q}_{\textbf{fan}}$ is the sensible thermal power dissipated directly into the air stream by the circulation and safety ventilation fans (W).

Equation (6) introduces multiple variables that must be determined in order to design the thermal needs of the chamber. The power of the test bench ($\dot{Q}_{testbench}$) is given by the user as well as the power of appliances ($\dot{Q}_{appliances}$). These appliances can be devices that are not part of the test bench itself but are essential for taking measures for example. The thermal power related to the fans ($\dot{Q}_{fan}$) is computed by using the required ventilation from a safety perspective (see section 9) and multiplying it by a constant SFP (Specific Fan Power) of 1.5. The objective is to estimate the heat produced by the fan inside the chamber and how it's impacts the whole energy balance. The last power ($\dot{Q}_{wall}$) represents the heat flux through the walls and uses the walls configured in the first expander to compute the power.

8.1 Heat transfer through the walls

Using the walls configured and their respective RC network, it is possible to estimate the heat flux going through each surface. Adding all these fluxes together thus gives us a global power that crosses the walls which can be used in equation (6).

For each different surface, the transient heat transfer is simulated for a defined period of time specified by the user. This simulation will compute for each time step the heat flux at each node (layer) as seen in equation (9). This result will then be used in equation (10) to update the temperature at each node. This effectively simulates the evolution of temperature inside the wall as well as the heat flux entering the chamber (which is necessary for the energy balance). The internal and external boundary temperatures are defined by the user. To avoid a warm-up period at the beginning of the simulation, the initial temperature at each internal node ($t = 0$) is computed by assuming the chamber has already been operating under steady-state conditions for an extended period.

Under this assumption, the thermal capacities are considered fully saturated (i.e., $\frac{dT}{dt} = 0$), resulting in a constant initial heat flux across the entire wall assembly. First, we calculate this steady-state heat flux:

$$q_{\text{steady}} = \frac{T_{\text{ext}} - T_{\text{int, target}}}{R_{\text{total}}} \tag{7}$$

$q_{\textbf{steady}}$ steady-state heat flux across the entire wall [W/m^2].

$T_{\textbf{ext}}$ temperature of the external environment [°C].

$T_{\textbf{int, target}}$ target temperature of the internal environment [°C].

$R_{\textbf{total}}$ total thermal resistance of the multi-layer wall [m^2 K/W].

The initial temperature profile is purely resistive, dropping across each layer proportionally to its thermal resistance. The temperature at any given node j is therefore:

$$T_j(t=0) = T_{\text{ext}} - q_{\text{steady}} \sum_{k=1}^{j} R_k \tag{8}$$

Where:

$T_j(t=0)$ is the initial steady-state temperature at node j [°C].

R_k is the thermal resistance of the individual layer segment k [m^2 K/W].

$\sum_{k=1}^{j} R_k$ is the cumulative thermal resistance from the external boundary up to the target node j [m^2 K/W].

Once this steady-state temperature gradient is established, the transient evolution of the heat fluxes and node temperatures is simulated at each time step using the following explicit finite-difference equations:

$$q_j = \frac{T_j - T_{j+1}}{R_k} \tag{9}$$

$$\frac{dT}{dt} = \frac{q_j - q_{j+1}}{C_j} \tag{10}$$

q_j transient heat flux passing through node j [W/m^2].

T_j current transient temperature at node j [°C].

T_{j+1} current transient temperature at the subsequent node $j+1$ [°C].

q_{j+1} transient heat flux leaving node j toward node $j+1$ [W/m^2].

C_j specific thermal capacity allocated to node j [J/m^2 K].

For each time step, a heat flux entering (or exiting) the chamber can then be computed, and repeating this step for all the surfaces configured gives the global heat transfer through the walls of the chamber which can be integrated in equation (6).

The energy balance and wall heat transfer computations are run once the *run simulation* button is triggered and displays the HVAC needs of the chamber as well as other important results.

9 Safety computations

The last important part of this web application is the *safety parameters* expander. This expander goal is to verify the validity of the design in respect to the regulations and standards. Therefore, multiple inputs are required from the user specifying the refrigerant, the charge of refrigerant in the test bench and other important parameters. The application then goes through a tree-based decision model to display the charge limit specified by EN 378. The method provided by EN 378-1 [16] is replicated hereunder.

a) Determine the access category a, b or c of the facility according to Table 4 of EN 378-1 reproduced as Table 8: a for general, b for supervised or c for authorized access. Identify the location classification of the refrigerating system as defined in section 5.3 of EN 378-1 [16]:

- **Class I:** Equipment within the occupied space.
- **Class II:** Compressors are located in a separate machinery room or outdoors, but some refrigerant-containing parts may be in the occupied space.
- **Class III:** All refrigerant-containing parts are situated in a machinery room or open air.
- **Class IV:** Ventilated enclosures.

b) Determine the toxicity class of the refrigerant used (A or B) by looking at Annex E of EN 378-1 [16]. The toxicity limit is set equal to the ATEL/ODL value or the practical limit (whichever is higher) which can be found in Annex E as well.

c) Determine the charge limit based on toxicity as the greater of:

1) Charge limit from Table C.1 of EN 378-1 which has been reproduced as Table 9 in Appendix C.

2) 20 m^3 multiplied by the toxicity limit (defined in point b) for sealed refrigerating systems.

3) 150g for sealed refrigerating systems using toxicity class A refrigerant.

d) Determine the flammability class of the refrigerant: 1, 2L, 2 or 3 and its LFL (Lower Flammability Limit) according to Annex E from EN 378-1.

e) Determine the charge limit based on flammability as the greater of:

1) Charge limit from Table C.2 of EN 378-1 which has been reproduced as Table 10 in Appendix C.

2) m_1[1] × 1.5 for sealed refrigerating systems using flammability class 2L.

3) m_1[1] for sealed refrigerating systems using flammability class 2 or 3.

4) 150 g for sealed refrigerating systems

f) Apply the lowest refrigerant charge obtained according to c) and e). For determination of charge limits for refrigerants of flammability class 1, e) is not applicable.

Based on the refrigerant charge provided by the user, the code then compares it to the value obtained by the model and determines if the current configuration is *safe* according to the standard.

Another parameter computed is the minimum ventilation requirement from EN 378-2 [27] and the emergency ventilation requirement from EN 378-3 [28] that follow the following formula:

$$Q_{\text{min}} = 15 \times s \frac{m_r}{\rho} \tag{11}$$

$$\dot{V}_{\text{emergency}} = 0.014 \times m_r \tag{12}$$

Where:

$Q_{\mathbf{min}}$ is the minimum mandatory safety ventilation volume flow rate ($m^3\,s^{-1}$).

s is the dimensionless safety factor defined by the EN 378 standard set to 4.

m_r is the flammable refrigerant charge of the test bench (kg).

ρ is the density of refrigerant at standard atmospheric conditions ($kg\,m^{-3}$).

$\dot{V}_{\mathbf{emergency}}$ is the emergency ventilation volume flow rate ($m^3\,s^{-1}$).

This result of the minimum ventilation (Q_{min}) is then used to estimate the heat produced as Q_{fan} from equation (6) using a SFP (Specific Fan Power) factor: $Q_{\text{fan}} = Q_{\text{min}} \times SFP$.

[1] with $m_1 = 4\ m^3 \times$ LFL.

Part III

Analysis & Synthesis

10 Results from simulation

Since the logic and physic engine behind the web application [25] have been explained in Part II. This section will focus on the usage of this application and show the results that can be obtained. A twin-chamber testing facility hosting a heat pump is therefore used as a test case to serve as input to the model. The psychrometric chamber itself is situated inside a building (not open air). All the inputs parameters are discussed hereunder and a user guide with visual representations of the application can be found in Appendix D. Each subsection follows the application architecture by matching each expander.

10.1 Wall configuration

The walls of the psychrometric chamber are assumed to be 150 mm thick sandwich panels made primarily of PIR (polyisocyanurate) which have great insulation properties. Similar panels where used in the psychrometric chamber visited in Aachen from Copeland [29]. The dimensions of the individual chambers are set for convenience at (4 m x 4 m x 4 m) so that the surface covered by the PIR panels and the volume of the chambers can be easily identified. Three surfaces must be defined: one for each individual chamber connected to the exterior of the facility and one shared surface between both rooms. Each zone defined by a room will now be defined by either a *indoor* or *outdoor* tag representative of which type of environment they simulate.

$$A_{\text{indoor}} = 5 \times (4 \times 4) = 64\,\text{m}^2$$
$$A_{\text{outdoor}} = 5 \times (4 \times 4) = 64\,\text{m}^2$$
$$A_{\text{shared}} = 4 \times 4 = 16\,\text{m}^2$$

$A_{\textbf{indoor}}$ area of the *indoor* chamber (3 walls + floor + ceiling) [m^2].

$A_{\textbf{outdoor}}$ area of the *outdoor* chamber (3 walls + floor + ceiling) [m^2].

$A_{\textbf{shared}}$ shared area between both rooms [m^2].

10.2 Simulation parameters

One of the goal of this application is to determine the power of the HVAC unit that will compensate the losses and the gains inside the chamber to maintain stable conditions. Therefore, multiple parameters are necessary to compute all the variables from the energy balance in equation (6).

10.2.1 Global settings

The global settings set the ambient temperature around the testing facility. In this case, because the chamber is situated inside a building, a constant temperature of 20°C is assumed. The simulation period is set at 24 hours with a time step of 60 seconds. Other ambient temperature profiles could be defined inside the application (sinusoidal evolution or file upload) but a constant temperature is more relevant in these circumstances.

10.2.2 Chamber setpoints

As both rooms are supposed to simulate two different environments to test a system, both chambers are set at different target temperatures. These temperatures must stay stable during the duration of the simulation and this is achieved by the HVAC units in each chamber which will compensate the heat fluxes entering or exiting the room. For the indoor room (Zone 1) the target temperature will be set at 20° while the outdoor room (Zone 2) stabilises at 0°C. Appliances like measuring tools or sensors are assumed to be present inside each room and emit 200 W.

10.2.3 Test bench

The test bench in this case is a heat pump with the condenser in Zone 1 and the compressor and evaporator in Zone 2. The refrigerant inside the evaporator will absorb the energy inside Zone 2 then be compressed to deliver heat inside Zone 1. The expander is used to reset the pressure of the refrigerant before entering the evaporator. A scheme of the psychrometric room is shown in Figure 6.

