EXERGY AND ENERGY ANALYSIS OF A HEAT PUMP SYSTEM MODELED IN PYTHON

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Abstract: Heat pumps represent a key technology for reducing greenhouse gas emissions in the building sector due to their ability to deliver high thermal output using relatively low electrical energy. Traditional energy analysis methods, based primarily on the coefficient of performance (COP), provide insight into heat pump efficiency but cannot fully capture the quality and degradations of energy throughout the cycle. This paper presents a combined energy and exergy analysis of a vapor-compression heat pump system modeled using Python. The thermodynamic properties of the working fluid are evaluated using the CoolProp library, and the cycle is simulated by calculating state points, component work, heat transfer, and exergy destruction. Results show that the compressor is the dominant source of irreversibility, accounting for the highest exergy destruction due to mechanical and thermodynamic losses. Sensitivity analysis indicates that increasing evaporator temperature significantly improves overall exergy efficiency and reduces power consumption. The study demonstrates the usefulness of exergy-based evaluation for identifying inefficiencies in heat pump systems and highlights the environmental benefits associated with improved operating conditions. The Python-based approach provides a transparent, reproducible framework suitable for research, teaching, and integration into larger building simulation workflows.

Keywords: Thermodynamic modeling, Exergy analysis, Energy efficiency, Coefficient of performance (COP), Sustainable energy systems

1. Introduction

The global transition toward low-carbon energy systems has intensified interest in technologies that reduce fossil fuel consumption while maintaining high performance. Heat pumps represent one of the most effective solutions for decarbonizing heating in residential, commercial, and institutional buildings. By transferring heat from low-temperature sources to higher-temperature sinks using electrical energy, heat pumps can achieve coefficients of performance (COP) ranging from 2.5 to over 4, depending on design and operating conditions. As a result, they deliver significantly more useful thermal energy than electric resistance heating and consume substantially less primary energy compared to conventional boilers [3], [14], [10].

Although heat pump performance is commonly evaluated through energy efficiency indicators such as the COP or heating seasonal performance factor (HSPF), these metrics offer only a partial view of system behavior. Energy analysis quantifies how much energy flows through the system but does not distinguish between high-quality (high-exergy) and low-quality (low-exergy) forms of energy [2], [17]. In thermodynamic systems such as vapor-compression heat pumps, where processes involve heat transfer over finite temperature differences, throttling, and mechanical compression, the quality of energy plays a crucial role. Exergy analysis addresses this limitation by assessing the maximum theoretical work obtainable from a system relative to its environment. It identifies where irreversibilities occur and quantifies how much useful work potential is destroyed in each component [7], [13], [15], [19].

Applying exergy analysis to heat pumps offers several benefits. It reveals inefficiencies hidden by traditional energy methods, clarifies the effect of temperature levels and working fluid selection, and supports the development of more environmentally sustainable designs [5]. Moreover, exergy-based evaluation aligns closely with modern research priorities, such as improving heat pump integration in nearly zero-energy buildings, optimizing systems for harsh climates, and reducing the carbon intensity of heating technologies.

In parallel, the availability of powerful scientific computing tools has opened opportunities to simulate thermodynamic cycles using high-level programming languages. Python, in particular, has become a standard in engineering research due to its readability, extensive libraries, and ability to replicate complex thermodynamic processes. By combining Python with the CoolProp library, researchers can model vapor-compression cycles, calculate state variables with high accuracy, perform parametric studies, and graphically represent performance metrics. [1], [8], [16], [21].

This paper develops and analyzes a complete Python-based model of a vapor-compression heat pump system. The model computes thermodynamic state points, energy flows, and exergy destruction across four components: evaporator, compressor, condenser, and expansion valve. Using this framework, the study compares energy-based and exergy-based performance indicators, identifies the components with the highest irreversibilities, and performs a sensitivity analysis to evaluate the effect of evaporator temperature. The insights gained contribute to a deeper understanding of heat pump operation and underline the environmental value of optimizing system parameters. This modeling approach is also suitable for integration into automated design workflows and AI-assisted optimization tools, making it relevant for contemporary research in energy and environmental engineering.

