Simulation and Data-Driven Investigation of Plate Heat Exchanger Performance in a Solar VARS Cold Storage System

Sri Varsha Dodda

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Supervisor **Dr. Advaith Sankar**

Contents

Abstract

Availability of cold storage facilities that are reliable is important for the minimisation of losses and maintenance of perishable products in areas where electricity is unstable or not available. This work presents the design, simulation, and partial experimental testing of a solar-powered cold storage system incorporating photovoltaic panels, evacuated tube collectors, and a vapour absorption refrigeration cycle utilizing R134a-DMF as the working pair. The system has a phase change material-based cold storage bank sized for 48-hour independence and uses copper-coated plate heat exchangers to increase thermal performance. Simulation workflows with REFPROP, Aspen Plus, and Aspen EDR deliver precise information on mass-energy balances, equipment sizing, and system behavior under different conditions. Validation with first principle energy balance calculations establishes a close agreement in energy duties and coefficient of performance, with errors within acceptable engineering tolerances. The project also includes real-time sensor integration in MATLAB for auto data acquisition and has a machine learning model for COP prediction. On the whole, the developed system provides a sustainable, off-grid option to diesel-based refrigeration and has far-reaching implications for smallholder agriculture and rural health infrastructure.

1 Introduction

Access to reliable cooling is vital for preserving food, medicine, and other perishables, yet many rural areas still depend on diesel sets or weak power lines that make continuous refrigeration costly and uncertain. Solar energy is abundant in countries like India and offers a clean way to meet the growing need for cooling while cutting fuel use and planet-warming emissions. Recent studies show that solar powered cold rooms can run fully on sunlight during the day and keep operating at night by drawing on stored cooling, giving farmers a practical tool to reduce losses.

A solar cold storage unit is usually a combination of two renewable subsystems. The first is a photovoltaic panels that turns sunlight into electricity for fans, pumps, and control devices. The second is a thermal loop that captures solar heat in evacuated tube collectors and drives a vapour absorption refrigeration system. Unlike a conventional vapour compression set, the absorption cycle needs only a small pump motor because the generator gets its heat from hot water rather than from an electric compressor. This shift trims electricity demand and fits well with direct solar heating.

Cooling must continue when sunlight is weak or during cloudy weather. National design guidelines therefore call for every solar cold room to store enough cold for at least two full days. That requirement is met with a thermal energy storage tank filled with a phase change material such as water salt slurry. The material solidifies while the sun shines and later melts to hold the room at the set temperature, so the system can stay off grid for long stretches.

The efficiency of any absorption plant depends on how well its heat exchangers move energy between strong and weak solution streams. Plate heat exchangers are popular because their corrugated channels create turbulence, but research has shown that adding a thin copper spray coating to the plates can lift the heat transfer rate by about 60 percent while raising pressure drop by only 25 percent. The overall thermal performance factor rises by roughly 44 percent, proving that surface modification is a simple way to boost capacity without larger pumps or bigger collectors.

Building on these insights, the present project couples evacuated tube collectors, photovoltaic panels, a R134a and dimethyl formamide absorption pair, storage tanks, copper coated plate heat exchangers into one integrated cold room prototype. The aim is to deliver steady cooling with minimal grid dependence and lower life cycle cost than diesel sets.

2 Research and Theory

2.1 Literature and Research Review

The growing need for cold storage in remote and rural areas has led to increased interest in solar-powered refrigeration systems. These systems provide a sustainable solution to food preservation, especially in off-grid regions where power supply is inconsistent or unavailable. Several researchers have contributed to the development of solar cold storage systems, vapour absorption refrigeration cycles, and thermal enhancements to improve overall system efficiency.

The vapour absorption refrigeration system (VARS) has emerged as a viable alternative to traditional vapour compression systems. Unlike VCRS, which requires high-grade electrical energy, VARS runs on low-grade thermal energy such as solar heat or industrial waste heat. Studies have shown that using working fluids like ammonia–water or water–LiBr can achieve satisfactory cooling, although challenges like corrosion and crystallization exist. New working fluid combinations, such as R134a and DMF, offer better thermal performance and are environmentally friendly.

To further improve VARS efficiency, solar collectors like evacuated tube collectors (ETCs) are commonly used to heat water for the generator. ETCs are more efficient than flat plate collectors, especially in tropical and humid climates. When integrated with thermal energy storage (TES) using phase change materials, solar systems can store cooling during the day and continue functioning at night or during cloudy periods. This setup ensures round-the-clock operation without relying on the electrical grid or diesel generators.