The condenser is set to deliver a constant 10 kW meaning $Q_{\text{testbench, zone 1}}$ is equal to 10 kW. The evaporator *consumption* is then computed by assuming a COP (Coefficient of Performance) of 4 for the heat pump resulting in a consumption of 10 - 2.5 = 7.5 kW.

$$COP = \frac{\dot{Q}_{\text{heating}}}{\dot{W}_{\text{comp}}} \quad \Leftrightarrow \quad \dot{W}_{\text{comp}} = \frac{\dot{Q}_{\text{heating}}}{COP} = \frac{10}{4} = 2.5 \text{ kW}$$

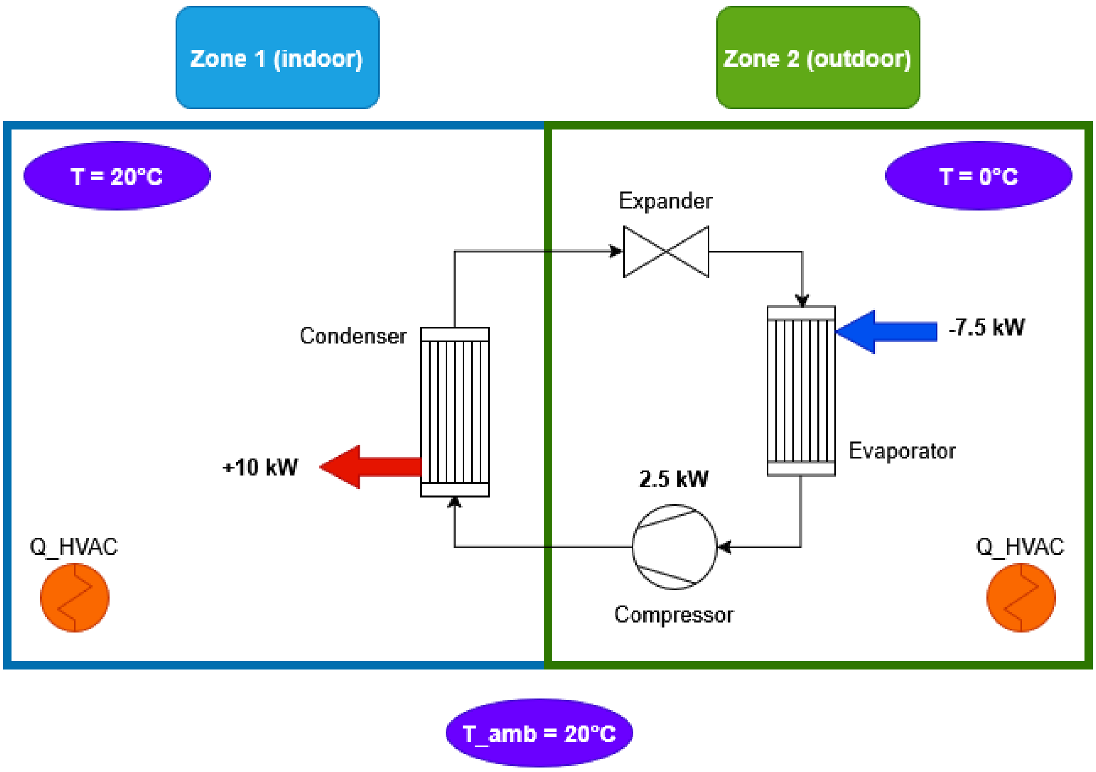


Figure 6: scheme of the psychrometric chamber.

10.2.4 Thermal simulation results

Now that all the heat fluxes have been defined, the energy balance from equation (6) can be resolved and the HVAC requirements of the chamber can be defined.

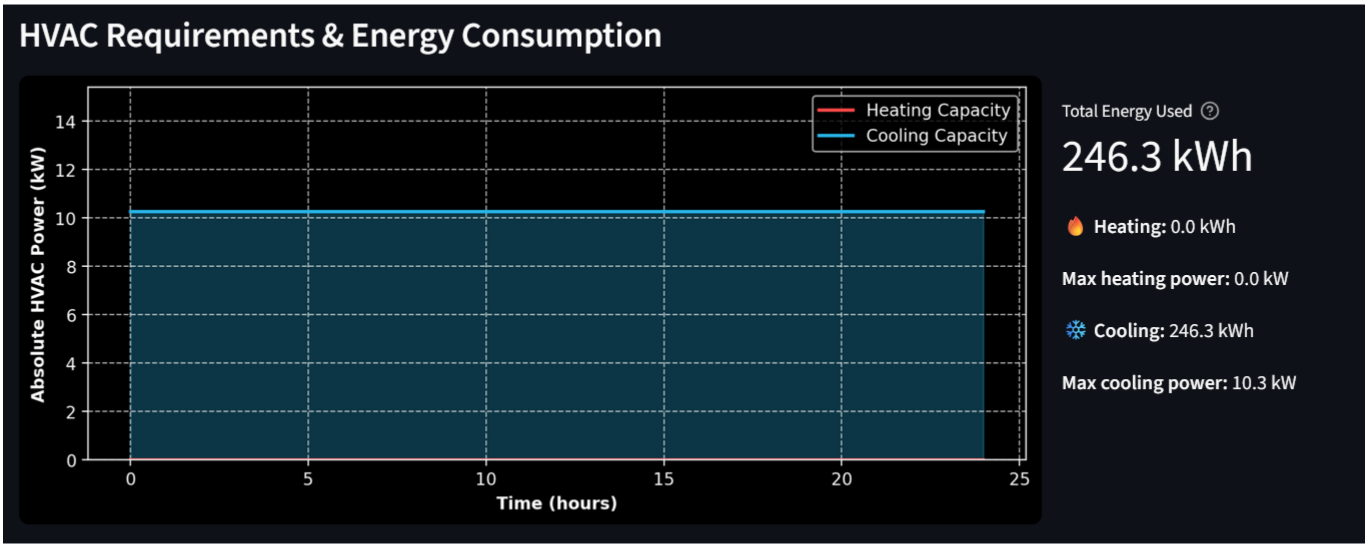


Figure 7: Results for the HVAC consumption for Zone 1.

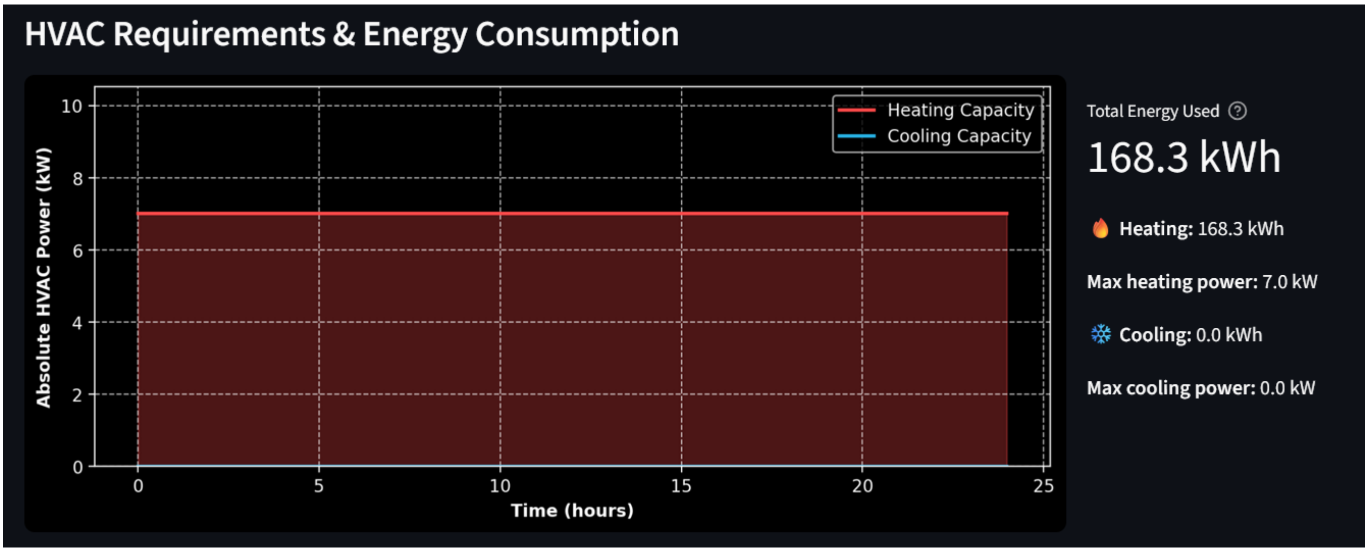


Figure 8: Results for the HVAC consumption for Zone 2.

Figure 7 and Figure 8 both show a constant compensation from the HVAC to maintain the target temperature. This is perfectly normal as no element introduced in the computation varies in function of time. This can be seen as well in Figure 9 where the temperature of the surface does not vary. This is due to the initialisation of the temperatures (see equation (8)) which assumes the heat transfer is in steady-state. As no other variable parameter disturbs this equilibrium, the evolution stays constant. This simulation still indicates the power requirements for the HVAC unit which is one of the objectives of this application. The powers determined by the simulation do not match perfectly with the test bench power as external heat fluxes also play a role in the computation of the HVAC power requirement (see equation (6)).