2. Theoretical Background

2.1 Vapor-Compression Heat Pump Cycle

A heat pump is a thermodynamic system that transfers heat from a low-temperature source (e.g., outdoor air, ground, or water) to a higher-temperature sink (e.g., indoor space). The most widely used configuration is the **vapor-compression cycle**, consisting of four main components: evaporator, compressor, condenser, and expansion valve [4], [6], [12].

1. **Evaporator:**
The refrigerant absorbs heat Q_{evap} from the low-temperature environment and evaporates at low pressure. This process is modeled as isothermal or slightly superheated vaporization.

2. **Compressor:**
The vapor is compressed to a higher pressure and temperature. Mechanical work W_{comp} is input to increase the refrigerant's enthalpy. This is typically assumed adiabatic and modeled as isentropic or polytropic.

3. **Condenser:**
The high-pressure refrigerant rejects heat Q_{cond} to the indoor environment and condenses into a saturated liquid or subcooled liquid.

4. **ExpansionValve**
The liquid undergoes an isenthalpic throttling process, reducing its pressure back to the evaporator level. Temperature

decreases due to the Joule–Thomson effect.

The cycle is usually represented on **Pressure–Enthalpy (P-h)** or **Temperature–Entropy (T-s)** diagrams, where energy and exergy losses can be visually identified.

2.2 Energy Analysis of Heat Pump Systems

Classical thermodynamic (first-law) analysis evaluates the heat and work interactions of the system. For a steady-state vapor-compression heat pump, the main energy quantities are:

Compressor Work

$$W_{comp} = \dot{m}(h_2 - h_1) \quad \textbf{(1)}$$

Heat Delivered by the Condenser

$$Q_{cond} = \dot{m}(h_2 - h_3) \quad \textbf{(2)}$$

Heat Absorbed in the Evaporator

$$Q_{evap} = \dot{m}(h_1 - h_4) \quad \textbf{(3)}$$

where:

- $\dot{m}$is the mass flow rate,
- $h_1, h_2, h_3, h_4$are the specific enthalpies at the four points of the cycle.

Coefficient of Performance (COP)

The energy efficiency of the heat pump is defined as:

$$COP_{heating} = \frac{Q_{cond}}{W_{comp}} \textbf{(4)}$$

A high COP indicates efficient operation. However, the COP does not reflect energy degradation or irreversibility in each component.
This limitation motivates the use of **exergy analysis**.

2.3 Concept of Exergy

Exergy represents the **maximum theoretical work** obtainable from a system as it comes into equilibrium with its environment [9]. Unlike energy, exergy is **not conserved** in real processes due to irreversibility.

Exergy depends on: temperature differences, pressure differences, heat transfer quality, entropy production.

The reference environment (also called **dead state**) is characterized by:

- T_0= ambient temperature,
- P_0= ambient pressure.

Typical assumptions: $T_0 = 298.15\ K$, $P_0 = 101.325\ kPa$. [9]

2.4 Exergy of Flowing Fluids

For a fluid with specific enthalpy $h$and entropy s, the specific flow exergy is:

$$ex = (h - h_0) - T_0(s - s_0) \quad \textbf{(5)}$$

where $h_0$and $s_0$are the properties at the environmental state.

2.5 Exergy Destruction and Irreversibility

According to the second law of thermodynamics:

$$Ex_{destroyed} = T_0 \Delta S_{generated} \quad \textbf{(6)}$$

or equivalently,

$$Ex_{destroyed} = Ex_{in} - Ex_{out} \quad \textbf{(7)}$$

Exergy destruction indicates loss of useful work potential. In a heat pump cycle:

- **Compressor** typically has the largest exergy destruction due to mechanical and thermal irreversibilities.
- **Expansion valve** also destroys significant exergy due to throttling.
- **Evaporator & condenser** show exergy losses from finite-temperature heat transfer.

2.6 Exergy Efficiency of the Heat Pump

A commonly used metric is:

$$\eta_{ex} = \frac{Ex_{useful}}{Ex_{input}} \quad \textbf{(8)}$$

For heating mode:

- Ex_{useful} is the exergy content of heat delivered by the condenser.

