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Process Electrification and Carbon Reduction through Heat Pump-assisted Distillation

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Under global climate change, issues related to decarbonization have become trending topics, drawing increasing attention worldwide. It is estimated that the industrial sector alone accounts for approximately 27 % of the global greenhouse gases (GHG) emissions, as roughly 70 % of its energy demand still relies on fossil fuels. To prevent irreversible environmental damage, energy transition of the industrial sector has become the scope of research, prompting the rapid development of low-carbon energy solutions and energy-efficient technologies. Considering the rapid development of renewable energy sources (RES), integration of RES with electrification technologies has emerged as a promising solution for industrial decarbonization. Among these, heat pump-assisted distillation (HPAD) demonstrates significant potential for industrial applications. This study aims to provide more detailed evaluation regarding the benefits of implementing HPAD in industrial processes from the perspective of energy, economics, and emissions reduction. Analysis results reveal that HPAD can achieve up to 80 % energy savings and over 95 % reductions in carbon emissions. Moreover, the estimated payback periods for HPAD are approximately 0.5 y in both cases, highlighting the strong potential of HPAD as a highly attractive solution for process electrification and carbon reduction.

1. Introduction

Under global warming and its widespread impacts on different aspects including climate, ecosystems, economies, and societies, the urgent need for energy system transformation and decarbonization has never been more pronounced. A recent study showed that, presently, fossil fuels still dominate the industrial production, supporting nearly 70 % of the energy requirement in industry processes (Madeddu et al., 2020), and this results in considerable GHG emissions, particularly carbon dioxide (CO_2). It was estimated that the industry sector alone accounts for approximately 27 % of the global GHG emissions (Woodall et al., 2022), with the chemical industry being a major GHG sources, contributing to 22 % of the sectoral emissions. Among the industrial unit operations, distillation is highly energy-intensive and poses a serious challenge to the industries in the wave of global decarbonization. It was estimated that among all separation technologies used in the processes, distillation alone is responsible for about 60 % of the total energy used (Sholl and Lively, 2016) and 3 % of the global energy demand (Kiss, 2013). Such scale of energy consumption makes decarbonization of distillation processes an enormous challenge since most of the energy demand is still met by fossil fuels. Thus, improvements to distillation processes are evidently crucial to pursue global industrial decarbonization.

With the rapid development of renewable energy sources (RES), the combination of RES and electrification technologies has been regarded as a promising solution for industry decarbonization. The International Energy Agency, IEA (2021) forecasted that the electrification of industrial processes could pave the way for “net-zero,” leading to a significant reduction of 20 % in global carbon emissions. As distillation is a major emission source in the industry sector, the electrification of distillation processes is undoubtedly essential for global industry decarbonization. For processes featuring distillation, heating is inevitable and the demands are usually fulfilled by the combustion of fossil fuels, resulting in large GHG emissions. Hence, a strategy for electrifying distillation processes is to replace conventional fossil-based heating units with power-to-heat (PtH) technologies. Among the PtH technologies, heat pumping is considered one of the most promising solutions to industrial

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decarbonization for its advantage in energy efficiency (Matsuda et al., 2012). Integration of heat pumps into processes allows both waste heat recovery and process electrification to be achieved at the same time.

Heat pump-assisted distillation (HPAD), as an external process intensification method to reduce the need for conventional process heating, is a promising strategy to electrify distillation processes. HPAD offers two benefits: (1) unlike conventional fossil-based heating methods, heat pumps operate solely on electricity and thus avoid direct GHG emissions during operation, achieving significant emission reductions; (2) in contrast to electric heaters, which provide heat energy using the same amount of electricity, heat pumps upgrade low-grade waste heat from the process to useful heat energy using a much smaller amount of electricity, significantly improving the overall energy efficiency of the process and reducing the overall energy consumption.

Previous studies of HPAD have focused on individual case studies, lacking the development of a generalized design method and in-depth analysis of the potential benefits of introducing heat pumping into distillation processes. This study addresses this research gap using the methanol/water system as an example. In addition to the process design of HPAD, further analysis of the benefits of HPAD is carried out from the perspectives of energy, economics and carbon reduction.

2. Method

2.1 Base case

To provide a basis for comparing various HPAD designs and analyzing the results, the base case is established first. The base case for the methanol/water system considers a conventional distillation column, of which the design parameters and specifications are adapted from Cui et al. (2024), as given in Table 1.