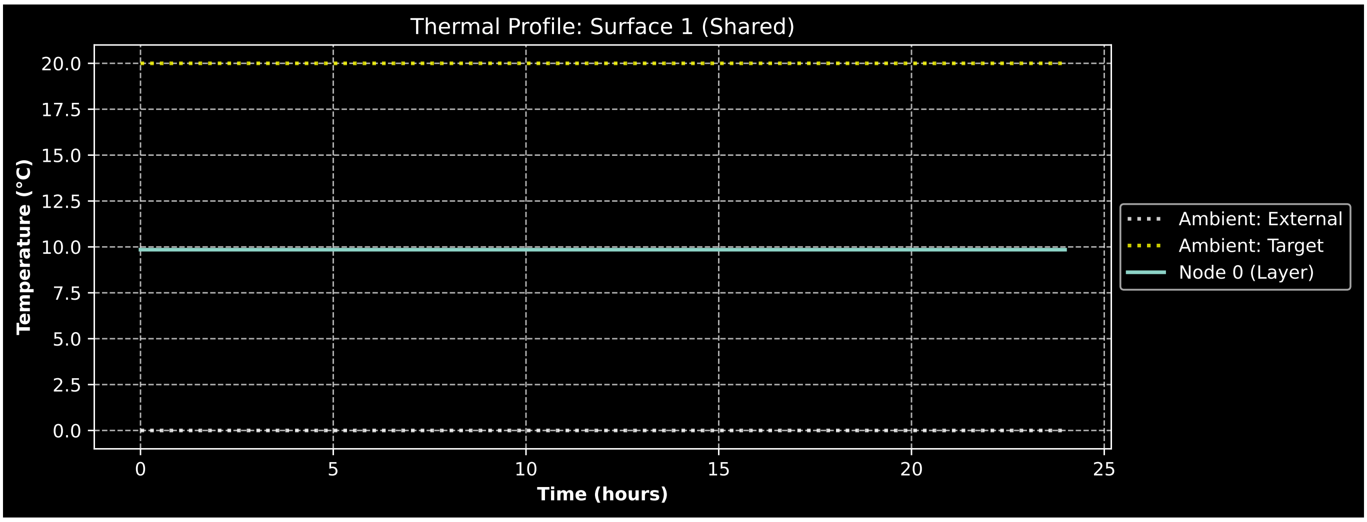


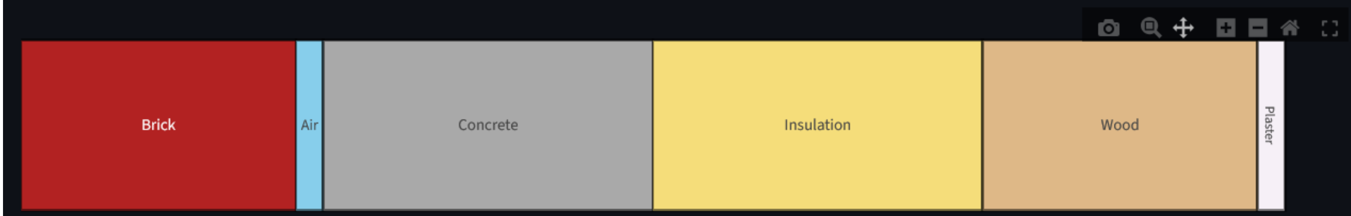
Figure 9: Evolution of the temperature in A_{shared} in function of time.

More interesting results can be observed when using variable parameters like a step cycle for the test bench, meaning the heat pump is turned on and off periodically. Combining this with a variable external temperature (psychrometric chamber in open air) and a more complex wall layering[3] (see Figure 10), the power of this application becomes more obvious. The simulation is done with a mono-chamber in this case. Cooling and heating capacity both show as positive in Figure 11 using colours to distinguish themselves.

Wall Area (m²): 64.00

External Boundary Condition: Open air

Material	Thickness (m)	k [W/(m.K)]	ρ [kg/m³]	Cp [J/(kg.K)]
Brick	0.1	1.1	1800	840
Air	1e-5	0.176	1.2	1000
Concrete	0.12	0.9	1200	1000
Insulation	0.12	0.026	35	830
Wood	0.1	0.14	500	2500
Plaster	1e-2	0.52	1300	840



Overall heat transfer coefficient: AU = 11.0665 W/(m².K)

Figure 10: Complex wall configuration input and scheme.

[3] Materials not really relevant for a psychrometric chamber.

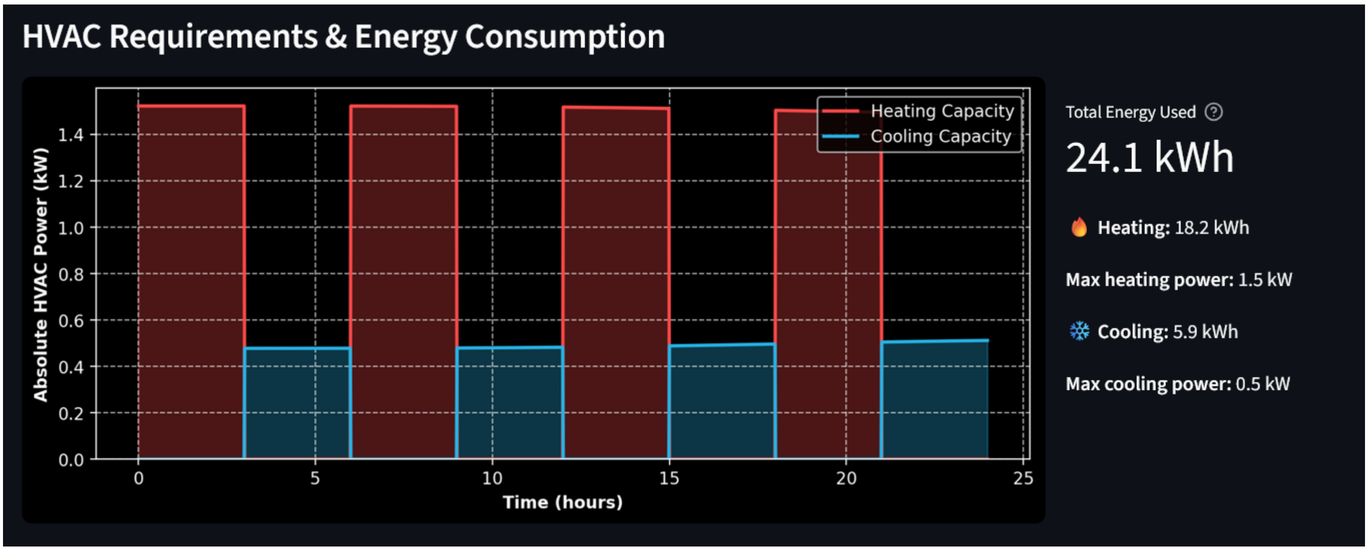


Figure 11: Results for the HVAC consumption for the mono-chamber configuration.

Figure 12 shows the evolution of temperatures but also highlights the neglecting feature of thin layers (in this case air and plaster). It also shows the dynamic aspect of the simulation and the role of the thermal capacities as thermal inertia.

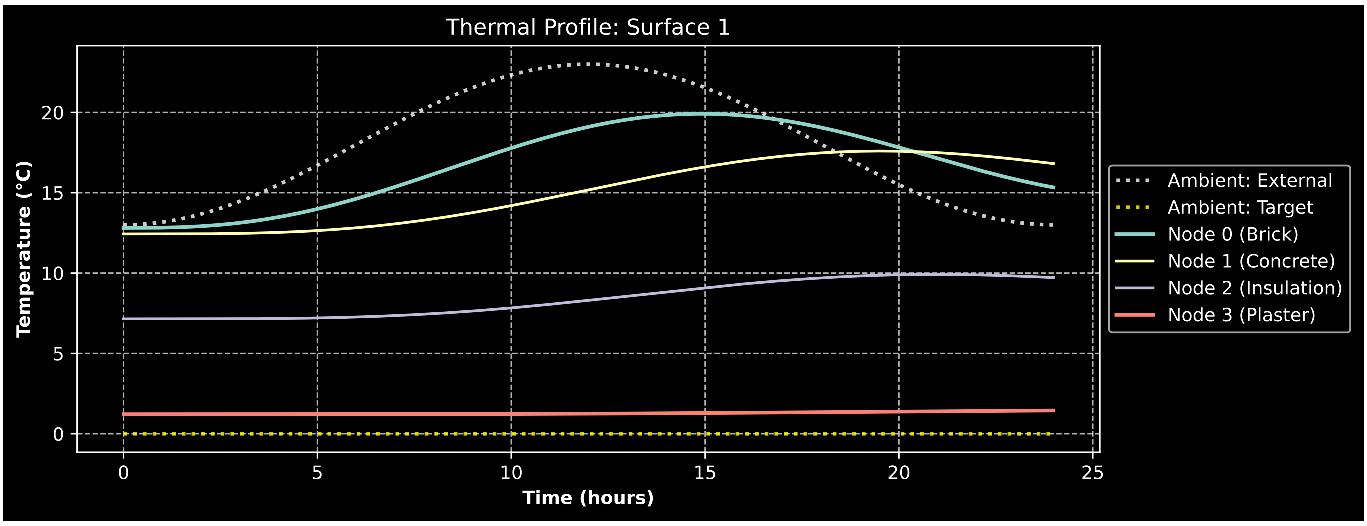


Figure 12: Evolution of the temperatures in each layer in function of time.

10.3 Safety parameters

This subsection will return to the original input parameters defined at the beginning of section 10 as the complex configuration was just used to highlight the possibilities of the web application.

10.3.1 Refrigerant

Now that the power of the test bench is clearly defined, one can choose the refrigerant and estimate the amount that will be contained in the test bench. Propane (R290) is selected for the baseline test bench due to its inherent hazards; as a highly flammable refrigerant, it enforces the strictest regulatory constraints and thus represents a worst-case scenario for the facility design. Multiple papers [30] and projects [31] studied this aspect of specific refrigerant charge, defining an amount of refrigerant depending on the power of the system. Figure 13 shows for example different specific charges for different applications. The project conducted by Frauenhofer ISE (Institute for Solar Energy Systems) [31] had the goal of reducing the amount of propane below 150 g for a refrigeration circuit achieving a specific refrigerant charge of 10 g/kW. This parameter however varies a lot depending on the application and papers do not specifically set a value for the test bench that is designed.

