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Technical and Economic Feasibility of Heat Pump in Integrated Distillation System to Reduce Energy Use - A Case Study of Abadan Refinery in Southern Part of Iran

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ABSTRACT─ Heat pump systems are a class of heat recovery equipment that allows the temperature of a waste heat stream to be increased to higher, more useful temperature. As the cost of energy continues to rise, it becomes imperative to save energy and improve overall energy. In this light, the heat pump becomes a key component in an energy recovery system with great potential for energy saving. This study investigates the technical and economic feasibility of liquid petroleum gas (LPG) separation process in Abadan petroleum refinery waste heat to power conversion by using a heat pump system. Based on this study, the use of heat pump in the associate separation process, would lead to an estimated 26.34 MMBTU/hr saving that could be achieved with a payback period of 6.03 years. It improve the system efficiency by more than 75 % approximately. Therefore, if the detailed engineering, component fabrication and construction can be achieved within the cost target, the installation of a heat pump waste heat converter on the LPG line would be technologically feasible and economically viable.
Keywords: Chemical process; Heat pump; Energy saving; CO2 reduction

Introduction

Distillation is the main separation technology one of the most important separation process in refineries and chemical process industry. It is estimated that 60 % of energy used by chemical industrial was for distillation [1]. The high energy demand in bulk distillation columns (1-100 MW) and the low thermodynamic efficiency (5-10%) remain the major drawbacks, because of rapid escalation in energy costs, the issue of security of supply, the emission of polluting substance as well as global climate change. Therefore to overcome these problems, alternative heat solutions must be studied which focus on the reduction of energy consumption and the improvement of heating performance while reducing adverse effect on environment. A number of improvement have been developed over the years directed at reducing both operating and capital cost. In extractive distillation (ED) a solvent or separating agent is added in order to increase the relative volatility of components to be separated. In azeotropic extractive distillation the separating agent is used to break the azeotrope. As a consequence the reflux ratio, column diameter and reboiler duty can be reduced and / or the column height can be lower. Commercial low volatility solvents include sulfolane, triethylene (TEG), NMP and NFM. The recovery cost of the solvent is an integral part of the economy of extractive distillation processes. ED is particularly effective for relative volatilities below 1.2. Industrial examples of ED processes are purification of aromatics in petro chemistry, butadiene recovery in naphtha cracking and separation of cycloparaffins from naphtha [1, 2, and 3]. Instead of affecting the thermodynamics of the system also selection of the column internals is a way to increase distillation efficiency. Random and structured packing with specific surface areas from 250 up to 900 m^2 / m^3 are continuously being improved with the objective to optimize height, pressure drop and liquid load and turn down ratio. The main recent advancements in toy columns focus on high capacity trays with centrifugal devices or structured packing demisters although at the cost of an increased pressure drop [4]. Since the 1980's dividing wall columns (DWC'S) have been introduced with allow the separation of three component feeds in a single column leading to interesting reduction in both energy consumption and investment cost. Recently even more complex DWC'S have been constructed to separate four component mixtures in pure products [4]. In contract to improvements of the relative volatility or the column internals, both inside the column, a number of energy reducing measures can be considered outside the column by addressing the reboiler and condenser. These include side reboilers [5], dephlegmators [6, 7] and heat pumps [8]. Side reboilers use waste heat at a lower temperature than the bottom reboiler and thus increase energetic efficiency. Dephlegmators or reflux condensers are compact heat exchangers, such as PFHE'S, used to reduce energy consumption in low temperature gas separators. Heat pumps lift the temperature level of the top vapor in order to use this as heat source for the reboiler [9]. This paper deals with heat pumps for distillation energy savings.

Materials and Methods

1- Industrial heat technology

A systematic approach in improving the energy efficiency of industrial processes is the onion-model developed in industrial heat technology (Figure 1). The pre-assumption is that one should first save on energy by optimizing the process and then go into thinking about the way in which the energy is exchanged within the process and then generated at the outside of the process.