The conventional column for methanol/water distillation is simulated in Aspen Plus and the results are compared with those reported by Cui et al. (2024) for validation. As shown in Table 2, the base case simulation results obtained in this work agree with the results of Cui et al. (2024). The base case is taken as a reference point for comparison with further scenarios where various HPAD systems are incorporated.

Table 1: Operating parameters and column specifications in the base case

Parameter/specification	Value/setting
Thermodynamic model	NRTL
Heating medium	Low pressure steam (LPS)
Feed stream	
MeOH composition	80 mol %
Water composition	20 mol %
Molar flowrate	100 kmol/h
Temperature	30 °C
Pressure	1.5 bar
Operating	
Reflux ratio	0.645
Minimum temperature approach	10 °C
Bottom reboiler duty	1,307 kW
Overhead condenser duty	1,426 kW
MeOH purity demand	99.00 mol %
Water purity demand	99.99 mol %
Equipment	
Total stage of the column	40 stages
Overhead condenser/bottom reboiler/feed stage	1st/40th/30th stage
Overhead condenser operating pressure	1 bar
Stage pressure drop	0.7 kPa
Compressor isentropic efficiency	0.75

2.2 Mechanical vapor recompression (MVR)

The first scenario of HPAD in this study is the integration of MVR into conventional distillation columns. MVR, as the name implies, involves compressing the overhead vapor from the column mechanically by means of compressors. To integrate MVR with a conventional distillation column, the overhead condenser and the bottom reboiler are removed first and then replaced with a combination of compressors and heat exchangers. By compression, the temperature of the overhead vapor stream is increased, making it a useful hot stream to vaporize the liquid from the bottom of the column. Figure 1 shows the configuration of the proposed MVR system.

The first (left) heat exchanger acts as an intercooler and preheater, while the second heat exchanger acts as a condenser and reboiler. A throttle valve and an auxiliary cooler are also used to ensure a saturated liquid refluxed to the column.

Table 2: Validation of the base case results

Parameter	This work	Cui et al. (2024)
Overhead product stream		
Molar flowrate (kmol/h)	80.80	80.81
Temperature (°C)	64.35	64.80
Pressure (bar)	1	1
MeOH composition (mol %)	99.0	99.0
Water composition (mol %)	1.0	1.0
Bottom product stream		
Molar flowrate (kmol/h)	19.20	19.19
Temperature (°C)	106.52	106.50
Pressure (bar)	1.273	1.273
MeOH composition (mol %)	99.99	99.99
Water composition (mol %)	0.01	0.01

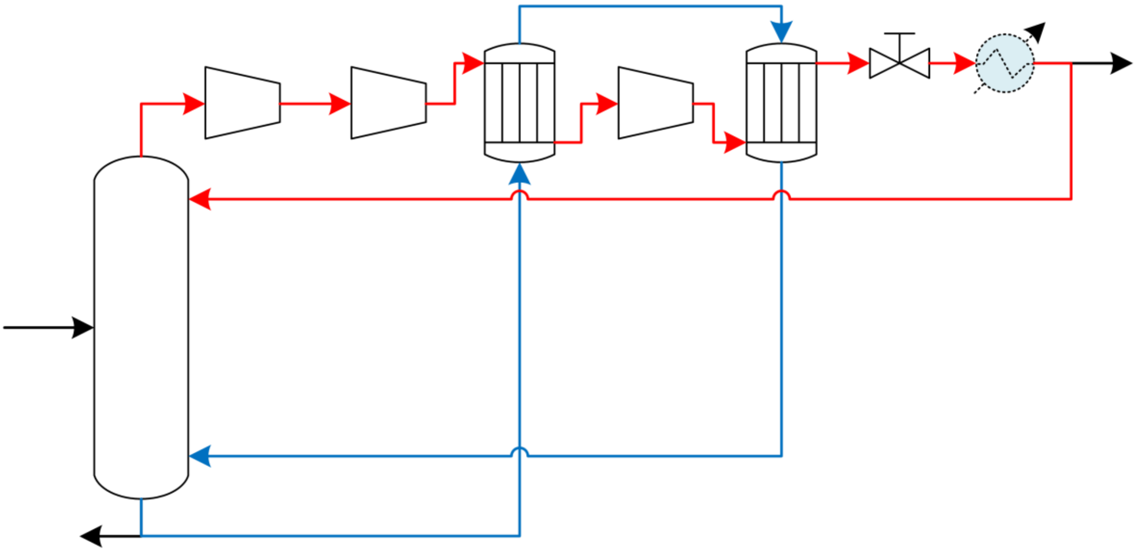

Figure 1: Configuration of the MVR system.

