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Performance enhancement of vapor recompression heat pump

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HIGHLIGHTS

- We developed various models for the enhancement of vapor recompression heat pump.
- Utilization of hot process or utility streams was considered in the models.
- Efforts were made to minimize heat losses and heat pump size.
- The thermoeconomic and environmental performances of the models were investigated.
- The applications of the models will reduce total annual cost and emission rate.

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ABSTRACT

The vapor recompression heat pump (VRHP) has the potentials of reducing the energy requirements of fractionating close-boiling mixtures. It improves the quality of low grade heat with the aid of heat pump to provide heat input to the reboiler. However, this technology does not utilize heat efficiently resulting in appreciable heat loss in the condenser. In this study, enhanced VRHP models were developed to reduce the heat loss and heat pump size. The strategies adopted rely on reducing the heat differential across the heat pump by utilizing external and utility streams, and process stream within the system. The thermoeconomic and environmental performances of the developed models were compared with the base case VRHP and the conventional distillation process. The results showed that the developed models yielded considerable energy savings. Considering the present trend of short process modification payback time, the use of an external process stream is recommended as the most preferred option to boost the plant performance. However, in situation where such streams are not available within the plant premises or uneconomical due to their influence in the chosen exchanger network, the utilization of process streams within the system will be a much more attractive alternative option.

1. Introduction

The conventional distillation system is widely use in the petroleum and chemical industries for the separation of fluid mixtures. This system of separation is highly energy intensive [1–5]. Reports have shown that about 40–60% of the energy used by the chemical and refining industry is for the separation of products by distillation [6–8]. The continuous rise in energy cost, the increasing public concern and the international environmental regulations makes it imperative for the process industries to look for ways to reduce energy demands. For this reason, any research thrust that will reduce energy consumption, environmental burden and satisfies product requirement in distillation processes is of high demand.

The quest to improve efficiency and lessen environmental impact associated with distillation processes is an on-going concern. Various techniques, such as heat integration, heat pumps, thermal couplings and others have been employed to achieve energy reductions [9–11]. One of the most promising strategies has been the introduction of heat pumps which was first proposed in the mid-1970s [12–14]. Today, different types of assisted heat pump distillation systems exist and have found practical applications in the industries. The most commonly used are the absorption heat pump (AHP) and mechanical heat pump (MHP) [15,16]. The MHP is categorized into three types, the vapor recompression heat pump (VRHP), bottom flash heat pump (BFHP) and closed cycle heat pump (CCHP) [17]. Of the aforementioned types, the VRHP has gained more recognition due to its outstanding benefits [10,17]. This technology pressurizes vapor of a low grade heat to a higher grade by using mechanical power and, then the pressurized vapor provides a heating effect when condensing. However,

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Nomenclature

T	temperature	W	work
P	pressure	I	irreversibility
m	mass flow rate	η	efficiency
E	energy		
Ex	exergy		
Q	duty		

despite the outstanding benefit this technology does not utilize the condensation heat efficiently in the heat exchanger therefore the effluent heat is often discarded as waste. In contrast, the condensation heat may be utilized to reduce the heat differential across the heat pump by increasing its suction temperature and reduction in the pressure balance. This means that the heat pump size can also be reduced by recirculating the process streams within the system without needing to use external heat source. It will be beneficial if such heating potential can create opportunity to further improve the "triple bottom line" of the system which focuses on product quality, economic and environment.