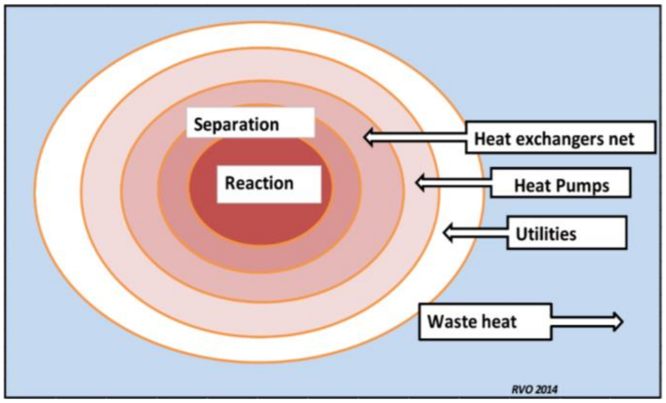

Figure 1: Onion model for process approach [10**]**

The model is explained for a chemical distillation process where in the first shell the processes occurring in reactors and separators (Process) are optimized. In practice this is done by an economic optimization in which energy and other operating cost are balanced with annualized investment cost for the equipment. In distillation "Process" refers to molecular improvements such as extractive distillation as well as optimization of internals, trays and column compartments. Energy consumption can be reduced further by heat integration using heat exchangers. As heat exchangers need a driving force there is a limit to what can be achieved by heat integration. Optimization of the heat exchanger networks is done using pinch technology leading to the rule of thumb: "Do not transfer heat across the pinch temperature". In addition the "grand composite curve" (enthalpy flow rate versus temperature) provides the minimum total cooling and heating power required for the plant [11]. Now the temperature difference at the pinch temperature, ΔTpinch, is optimized by the economy: a higher value leads to smaller investment cost in heat exchanger area but also to increased utility cost. Since the 1980's heat integration has become a standard tool in optimizing process designs based on pinch technology. With the introduction of compact heat exchangers in the 1990's with exchange areas in the range of 200 - 700 m^2/m^3, the optimum temperature difference gradually decreased [12]. Currently multi-effect evaporators are in operation having aluminum compact heat exchangers with a temperature difference as low as 1 – 2 degree of Kelvin. The standard heat integration in stand-alone distillation columns is pre-heating the feed with the bottom stream. Further energy savings can be realized between condensers and reboilers of different distillation columns and applying side reboilers. After heat integration has been optimized, further reduction of energy consumption can be achieved in the third shell: the heat pump (HP). A heat pump is a device that upgrades heat from a lower temperature. Originally heat pumps were only used for refrigeration as heating was done by burning cheap fossil fuels [13]. Interest to use heat pumps also for heating purposes increased with global awareness of the limited availability of fossil fuels in combustion with greenhouse effect.

2- Physical principles

A heat pump is a device that upgrades heat from a lower temperature source to a higher temperature (Figure 2); some required external work while others require external thermal energy. From the first law of thermodynamics, the amount of heat delivered to the hot reservoir (Qh) at the higher temperature (Th) is related to the amount of heat extracted (Qc) from the cold reservoir at the low temperature (Tc) and the external work by the following equation:

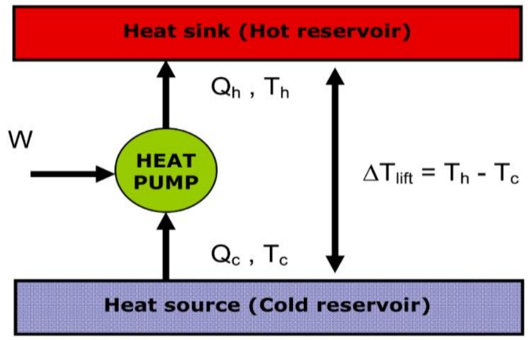

Figure 2: Schematic of a heat pump

$$Q_h = Q_c + \mathrm{W} \tag{1}$$

The measure of the heat pump performance is the coefficient of performance (COP). For heating applications this is the ratio of heat rejected at high temperature to the work input.

$$\mathrm{COP} = Q_h / \mathrm{W} \tag{2}$$

The upper theoretical value of COP obtainable in a heat pump is COPc related to the Carnot cycle.

$$COP_c = T_h / (T_h - T_c) \tag{3}$$

Where the temperature lift, $T_h - T_c$, is the sum of the temperature difference over the column and the temperature differences over the heat exchangers.

