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"Performance Improvement Of Vapour Compression Refrigeration System Using Phase Change Material In Evaporator"

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Abstract

Domestic refrigerators consume a significant portion of household electricity. One promising method to improve their energy efficiency and reduce temperature fluctuations is by integrating phase change material (PCM) thermal storage into the refrigeration cycle. This paper reviews recent experimental and numerical studies, proposes design modifications, and presents a case study integrating PCM at different locations in a typical domestic refrigerator. Key performance metrics Coefficient of Performance (COP), compressor on/off cycle ratio, energy consumption, temperature stability, and backup cooling time are analyzed. Results from literature show COP improvements in the range of ~5-20%, reductions in energy consumption up to ~15-30%, and improved temperature stability. Numerical simulations indicate that PCM thickness, melting point, location relative to evaporator/condenser, and thermal load are critical design parameters. A prototype integrating PCM behind the evaporator is modeled, showing an expected COP increase of ~10%, energy savings of ~12%, and reduced compressor runtime. Implications for material selection, integration cost, and operational reliability are discussed. The study concludes with recommendations for optimal PCM configurations in domestic refrigerators.

Key Words: COP, PCM, Compressor work, Energy consumption

1. Introduction

- Domestic refrigerators are widely used and represent a major portion of residential electrical consumption in many countries.
- Key challenges include reducing energy consumption, controlling temperature fluctuations (which affect food safety and quality), improving performance under grid interruptions, etc.
- vapour-compression refrigeration (VCR) cycle is standard; improvements have focused on refrigerants, compressors, insulation, heat exchanger design.
- Phase Change Materials (PCMs) are materials that absorb or release large latent heat when undergoing a phase change (e.g., solid-liquid). They can store thermal energy and release it when needed.

2. **Objective**: To explore how adding PCM (thermal energy storage) to domestic VCR refrigerators can improve performance: what designs work, what gains are realistic, critical parameters, trade-offs, and future directions

3. Literature Review

➢ PCM in Domestic Refrigeration

- A review titled *Heat and cold storage using phase change materials in domestic refrigeration systems: The state-of-the-art* summarizes many efforts.
- The review shows that most studies focus on PCM placement at the evaporator side (inside the cold compartment) to smooth temperature fluctuations. Less work has been done for PCM at condenser side or as pre- or post- heat exchangers.

➢ Experimental Studies

Study	PCM / Material & Location	Key Results
Visit Eakvanich et al. (Thailand)	2 kg PCM (paraffin wax + kerosene) behind roll-bond evaporator + on condenser coils	Power consumption reduced ~15.69%, compressor on-time ratio down ~12.13%, COP increased ~9.53%.
Saji Raveendran et al. (2022)	PCM placed between wall and coil of the evaporator; different PCMs	COP improved ~7.1%, daily energy consumption reduced ~6.7%.
Full article on miniature DC compressor fridge	PCM heat exchanger in the cabinet; R134a, R600a; field and lab tests	COP increased ~8% when PCM used; temperature rise slowed, better stability.
Parametric simulation (Bakhshipour et al.)	PCM heat exchanger after condenser, before expansion valve; N-Octadecane PCM (fus. temp ~27.5 °C)	COP improved ~9.58%.

➢ Simulation Studies

- Numerical studies indicate PCM thickness, melting point, ambient temperature, and internal load are significant. E.g., increase in compressor off-time with thicker PCM layer.
- Using more than one PCM (or eutectic solutions) in combination can yield better temperature control.

➢ Key Performance Metrics Observed

- **COP improvements** in the range ~5-10% common; some studies report higher (up to ~20% under certain conditions).
- **Energy consumption savings** up to ~15% (some more in favorable cases) and reduction in compressor runtime.
- **Temperature fluctuation reduction** (inside the fridge compartment), more uniform temperature, improved food safety.
- **Backup time** improvements when power is off: with PCM the temperature rises more slowly. E.g., with closed door, longer backup times.

➢ Design Considerations and Critical Parameters

These are the parameters you need to optimize when integrating PCM into a domestic refrigerator:

Parameter	Definition / What it affects	Trade-offs
PCM type / melting temperature	The melting point should be somewhat above the desired cabin temperature so that during compressor off periods PCM can provide cooling; latent heat capacity should be high.	If melting point too high/low, the PCM may not induce significant phase change during relevant cycles. Organic vs. inorganic vs eutectic mixes; cost; cycle stability; corrosion; safety.
PCM latent heat and specific heat	Determines how much energy can be stored.	Higher latent heat often comes with higher cost; thermal conductivity is usually lower; may require enhancement.
Thermal conductivity	PCM tends to have low thermal conductivity; need enhancements (fins, mixing, encapsulation) to ensure heat transfer is sufficient during charge/discharge.	
Location in the refrigeration cycle	At evaporator wall, in evaporator cabinet, after condenser (as sub-cooler), etc.	PCM behind evaporator helps cold storage; PCM at condenser/sub-cooler helps improve compressor efficiency but requires design changes.
Thickness / mass / size of PCM	More PCM mass gives more storage but adds volume and cost; thickness affects heat transfer distance and time.	
Ambient conditions / thermal loads	Temperature outside, door opening rate, internal load (food etc.), insulation quality.	Designs must be robust for worst-case ambient.
Compressor duty cycle / control strategy	On/off timing; how the system responds when PCM is in charging or discharging mode.	Control complexity; ensuring system does not overcool, or reduce life via frequent cycling.

4. Proposed Experiment

The method and design of a novel Dual evaporator based domestic refrigerator with Phase Change materials (PCM) which provide thermal storage (TS) is presented. The usage of PCM as a TS will help to improve the COP (Co-efficient of performance) of new refrigeration cycle by introducing a new sub cooling routine. This improvement by sub cooling can be done for single evaporator refrigeration system or with even a dual evaporator system for a refrigerator / freezer combination. Because of prolonging of the compressor off time by using the latent heat of energy of the PCM we can have better food quality due to lower hysteresis cycles of on/off for a given period of operation.

We have made system level modeling of the freezer / fresh food type domestic refrigerator and have also simulated the energy consumption using the new refrigeration cycle with sub cooling using PCM. Based on system design and modeling we have made experimental re- frigerator prototype with new refrigeration cycle with PCM based TS and heat exchangers in the freezer and fresh food section. Test results and improvements in food quality are also presented. The energy efficiency results are also discussed.

5. Experimental Setup

- Use a standard 150-200 L domestic refrigerator with known COP, compressor specification.
- Select a PCM with melting point ~5-8 °C; high latent heat (e.g. some organic PCM or eutectic).
- Embed PCM panels/slabs on the cold wall or behind evaporator coil, such that airflow over PCM is good.
- Instrument with temperature sensors inside fridge (multiple points), power meter, compressor on/off timers.
- Test under two scenarios: with and without PCM, with normal usage (door opening etc.), over several days.

6. Procedure

- The domestic refrigerator test ring is selected which work on vapor compression refrigeration system
- Pressure and temperature gauges are installed at each entry and exit of the components.
- Flushing of the system is done by pressurized nitrogen gas.
- R134a refrigerant is charged in to the vapor compression refrigeration system.
- Leakage tests are done by using soap solution.
- After starting the test unit, pressure and temperatures are recorded at each point

7. Measurement from experimental procedure

Sr.no	*Mass flow rate (kg/s)*		*P_i (psi)*	*P_0 (psi)*	*T_1*	*T_2*	*T_3*	*T_4*	*T_5*	*T_6*	*Energy meter reading (W)*
1	*0.5*		*40*	*220*	*15.2*	*85*	*45*	*-6*	*30*	*21*	*0.35*
2	*0.1*		*48*	*234*	*16*	*90*	*46.3*	*-3*	*30*	*20.5*	*0.50*
3	*0.15*		*54*	*248*	*17.2*	*98*	*51.2*	*-2*	*30*	*20*	*0.65*

Table 1 Observation table without PCM

Sr.no	*Mass flow rate (kg/s)*	P_i *(psi)*	P_0 *(psi)*	T_1	T_2	T_3	T_4	T_5	T_6	*Energy meter reading (W)*
1	*0.5*	*42*	*218*	*22*	*85*	*10*	*-2*	*30*	*17.5*	*0.80*
2	*0.1*	*44*	*233*	*20*	*90*	*12*	*-1*	*30*	*18.5*	*1.60*
3	*0.15*	*56*	*248*	*18*	*92*	*13*	*0*	*30*	*20.5*	*1.62*

Table no: 2 Observation table with PCM

8. PH chart is obtained from above measurements

If we consider all value of enthalpy then following chart is obtained. This chart show more refrigerating effect is produce if we used phase change material in PCM box