A major focus of recent research has been improving the heat transfer efficiency of the system. One effective strategy is the use of plate heat exchangers (PHEs). These are preferred over tubular heat exchangers due to their compact size and better thermal performance. A recent study explored enhancing PHEs by applying copper spray coatings to their surface. This passive surface modification increased the heat transfer coefficient by up to 1.59 times. Although it also increased the pressure drop slightly, the overall thermal performance improved by 1.44 times. This suggests that such surface enhancements can play a crucial role in increasing system effectiveness without significantly increasing energy consumption.

Field trials and laboratory experiments confirm that combining these technologies like VARS, ETCs, PHEs, and TES can create efficient, low-cost, and eco-friendly cold storage systems. These systems help reduce post-harvest losses, particularly for small farmers in India, where the lack of cold chains leads to billions in produce waste each year.

Government-supported guidelines have also been released, specifying design and testing standards to ensure reliability and promote widespread adoption.

In summary, the literature strongly supports solar-powered VARS systems integrated with enhanced plate heat exchangers and thermal energy storage. These innovations provide sustainable and efficient cold storage solutions that can meet the demands of rural and agricultural sectors.

3 Simulation Software

REFPROP, Aspen Plus, and Aspen EDR together form a consistent and streamlined workflow for thermodynamic modeling and equipment design. REFPROP provides accurate and reliable fluid property data, which Aspen Plus uses to construct a comprehensive mass and energy balance of the entire cycle. Aspen EDR then takes this data to precisely size equipment like gasketed plate heat exchangers (PHEs) using the Design Given Plate mode while keeping vendor specified geometry fixed while calculating required heat transfer area, pressure drops, and plate counts for both plain and coated plates. This integrated chain of software ensures consistency across every level of design, speeds up iterations, and enables detailed equipment-level insight from system-wide simulations.

Aspen Plus offers a rich library of unit operation models including compressors, pumps, heaters, valves, and columns and also supports full automation through its COM interface. This allows engineers to script workflows using simple VBA code: opening backup files, modifying input variables, running simulations, extracting stream data or stage-wise temperatures, and even exporting results directly to Excel. This capability eliminates repetitive GUI interactions and enables rapid execution of batch design studies, making Aspen Plus an efficient and flexible platform for process optimization and digital design.

Software	**Main purpose in this project**	**Key strengths**	**Typical inputs and outputs**
REFPROP	Physical property lookup for pure fluids and mixtures	Accurate data from NIST and large fluid library	Two state properties in, full set of thermodynamic and transport properties out
Aspen Plus	Steady state process modeling and overall mass energy balance	Wide unit operation library and Excel link for automation	Stream composition, pressure, temperature in; updated flows, duties, work, and warnings out
Aspen EDR	Detailed heat exchanger design and rating	Plate geometry wizard and direct link to Aspen Plus blocks	Flow rates, inlet temperatures, and fouling factors in; required area, number of plates, pressure drop, and overall U value out

Table 1: Simulation programs used

3.1 Flowsheet

To begin my simulation, I first designed the plate geometry using EDR software and validated it by testing with a single component. This EDR-verified plate design was then integrated into Aspen Plus for individual component simulations, including the absorber, evaporator, solution heat exchanger, condenser, and generator. Following the single component analysis, I progressed to two-component simulations specifically pairing the evaporator with the condenser, and the generator with the absorber. Finally, a full system level simulation was conducted. At each stage of the Aspen Plus simulations, EDR remained linked to provide accurate plate heat exchanger design data.

