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Towards Sustainable Separations: Integration of Heat Recovery and Heat Pump Technologies in Pressure Swing Distillation

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INTRODUCTION & AIM

- ✓ Distillation remains the powerhouse of separation processes in the chemical industry, yet its high energy demand presents economic and environmental challenges, especially when dealing with azeotropic mixtures.
- ✓ The decarbonization of energy-intensive distillation is critical for achieving net-zero goals in the chemical industry.
- ✓ Pressure Swing Distillation offers an effective method for breaking azeotropes by exploiting pressure-dependent volatility changes.
- ✓ Integrating process-intensification strategies, especially heat recovery between columns, can significantly reduce utility consumption.
- ✓ Combining heat recovery and heat pump systems aligns PSD with sustainable processing principles and reduces total annual cost (TAC), energy consumption, and CO_2 emissions.
- ✓ This study explores process intensification strategies, namely thermal coupling and heat pump techniques, to enhance energy efficiency in pressure swing distillation (PSD) of THF/water and acetone/chloroform azeotropes.
- ✓ Aligning PSD innovation with global sustainability transitions and the future of electrified industrial separations.

METHOD

- ➢ Four PSD configurations were evaluated:

1) **CPSD:** Conventional PSD (baseline)
2) **PHIPSD:** Partial heat-integrated PSD
3) **FHIPSD:** Full heat-integrated PSD
4) **HPAPSD:** Heat pump-assisted PSD using vapour recompression

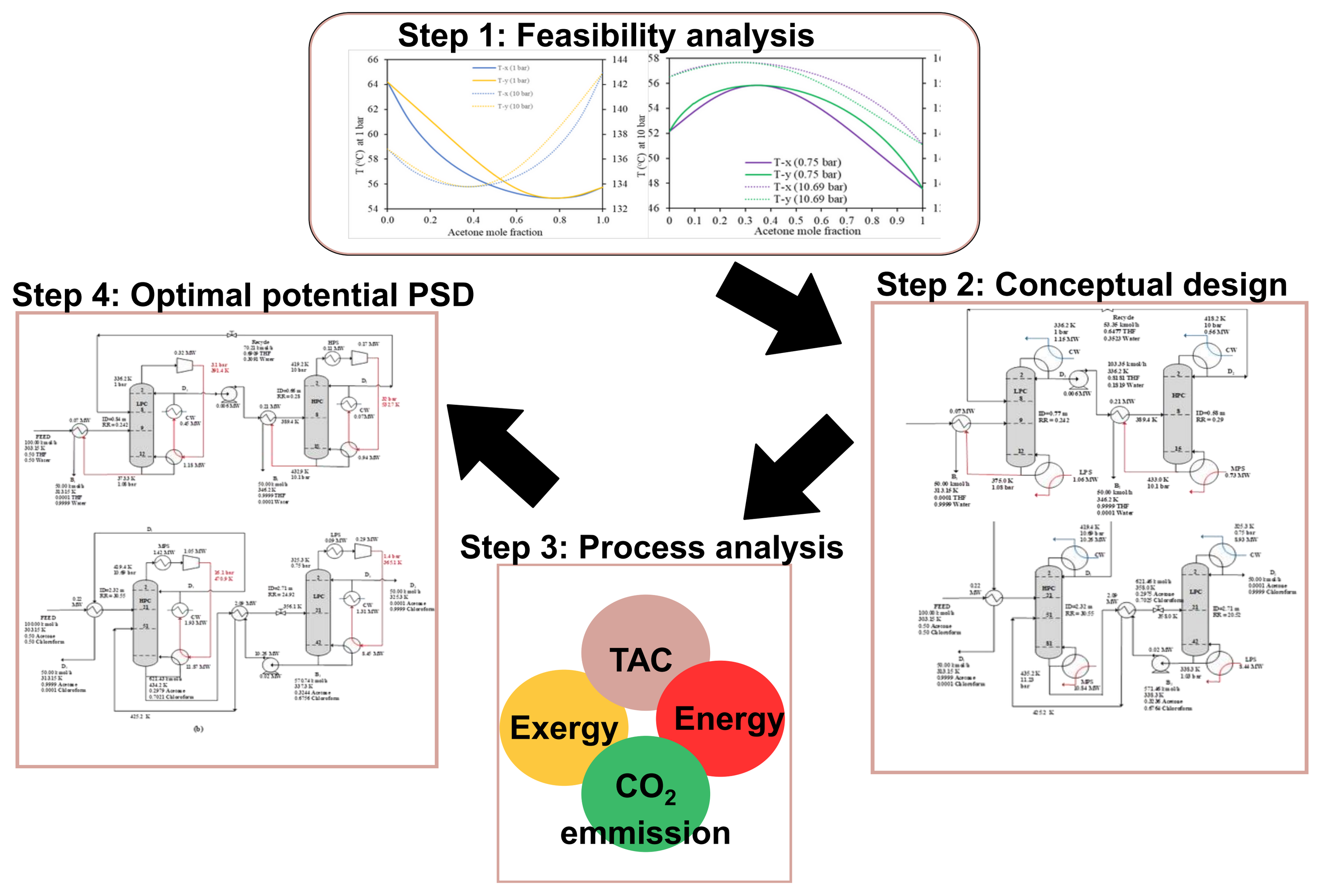


Figure 1: A structured four-step design and evaluation framework.