Commercial heat pumps based on the vapor compression cycle are operational in numerous applications in various industries. Table (1) presents an overview of heat pump applications in industry processes [14]. This table highlights the most common industrial applications and heat pump types. In contrast to heat actuated systems, it is readily observed that mechanical vapor compression heat pumps are extensively applied in many manufacturing industries.

3- Abadan petroleum refinery as a prospect waste heat power conversion

The Abadan refinery is located in Abadan rear the coast of the Persian Gulf in Khuzestan province - Iran. It was completed in 1912 and was one of the world’s largest oil refineries up to 1980. Its capacity is now listed as 460000 crude oil. The primary aim of this study is to conduct a technical feasibility study on installation of a heat pump using waste heat from the vacuum column distillation process, and to evaluate the economic viability of such a project. A simplified schematic flow diagram of streams is duplicated in figure (3).In this process, the gas treatment process made from three separate towers debutanizer, deethanizer and depropanizer. Light liquids and gases produced by distillation units in the atmosphere, catalytic Converter and isomax consisting of a mixture methane, ethane, propane, butane and pentane collected and then Separated into its constituent components. Since the objective of a heat pump in distillation is to use the heat of condensation released at the condenser for evaporation in the reboiler, then the hot stream passing through condenser (E-14155) as low temperature heat source and the stream passing through reboiler (E-14157) as heat sink with higher temperature have been chosen [14].

Table 1: Representative Overview of Heat-Pump Applications in Industrial Manufacturing Activities [14]

Industry	Manufacturing Activity	Process	Heat-Pump Type
Petroleum Refining and Petrochemical	Distillation of petroleum and petrochemical products	Separation of propane/ propylene, butane/butylene and ethane/ethylene	Mechanical Vapor Compression, Open cycle
Chemicals	Inorganic salt manufacture including salt, sodium sulfate, sodium carbonate, boric acid	Concentration of product salt solutions	Mechanical Vapor Compression, Open cycle
	Treatment of process effluent	Concentration of waste streams to reduce hydraulic load on waste treatment facilities	Mechanical Vapor Compression, Open cycle
	Heat recovery	Compression of low-pressure waste steam or vapor for use as a heating medium	Mechanical Vapor Compression, Open cycle
Wood Products	Pulp manufacturing	Concentration of black liquor	Mechanical Vapor Compression, Open cycle
	Paper manufacturing	Process water heating	Mechanical compression, Closed cycle
	Paper manufacturing	Flash-steam recovery	thermo compression, Open cycle
	Lumber manufacturing	Product drying	Mechanical Compression Closed cycle
Food and Beverage	Manufacturing of alcohol	Concentration of waste liquids	Mechanical Vapor Compression, Open cycle
	Beer brewing	Concentration of waste beer	Mechanical Vapor Compression, Open cycle
	Wet corn milling/corn syrup manufacturing	Concentration of steep water and syrup	Mechanical Vapor Compression, Open cycle thermo compression, Open cycle
	Sugar refining	Concentration of sugar solution	Mechanical Vapor Compression, Open cycle Thermo compression, Open cycle
	Dairy products	Concentration of milk and of whey	Mechanical Vapor Compression, Open cycle Thermo compression, Open cycle
	Juice manufacturing	Juice concentration	Mechanical Vapor Compression, Open cycle
	General food-product manufacturing	Heating of process and cleaning water	Heating of process and cleaning Closed cycle
	Soft drink manufacturing	Concentration of effluent	Mechanical Compression, Closed cycle
Utilities	Nuclear power	Concentration of radioactive waste	Mechanical Vapor Compression, Open cycle
		Concentration of cooling tower blow down	Mechanical Vapor Compression, open cycle
Miscellaneous	Manufacturing of drinking water	Desalination of sea water	Mechanical Vapor Compression, Open cycle
	Steam-stripping of waste water or process streams	Flash steam recovery	Thermo compression, Open cycle
	Electroplating industries	Heating of process solutions	Mechanical Compression, Closed cycle
		Concentration of effluent	Mechanical Vapor Compression, Open cycle
	Textiles	Process and wash-water heating	Mechanical Compression, Closed cycle
		Space heating	Mechanical Compression, Closed cycle
		Concentration of dilute dope stream	Mechanical Compression, Closed cycle
	General manufacturing	Process and wash water heating	Mechanical Compression, Closed cycle
		Space heating	Mechanical Compression, Closed cycle
	District heating	Large-scale space heating	Mechanical Compression, Absorption Closed cycle
	Solvent recovery	Removal of solvent from air streams	Mechanical Compression, Open cycle