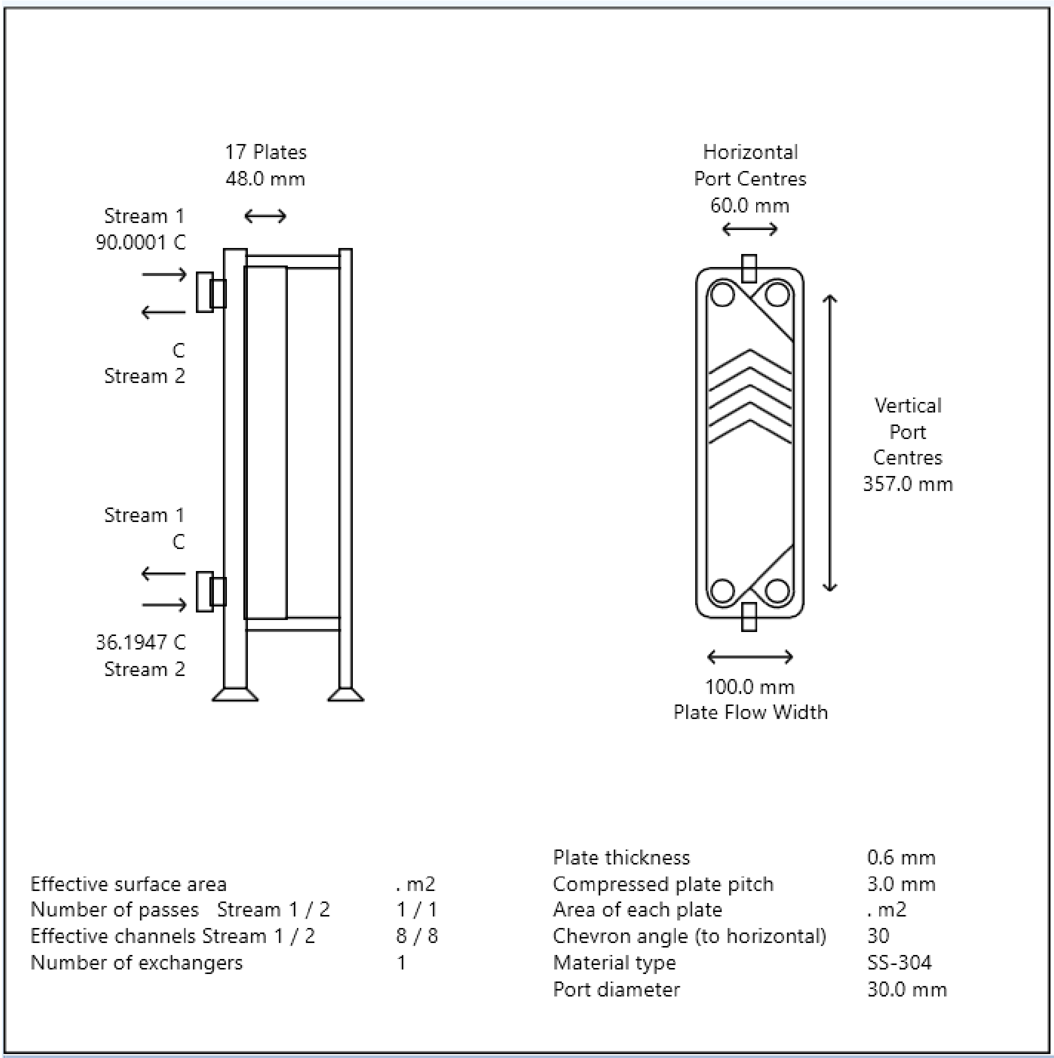

Figure 1: Plate Heat Exchanger (Aspen EDR):

This figure shows a 17-plate gasketed PHE designed in Aspen EDR using the Design Given Plate mode. The exchanger has 8 effective channels per stream, a single-pass layout, and operates between 90.0°C and 36.2°C for Stream 2. With SS-304 material, a 30° chevron angle, and fixed geometry, the model returns required heat transfer area, pressure drops, and plate count based on Aspen Plus stream data.