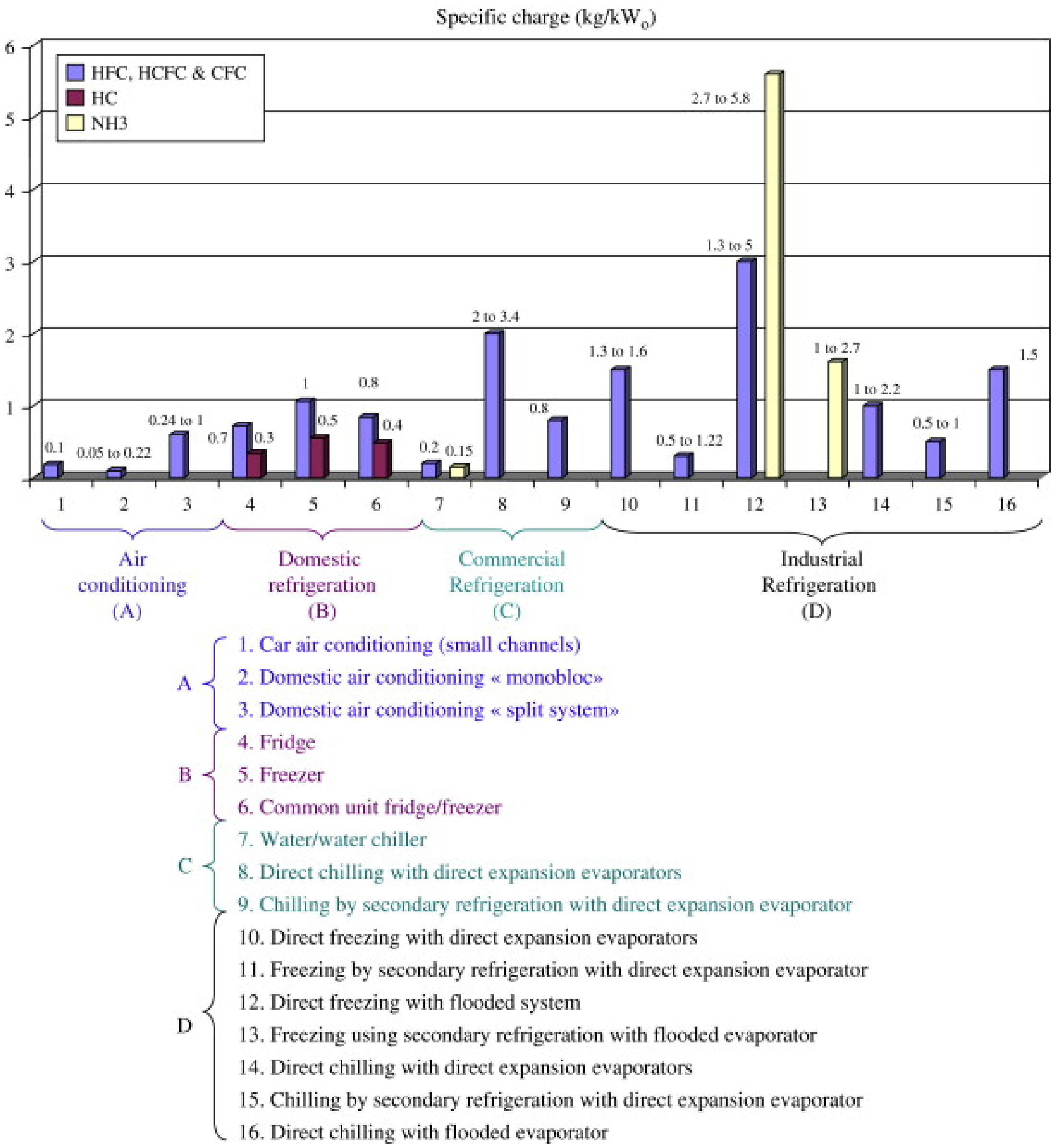


Figure 13: Specific refrigerant charge depending on the application [30].

A good solution is thus to look at split heat pumps from the commercial world. A 10 kW air-to-water heat pump from Toshiba [32] uses 2 kg of propane. This value of 2 kg will thus be used to assess the safety requirements. One could be tempted to divide this quantity by two as only half of the refrigerant charge (approximately) is present in a zone. This is however a wrong assumption to make as when a leak occurs, the entire charge of refrigerant contained in the test bench can flow out of the system in one zone. It is therefore important to take the whole refrigerant charge in the safety assessment.

10.3.2 Volume and location

The volume of each chamber can be easily obtained as the dimensions of each individual chamber were set previously (4 x 4 x 4). Both volumes are equal as the dimensions are the same.

$$V_{z_1,\, z_2} = 4 \times 4 \times 4 = 64\,\mathrm{m}^3$$

The remaining inputs are directly linked to the EN 378 standard and define the location class and access category. The definitions of these can be found in section 4 or directly in the wiki provided in the application. For this case, the twin-chamber psychrometric testing facility is considered as a machinery room (location class III) and only authorized personnel are able to access it (access category c). This is the standard for academical and industrial chambers that were visited like the one at Copeland [29].

10.3.3 Safety assessment results

Now that all the safety parameters have been defined, the results of the assessment can be obtained. As both chambers use the same parameters (volume, refrigerant...), the assessment results are the same for both individual chambers. As shown in Figure 14, there is actually no restriction on the refrigerant charge in this configuration, permitting thus a charge of 2 kg. The minimum and emergency ventilation rates computed from the EN 378 standard provide key operational requirements for the chambers. Nonetheless, meeting these EN 378 criteria does not mean the entire facility is fundamentally *safe*. These results serve as an initial indication rather than a final verification; executing a detailed study of adjacent standards like the EN 60079 series is mandatory to draft a legally compliant Explosion Protection Document (EPD) and officially certify the psychrometric installation.

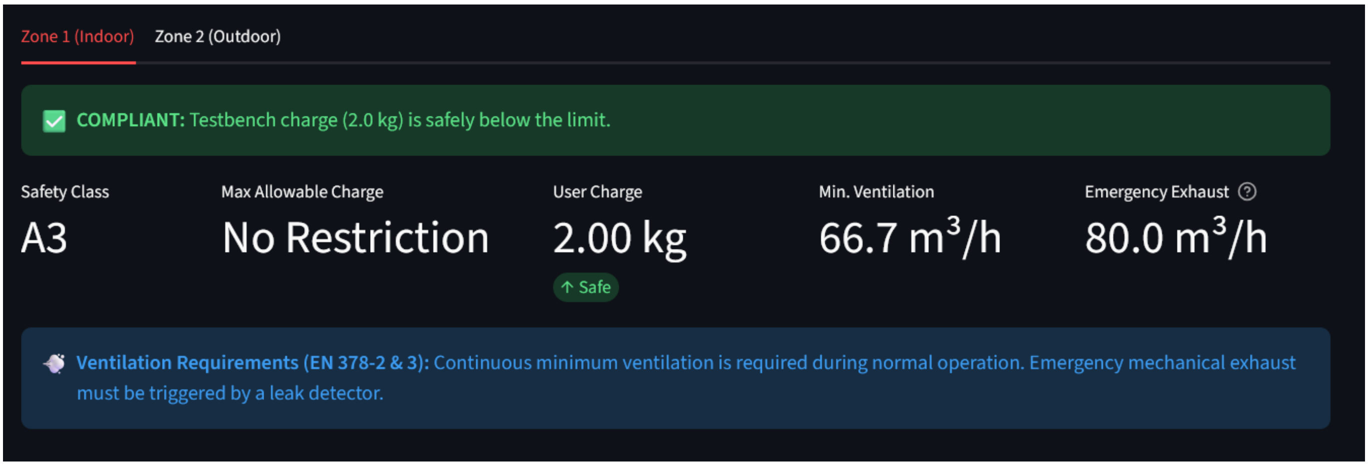


Figure 14: Safety results obtained after assessment for the twin-chamber configuration.

11 Techno-economic analysis

The objective of this thesis was to establish a framework for the design of an ATEX certified psychrometric chamber. Part of this framework is also economical, as such a chamber would require a significant budget to install. Therefore, contacting an industrial building testing facilities to obtain a budget offer would provide a good estimation of a cost if the laboratory chose to outsource the installation of the chamber. A comparison will also be made with a *self-made* chamber which is just the addition of all the components to estimate the cost of the *service*.

11.1 Baseline scenario

To effectively compare both budget, it is important to have the same specifications for both cases. This is why a baseline scenario is defined which is a borderline case that encompasses all the potential test benches that the laboratory would want to test inside this chamber.

Table 5: Technical specifications and dimensions of the baseline scenario.

Parameter	Specification
Configuration	Twin chamber system
Temperature Range	-30°C < T < +60°C
Humidity Range	30% < RH < 90%
Heating Rate	4.0 K/min
Cooling Rate	3.0 K/min
Heat Load Compensation	30 kW @ +20°C
Safety System	Integrated ATEX protection provided
Individual Chamber Dimensions (Length × Width × Height)	3200 × 3140 × 3204 mm
Individual Chamber Volume	32.19 m^3
Overall Facility Dimensions (Length × Width × Height)	6717 × 4442.5 × 3447 mm

11.2 Aralab commercial offer

Aralab provided a ballpark budgeting based on the initial demand made by the laboratory. As the requirements were not completely fixed, the baseline scenario was adjusted afterwards to match the description given by Aralab in the offer. They also provided a technical drawing of the chamber shown in Figure 15 and gave precisions concerning the integrated ATEX system and the HVAC system.

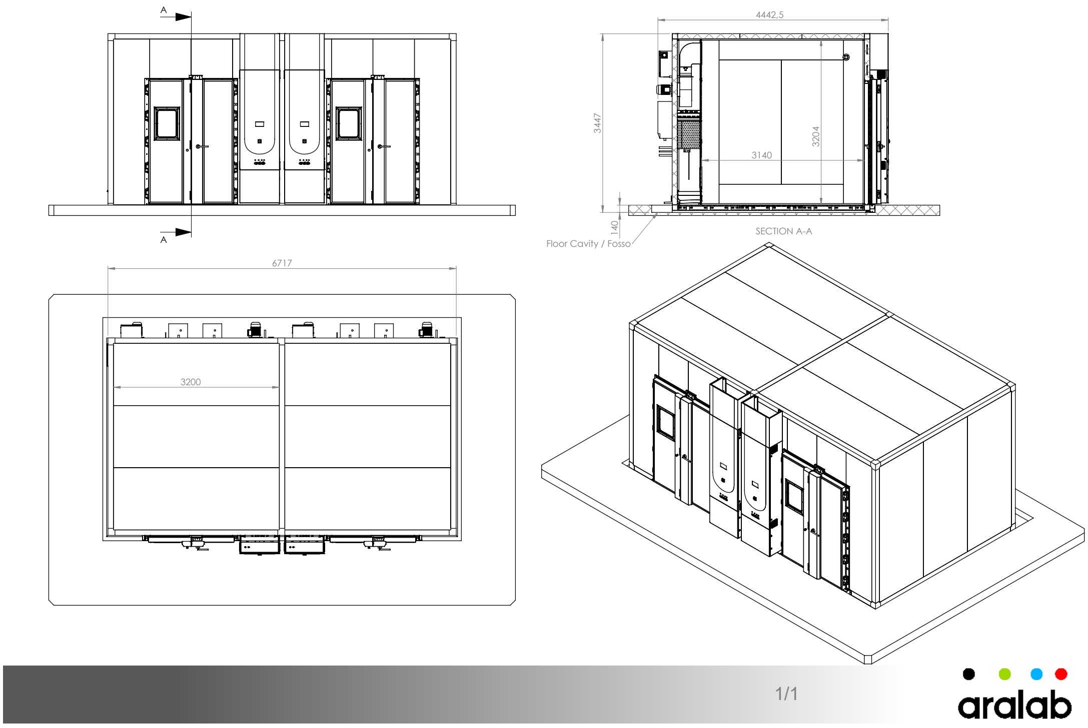


Figure 15: Technical drawing of the psychrometric twin-chamber provided by Aralab [7].

The ATEX system is composed of:

- A control unit to manage the system,

- Two to three gas sensors mounted externally on a panel which collects samples from inside the chamber,
- A fire detection sensor installed inside the chamber,
- ATEX-certified lighting,
- Magnetic door locks supported by two emergency buttons located inside and outside the facility,
- Sprinklers for fire suppression,
- ATEX air renovation system composed of two outlets with a 160 mm diameter that are connected to valves installed on top of the chamber for exterior air routing as well as ATEX-certified fans.