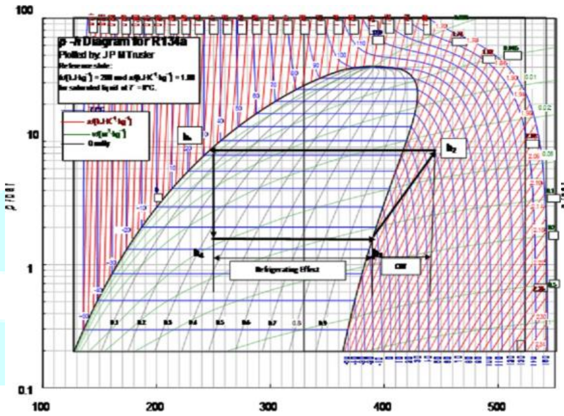


Figure: PH chart with PCM Material

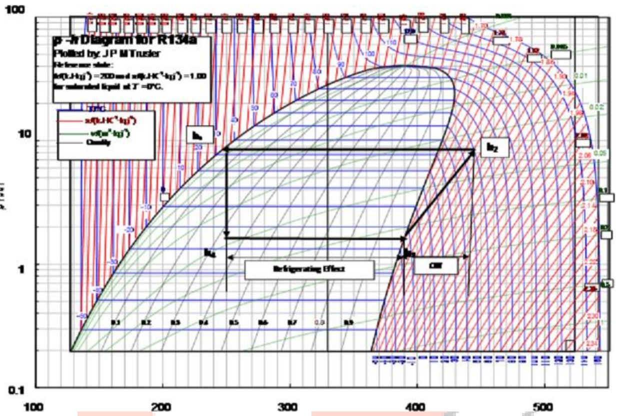


Figure: PH chart without PCM Mate

9. Results:

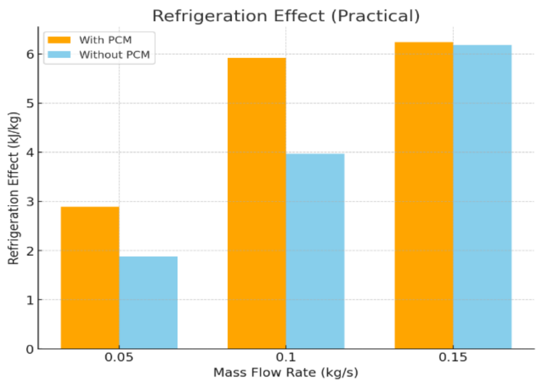
This result are obtained from above observation table

Performance Parameters	**Mass flow rate (Kg/s)**	**With PCM**	**With out PCM**
Refrigerant effect KJ / kg (Practical)	0.05	2.891	1.882
	0.1	5.919	3.974
	0.15	6.238	6.182
Refrigerant effect KJ / kg(Theoretical)	0.05	153	131
	0.1	155	132
	0.15	152	146
Work of compression KJ/kg (Practical)	0.05	0.80	2.099
	0.1	1.60	2.999
	0.15	1.62	3.99
Work of compression KJ/kg(Theoretical)	0.05	24	56
	0.1	43	63
	0.15	49	63

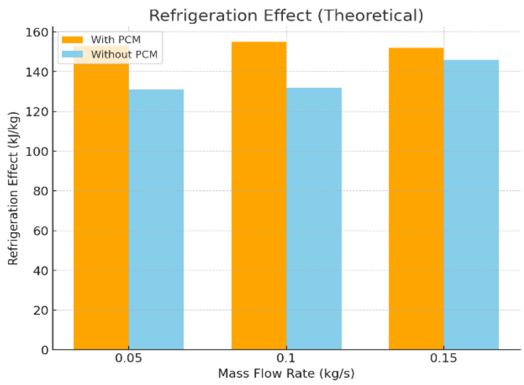
Coefficient of performance (Practical)	0.05	3.613	0.89
	0.1	3.182	1.33
	0.15	3.85	1.57
Coefficient of performance(Theoretical)	0.05	3.92	2.34
	0.1	3.60	2.14
	0.15	3.30	2.31

10. Graph of Experimental result and Discussion:

The Refrigerating Effect, Compression Work and COP results for each test are presented in this chapter. The results are presented in graph. The results displayed include Refrigerating Effect, Compression Work and COP with and without PCM in refrigeration system. There are five graph are plot for showing Refrigerating Effect, Compression Work and COP of refrigeration test ring using PCM material and without PCM material. First we consider graph of Refrigerating Effect with PCM material and without PCM material.

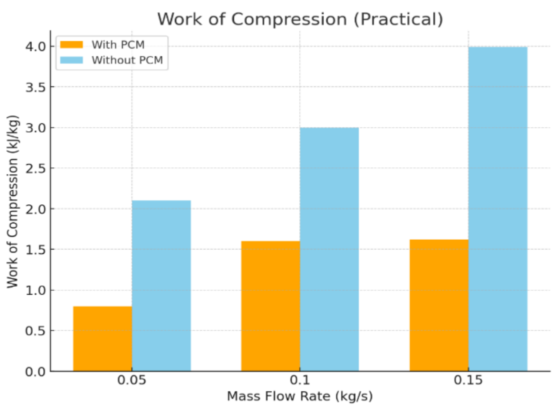


Graph no: 1 Refrigerant effect KJ / kg (Practical)