It is important to point out that in Figure 1, multi-stage compression is used to prevent a practically inappropriate compression ratio that might be a challenge for equipment design. Another reason for this design is to reserve a margin for applying intercooling in case of various systems of components. Although a higher temperature would be desired for heating purposes, the compressor discharge temperature (CDT) is limited to practical factors, mainly the operating temperature limit for the compressor. If the CDT is beyond the tolerance of the compressor, the HPAD system may fail from worn rings, acid formations, and oil breakdown (Luo et al., 2015). Thus, for process safety reasons, the CDT is limited to 200 °C for all compressors in this study.

2.3 Self-heat recuperation technology (SHRT)

Although the integration of MVR can bring a considerable improvement in energy savings to the conventional distillation column, given the urgent need for global decarbonization and industrial energy transformation, opportunities for further improvements may be explored. To pursue better energy performance, Kansha et al. (2010) first proposed the concept of self-heat recuperation technology (SHRT) as an advanced version of MVR. Furthermore, Matsuda et al. (2011) established more specific SHRT models in a study regarding aromatic separation. In this study, a similar SHRT scheme is introduced to the conventional distillation column, and the results are evaluated and compared with the base case.

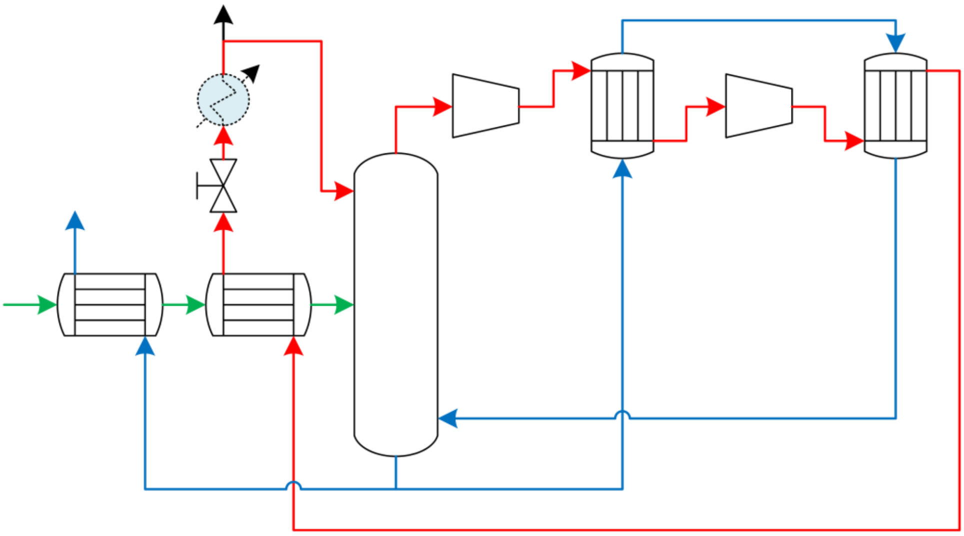

Figure 2: Design structure of the self-heat recuperation technology HPAD model.

Basic HPAD schemes such as MVR employ compression to increase the temperature of the vapor stream, and make use of only the latent heat, leaving the sensible heat unutilized. Different from basic HPAD, SHRT has the following features: (1) After vaporizing the bottom liquid stream, the compressed overhead vapor stream is used to preheat the feed stream with its remaining sensible heat before leaving as the product stream; (2) the bottom product stream is also used to preheat the feed stream before leaving. SHRT thus allows additional heat recovery and further improved overall energy efficiency of distillation processes. Figure 2 shows the configuration of the proposed SHRT system. The feed stream is marked green. It is worth noting that multi-stage compression is also incorporated in the SHRT system for the same reason as with MVR.