The heating and cooling of the chamber to obtain stable conditions is achieved through stainless steel electric heaters (heating) and an internal evaporator (cooling) connected to a water-cooled compressor/condenser.

Aralab proposed a ballpark budget of €265.000 for each individual chamber as well as 2 times €35.000 for the ATEX system. The installation costs are not provided as a on-site visit is necessary to estimate the cost of installation. The global ballpark budget is thus:

$$Cost_{Aralab} = 2 \times 265000 + 2 \times 35000 = €600000 \tag{13}$$

11.3 Self-made chamber cost estimation

To estimate the cost of a *self-made* psychrometric chamber similar to the one designed by Aralab, it is important to look at all the components that are necessary to set up such a testing facility. A non exhaustive list of components will thus be studied and their cost estimated to finally assess the global cost of the assembly.

11.3.1 Enclosure

One of the prime component of a psychrometric chamber is obviously the enclosure it creates to isolate the inner environment from the outside. Combined with a frame for structural stability, the enclosure often achieves a good thermal isolation using sandwich panels made of insulating materials (e.g. polyurethane foam) which help the chamber maintain stable conditions.

The frame can be made out of wood or metal and depending on the stability required, the cost can vary significantly. A metal framework specifically designed to avoid thermal bridges using insulating material for connections, can be estimated at 40 to 70 €/m^2 which would result in a cost of minimum €6000 up to €10500. Such profiles can be found on Alusic.com [33], an Italian producers of aluminium profiles and accessories.

To estimate the cost of these panels, the surface they will occupy must first be determined. Based on the dimensions found in Table 5, the total surface of panel needed can be computed as followed:

- **Roof and floor panels**

$$2 \times 6.717 \times 4.4425 = 59.68 \text{ m}^2$$

- **Exterior walls**

$$2 \times 6.717 \times 3.447 + 2 \times 3.447 \times 4.4425 = 46.31 + 30.63 = 76.94 \text{ m}^2$$

- **Internal shared wall**

$$3.14 \times 3.204 = 10.06 \text{ m}^2$$

This estimation of the surface is quite conservative (using the external dimensions instead of the internal ones) taking into account some integrated components like fans which could be integrated differently in the *self-made* chamber compared to the Aralab proposal. Taking an additional 10% surface accounting for manufacturing losses, the total surface can be estimated at:

$$(59.68 + 76.94 + 10.06)(1 + 10\%) = 150.282 \text{ m}^2$$

The thickness of the panels is assumed to be equal to 100 mm. This assumption is made because the total length of the chamber is ≈ 300 mm longer than the sum of the internal lengths of the individual chambers (see equation (14)). Since there are three walls along the length of the facility, a thickness of 100 mm can be assumed for each panel.

$$6717 - 2 \times 3200 = 317 \,\text{mm} \tag{14}$$

The cost of the panels can be estimated by taking a price per meter squared [34]:

$$150.282 \times 51.12 = €7682.42 \tag{15}$$

If structural insulated panels would be used (SIP), then the cost per square meter can evolve between 100 and 180 €/m2. In such case the total cost for the panels could be as high as €27000. Advantage could be that the cost of the framework would be less.

With such panels also be used for the floor some additional measures will be needed to be able to walk and work in the chamber. For approximately 30 square meter the cost of wooden panels and a floor covering can be kept inexpensive around 40 €/m2 or for a total of €1200. Depending on the desired finish, this can obviously become much higher. In case an antistatic or conductive flooring is needed in order to prevent electrostatic discharges leading to sparks, 2 systems are recommended: one using permanent antistatic PVC tiles at 85 €/m2 totalling at €2550 [35] or a conductive epoxy coating at 95 €/m2 totalling at €2850 [36]. In case a conductive epoxy coating is selected, a very stable floor like a concrete floor will be needed. In both cases some costs will be involved for earthing kits and copper tape grids at a cost of around 500 €/room. Flooring cost will thus vary from as little as €1200 to €3850.

With the walls, ceiling and roof determined, two doors must still be installed to access both rooms. The cost of one single cold room door (dimensions 800mm x 2000mm) on the Noma website [37] is €1281,23 thus resulting in a total price for two doors of €2562,46. For double doors as used in the Aralab offer (dimensions 1600mm x 2000mm) the cost would be 2389,49 €/door or €4778,98 for 2 doors. An additional €500 should be spent on magnetic ATEX approved doorlocks from e.g. Securex [38]. For the 2 doors this could be another €1000.

11.3.2 Cooling and heating

The evaporator found to answer the cooling demand is a nearly 30 kW [39] evaporator costing €10148 [40] (see Figure 16. Combining it with a low-temperature water-cooled condensing unit and a two stage compressor evaluated at €3471.22 [41], the budget for cooling is estimated at €13619.22.

Each individual room will also need a heating element. Special ATEX room heaters can be found in the industry at Kuhlmann for water heaters [42] or Vulcanic for fan heaters [43]. For this thesis the Vulv=canic ATEX 112G IIC T3 Fan heater of 15 kW and 400 V connection was selected for each room (see Figure 17). An accurate price is only available after a study from the supplier, but will vary between €3500 and €7000 per heater depending on the custom configuration and selected optional accessories. For this calculation we will take the average of €5250 x 2 = €10500.

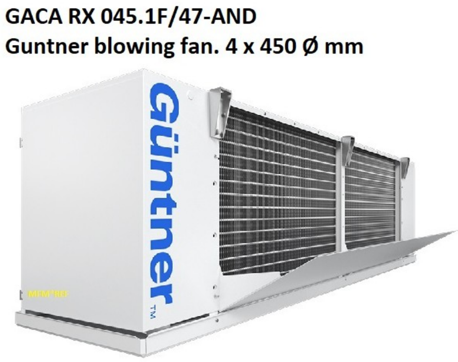


Figure 16: Guntner 30 kW evaporator.

Figure 17: Vulcanic fan heater.

11.3.3 ATEX electrical equipment

In such rooms good lighting is indispensable. From a simple light bulb to a fully studied lighting solution by specialists are all possible. Several producers can be found like ATEX or with their Slam-Fixed R Ex Luminaires and auxiliary equipment or Trilux with several products like their Kratex, Orex or Acquex luminaires. For this estimation the Acquex LED - M 1.2 40-840 ET PC of 1200 mm long with 4000 lumen and 27 W has been used. Such lights can be found on groothandel.be [44] for the price of 276.25 €/piece (see Figure 18). For our chamber it is safe to apply two of such luminaires per room or in total 4 x 276.25 = €1505.

Gas sensors are also indispensable in an ATEX chamber. Draeger is a well-known company for gas detection equipment. A fixed and continuous model Polytron PIR 7000 has been selected (see Figure 19). For safety reasons we will install 2 gas sensors per room for a total of 4 gas sensors. Prices on the internet vary between €850 (second-hand) and €3500 per device [45]. The price is influenced by the accessories or the distributor found. Total cost is between €3400 and €14000.

Figure 18: Trilux acquex LED ATEX light.

Figure 19: Draeger gas detector.

A control unit with safety features has also to be included. For this the Siemens Simatic ET200SP Safety PLL

3500 can be used and integrated into the electrical installation. This module will enable the communication between different safety features and the electrical system. A cost of €3500 to €5000 has been estimated through a search on the internet for both the safety module and the basic electrical unit and accessories.

Last but not least is the cost for ventilation of both rooms. The ventilation system includes ATEX certified fans, exhaust outlets and ATEX certified valves. Many producers of ATEX approved fans can be found. An example are the ATEX fans from Ziehl-Abegg [46]. Such fans can easily cost up to 2500 €/fan and in order to have maximum safety, 2 per room are needed for a total cost of €10.000. Exhaust valves can be found with Mecafluid and the outlets can be found made in polypropylene in many dimensions, forms and colours. A total cost can be estimated around €2000 for both rooms.

Finally, some additional costs will incur for small supplies and certification of the ATEX label. With material cost from above estimated at a bear minimum of €58587 up to €100453 we can definitely conclude that a whole self-made chamber will be cheaper than the Aralab offer (not negotiated). The disadvantage is that a lot more work and study will have to be done before being capable of installing the chambers.

Part IV

Conclusion

12 Synthesis of research objectives

The HVAC/R industry has constantly evolved in response to environmental regulations, performance requirements, and mandatory safety measures. These developments have led to a renewed adoption of natural refrigerants, particularly hydrocarbons such as propane ($R290$). While these natural fluids offer high thermodynamic performance and low environmental impact, their high flammability introduces significant safety challenges, creating a need for specialized testing facilities in both academic and industrial research environments.

In this context, the University of Liège aims to define the design and safety requirements for an advanced psychrometric testing chamber capable of safely accommodating HVAC/R systems operating with flammable refrigerants. A key objective is to comply with the European ATEX framework. Although the ATEX directives establish the regulatory requirements, conformity is generally demonstrated through the application of standards that provide a presumption of compliance and ensure an adequate level of safety. The complexity of the applicable standards results from the interaction between overarching safety principles, engineering methodologies, and product-specific requirements

To address this challenge, this thesis opts for a *zone-avoidance strategy* aimed at reducing the amount of restrictions that are imposed on the facility. By providing sufficient ventilation, potential refrigerant leaks can be immediately diluted below critical flammability limits, thereby enforcing a *Zone of Negligible Extent* in which an explosive atmosphere is not able to form. Furthermore, the implementation of automatic shutdown procedures triggered by refrigerant leak detection or ventilation system failure ensures that, should an explosive atmosphere occur, no spark could generate and ignite a potentially leaked refrigerant.

13 Design & modelling overview

To bridge the gap between the regulatory framework and the technical requirements, a comprehensive engineering design tool was successfully developed as a Python-based Streamlit web application [25]. The application orchestrates a three-tier computational engine:

(1) A transient, one-dimensional thermal RC network model for calculating the heat transfer through the walls.

(2) A dynamic energy balance module that tracks real-time thermal heat fluxes across the chamber boundaries and thermal loads within the chamber, enabling the sizing of the heating and cooling capacity required to maintain stable operating conditions.

(3) A tree-based decision model that maps EN 378 compliance pathways, calculates mandatory volumetric dilution air flow rates and maximum allowable refrigerant charges to assess the safety of the psychrometric chamber.

The developed web application offers the possibility to simulate either a twin-chamber or a mono-chamber configurations. By combining thermal modelling with safety assessment, it provides a practical decision-support tool for evaluating design alternatives and identifying configurations that satisfy both performance and regulatory requirements.