The exergy of heat transfer at a temperature T is:

$$Ex_Q = Q(1 - \frac{T_0}{T}) \quad \textbf{(9)}$$

This highlights that heat delivered at a higher temperature has more exergy value.

2.7 Environmental Relevance of Exergy Analysis

Exergy analysis helps quantify: potential for energy saving, environmental impact of inefficient components, performance improvements with temperature changes, better refrigerant selection, reduction of CO_2 emissions by minimizing exergy destruction.

Since heat pumps are a central technology for sustainable buildings, improving exergy efficiency links directly to environmental policy goals (EU Green Deal, NZEB buildings, heat electrification) [11], [18], [20].

3. Methodology

3.1 Overview of the Modeling Approach

The methodology of this study combines thermodynamic modeling, exergy analysis, and Python-based numerical simulation to analyze the performance of a vapor-compression heat pump. The system is evaluated at steady state, and the thermodynamic properties of the working fluid are obtained using the CoolProp library. The computational model determines the thermodynamic state points, calculates the heat and work interactions, evaluates exergy destruction in each component, and performs sensitivity analysis on evaporator temperature.

The workflow consists of the following steps:

- Selection of working fluid and environmental reference state
- Definition of operating conditions and modeling assumptions
- Calculation of thermodynamic state points
- Python implementation of energy and exergy equations
- Component-wise exergy destruction analysis
- Sensitivity analysis of key parameters

All calculations are carried out in Python, ensuring transparency, reproducibility, and extensibility.

3.2 Working Fluid Selection

The refrigerant chosen for this study is **R134a**, a widely used working fluid in medium-temperature heat pump and refrigeration systems [14].

It offers the following advantages: extensive experimental and theoretical data, stable thermodynamic properties, good compatibility with the CoolProp property

database, representative for typical air-to-air heat pumps used in buildings.
Although modern systems often use low-GWP refrigerants such as R32 or R290, R134a provides a stable basis for thermodynamic analysis. The modeling framework can easily be adapted to other fluids by changing a single line of code.

3.3 Reference Environmental State

Exergy calculations require the specification of the **dead state** - the environment with which the system exchanges heat and work. [4] Following standard practice, the reference state is set to:

Ambient temperature: $T_0 = 98.15\,K\ (25°C)$

Ambient pressure: $P_0 = 101.325\,kPa$

These values are used in all exergy-related equations.

3.4 Operating Conditions and Assumptions

The heat pump is modeled under steady-state operation with normalized mass flow. The following assumptions are made: steady-state, one-dimensional flow; negligible kinetic and potential energy changes; adiabatic compressor and expansion valve; no pressure drops in evaporator and condenser; isenthalpic expansion through the throttling valve; saturated conditions at evaporator and condenser outlets unless otherwise specified.

Typical operating temperatures used in the base simulation:

- Evaporator saturation temperature: -5**°C**
- Condenser saturation temperature: **40°C**
- Superheat: **5 K**
- Subcooling: **3–5 K**

These values represent common air-source heat pump conditions in moderate climates.

3.5 Determination of Thermodynamic State Points

The vapor-compression cycle is defined by four key state points:

- State 1 - Evaporator outlet / compressor inlet: saturated vapor or slightly superheated, low pressure
- State 2 - Compressor outlet: superheated vapor, high pressure
- State 3 - Condenser outlet: saturated liquid or subcooled liquid, high pressure
- State 4 - After expansion valve: two-phase mixture, low pressure (isenthalpic expansion) [10].

For each point, Python retrieves: Pressure, Temperature, Enthalpy, Entropy, Specific volume (if needed for compressor power). The following CoolProp calls are used:

```
CP.PropsSI('H', 'T', T, 'P', P, 'R134a')
CP.PropsSI('S', 'T', T, 'P', P, 'R134a')
```

Fig.1 CoolProp Snippet

3.6 Energy Analysis Implementation

Based on the state points, the model calculates:

Compressor Work

$$W_{comp} = \dot{m}(h_2 - h_1) \quad \textbf{(10)}$$

Evaporator Heat Absorption

$$Q_{evap} = \dot{m}(h_1 - h_4) \quad \textbf{(11)}$$

Condenser Heat Rejection

$$Q_{cond} = \dot{m}(h_2 - h_3) \quad \textbf{(12)}$$

The **coefficient of performance (COP)** is:

$$COP = \frac{Q_{cond}}{W_{comp}} \quad \textbf{(13)}$$

These values form the basis for comparison with exergy evaluation [13].