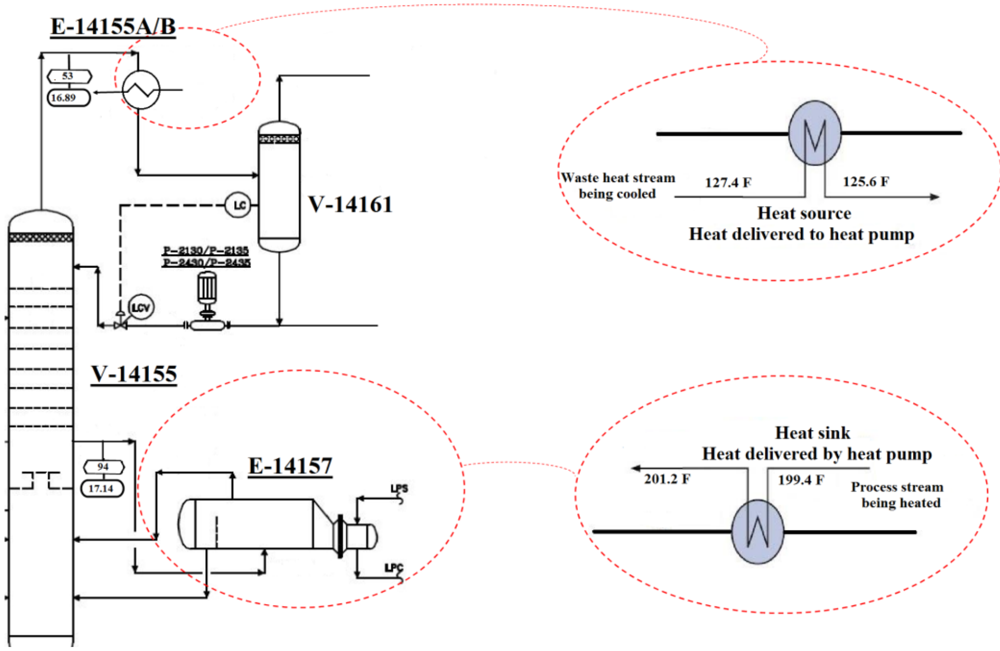

Figure 3: Simplified schematic flow diagram of streams

Figure (4) shows a schematic diagram of the conventional column together with the integration of the heat pump and the distillation column. The working fluid is evaporated at the condenser, compressed to a higher (saturated) temperature, condensed, in the reboiler and cooled down by expansion over a throttle valve to a (saturated) temperature below the condenser temperature.

