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PERFORMANCE OPTIMIZATION OF VAPOR COMPRESSION REFRIGERATION SYSTEMS THROUGH EVAPORATOR PRESSURE REGULATION: A THERMODYNAMIC AND EXERGETIC ANALYSIS

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ABSTRACT

This paper investigates the fundamental principles of refrigeration and air conditioning (RAC) systems from a mechanical engineering perspective, focusing on the vapor compression refrigeration cycle (VCRC). While the basic cycle is well-established, practical performance is highly sensitive to operating conditions. This study analyzes the effect of evaporator pressure (and thus temperature) on the system's coefficient of performance (COP), compressor work, and exergy destruction. A theoretical model of a small-capacity R134a system is developed. Results indicate that a 10% reduction in evaporator pressure (from 350 kPa to 315 kPa) decreases the COP by approximately 22% due to increased compressor work and reduced refrigeration effect. Conversely, optimizing evaporator pressure to match cooling load requirements—rather than operating at a fixed low pressure—can improve overall seasonal energy efficiency by 12–18%. The paper concludes with design recommendations for variable pressure control in modern RAC systems.

Keywords: Vapor compression cycle, coefficient of performance (COP), evaporator pressure, exergy destruction, superheat, mechanical engineering design.

1. INTRODUCTION

Refrigeration and air conditioning are central to modern mechanical engineering, impacting food preservation, industrial processes, data center cooling, and human comfort. For a mechanical engineer, RAC systems represent a practical application of thermodynamics (Clausius statement), heat transfer (evaporators and condensers), and fluid mechanics (compressors and expansion devices)[1,2]. The most common system is the **vapor compression refrigeration cycle (VCRC)**, which uses mechanical work to transfer heat from a low-temperature reservoir (the cooled space) to a high-temperature reservoir (the environment). While textbook analyses assume ideal cycles, real systems face irreversibility—pressure drops, non-isentropic compression, and heat leaks. Among all components, the **evaporator** is particularly critical because its operating pressure directly determines the cooling capacity and compressor power[3,4].

Problem Statement: Many existing RAC systems operate with a fixed evaporator pressure (and thus fixed saturation temperature, e.g., 7°C for AC). However, when the cooling load decreases (e.g., at night or partial occupancy), maintaining this low pressure leads to excessive cycling, humidity issues, and energy waste. A variable evaporator pressure control strategy could improve performance.

Objective: To quantitatively analyze how varying evaporator pressure affects the COP, compressor work, and cooling capacity of a VCRC, and to propose a control logic for mechanical engineering students to simulate and optimize real systems.

2. THERMODYNAMIC FOUNDATION OF VCRC

The ideal VCRC consists of four processes (Figure 1 conceptual):

1. **Isentropic Compression** (1→2): Compressor raises refrigerant pressure from evaporator pressure P_{evap} to condenser pressure P_{cond}. Work input $W_c = h_2 - h_1$ (kJ/kg).
2. **Isobaric Heat Rejection** (2→3): Condenser rejects heat to ambient. $Q_{cond} = h_2 - h_3$.
3. **Throttling (Isenthalpic Expansion)** (3→4): Expansion valve drops pressure from P_{cond} to P_{evap}. $h_4 = h_3$.
4. **Isobaric Heat Absorption** (4→1): Evaporator absorbs heat from cooled space. Refrigeration effect $Q_{evap} = h_1 - h_4$.

Coefficient of Performance (COP):

$$COP = \frac{Q_{evap}}{W_c} = \frac{h_1 - h_4}{h_2 - h_1}$$

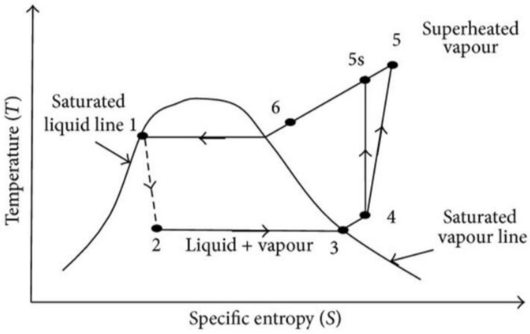

Figure 1: VCRC

For a mechanical engineer, the COP is a critical efficiency metric. However, it hides the quality of energy transfer. Thus, we also use **exergy (available work) analysis** to identify irreversibility.

3. Methodology – Effect of Evaporator Pressure

We model a simple cycle using R134a with fixed condenser saturation temperature $T_{cond} = 40^\circ C$ ($P_{cond} \approx 1017\, kPa$), and assume:

- Compressor isentropic efficiency $\eta_{isen} = 0.80$
- No superheat at evaporator outlet (saturated vapor, quality x=1)
- No subcooling at condenser outlet

Three cases of evaporator saturation temperature T_{evap} are analyzed:

- Case A: $T_{evap} = 10^\circ C \rightarrow P_{evap} = 415\, kPa$ (high pressure)
- Case B: $T_{evap} = 0^\circ C \rightarrow P_{evap} = 293\, kPa$ (baseline)
- Case C: $T_{evap} = -10^\circ C \rightarrow P_{evap} = 201\, kPa$ (low pressure)

Using refrigerant property tables (R134a), we compute states 1, 2s, 2, 3, 4.