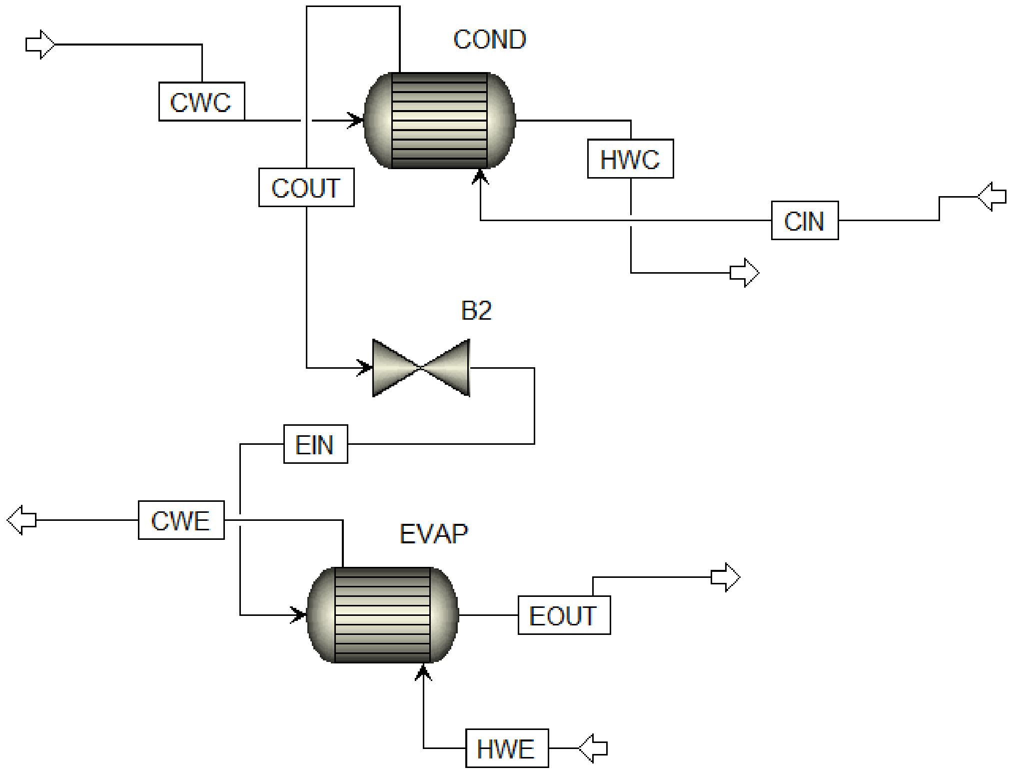

Figure 2: 2 component Evaporator and Condenser

This schematic models a simplified test loop focused on evaporation and condensation processes. This section is responsible for releasing and absorbing heat during the phase change of the refrigerant (R134a), enabling effective cooling in the system.The expansion valve (B2) ensures the correct pressure drop between condenser and evaporator. Used for validating the EDR-sized exchanger, the loop ensures consistent temperature and flow conditions before integrating into the full system.

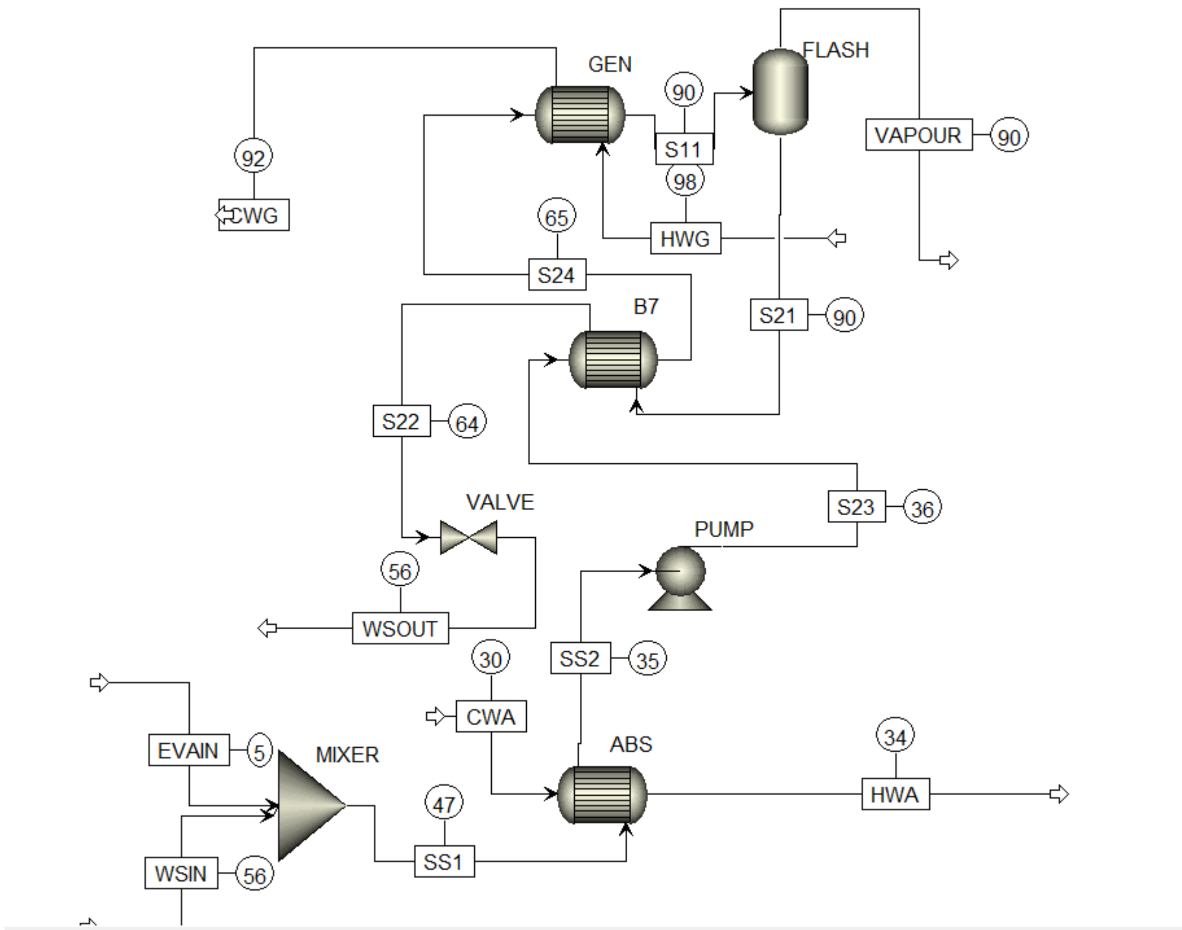

Figure 3: 2 component Absorber and Generator

This schematic models a simplified test loop focused on core absorption and generation processes. The system comprises the key components: generator (GEN), flash separator (FLASH), solution heat exchanger (B7), absorber (ABS), pump, expansion valve, and supporting heat exchangers and mixers.Flow streams are labeled to track heat and mass transfer throughout the loop.Streams like CWG, CWA, and HWA manage the heating and cooling water loops. Used for validating the EDR-sized exchanger, the loop ensures consistent temperature and flow conditions before integrating into the full system.