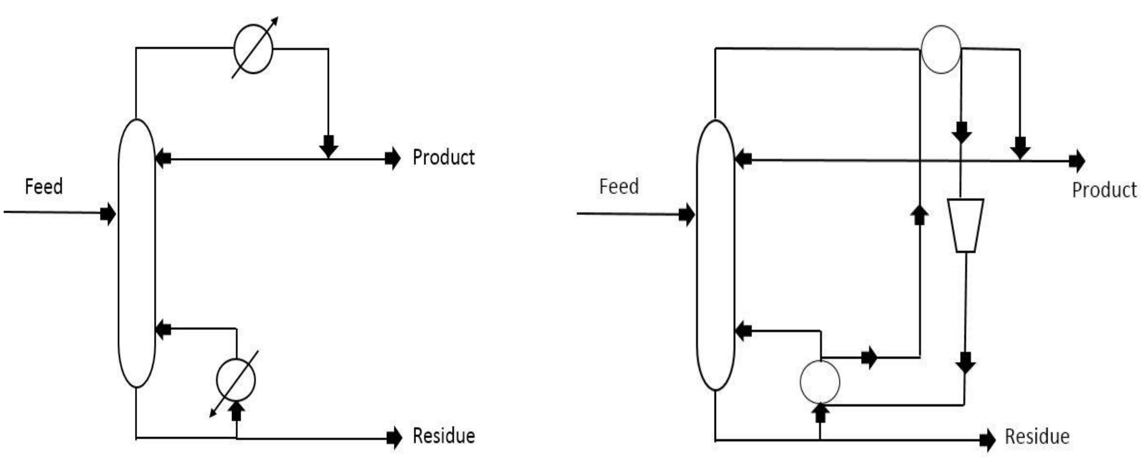

Figure 4: Distillation tower without heat recovery and with

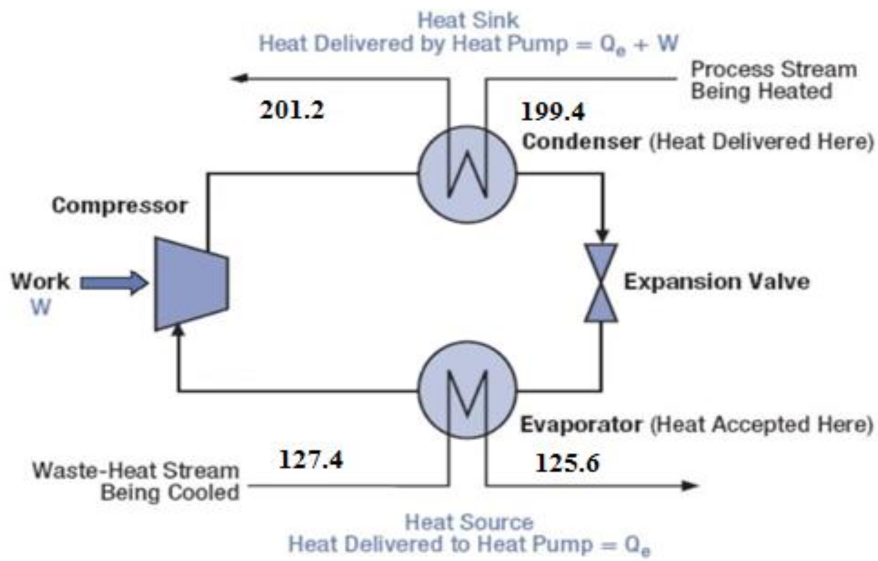

Figure 5: simple schematic of mechanically driven Heat pump

According to the information given in table (1) and temperature working [14], a closed mechanical heat pump has been chosen for our project. Thus consider E-14155 as heat pump evaporator and reboiler E-14157 heat pump condenser are selected. Figure (5) shows a schematic of heat pump system. The stream process passing evaporator E-14115 from 127.4˚F to 125.6˚F is cooled and chosen heat source with 19.95 MMBtu/h, and the process stream heating from 201.2˚F to 199.4˚F is the sink heat. Then in accord with the figure (5), Q_e is the heat delivered to the heat pump, W is the work supplied to the heat pump compressor and Q_e + W is the amount of energy saving. Also, the actual heat pump coefficient of performance (COP_{HP}) is assumed 70% of the ideal condition.

