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Refrigeration Cycle Performance Improvement of a Condensate Recovery Unit in Operation

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Abstract

The aim of the present study is to enhance the performance of the refrigeration cycle in a condensate recovery plant existed in Egypt. In the current work, two proposals were suggested to increase the efficiency of the refrigeration system. The first proposal is the optimization of the operating conditions of the current cycle, which uses propane as a refrigerant. The second proposal is based on using vapor compression cycle with ammonia as a refrigerant instead of propane with the same equipment of the current system. The two proposals are simulated using HYSYS software program. Additionally, an economical study is introduced for each proposal based on capital cost, operating cost and expected profit. Regarding the first proposal, the simulation results demonstrated that the flowrate of the refrigerant and the intermediate pressure are the key factors affecting the refrigeration system. These factors are studied to select the optimum operating conditions to maximize the benefit of the present cycle. However, the second proposal results showed that using ammonia as a refrigerant is more economical and more efficient than propane.

Keywords*: Ammonia refrigerant; Condensate recovery; Vapor compression.*

1. Introduction

Natural gas is considered as the fastest-growing primary energy source in the International Energy Outlook 2003 [1] forecast. Raw natural gas consists mainly of methane, in addition to some gaseous hydrocarbons, acid gases, nitrogen, helium, mercury, water and liquid hydrocarbons. It must be treated and processed in order to produce the pipeline quality dry natural gas for commercial, residential and industrial consumers. The existing natural gas processing plants often roughly separates the raw natural gas into gaseous phase dry natural gas and liquid-phase gas condensate [2]. The condensate recovery from natural gas is not only needed for the production of high quality dry natural gas, but is also considered as an important source of revenue, since it may include up to nearly 50 vol% of heavier hydrocarbons recovered as liquid condensates [3]. Moreover, it helps in controlling the natural gas hydrocarbon dew point [4].

The high economic value associated with recovery of gas condensates, determined the importance of developing technologies in natural gas condensate recovery system [5]. Several processes are used to separate these valuable liquid hydrocarbons; these processes include refrigeration, expansion, solid bed adsorption, membrane separation, lean oil absorption, and twister device technology [4, 6]. Refrigeration systems are highly recommended for chemical/petrochemical industries, since their performances are tightly related to energy usage efficiency, product quality, and plant profitability [7]. A refrigeration system works generally by indirect transfer of heat energy from higher temperature streams (sources) to lower temperature streams (sinks), at the expense of electricity or mechanical work; this will consequently lower or maintain the source temperature at a certain value.

The refrigeration processes include mechanical refrigeration; Joule-Thomson (JT) valve refrigeration, and cryogenic refrigeration by turboexpander [6, 8]. It is reported in BRE [9] that gas condensate recovery via mechanical refrigeration is an important economic methodology. Shoaib *et al.* [10] have compared the use of Joule-Thomson (JT) valve and turboexpander and their effect on the condensate recovery percent.

Absorption refrigeration is another widely applied system aims at utilizing heat from industrial processes. It is considered as one of the promising technologies from the viewpoint of energy-saving, since it could be driven by solar power or surplus heat [11-13]. Moreover, it uses environmentally friendly working pairs without ozone depletion potential or global warming potential [14-15]. John Leslie in 1810 has introduced the first vapor absorption system with sulfuric acid as an absorbent with high affinity for water. The Sulfuric acid has to be recycled to get rid of absorbed water vapor for continuous operation. Ferdinand Carre invented the aqua-ammonia absorption system in 1860 with the same principals of previous cycle, but with ammonia as a refrigerant, since water is a strong absorbent of ammonia [16]. The performance and operational characteristics of absorption refrigeration system have been encountered and reviewed in a wide variety of research work [12, 17-20].

Vapor compression refrigeration cycle is also considered as one of the most common refrigeration cycles among all refrigeration systems, as it is nearly 200 years old [18, 21-23]. Propane is used as a common natural refrigerant in most of the refrigeration cycles [24-27]. However, some other refrigeration cycles use ammonia as a refrigerant [23, 28-30]. Recently, mixed refrigerants proved their effectiveness in many refrigeration cycles [19, 31-34].

Despite vapor compression cycle has many advantages, it consumes higher energy than other types of refrigeration cycles. Nowadays companies are trying to find an alternative way to reduce the energy consumption cost. Beside, more maintenance is required for mechanical equipment like the compressor. Each time compressor is stopped due to maintenance, amount of propane is wasted due to flaring. This amount is expected to increase with time as more maintenance will be required for the compressor due to gradually decrease in efficiency of the compressor with time until the next major overhaul of the compressor.

In this study, two alternative proposals are suggested to be applied in an existing vapor compression refrigeration cycle using propane as a refrigerant, to improve the performance and increase the profitability. The first proposal is to increase the efficiency of the current cycle by optimizing its operating conditions. The second proposal is directed to use ammonia instead of propane as a refrigerant for the current vapor compression refrigeration system with the same equipment. The case study details and the impact of the proposed modifications are discussed in the following sections.