14 Techno-economic assessment

The techno-economic evaluation reveals a significant trade-off between the capital expenditure for the installation and the engineering workload required from the laboratory. To ensure a meaningful comparison, a reference case corresponding to a realistic twin-chamber psychrometric facility was established.

Based on the commercial proposal received from Aralab, the estimated investment costs (without the installation costs) amount to approximately €600,000, including €265,000 for each individual climate chamber and €35,000 per room for the fully integrated ATEX safety system. On the other hand, the estimated material cost for a self-built twin-chamber facility, including PIR sandwich panels, a custom frame, antistatic flooring, ATEX-certified heaters, refrigeration units, gas sensors, and extraction fans, ranges between €58,587 and €100,453.

Although the self-built solution offers a substantially lower initial investment cost, it transfers the responsibility for the design, integration, validation, and regulatory compliance of the installation entirely to the laboratory. Most importantly, a self-built facility lacks a conformity assessment. The university would need to undertake a unit verification procedure with an external Notified Body to officially certify the installation. As such, the final decision should balance financial considerations against the available internal expertise, project timeline, and long-term operational responsibilities. Sourcing a solution from Aralab is therefore more expensive, but it represents a significantly less stressful option for the laboratory.

15 Future perspectives

While this framework successfully outlines the physical, safety, and economic requirements for the psychrometric chamber, several further steps remain to transition this study into a fully operational testing facility:

- **Investigation of EN 60079 dilution mechanics:** the current safety framework relies on the empirical formulas provided by the EN 378 standard. The next step is the thorough integration of the EN IEC 60079 framework. This includes defining the specific gas release rate under realistic rupture geometries, calculate the corresponding ventilation required for safe dispersion, and formally assess the resulting *degree of dilution* to support the Zone 2 (NE) classification within the EPD (Explosion Protection Document).
- **Integration of HVAC heat recovery systems:** To optimize the operational efficiency of the facility, future studies could investigate the feasibility of an integrated heat recovery system. Capitalizing on the simultaneous thermal demand of the twin-chamber system for example would drastically reduce the net thermal load, directly reducing the long-term energy consumption of the installation.
- **Refinement of the financial sizing for a *self-made* chamber:** The techno-economic evaluation could be transitioned from a preliminary estimate into a more accurate budget by engaging directly with industrial manufacturers. Obtaining formal quotations for the specialized sandwich panels, ATEX component packages, and HVAC units would reduce pricing uncertainty and provide a reliable basis for estimating self-made assembly costs, transportation logistics, and unit certification fees.

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Appendices

Appendix A – EN 60079 protection modes

Table 6: Common electrical protection types and associated standards within the EN IEC 60079 series.

Code	Protection concept	Standard	Basic engineering principle
Ex d	Flameproof enclosure	EN IEC 60079-1	Contains the explosion internally and prevents external flame transmission through specialized threaded joints.
Ex e	Increased safety	EN IEC 60079-7	Prevents arcs, sparks, and hot spots through strict structural clearances and impact-resistant terminals.
Ex i	Intrinsic safety	EN IEC 60079-11	Limits the total available electrical energy within the circuit to levels below the minimum ignition energy (MIE) of the gas.
Ex p	Pressurized enclosure	EN IEC 60079-2	Prevents the ingress of surrounding flammable gas by maintaining a continuous positive internal overpressure with an inert gas or clean air.
Ex n	Non-sparking	EN IEC 60079-15	Provides a simplified level of protection restricted to zone 2 applications, ensuring no ignition sources are active during normal operation.
Ex m	Encapsulation	EN IEC 60079-18	Seals potential ignition sources inside a specialized compounds or resin to isolate them physically from the explosive atmosphere.
Ex o	Oil immersion	EN IEC 60079-6	Submerges electrical contacts or parts in an oil barrier to prevent contact with the surrounding explosive gas mixture.
Ex q	Powder filling	EN IEC 60079-5	Fills the internal enclosure volume with quartz sand or glass particles to capture and extinguish any developing internal flames.
Ex t	Dust tight enclosure	EN IEC 60079-31	Prevents combustible dust layers from entering the housing using tight physical seals, preventing surface temperature ignition risks.

Appendix B – EN 80079 protection modes

Table 7: Non-electrical types of protection according to EN ISO 80079-37 [22].

Protection type	Protection concept	Basic engineering principle
Ex h - 'c'	Constructional safety	**Design-based prevention:** Eliminates risks through mechanical design by utilizing non-sparking material pairings, legally mandated clearances, and robust bearing seals to prevent friction or impact sparks.
Ex h - 'b'	Control of ignition sources	**Sensor-based mitigation:** Introduces active monitoring loops (such as thermal, vibration, or oil-level sensors) to identify mechanical anomalies and trip safety relays before hot spots reach the auto-ignition temperature of the gas.
Ex h - 'k'	Liquid immersion	**Isolation-based containment:** Submerges moving mechanical interfaces entirely within a protective fluid barrier (e.g., oil) to physically isolate potential sparks or frictional heat from contact with the surrounding explosive atmosphere.

Appendix C – EN 378-1 tables

Table 8: Access categories.
Reproduction of Table 4 from EN 378-1 [16].

Categories	General characteristics	Examples
General access **a**	Rooms, parts of buildings, buildings where sleeping facilities are provided, people are restricted in their movement, an uncontrolled number of people are present, any person has access without being personally acquainted with the necessary safety precautions.	Hospitals, courts or prisons, theatres, supermarkets, schools, lecture halls, public transport termini, hotels, dwellings, restaurants.
Supervised access **b**	Rooms, parts of buildings, buildings where only a limited number of people may be assembled, some being necessarily acquainted with the general safety precautions of the establishment.	Business or professional offices, laboratories, places for general manufacturing and where people work.
Authorized access **c**	Rooms, parts of buildings, buildings where only authorized persons have access, who are acquainted with general and special safety precautions of the establishment and where manufacturing, processing or storage of material or product take place.	Manufacturing facilities, e.g. for chemuicals, food beverage, ice, ice cream, refineries, cold stores, dairies, abattoirs, non-public areas in supermarkets.

Table 9: Charge limit requirements for refrigerating systems based on toxicity. Reproduction of Table C.1 from EN 378-1 [16].

<table>
<tr><th rowspan="2">Toxicity class</th><th rowspan="2" colspan="2">Access category</th><th colspan="4">Location classification</th></tr>
<tr><th>I</th><th>II</th><th>III</th><th>IV</th></tr>
<tr><td rowspan="5">A</td><td colspan="2">a</td><td colspan="2">Toxicity limit × Room volume</td><td rowspan="5">No charge restriction[a]</td><td rowspan="11">The charge requirements based on toxicity shall be assessed according to location I, II or III, depending on the location of the ventilated enclosure</td></tr>
<tr><td rowspan="2">b</td><td>Upper floors without emergency exit or below ground floor level</td><td>Toxicity limit × Room volume</td><td rowspan="4">No charge restriction[a]</td></tr>
<tr><td>Other</td><td>No charge restriction[a]</td></tr>
<tr><td rowspan="2">c</td><td>Upper floors without emergency exit or below ground floor level</td><td>Toxicity limit × Room volume</td></tr>
<tr><td>Other</td><td>No charge restriction[a]</td></tr>
<tr><td rowspan="6">B</td><td colspan="2">a</td><td colspan="2">Toxicity limit × Room volume[b]</td><td rowspan="6">No charge restriction[a]</td></tr>
<tr><td rowspan="3">b</td><td>Upper floors without emergency exit or below ground floor level</td><td>Toxicity limit × Room volume</td><td>Charge not more than 25 kg[a]</td></tr>
<tr><td>Density of personnel < 1 person / 10 m^2</td><td rowspan="2">Charge not more than 10 kg[a]</td><td>No charge restriction[a]</td></tr>
<tr><td>Other</td><td>Charge not more than 25 kg[a]</td></tr>
<tr><td rowspan="2">c</td><td>Density of personnel < 1 person / 10 m^2</td><td>Charge not more than 50 kg[a] and emergency exits are available</td><td>No charge restriction[a]</td></tr>
<tr><td>Other</td><td>Charge not more than 10 kg[a]</td><td>Charge not more than 25 kg[a]</td></tr>
</table>

[a] For open air, EN 378-3 section 4.2 applies and for machinery rooms, EN 378-3 section 4.3 applies.
[b] For sealed sorption systems, toxicity limit × volume and not more than 2.5 kg.

Table 10: Charge limit requirements for refrigerating systems based on flammability. Reproduction of Table C.2 from EN 378-1 [16].

Flammability class	Access category			Location classification I	Location classification II	III	IV
2L	**a**	Human comfort		According to C.2 and $\leq m_2$[a] $\times$ 1.5 or According to C.3 and $\leq m_3$[b] $\times$ 1.5		No charge restriction[c]	Refrigerant charge $\leq m_3$[b] $\times$ 1.5
		Other applications		20% $\times$ LFL $\times$ Room volume and $\leq m_2$[a] $\times$ 1.5 or According to C.3 and $\leq m_3$[b] $\times$ 1.5			
	b	Human comfort		According to C.2 and $\leq m_2$[a] $\times$ 1.5 or According to C.3 and $\leq m_3$[b] $\times$ 1.5			
		Other applications		20% $\times$ LFL $\times$ Room volume and $\leq m_2$[a] $\times$ 1.5 or According to C.3 and $\leq m_3$[b] $\times$ 1.5	20% $\times$ LFL $\times$ Room volume and $\leq$ 25 kg[c] or According to C.3 and $\leq m_3$[b] $\times$ 1.5		
	c	Human comfort		According to C.2 and $\leq m_2$[a] $\times$ 1.5 or According to C.3 and $\leq m_3$[b] $\times$ 1.5			
		Other applications		20% $\times$ LFL $\times$ Room volume and $\leq m_2$[a] $\times$ 1.5 or According to C.3 and $\leq m_3$[b] $\times$ 1.5	20% $\times$ LFL $\times$ Room volume and $\leq$ 25 kg[c] or According to C.3 and $\leq m_3$[b] $\times$ 1.5		
2	**a**	Human comfort		According to C.2 and $\leq m_2$[a]		No charge restriction[c]	Refrigerant charge $\leq m_3$[b]
		Other applications		20% $\times$ LFL $\times$ Room volume and $\leq m_2$[a]			
	b	Human comfort		According to C.2 and $\leq m_2$[a]			
		Other applications		20% $\times$ LFL $\times$ Room volume and $\leq m_2$[a]			
	c	Human comfort		According to C.2 and $\leq m_2$[a]			
		Other applications	Below ground	20% $\times$ LFL $\times$ Room volume and $\leq m_2$[a]			
			Above ground	20% $\times$ LFL $\times$ Room volume and $\leq$ 10 kg[c]	20% $\times$ LFL $\times$ Room volume and $\leq$ 25 kg[c]		