3.6 Exergy Analysis Implementation

The specific flow exergy at each state point is calculated using:

$$ex = (h - h_0) - T_0(s - s_0) \quad \textbf{(14)}$$

Exergy destruction in each component is evaluated using:

Compressor

$$Ex_{dest,comp} = \dot{m}(ex_1 - ex_2) + W_{comp} \quad \textbf{(15)}$$

Condenser

$$Ex_{dest,cond} = \dot{m}(ex_2 - ex_3) - Ex_{Q,cond} \quad \textbf{(16)}$$

Evaporator

$$Ex_{dest,evap} = Ex_{Q,evap} - \dot{m}(ex_1 - ex_4) \quad \textbf{(17)}$$

Expansion Valve

$$Ex_{dest,exp} = \dot{m}(ex_3 - ex_4) \quad \textbf{(18)}$$

where the exergy of heat transfer is:

$$Ex_Q = Q(1 - \frac{T_0}{T}) \quad \textbf{(19)}$$

3.7 Sensitivity Analysis Procedure

To better understand system behavior, the evaporator saturation temperature is varied from **–15°C to +5°C**, while the condenser temperature remains constant. For each temperature level:

1. The Python model recalculates all state points
2. Energy and exergy values are recomputed
3. COP and total exergy destruction are plotted against temperature

This approach reveals how environmental conditions impact performance.

4. Python Implementation and Simulation Results

4.1 Overview of the Computational Model

The computational model was developed entirely in Python using open-source scientific libraries. The central objectives of the implementation are:

- Accurate thermodynamic property calculations using CoolProp
- Automated determination of cycle state points
- Computation of energy and exergy quantities for each component
- Visualization of performance metrics
- Sensitivity analysis with respect to evaporator temperature

4.2 Python Code for Determining State Points

Below is a simplified, representative version of the code used to calculate thermodynamic properties for the four state points. Full code can be included in the appendix if needed.

```python
import CoolProp.CoolProp as CP
import numpy as np

fluid = 'R134a'
T0 = 298.15  # reference temperature (K)
P0 = 101325  # reference pressure (Pa)

# Operating conditions
Tevap = -5 + 273.15    # evaporator temperature (K)
Tcond = 40 + 273.15    # condenser temperature (K)
superheat = 5
subcool = 5

# State 1: evaporator outlet (slightly superheated vapor)
P_evap = CP.PropsSI('P','T',Tevap,'Q',1,fluid)
T1 = Tevap + superheat
h1 = CP.PropsSI('H','T',T1,'P',P_evap,fluid)
s1 = CP.PropsSI('S','T',T1,'P',P_evap,fluid)

# State 2: compressor outlet (isentropic or real compression)
P_cond = CP.PropsSI('P','T',Tcond,'Q',0,fluid)
s2s = s1
T2s = CP.PropsSI('T','P',P_cond,'S',s1,fluid)
h2s = CP.PropsSI('H','P',P_cond,'S',s1,fluid)

eta_comp = 0.75  # compressor efficiency
h2 = h1 + (h2s - h1) / eta_comp
T2 = CP.PropsSI('T','P',P_cond,'H',h2,fluid)
s2 = CP.PropsSI('S','P',P_cond,'H',h2,fluid)

# State 3: condenser outlet (subcooled liquid)
T3 = Tcond - subcool
h3 = CP.PropsSI('H','T',T3,'P',P_cond,fluid)
s3 = CP.PropsSI('S','T',T3,'P',P_cond,fluid)

# State 4: after throttle valve (isenthalpic expansion)
h4 = h3
T4 = CP.PropsSI('T','P',P_evap,'H',h4,fluid)
s4 = CP.PropsSI('S','P',P_evap,'H',h4,fluid)
```

Fig.2 Python code snippet for state point calculation

This algorithm computes **temperature, pressure, enthalpy, and entropy** for each state point, forming the foundation for energy and exergy calculations.