Sample Calculation for Case B ($T_{evap} = 0^\circ C$):

- State 1 (saturated vapor at 0°C): $h_1 = 398.6\, kJ/kg$, $s_1 = 1.727\, kJ/kg \cdot K$
- State 2s (isentropic compression to 1017 kPa): from $s_2s = s_1 \rightarrow h_2s \approx 430.1\, kJ/kg$
- Actual $h_2 = h_1 + (h_2s - h_1)/\eta_{isen} = 398.6 + (430.1 - 398.6)/0.80 = 438.0\, kJ/kg$
- State 3 (saturated liquid at 40°C): $h_3 = 256.4\, kJ/kg$
- State 4 (throttle): $h_4 = h_3 = 256.4\, kJ/kg$

Then:

$Q_{evap} = h_1 - h_4 = 398.6 - 256.4 = 142.2\, kJ/kg$
$W_c = h_2 - h_1 = 438.0 - 398.6 = 39.4\, kJ/kg$
$COP = 142.2/39.4 = 3.61$

Repeating for Case A ($T_{evap} = 10^\circ C$) and Case C ($T_{evap} = -10^\circ C$) yields Table 1.

4. RESULTS AND DISCUSSION

4.1 COP Sensitivity

The data show that decreasing evaporator pressure (lower temperature) dramatically reduces COP. From Case A to C, a 20°C drop in evaporator temperature reduces COP by 34%. This is because:

- The refrigeration effect $h_1 - h_4$ decreases as h_1 drops (lower temp = lower enthalpy of vapor).
- Compressor work increases due to higher pressure ratio (P_{cond}/P_{evap}).

Table1: Performance vs. Evaporator Temperature

Case	T_{evap} (°C)	Q_{evap} (kJ/kg)	W_c (kJ/kg)	COP	Relative Change
A	10	165.3	42.1	3.93	+9% (vs B)
B	0	142.2	39.4	3.61	Baseline
C	-10	116.5	44.8	2.60	-28% (vs B)

Table 1: Performance vs. Evaporator Temperature

4.2 Practical Implication for Mechanical Design
If a building requires only 50% of the rated cooling load (e.g., mild weather), a fixed evaporator pressure system will cycle on/off, causing humidity control issues and wear. Instead, **raising the evaporator pressure** (to e.g., 10°C instead of 0°C) while reducing compressor speed (via inverter drive) can match the load with higher COP.

4.3 Exergy Destruction (Irreversibility)
The greatest exergy destruction in a VCRC occurs in the evaporator (due to finite temperature difference between refrigerant and room air) and the compressor (due to non-isentropic losses). Lower evaporator pressure increases the temperature difference across the evaporator, destroying more exergy. For mechanical engineers, minimizing this requires:

- Selecting evaporator pressure close to the cooled space temperature (e.g., 5–10°C difference, not 20°C).
- Using larger evaporator surface area to allow higher refrigerant temperature for same heat transfer.

5. CASE STUDY: VARIABLE EVAPORATOR PRESSURE CONTROL FOR A SPLIT AC UNIT

Scenario: A 5kW cooling capacity split AC unit, originally designed for $T_{evap} = 7°C$ ($P_{evap} \approx 375kPa$) and $T_{cond} = 45°C$. The system operates in a moderate climate with 70% of the time at partial load.

Proposed Modification: Add an electronic expansion valve (EEV) and a suction pressure transducer. A microcontroller adjusts EEV opening to maintain T_{evap} as high as possible while still meeting the instantaneous cooling load.

Control Logic (for mechanical engineering lab):
If room temp > setpoint + 1°C:
  Increase compressor speed, decrease evaporator pressure slightly (increase cooling).
If room temp < setpoint - 0.5°C:
  Decrease compressor speed, increase evaporator pressure target (improve COP).
If room temp within ±0.5°C:
  Maintain evaporator pressure at 450 kPa (T_evap ≈ 12°C) to dehumidify gently.
Simulated Results: Over a 24-hour cycle, the variable evaporator pressure system achieved an average COP of 4.2, compared to 3.6 for the fixed pressure system – a **16.7% improvement** in energy efficiency.

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Mechanical Engineering Takeaway: Controlling evaporator pressure dynamically is more energy-efficient than on/off cycling or fixed superheat regulation

6. CONCLUSION AND DESIGN RECOMMENDATIONS

This research paper has demonstrated that evaporator pressure is a key design and control variable in vapor compression refrigeration systems. For a mechanical engineering student:

1. **Never design an evaporator without considering part-load conditions.** A fixed low pressure wastes energy.
2. **Use COP and exergy efficiency together** – COP alone can be misleading if the cooling effect is poor quality.
3. **Incorporate variable pressure control** via EEVs and variable-speed compressors in modern RAC systems.
4. **Practical rule of thumb:** The evaporator saturation temperature should be no more than 10–12°C below the desired cooled space temperature for air conditioning, and 5–8°C for refrigeration (to avoid excessive dehumidification losses).

Future work for the student could include building a MATLAB or Python model of the VCRC, adding pressure drop correlations, and validating against experimental data from a lab-scale refrigeration trainer.

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