The metrics evaluated were:

i. **Total Annual Cost (TAC)**
ii. **Total Energy Consumption (TEC)**
iii. **CO_2 emissions**
iv. **Second-law (exergy) efficiency**

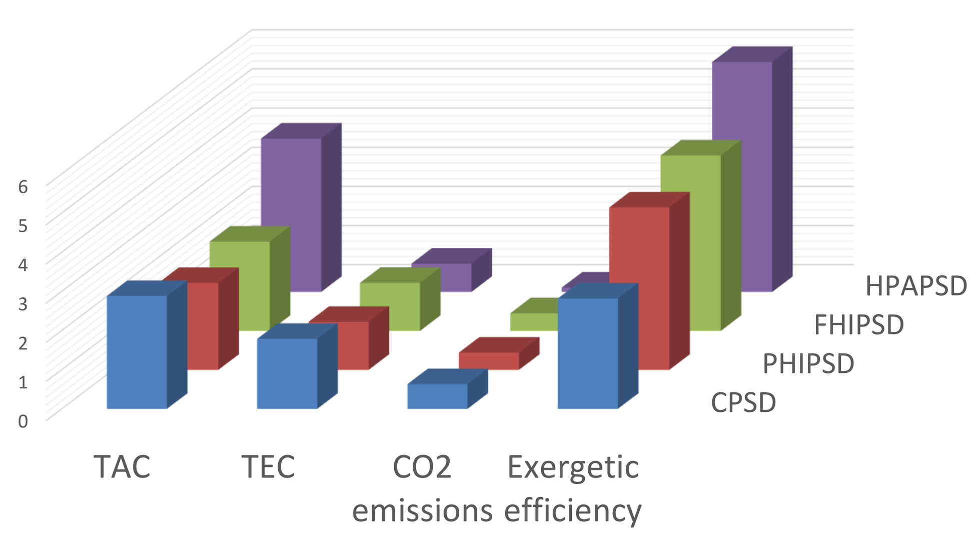
- ➢ PHIPSD and FHIPSD applied heat recovery between high- and low-pressure columns, reducing steam and cooling utility loads. HPAPSD introduced a mechanical vapour recompression cycle to boost thermal efficiency further.

RESULTS & DISCUSSION

THF/Water System

- ✓ **Up to 50% reduction** in TAC
- ✓ **60% decrease** in TEC
- ✓ **83% lower CO_2 emissions**
- ✓ Thermodynamic efficiency up to **24%**

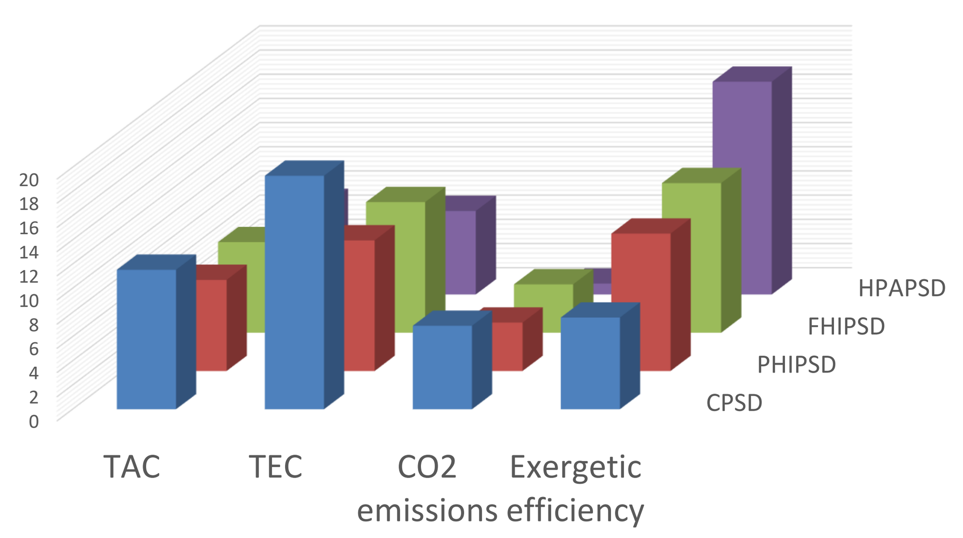
Performance comparisons for the THF /water



Acetone/Chloroform System

- ○ TAC savings up to **71%**
- ○ CO_2 emissions reduced by **87%**
- ○ Achieved **18%** second-law efficiency

Performance comparisons for the acetone /chloroform



Comparative Insights

- ❑ **HPAPSD** delivered the greatest energy and emissions reductions across both systems.
- ❑ Although HPAPSD requires higher capital costs (compressor installation), its **operational savings and environmental benefits** justify the investment.

Table 1: Comparison Table (HPAPSD vs CPSD)

Metric	THF/Water	Acetone/Chloroform
TAC	-36%	-35%
TEC	-60%	-64%
CO_2	-83%	-87%
Exergy Efficiency	+109%	+125%

CONCLUSION

- ❑ Integrated and electrically driven PSD schemes offer substantial potential for reducing energy use, operational costs, and environmental impact.
- ❑ The study highlights HPAPSD as a **superior sustainable intensification strategy** for azeotropic separations.
- ❑ Electrified Pressure Swing Distillation is a major step toward Net Zero separations

FUTURE WORK

- ❑ Integration of **renewable electricity sources** to further decarbonize HPAPSD.
- ❑ Experimental validation and pilot-scale demonstration.

REFERENCE

Mtogo, Jonathan Wavomba, Gladys Wanyaga Mugo, and Peter Mizsey. "Enhancing exergy efficiency and environmental sustainability in pressure swing azeotropic distillation." *Cleaner Energy Systems* 9 (2024): 100134.