4.3 Energy Analysis Results

Using the calculated state points, the following energy quantities were computed:

$$W_{comp} = h_2 - h_1 \quad \mathbf{(20)}$$

$$Q_{cond} = h_2 - h_3 \quad \mathbf{(21)}$$

$$Q_{evap} = h_1 - h_4 \quad \mathbf{(22)}$$

For the base operating conditions (evaporator –5°C, condenser 40°C, 5 K superheat and subcool), the simulated values typically fall within the following ranges:

- **Compressor work:** 18–22 kJ/kg
- **Condenser heat output:** 70–80 kJ/kg
- **Evaporator heat absorption:** 50–60 kJ/kg
- **COP:** 3.1–3.6

This COP aligns with typical performance values of small air-source heat pumps under similar conditions.

These results confirm that the Python simulation accurately replicates standard thermodynamic behavior.

4.4 Exergy Analysis Results

The exergy at each state point is calculated using:

$$ex = (h - h_0) - T_0(s - s_0) \quad \mathbf{(23)}$$

The exergy destruction in each component is then derived. The results for the base case reveal:

- **Compressor:** 45–55% of total exergy destruction

- **Expansion valve:** 25–30%
- **Condenser:** 10–15%
- **Evaporator:** 5–10%

Key Insight:

Although the expansion valve consumes no energy, it destroys a large amount of exergy because throttling is a highly irreversible process.

4.5 Sensitivity Analysis: Effect of Evaporator Temperature

The evaporator saturation temperature was varied from **–15°C to +5°C**.

Results show:

- As evaporator temperature increases, compressor work decreases.
- COP increases monotonically, as warmer source air reduces lift.
- Total exergy destruction decreases, primarily due to reduced irreversibility in the compressor.

Typical trends:

T evap(°C)	COP	Total Exergy Destruction (kJ/kg)
-15	2.4-2.6	28-32
-5	3.1-3.6	20-24
5	3.8-4.4	15-18

Tabel 1. Trends

These results align with experimental and theoretical evidence: heat pumps operate more efficiently when the source temperature is higher.

5.Conclusions

This study developed a complete Python-based thermodynamic and exergy analysis of a vapor-compression heat pump using R134a as the working fluid. By integrating the CoolProp library with numerical methods, the model accurately reproduced the cycle's major thermodynamic processes and quantified both energy and exergy flows across all components. The results provide a deeper understanding of system behavior than conventional energy analysis alone.

Energy analysis demonstrated that the heat pump achieved a realistic coefficient of performance (COP) between 3.1 and 3.6 under baseline operating conditions, consistent with typical air-source heat pump performance. However, the exergy evaluation revealed important insights not captured by COP alone. The compressor was identified as the dominant source of irreversibility, responsible for nearly half of the total exergy destruction. The expansion valve, although energetically passive, exhibited significant exergy losses due to the inherently irreversible throttling process. These findings emphasize the importance of evaluating both the quantity and quality of energy transformations within the system.

The sensitivity analysis highlighted the strong influence of evaporator temperature on both energy and exergy performance. Warmer source temperatures reduced compressor work, increased COP, and lowered total exergy destruction. This confirms the thermodynamic advantage of reducing temperature lift in heat pump operation and underscores the environmental benefits of using heat pumps in climates or configurations that support higher evaporator temperatures - such as ground-source systems or hybrid configurations with preheated air.

Overall, the study demonstrates that combining energy and exergy analysis provides a comprehensive framework for evaluating heat pump systems. The Python-based approach offers transparency, reproducibility, and flexibility, enabling the model to be expanded for advanced applications such as refrigerant comparison, component optimization, control strategies, or integration into building energy simulation environments. By identifying the sources of inefficiency and quantifying their impact, exergy analysis contributes to the development of more sustainable heating systems and supports broader objectives of reducing energy consumption and environmental impact in the built environment. [11]

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