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Heat integration of heat pump assisted distillation into the overall process

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HIGHLIGHTS

- Heat integration of heat pumps, distillation columns and background processes.
- An approach to identify the placement of a heat pump via pinch technology.
- A smaller temperature lift of heat pumping for a distillation column.
- The heat integration scenario reduces the energy consumption of the overall process.

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ABSTRACT

Reducing the energy consumption of distillation processes can lead to significant cost savings in refineries and the chemical process industry because distillation is a widely used and energy-intensive separation technology. A distillation column can be heat integrated with heat pumps to reduce the energy supplied by the utility, and it can also be integrated into the overall process to save energy for the overall process. However, previous studies have not adequately investigated the synergistic effect of integrating heat pump assisted distillation into overall processes. In this paper, a systematic design methodology is proposed for the simultaneous heat integration of distillation, its background process and heat pump systems. Such a holistic heat integration approach can lead to considerable energy savings for the overall process. The proposed methodology also includes systematic identification for the energy-optimum placement of the heat pump and its matching with process streams. Furthermore, the impacts of distillation process modifications on the holistic heat integration strategy are examined. A case study is presented to illustrate how the proposed design method is applied and to demonstrate its effectiveness in saving energy. For the case study, the hot and cold utilities are reduced by 61.5% and 20.6% compared to energy consumptions for the base case.

1. Introduction

The chemical industry consumes vast amounts of energy which is mainly obtained from burning fossil fuels, e.g., coal, natural gas and crude oil. This results in unsustainable life cycle impacts on the environment [1]. In process industries, separation processes are an essential step to recover or purify the desired products, or to remove undesired wastes or byproducts. Distillation is a widely used and energy-intensive separation technology [2,3], as energy consumption associated with distillation processing accounts for 40–60% of the total energy consumption of the chemical industry [4,5]. Due to the rising cost of energy and the increasingly strict environmental regulations, reducing the energy consumption of distillation processes is of high demand and has received considerable research attention.

In a conventional distillation column, high quality heat is supplied to a bottom reboiler and waste heat is rejected from an overhead condenser. Many studies have proposed different ways to reduce the energy consumption of distillation processes. Some options for improving the energy efficiency of distillation operations include making changes to the design or operating conditions of the column, such as preheating the feed [6] and adjusting the reflux ratio [5,7]. System-wide approaches that utilize energy in an integrated manner within the distillation process are another attractive option to improve energy efficiency. For example, the concept of heat integration may be used to systematically realize heat recovery of distillation columns by making use of heat sources and heat sinks available within the distillation process [8]. Such heat integrated design options include thermally-coupled

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Nomenclature

COP	coefficient of performance of heat pump
CP	heat capacity flow rate, kW/°C
H_1	heat flux at temperature T_1 on the GCC, kW
H_2	heat flux at temperature T_2 on the GCC, kW
H_{poc}	heat flux at the heat pocket, kW
Q_C	total required cold utility of overall process, kW
$Q_{C,min}$	minimum cold utility of background process, kW
Q_{cond}	heat load of overhead condenser, kW
Q_H	total required hot utility of overall process, kW
$Q_{H,min}$	minimum hot utility of background process, kW
Q_{reb}	heat load of bottom reboiler, kW
Q_1	rejected heat of heat pump, kW
Q_2	heat taken in by heat pump, kW
T_{cond}	temperature of overhead condenser, °C
T_P	temperature of the pinch point, °C
T_{reb}	temperature of bottom reboiler, °C
T_{sup}	supply temperature, °C
T_{tar}	target temperature, °C
T_1	temperature of heat pump condenser, °C
T_2	temperature of heat pump evaporator, °C
ΔT_{min}	minimum temperature difference for heat exchange, °C
W	external work, kW
η_C	Carnot efficiency

Superscripts

1	heat pump 1
2	heat pump 2
real	corresponding real value

distillation [9], multiple-effect distillation [10], introduction of side reboilers and/or side condensers [11] and heat pump assisted distillation [12].