3. Results

3.1 Energy performance

The purpose of applying HPAD in industrial processes is to improve overall energy efficiency and reduce energy consumption. To demonstrate the energy savings from introducing HPAD into a conventional column/process, simulation results of the base case and the proposed MVR and SHRT systems are compared. Figure 3 shows that 1,426.36 kW of steam is required to supply the reboiler duty in the base case. The same reboiler duty is provided by the compressed overhead vapor stream in the MVR and SHRT systems, requiring 360.78 kW and 282.21 kW of compressor power, respectively. Besides the steam and electricity requirements, the coefficient of performance (COP) values of the MVR and SHRT systems are calculated and compared using Eq(1).

$$COP = \frac{\text{Reboiler duty}}{\text{Compressor power}} = \frac{Q}{W} \tag{1}$$

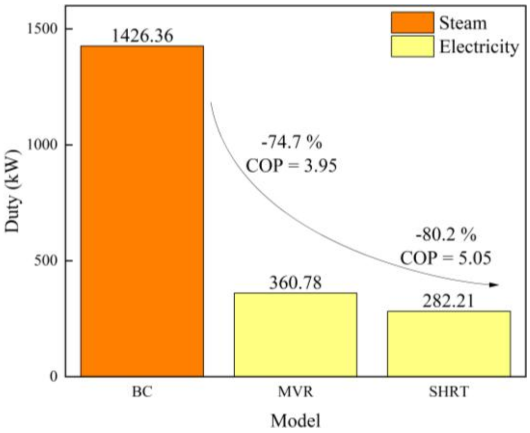

Figure 3: Energy performance of the MVR and SHRT systems.

As shown in Figure 3, the COP of the SHRT system (5.08) is higher than that of the MVR system (3.95). This indicates that further improved energy performance in terms of energy consumption and energy efficiency, as well as better economics, can be achieved by preheating the feed stream of the column.

3.2 Carbon reduction

Apart from energy performance, the carbon reduction potential of applying HPAD in industrial processes is also assessed. The annual carbon emissions for each case are calculated based on the US mode (Figure 4a) and the EU mode (Figure 4b). The assessment is based on the consumption of steam, electricity, and cooling water in the process, which are recognized as major sources of carbon emissions in this study.

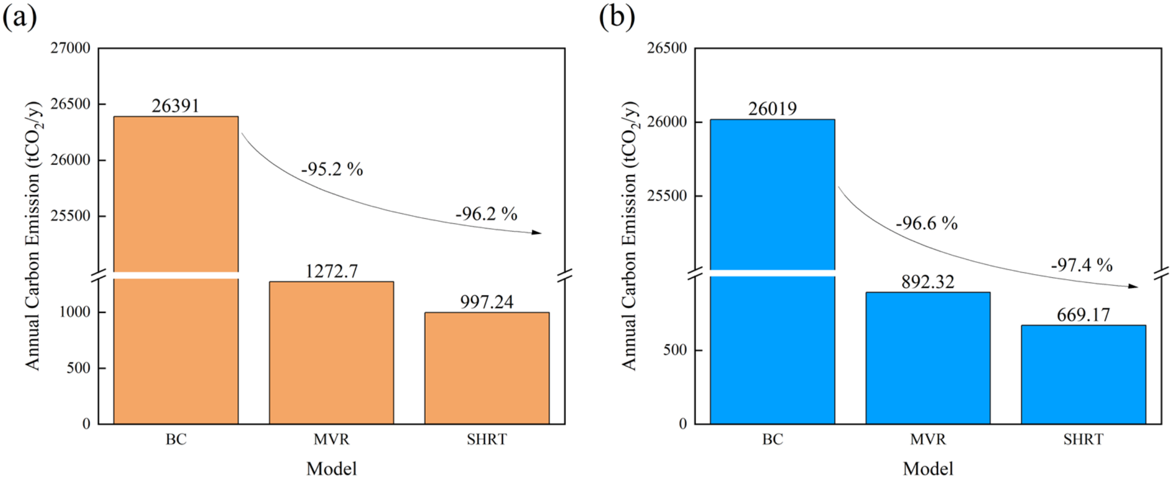

Figure 4: Estimation of annual carbon emissions for HPAD cases using (a) US and (b) EU modes.

As shown in Figure 4, the use of HPAD can contribute to over 95 % carbon reductions in both modes. With rapid development of RES in recent years, HPAD is evidently a promising solution for process electrification and carbon reduction.