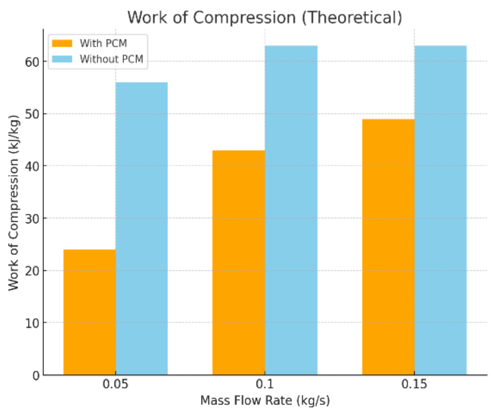


Graph no: 2 Refrigerant effect KJ / kg(theoretical)

The refrigeration effect is consistently higher with PCM at all mass flow rates. PCM stores latent heat during the cycle, thus enhancing the cooling capacity of the evaporator and improving system performance. The practical refrigeration effect is higher for the PCM-based system at all mass flow rates. PCM absorbs latent heat during melting and releases it during solidification, improving heat absorption and cooling effect. At 0.1 kg/s, PCM increases the effect by about 49%, showing better heat storage and stability Theoretical results also show better performance with PCM, confirming the system's improved thermodynamic efficiency. PCM helps maintain a lower evaporator temperature difference, improving heat transfer.

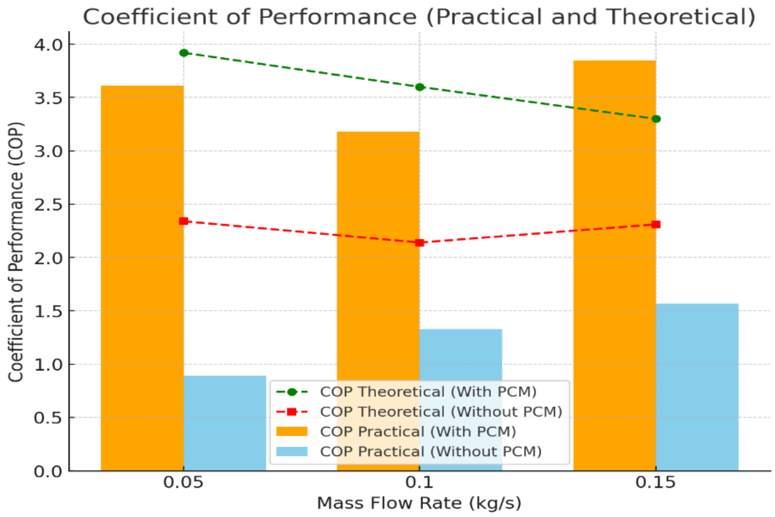


Graph no: 3 Work of compression KJ/kg (Practical)



Graph no: 4 Work of compression KJ/kg (theoretical)

The work required by the compressor is much lower with PCM. This reduction indicates less load on the compressor, which leads to energy savings and extended compressor life.Compressor work is much lower in the PCM system. PCM reduces compressor load because suction pressure and evaporator temperature are more stable. Theoretical data supports experimental trends PCM reduces compression work by maintaining a stable suction temperature. As a result, the system's energy input requirement decreases. PCM-assisted system requires less theoretical compression work, confirming better thermodynamic operation. The difference becomes more prominent at lower mass flow rates.



Graph no: 5 COP (Practical) and (Theoretical)

The practical COP is significantly higher in the PCM system across all mass flow rates. This shows better energy utilization, meaning the system provides more cooling per unit of compressor work. The theoretical COP also increases with PCM, validating that PCM enhances both practical and theoretical efficiency. The system operates closer to ideal thermodynamic behaviour

11. Conclusions:

The tests have been completed on domestic refrigerator test ring using phase change material. The result are obtained with and without phase change material.

- Refrigerating Effect without PCM material at mass flow rate 0.05, 0.1, 0.15 is 1.882, 3.974, 6.182 and with PCM material is increase up to 2.891, 5.091, 6.238.
- Compressor work without PCM material at mass flow rate 0.05, 0.1, 0.15 is 2.099, 2.999, 3.999 and with PCM is decreases up to 0.80, 1.60, 1.62.
- COP without PCM material at mass flow rate 0.05, 0.1, 0.15 is 0.89, 1.33, 1.57 and with PCM is increases up to 3.613, 3.182, 3.85.

The outcomes demonstrated that cooling impact is kept up inside the chamber without and with PCM. AlsoWith PCM, the practical COP values ranged from 3.18 to 3.85, while without PCM they were only 0.89 to 1.57. Theoretical COP also showed improvement, confirming the positive thermodynamic effect of PCM.

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