Among the aforementioned options, considerable attention has been paid by the academic and industrial communities [13–15] to the benefits of heat pumps for distillation processes as heat pumps can upgrade heat from a lower temperature level to a higher one. There are great potentials to reduce the energy consumption of distillation processes when they are appropriately integrated with heat pumps. Different schemes have been proposed for upgrading energy within a distillation column through heat pumps. One scheme is to use an external heat pump circuit in which a refrigerant fluid, different from the mixture in the column, is employed. This circuit has an evaporator and a condenser, which is coupled with the condenser and the reboiler of a distillation column, respectively [5]. Another scheme, known as mechanical vapor recompression heat pump, compresses the column overhead vapor stream in the compressor directly and uses it as a heating medium [16]. The bottom product also can be taken as a heat-exchanging medium of the heat pump with a bottom flashing arrangement [14,17]. A thermal vapor recompression heat pump is similar to the mechanical vapor recompression heat pump, in which the compressor is replaced by a stream ejector [13]. Also, an absorption heat pump transfers the heat using absorption pairs and can also be integrated in distillation processes [18,19].

Although the heat pump schemes described above are operated with different operating principles and integration concepts, all of them are applied to recover heat from the overhead condenser for use by the bottom reboiler. To allow heat exchange between a heat pump and a distillation column, the temperature lift via the heat pump should be greater than the temperature difference between the reboiler and the condenser. However, as an increase in the temperature lift of a heat pump decreases the coefficient of performance (COP), which is the ratio of the heat rejected to the external energy consumed by the heat pump, care must be taken to avoid excessive temperature lift [20]. In addition, with the aid of Column Grand Composite Curve [21], it is thermodynamically feasible to use heat pumps to exchange heat with side streams from intermediate trays of a distillation column, which requires a small temperature lift [22] but is rarely applied in practice.

The basic idea of the aforementioned methods is to improve the internal energy utilization within distillation columns so that the demand for external energy, namely utility [8], can be reduced. Besides, a distillation column can also be designed in the context of the overall process with the aim of utilizing energy from other processing units to reduce the energy consumption of the overall process. For the sake of simplicity, the overall process without considering the distillation process is referred to as the background process in this paper.

In the early 1980s, Linnhoff et al. applied the concept of pinch analysis and proposed a tool based on Heat Flow Cascade to optimize the allocation of available heat between a distillation process and its background process [23]. Their research indicates that if the operating temperatures of both the condenser and the reboiler are above or below the pinch temperature of the background process, distillation columns may be heat-integrated with the background process. If this is not the case (i.e. the distillation process is located across the pinch point), heat integration between the distillation column and its background process is not favored. In such situation, the column operating conditions can be modified so that the reboiling temperature is below the pinch or the condensing temperature is above the pinch. Subsequently, Bandyopadhyay [24] proposed two modifications: through side exchangers and through feed preheating, for the heat integration of a distillation column with the background process. Kravanja et al. [25] investigated the heat integration of a biochemical plant with the process modifications of heat loads and temperature levels. However, making process modifications to distillation columns requires careful consideration when the products are very sensitive to any changes in the operating conditions.

Moreover, for the purpose of saving energy, heat pumps can also be heat integrated with the background process. Townsend and Linnhoff [26] proposed that a heat pump should absorb heat below the pinch temperature and reject it above, namely the across-pinch rule. In further research, Wallin et al. [27] adopted Composite Curves to guide the choice of heat pump types for various industrial processes and revealed the heat load limits of heat pump installations. Benstead and Sharman [28] matched heat pump with the Grand Composite Curve (GCC) of a process using the mirror image technique, which is relatively simple and clear. Besides, the shape of the GCC can also suggest which type of heat pump is most suitable [29]. Yang et al. [30] analyzed the dynamic changes of pinch temperature and GCC of industrial processes with heat pumps integrated. However, since both Composite Curve and GCC are composed of two sets of process streams (i.e. hot and cold streams), these pinch-based methods did not consider the matches between process streams and heat pumps, and such work was mainly done by computer programs [28,31,32].

In summary, three energy-efficient approaches have been explored so far: heat pump assisted distillation, heat integration