The triple bottom line conditions of the VRHP are attained when the compression ratio of the compressor is minimized [18], this can often be achieved by reducing the heat differential across it. The early works on the application of MHP technology was focused on the selection and appropriate placement of heat pump. The pioneering work of Omideyi et al. [19–22] was limited to the evaluation and design algorithm for selecting heat pump assisted distillation system of a CCHP type. Further works by Meszaros and Fonyo [23] and Fonyo and Mizsey [24] describes the most advantageous strategies of selecting any of the three types. However, their algorithms did not considered the possibilities of reducing the heat pump size and utilizing the effluent heat within the system to reduce the heat differential across it; rather emphasis was placed on alternative options such as heat integration, AHP and modification of process parameters. Furthermore, in situation where process operates on standalone basis the aforementioned options are not applicable thus the choice of implementing a heat pump is decided by its economy. In another early work by Linnhoff et al. [25], it was shown on a grand composite curve that the most appropriate way to place a heat pump is across the pinch. According to Wallin and Berntsson [26] and Wallin et al. [27], heat pump that work across the pinch will always save energy, but it will not necessarily reduce the annual cost associated with the capital investment of the heat exchanger network and the heat pump itself. Benstead and Sharman [28] applied heat pump and pinch technology to a whisky distillation process. The heat pump size and temperature range was determined from the analysis of the grand composite curve. However, to obtain a reliable capital cost estimate the maximum energy recovery of the network was compromised by simplifying its heat exchanger sizes. Their study did not consider reducing the heat differential across the heat pump. Again, for a standalone distillation process the application of this concept is not practicable since an external heat source is required. The recent works on the application of the VRHP technology are focused on designing considerable investment within the shortest payback time by reducing or eliminating the use of steam as the reboiler energy source. Kurum and Fonyo [29] compared the VRHP and multi-effect distillation technique to the conventional acetic acid recovery scheme. In the VRHP scheme, the compressor power was compensated by introducing a process stream in the reboiler unit. Although, the VRHP is not the most preferred configuration, the utility cost reduction and payback time are still much more attractive over the conventional process. Notable example of a VRHP and other MHP schemes applied to a C4 splitter was well described by Fonyo et al. [30] and Fonyo and Benko [31]. Their analysis shows that the use of steam can be replaced with heat added from a mechanical energy source for a standalone distillation process. Since the main effort of the analysis is to compare the economic feasibility of the heat pumps schemes and not to improve them, it may be worthwhile to probe further on improving the systems. There are other important and deductive works, showing potential means of improvement by reducing or eliminating the use of steam as boiling medium. Diez et al. [32] investigated the separation of *i*-butane and *n*-butane mixture by considering the conventional distillation process, along with the VRHP, BFHP and AHP integrated systems in order to determine the best economic alternative. Their result shows that the VRHP gave the best energy savings. Ferre et al. [33] showed that the application of a VRHP to an ethyl benzene/xylene separation and to an ethyl benzene/styrene separation resulted in reduced energy consumption. Quadri [34] shows that the design of propylene/propane system can be improved using single and double stage VRHP systems. Annakou and Mizsey [16] found that for single or double stage VRHP system, the annual costs could be reduced by 37%. Danziger [10] also studied the integration of VRHP to distillation column. He concluded that for the separation of close boiling components, the energy saved by the application of a VRHP is over 80% compared to conventional distillation. Despite the volume of work the quest for further reduction is still paramount to reduce the cost of owning and operating a VRHP system.

Although previous reports have demonstrated the advantages of the VRHP technology over the conventional distillation system, little or no extensive study has been done to elucidate the possibility of reducing the required heat pump size by the effective utilization of useful process streams or utility streams thus reduction in the overall cost of owning and operating the system. Therefore, the main aim of this study is to investigate the possibility to further improve the thermoeconomic and environmental performances of the conventional VRHP distillation process. A deethanizer unit (DEU) of a Nigerian refinery was used as case study. A comprehensive examination was carried out to measure and record the operating conditions of the unit. Different VRHP models were developed. The strategies adopted rely on reducing the heat differential across the heat pump by utilizing process stream within the system, external process stream and utility streams. The thermoeconomic and environment benefit was then compared with the base case VRHP and the conventional distillation process.

1.1. Thermoeconomic and environmental analysis

During the past few decades, thermoeconomic and environmental analyses has emerged a significant engineering tool for system design, performance evaluations and optimization. The analyses combine the environmental aspect of industrial processes with energy, exergy and economic principles. The concept of exergy has been introduced to establish a universal standard for quality and efficient use of energy [35]. The energy analysis is based on the first law of thermodynamics, which expressed the principle of the conservation of energy. However, it provides no information about