Table 2: The effect of heat pump on efficiency

	CO_2 emission (lb/yr)	**Energy consumption (MMBtu/hr)**
Conventional system	27.96*10^6	26.3425
New system	19.11*10^6	6.3858

Table 3: Results of the calculation

Heat pump	T_{in} (˚F)	T_{out} (˚F)
Condenser	199.4	201.2
Evaporator	127.4	125.6
Refrigerant fluid	Compressor Inlet	Compressor Outlet
	105.6˚F	221.2˚F
Actual COP_{HP}	4.125	
Q_e (MMBtu/hr)	19.95668491	
W (MMBtu/hr)	6.3858	
Consume Power Cost ($/yr)	864693.27	
Q_{out} (MMBtu/hr)	26.3425	
Steam Cooling ($/yr)	1153801.5	
Net Saving ($/yr)	574403.9826	
Investment ($)	3463274.772	
Payback (yr)	6.03	
CO_2 reduction (lb)	8.5876*10^6	

Result and discussion

Tables (2) and (3) show a summary of calculation and the estimation of the feasibility study of our case study. The work, W, to derive the system is equal to 6.38 MMBtu/h and the useful supplied heat to the process will be 26.34 MMBtu/h. That is, our heat pump is going to save 19.957 MMBtu/h of heat input to the process. If the process runs 8760 hours per year, the project could save 574403.98 $ in annual. As shown in figure (6), it will improve the efficiency system by 75%.
The investment cost to insulate the closed cycle mechanical heat pump with respect to above condition, is 393000 $/MMBtu to drive the compressor. Thus with the act of annual cost index [15], the total cost investment of installing and running this system is equivalent to 3.5 million dollars approximately.

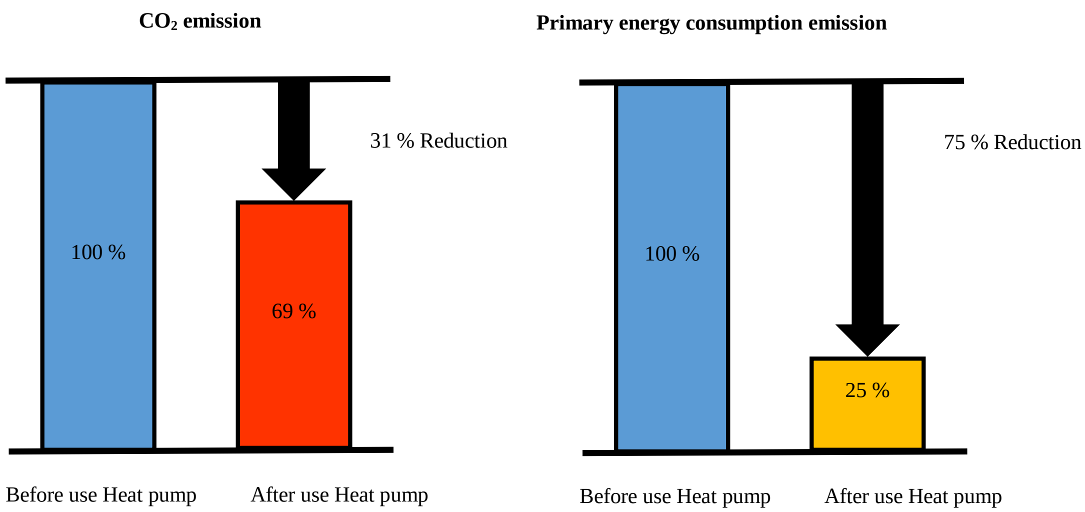

Figure 6: Efficiency result from heat pump

Conclusion

Based on the feasibility study, the integration of heat pump would lead to an estimated 19.956 MMBtu/hr saving that could be achieved with a payback of 6.03 years. It improves the system efficiency by more than 75 % approximately. This study also showed that a reduction in CO_2 emission of approximately 31%. Therefore, if the detailed engineering, component fabrication and construction work can be achieved within the cost target, then the insulation of heat pump waste heat power converter on the LPG cooling line would be technically feasible and economically viable. As observed, chemical process facilities offer great opportunities for waste heat recovery. The use of heat pumps to raise the temperature of low temperature waste heat to a more suitable level for distillation offers great potential. An added benefit of waste heat recovery is the reduction in greenhouse gas (GHG) emissions. Ultimately, a greater use of waste heat recovery equipment by the industry will increase the industry's global competitiveness.

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