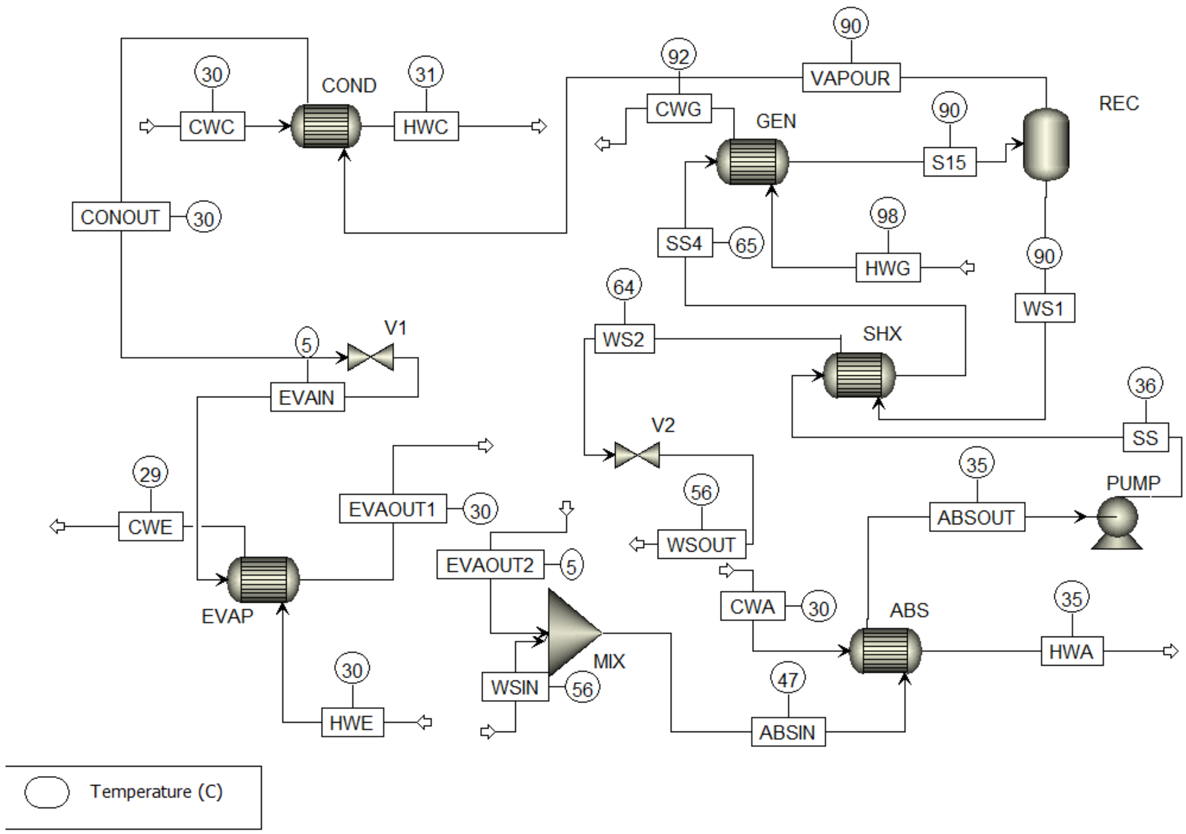

Figure 4: Full Cycle Simulation (Aspen Plus):

The flow diagram illustrates the complete operation of a solar-powered vapour absorption refrigeration system (VARS) using R134a-DMF as the working pair. The cycle begins at the generator (GEN), where the strong solution is heated by hot water (HWG) supplied through solar thermal collectors. This heat separates the refrigerant (R134a) from the absorbent (DMF), and the resulting vapor moves to a receiver vessel (REC) via stream S15, while the weak solution exits as WS1. The refrigerant vapor is further routed through stream VAPOUR toward the condenser.

In the condenser (COND), the vapor condenses into a high-pressure liquid by rejecting heat to a cooling water loop (CWC). The removed heat exits via the hot water stream HWC, and the condensed refrigerant is then sent through the expansion valve V1, where it experiences a pressure drop. This low-pressure liquid enters the evaporator (EVAP), where it absorbs heat from an external source (e.g., a cold room) via hot water (HWE), thus evaporating into a vapor. This refrigerant vapor flows through EVAOUT1 and EVAOUT2 toward the mixer (MIX).