Continued on next page

Table 10 – Continued from previous page

<table>
<tr><th rowspan="2">Flammability class</th><th rowspan="2" colspan="3">Access category</th><th colspan="4">Location classification</th></tr>
<tr><th>I</th><th>II</th><th>III</th><th>IV</th></tr>
<tr><td rowspan="9">3</td><td rowspan="3">a</td><td colspan="2">Human comfort</td><td colspan="2">According to C.2 and $\leq \max(m_2, 1.5\ kg)$</td><td rowspan="3">$\leq$ 5 kg[c]</td><td rowspan="9">Refrigerant charge $\leq m_3$[b]</td></tr>
<tr><td rowspan="2">Other applications</td><td>Below ground</td><td colspan="2">Only sealed systems:
20% $\times$ LFL $\times$ Room volume and $\leq$ 1 kg</td></tr>
<tr><td>Above ground</td><td colspan="2">Only sealed systems:
20% $\times$ LFL $\times$ Room volume and $\leq$ 1.5 kg</td></tr>
<tr><td rowspan="3">b</td><td colspan="2">Human comfort</td><td colspan="2">According to C.2 and $\leq \max(m_2, 1.5\ kg)$</td><td rowspan="3">$\leq$ 10 kg[c]</td></tr>
<tr><td rowspan="2">Other applications</td><td>Below ground</td><td colspan="2">20% $\times$ LFL $\times$ Room volume and $\leq$ 1 kg[a]</td></tr>
<tr><td>Above ground</td><td colspan="2">20% $\times$ LFL $\times$ Room volume and $\leq$ 2.5 kg</td></tr>
<tr><td rowspan="3">c</td><td colspan="2">Human comfort</td><td colspan="2">According to C.2 and $\leq \max(m_2, 1.5\ kg)$</td><td rowspan="3">No charge restriction[c]</td></tr>
<tr><td rowspan="2">Other applications</td><td>Below ground</td><td colspan="2">20% $\times$ LFL $\times$ Room volume and $\leq$ 1 kg[c]</td></tr>
<tr><td>Above ground</td><td>20% $\times$ LFL $\times$ Room volume and $\leq$ 10 kg[c]</td><td>20% $\times$ LFL $\times$ Room volume and $\leq$ 25 kg[c]</td></tr>
</table>

[a] $m_2 = 26\ m^3 \times$ LFL.

[b] $m_3 = 130\ m^3 \times$ LFL.

[c] For open air, EN 378-3 section 4.2 applies and for machinery rooms, EN 378-3 section 4.3 applies.

Appendix D – User guide for web application

The web application can be accessed by following this link `https://psychrometric-simulator.streamlit.app/`. The application itself is hosted on Streamlit servers and may require the user to *wake up* the application before it can be used. The program is composed of three main elements (see Figure 20 for visual annotations):

(1) A sidebar which serves as the scenario manager can be found on the left-side.

(2) Three expanders on the main page under a *master switch*. The *master switch* defines if the psychrometric chamber that will be simulated is a mono-chamber or a twin-chamber configuration. The expanders are structures that can be expanded to reveal data entry boxes and representation of some inputs. These expanders are the following:

  i. Wall configuration expander (see Figure 21): includes all the data relevant for the structure of the walls.

  ii. Simulation parameters expander (see Figure 22)r: includes all the data necessary for the thermal simulation.

  iii. Safety parameters expander (see Figure 23): includes all the data relevant for the safety assessment of the facility.

(3) Two buttons towards the end of the main page which launch either the thermal simulation or the safety assessment. Underneath these buttons, the results of the simulation and safety assessment will be displayed once the buttons have been triggered.

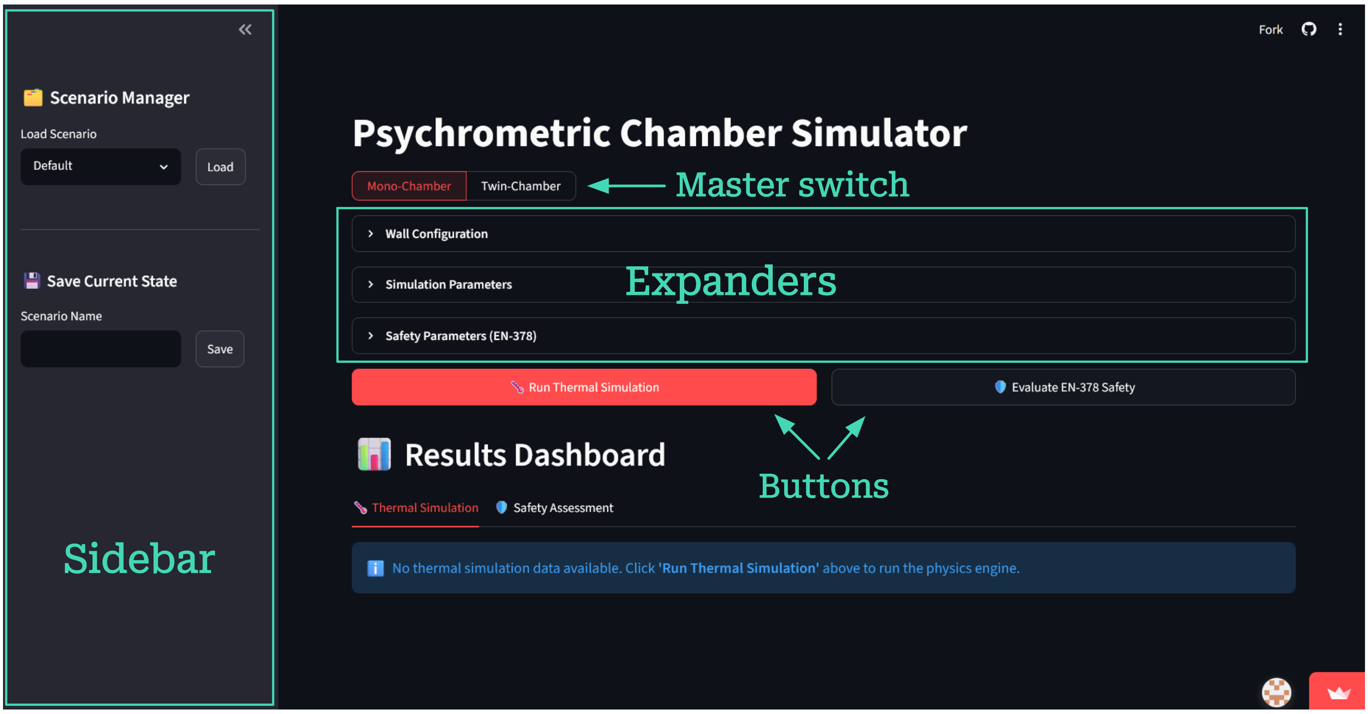

Figure 20: Snapshot of the application with annotations.

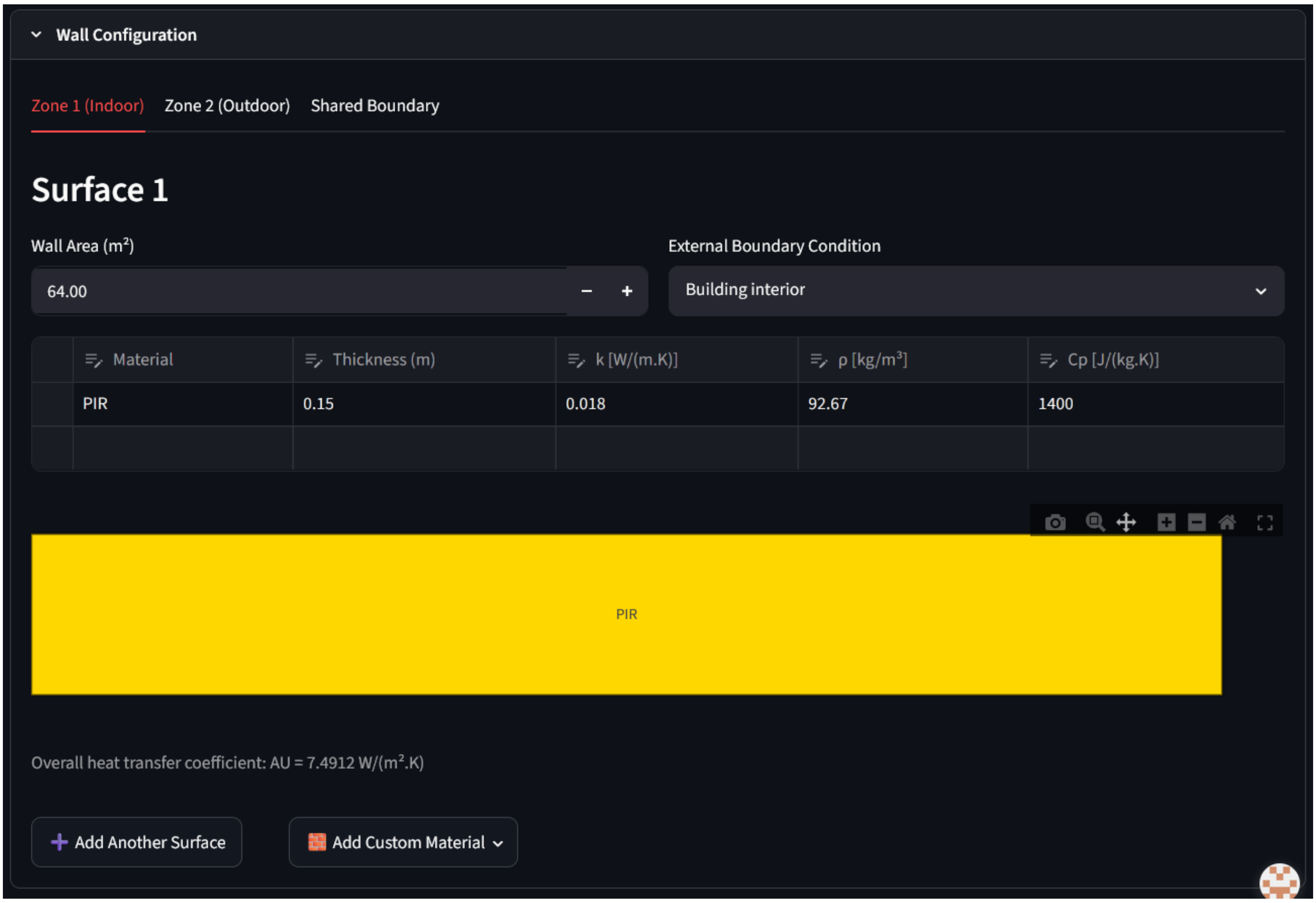

Figure 21: Snapshot of the *wall configuration* expander.