3.3 Economic analysis

Figure 5 shows the economic analysis results including the estimation of carbon taxes (Figure 5a) and payback periods (PPs; Figure 5b) for the HPAD cases based on the US and EU modes. Eq(2) is used to calculate the PP for each case.

$$PP = \frac{TCC_2 - TCC_1}{(UC_1 - UC_2) + (CT_1 - CT_2)} \tag{2}$$

where *TCC* is the total capital cost; *UC* is the annual utility cost; *CT* is the annual carbon tax; subscripts 1 and 2 denote the base case and HPAD results, respectively. The details are provided in Table 3.

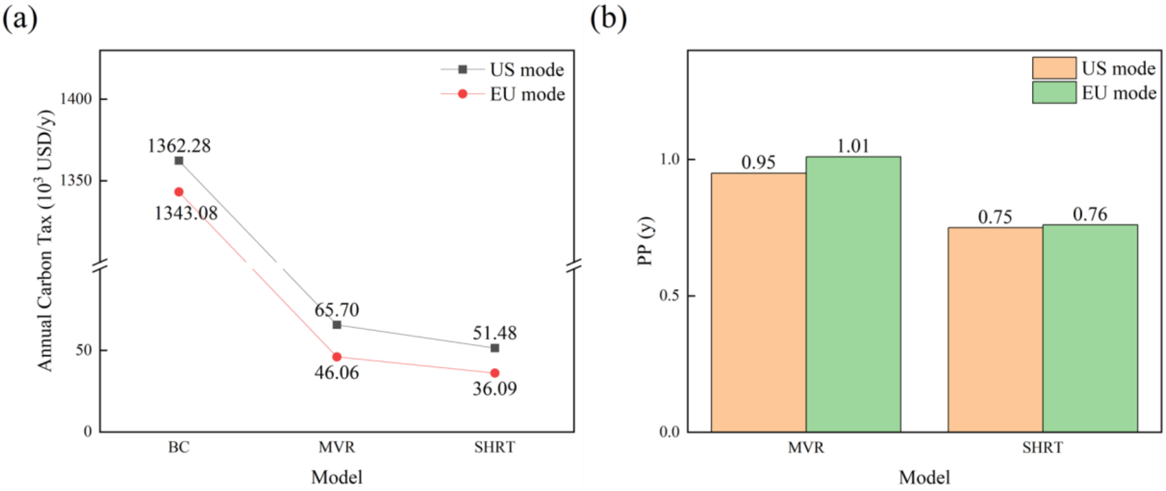

Figure 5: Estimation of (a) annual carbon tax and (b) PPs for HPAD cases.

Table 3: Cost summary for the methanol/water system.

Result	Base case	MVR	SHRT
Total capital cost (10^3 USD)	969.19	2,304.39	2,074.59
Utility cost-US (10^3 USD/y)	356.63	244.6	191.49
Carbon tax-US (10^3 USD/y)	1362.28	65.7	51.48
Utility cost-EU (10^3 USD/y)	614.55	591.07	462.54
Carbon tax-EU (10^3 USD/y)	1,343.08	46.06	36.09

It can be observed from Figure 5 that the use of HPAD can significantly reduce the impact of carbon tax on the industry sector, and with such advantages, the estimated PPs for the MVR and SHRT cases are approximately 1 and 0.75 y, respectively, indicating a high level of economic feasibility.

4. Conclusion

Preceding analysis results demonstrated that HPAD can significantly improve the performance of distillation columns—achieving up to 80 % energy savings and over 95 % reductions in carbon emissions. Additionally, the estimated PPs for both cases are approximately 1 and 0.75 y, respectively, indicating excellent economic feasibility of HPAD. These underscore the strong potential of HPAD as a highly attractive solution for process electrification and carbon reduction from the perspective of energy, carbon emissions, and economics. With the rapid development of RES, the advantages of HPAD in improving conventional distillation processes are expected to become more pronounced, paving the way for its broader industrial application in the foreseeable future.

Nomenclature

COP – coefficient of performance, -
CT – annual carbon tax, USD/y
PP – payback period, y
Q – reboiler duty, kW
TCC – total capital cost, USD
UC – annual utility cost, USD/y
W – external work required, kW

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