Meanwhile, the weak solution returning from the generator (WS2) is cooled using a solution heat exchanger (SHX) and passed through expansion valve V2 to reduce its pressure. The weak solution (WSOUT) is then mixed with the refrigerant vapor in the MIX block. This mixed stream enters the absorber (ABS) via stream ABSIN, where the refrigerant vapor is absorbed by the weak solution to regenerate a strong solution. The absorber is continuously cooled by cooling water (CWA) to remove the heat of absorption, and the outlet water exits as HWA.

The newly regenerated strong solution (ABSOUT) is then pumped by the PUMP to a higher pressure and sent to the solution heat exchanger (SHX) via stream SS, where it is preheated using the exiting weak solution before entering the generator. This internal heat exchange increases cycle efficiency by reducing the heat load on the generator. Auxiliary water loops (CWG, CWE, and others) are used to manage the temperature across various components like the generator, absorber, and evaporator.

Table 2: Principal blocks and convergence settings.

Block	**Model**	**Main Spec.**	**Notes**
Generator	*HeatX*	T_{out}	Heat input from solar loop
Condenser	*HeatX*	T_{out}	Cooling water $30\,^{\circ}\text{C}$
Absorber	*HeatX*	T_{out}	$40\,^{\circ}\text{C}$; duty auto
Evaporator	*HeatX*	T_{out}	Chilled brine temperature adjusted
Solution HX	*HeatX*	DEsign	Area fixed from EDR rating
Rectifier	*Flash*	T_{approach}	Only separation done
Pump	*Pump*	$\eta_s = 0.99$	Head auto from pressure nodes
Throttle valve	*Valve*	P_{out}	Generator $\rightarrow$ evaporator

4 Validation of the Aspen Plus Simulation

This section demonstrates that the *Aspen Plus* flowsheet of Full simulation faithfully reproduces the thermodynamic behaviour predicted from the manual energy balances presented in thoery. The comparison focuses on the four energy bearing components of the R134a/DMF vapour absorption cycle generator, condenser, evaporator and absorber as well as the overall coefficient of performance (COP).

4.1 Method adopted

1. **Boundary conditions replicated.** The flowsheet was forced to the same operating states used in the theoretical sizing:

   - Generator temperature: $95\,^{\circ}\text{C}$
   - Condenser / absorber cooling-water temperature: $40\,^{\circ}\text{C}$
   - Evaporator temperature: $5\,^{\circ}\text{C}$
   - Solution heat-exchanger effectiveness: $90\,\%$
   - Mass-flow split and composition targets taken directly from the manual balance.

2. **Property package and convergence.** *NRTL-RK* was selected for R134a and DMF, with separate steam tables for the cooling circuit.

3. **Data extracted.** Once converged, heat duties and mass flows were exported as CSV for consistent rounding before comparison.

4.2 Challenges and Errors

- *Thermophysical properties.* The hand calculations assume fixed specific and latent heats, whereas Aspen uses temperature-dependent correlations. This explains most of the 1–2 % divergence in condenser and absorber duties.

- *Enthalpy rounding.* Manual enthalpies were quoted to two decimal places; *Aspen* carries five-digit precision, so small propagation errors appear when differences of large numbers are taken.

- *Solution HX effectiveness.* The 90 % target in theory translates to 89.6 % when the plate count in *Aspen* is discretised, producing a $0.05\,\mathrm{kW}$ shift in generator and absorber loads.

- *Solver tolerances.* The run closes the overall heat balance to better than 0.1 %, well inside acceptable engineering uncertainty.

5 Supplementary Work

5.1 Experimental Setup Assistance:

In addition to simulation work, I contributed to the experimental setup by labeling and organizing 16 temperature sensors and 25 pressure sensors for accurate data acquisition. While supporting the team, I also took the opportunity to closely observe and learn the working principles of each component involved in the test bed. Through this experience, I not only contributed to streamlining the experimental monitoring process but also deepened my practical knowledge of data automation and sensor-network integration in a research environment.

5.2 Real-Time Data Monitoring with MATLAB:

To streamline the experimental data acquisition and monitoring process, I developed a direct communication bridge between the Keysight DAQ system and the ThingSpeak cloud platform using MATLAB. The Keysight device, identified by its VISA address:

```
USB0::0x2A8D::0x5101::MY58007710::0::INSTR
```

was configured in MATLAB to interface with the sensor hardware. This setup enabled seamless, automated reading of temperature and pressure data from 16 thermocouples and 25 pressure sensors.