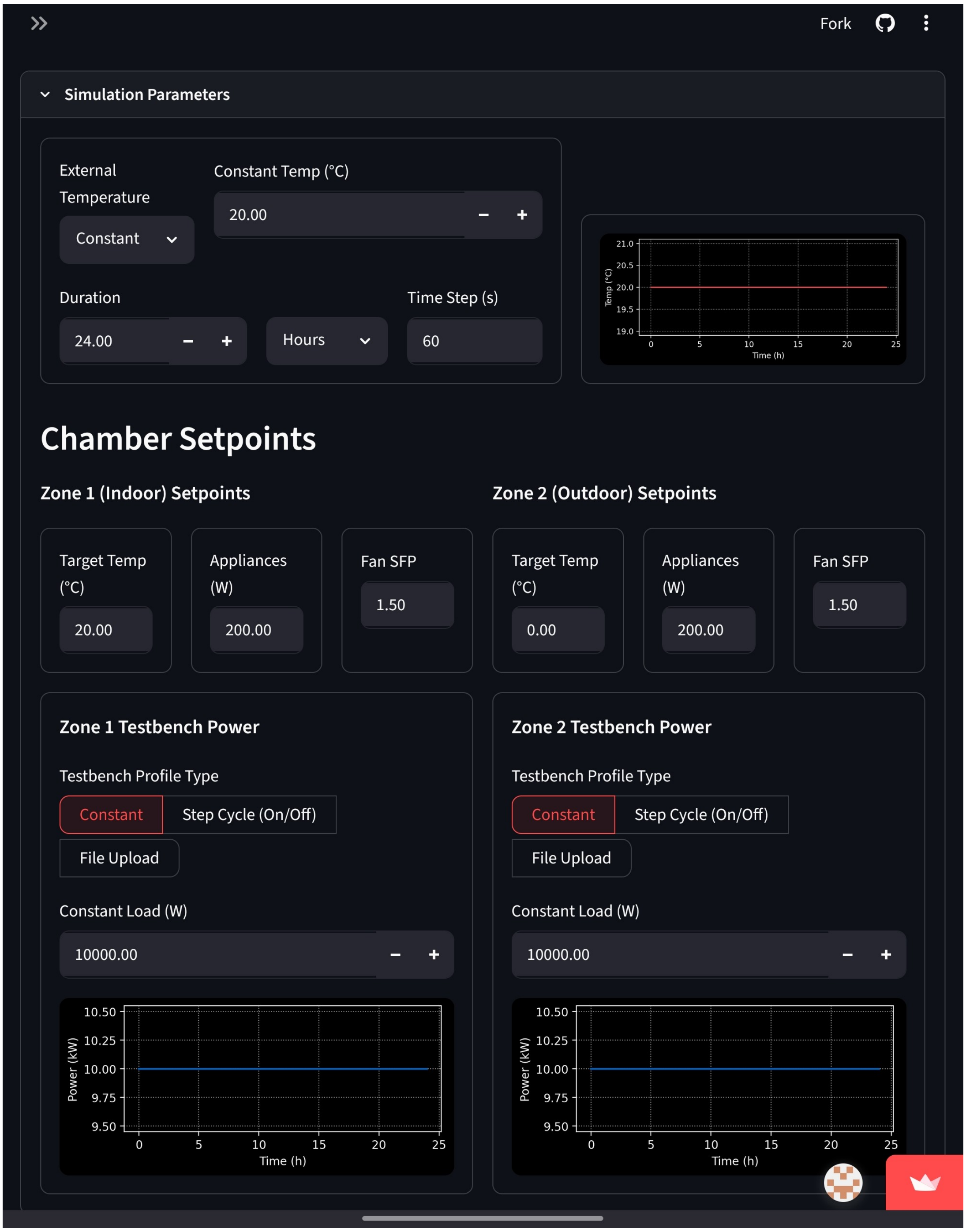

Figure 22: Snapshot of the *simulation parameters* expander.

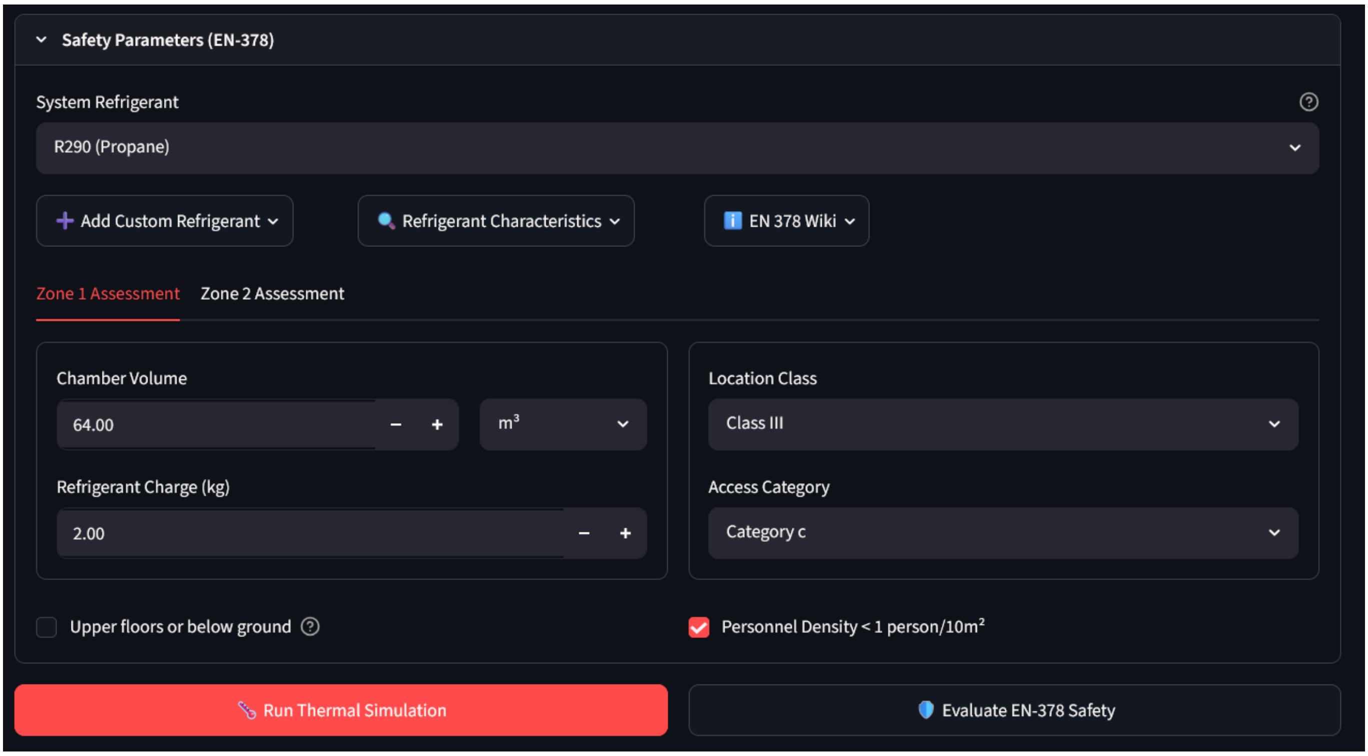

Figure 23: Snapshot of the *safety parameters* expander.

Appendix E – Strategic Analysis of the Internship Enclosure

E.1 Institutional and Human Resources Structure

The Applied Thermodynamics Laboratory (*Laboratoire de Thermodynamique Appliquée* or LaboThAp), integrated within the Faculty of Applied Sciences at the University of Liège, operates with a workforce of approximately thirty members. This team includes professors, senior researchers, PhD candidates, post-doctoral fellows, and specialized technical staff working within a collaborative structure.

The human resources strategy focuses on connecting theoretical modelling with experimental validation by pairing academic researchers with laboratory technicians. Maintaining a continuous rotation of international post-doctoral researchers alongside stable academic chairs allows the laboratory to update its research methodologies, adapt to new engineering challenges, and ensure continuity in its long-term experimental projects.

E.2 Research, Development, and Technology Transfer Strategy

The laboratory focuses on applied thermodynamics and energy systems, organizing its research activities around three primary pillars aligned with the requirements of the energy transition:

- **Advanced thermodynamic cycles:** Studying and optimizing thermal frameworks, such as Organic Rankine Cycles (ORC) and Carnot batteries, to improve global energy efficiency and waste heat recovery.
- **Heat and mass transfer analysis:** Evaluating transport mechanisms across industrial components and customized experimental prototypes developed within the facility.
- **Systemic optimization:** Modelling energetic systems by integrating thermodynamic performance parameters with environmental life-cycle indicators and economic constraints.

An important factor in the laboratory's international recognition is its involvement in open-source software development, highlighted by the co-publication of the open-source thermodynamic library `CoolProp` in 2014.

Widely used by the scientific community and industrial R&D departments, this library computes the thermophysical properties of numerous fluids and fluid mixtures. Because it integrates into industry-standard computational environments such as EES, Python, and MATLAB, `CoolProp` serves as a reliable tool that supports academic citations and increases the visibility of the laboratory's research.

E.3 Market Positioning and Industrial Partnerships

The laboratory positions itself as a bridge between fundamental academic research and practical industrial applications. By participating in regional, national, and international consortiums, the laboratory maintains a network of direct partnerships with industrial operators.

This configuration enables a structured research loop: theoretical mathematical models are validated using experimental data gathered from custom-built test benches and prototypes, after which the validated models and results are transferred back to industrial partners for commercial scaling. This capability to combine numerical modeling with physical experimental validation distinguishes the laboratory from purely simulation-based research institutes and helps secure international research grants.

E.4 Educational Integration and Talent Pipeline

Beyond its core research activities, the laboratory supports its long-term operations through its involvement in academic talent development. By managing specific master's programs at the University of Liège and regularly hosting master's theses, industrial internships, and doctoral projects, the laboratory maintains an internal recruitment pipeline. Embedding students directly within active scientific and industrial projects ensures a continuous supply of qualified researchers while reinforcing links between the university and the surrounding industrial ecosystem.

Appendix F – AI usage

Artificial Intelligence has been mainly used to produce tables and schemes in LateX and reformulate some sentences when judged necessary. AI has also been used in the development of the web application to familiarise myself with the specific functions of Streamlit as this Python library was unknown to me. Finally, researches have also been conducted by AI to obtain context and sources.