Instead of relying on Excel-based logging or manual intervention, I used ThingSpeak's API key to push data directly from MATLAB into the cloud. This allows the system to automatically log measurements and generate real-time plots of temperature-pressure correlations on the ThingSpeak dashboard. As a result, we can instantly visualize system behavior, identify anomalies, and track experimental trends across different components.

This integration significantly enhances data reliability, traceability, and efficiency, while reducing delays typically associated with manual data handling. It offers a robust and scalable solution for live experimental monitoring, and simplifies the comparison of simulated and experimental outputs in near real-time.

5.3 Machine Learning Based COP Prediction Model:

I also developed a machine learning model aimed at predicting the Coefficient of Performance (COP) of the system based on input temperature and load values. Using experimental data from NLC (September–October), I performed data cleaning and tested several models. A hybrid approach combining Random Forest and XGBoost yielded the highest R^2 value. While the model shows less promising accuracy on training and test sets, it requires more comprehensive data to be deployed reliably for real-time predictions.

Random Forest Performance Visualization

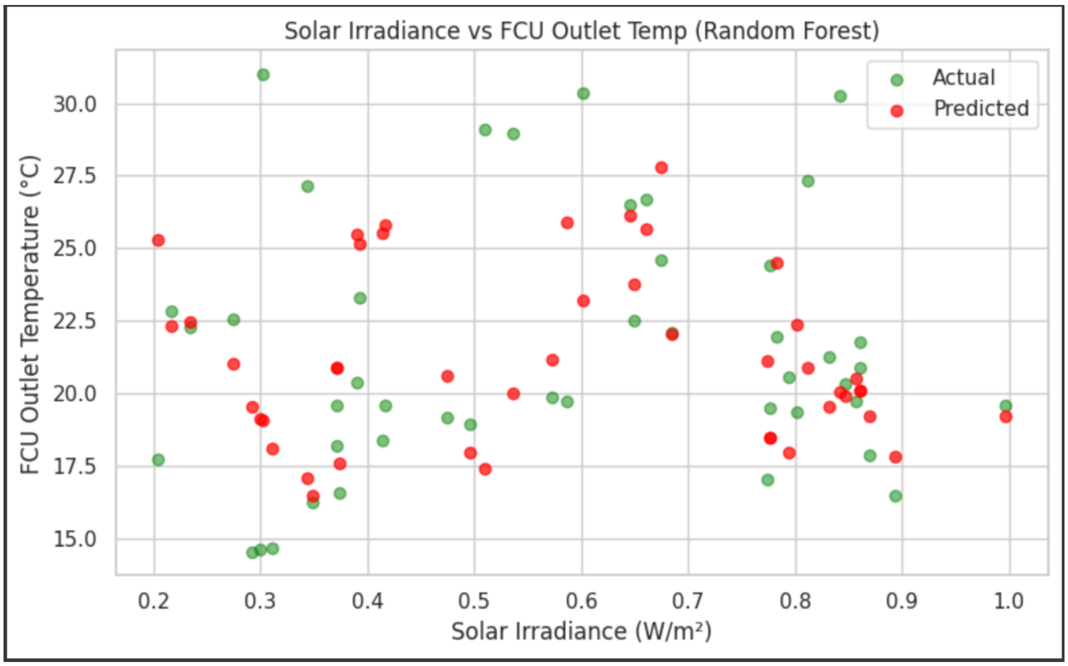

Figure 5: Actual vs Predicted FCU Outlet Temperatures using Random Forest

Figure 5 shows the model prediction results using a Random Forest regressor. Green dots represent actual FCU outlet temperatures from experimental data, while red dots show predicted values. Though the model generally follows the trend, certain deviations at higher irradiance levels suggest potential improvements through feature engineering or hybrid modeling.

Model Benchmarking and Comparison

	Model	R^2	RMSE	MAE
0	Linear Regression	-2.728694e+04	1090.7113	195.3454
1	Polynomial Regression (deg=2)	-5.808477e+09	497042.1752	84022.9958
2	Random Forest	1.392000e-01	14.7782	10.5248
3	XGBoost	-2.533000e-01	17.9664	12.4327
4	Gradient Boosting	1.389000e-01	14.8387	10.4565
5	SVR	5.160000e-02	15.8453	13.5216
6	Extra Trees	6.300000e-03	15.8604	11.4296
7	CatBoost	1.943000e-01	14.4210	10.1944
8	AdaBoost	2.700000e-01	13.8366	10.1849
9	KNN	2.281000e-01	14.2918	10.0838
10	MLP (Neural Net)	-6.157542e+05	5134.6383	881.2452

Figure 6: Performance Metrics (R^2, RMSE, MAE) for Various Regression Models

Figure 6 compares the performance of eleven regression algorithms, including Linear Regression, Polynomial Regression, Random Forest, Gradient Boosting, CatBoost, SVR, and neural networks. The metrics used were:

- R^2 – Coefficient of Determination (higher is better)
- RMSE – Root Mean Square Error (lower is better)
- MAE – Mean Absolute Error (lower is better)

Traditional models like Linear and Polynomial Regression showed poor generalization, with large errors and negative R^2 values. In contrast, tree-based ensemble models such as CatBoost, Random Forest, and AdaBoost achieved significantly better accuracy. CatBoost offered the best trade-off with an R^2 value of approximately 1.94 and a low MAE around 10.2°C.

This comparative study shows that ensemble models, particularly CatBoost and Random Forest, are well-suited for temperature prediction in solar cold room applications.

6 Future Work

With the full cycle simulation successfully replicating theoretical calculations, the next phase will focus on sensitivity analysis by varying loads on each heat exchanger to identify their interdependencies and performance trends. Additionally, future work aims to integrate advanced surface designs such as copper-coated plates and metal foam structures into the Aspen EDR file. These enhancements will then be linked to Aspen Plus to evaluate their impact on system efficiency, pressure drops, and overall heat transfer characteristics. This approach will help develop a deeper understanding of material and geometry influence on absorber system behavior

7 Summary

This project demonstrates the technical feasibility and performance reliability of a solar-powered cold storage system using a vapour absorption refrigeration cycle coupled with thermal energy storage. The integration of evacuated tube collectors, photovoltaic panels, and copper-coated plate heat exchangers into a unified prototype delivers consistent cooling with minimal grid dependence. Simulation results from Aspen Plus and EDR closely match theoretical calculations, affirming the accuracy of the model and validating its core assumptions. The inclusion of a phase change material bank ensures autonomous operation for up to two days without sunlight, aligning with national design guidelines. Experimental support systems, including real-time data acquisition and ML-based COP prediction, enhance monitoring and future control potential. Moving forward, further optimization through advanced surface geometry, material enhancement, and expanded data collection will help improve performance and scalability. This work lays a foundation for deploying cost-effective, climate-resilient cold chain solutions in underserved rural communities

8 Acknowledgment

I would like to express my sincere gratitude to my mentor, PhD Vijaya Kumar, for his invaluable guidance, encouragement, and insightful feedback throughout the course of this research internship. His expertise and mentorship played a crucial role in shaping my understanding and approach to the project.

I am also thankful to all my fellow interns for their constant support, stimulating discussions, and collaborative spirit. Working alongside such a motivated and helpful team made this internship both intellectually enriching and personally enjoyable.

Finally, I would like to acknowledge the Refrigeration and Air Conditioning Lab at the Indian Institute of Technology Madras for providing the opportunity and resources needed to carry out this work.

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Glossary

- **VARS** – Vapour Absorption Refrigeration System, a cooling technology that uses thermal energy instead of electricity to drive the cycle.
- **PHE** – Plate Heat Exchanger, a compact heat exchanger made of corrugated plates that improves heat transfer efficiency.
- **SHX** – Solution Heat Exchanger, used to preheat the strong solution using the heat from the weak solution in VARS systems.
- **R134a** – A refrigerant commonly used in cooling systems due to its favorable thermodynamic properties and environmental friendliness.
- **DMF** – Dimethylformamide, a liquid absorbent used with R134a in absorption refrigeration cycles.
- **ETC** – Evacuated Tube Collector, a type of solar collector used to heat water by absorbing solar radiation efficiently.
- **TES** – Thermal Energy Storage, a method to store heat or cold for later use, allowing the system to operate during off-sunlight hours.
- **COP** – Coefficient of Performance, a measure of the efficiency of a refrigeration or heat pump system.
- **DAQ** – Data Acquisition, the process of collecting and measuring electrical or physical parameters using sensors and electronic instruments.
- **ThingSpeak** – An IoT analytics platform that enables storage and visualization of real-time sensor data using MATLAB.
- **Aspen Plus** – Process simulation software used to model the mass and energy balance of chemical and thermal systems.
- **Aspen EDR** – Equipment design and rating software used for sizing heat exchangers and other process equipment.
- **REFPROP** – A fluid property database developed by NIST used to obtain thermodynamic and transport properties.
- **NRTL-RK** – Non-Random Two-Liquid with Redlich-Kwong equation of state, a thermodynamic model used for property prediction in mixtures.
- **CSV** – Comma Separated Values, a file format used to store tabular data such as simulation results.
- **VISA Address** – A standard format used to identify instruments (like DAQ systems) for communication in programming environments.