2. Case study

Abu Sannan condensate recovery plant is a gas condensate extraction plant located about 300 km west of Cairo in the Western Desert of Egypt. This plant, owned by The General Petroleum Company (GPC), is designed to process 85 MMSCFD of high pressure gas and about 3000 bbl of Condensate. Figure 1 shows the process flow diagram of the existing propane refrigeration cycle. The overall scheme of Abu Sannan condensate recovery plant can be broken down into four main sections; gas receiving, liquid extraction, condensate stabilization and gas compression. Liquid extraction section consists of two heat exchangers in parallel with each other and a refrigeration system. The present work considers the improvement of this refrigeration system. The refrigeration unit under consideration is a conventional mechanical system using reciprocating compressor, condenser, receiver, economizer, expansion valves and chiller. The refrigerant medium used in this design is propane. The propane refrigeration cycle is used to cool the stream from 8°C to -5°C. Table 1 lists the conditions and composition of the gas feed entering the chiller of the propane refrigeration cycle.

Table 1. Conditions and composition of the gas feed

Gas conditions		Gas composition	
Temperature, oC	8	Component	Mole%
Pressure, bar	49	i-Butane	1.15
Phase Fraction	0.9879	n-Butane	1.44
Mass flow rate, kg/hr	82850	i-Pentane	0.34
Gas composition		n-Pentane	0.24
Component	Mole%	Hexane	0.20
Methane	79.92	CO_2	0.91
Ethane	10.03	Nitrogen	0.55
Propane	5.22	Total	100

In the current refrigeration cycle, liquid propane from the high pressure refrigerant drum V-13 at 60°C and 15 kg/cm^2 is expanded through LV 13-7 to the medium pressure (MP) refrigerant drum V-12 (economizer), which operates at 8.0 kg/cm^2. The purpose of this economizing step is to reduce the overall size of the refrigeration system. By flashing to the intermediate pressure of 8.0 kg/cm^2, the propane is cooled to 29°C; nearly 30% of liquid propane is vaporized. The flash vapor from MP drum is fed to inter-stage line of the refrigerant compressor K-3, where it joins the refrigerant vapor discharged from the first stage of compressor. The remaining liquid propane from MP drum is further expanded through LV 13-6 to the gas chiller E-3, operating at a pressure of 2.3 kg/cm^2. The warm gas entering the tube side of the gas chiller is cooled from 8°C to -5°C as the propane evaporates on shell side at -13°C and a pressure of 2.3 kg/cm^2.

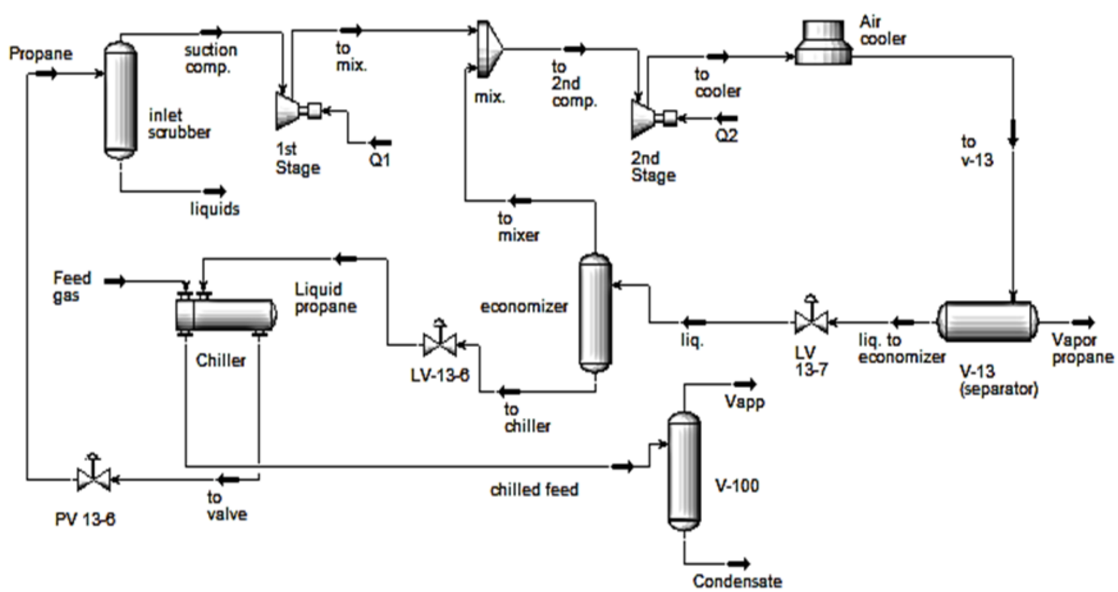

Figure 1. Process flow diagram of propane refrigeration unit

Regarding this current design, the liquid propane is completely vaporized and the vapor propane leaving the chiller is in equilibrium with liquid boiling in the chiller; the gas then is at its dew point. The propane vapor from the Gas Chiller flows through the low pressure (LP) refrigerant drum V-11 to remove any liquid from the gas prior to compression. Since the compressor is a positive displacement compressor, any liquid carried into compressor cylinder can result in damage to cylinder head, pistons and valves. The first stage compressor cylinder compresses the propane gas to 8.0 kg/cm^2; at this point, it is joined by the flash gas from the MP refrigerant drum. The combined stream is then compressed to design condensing pressure of 15 kg/cm^2 by the compressor second stage. The entire propane vapor is condensed in the condenser, and the condensed liquid is accumulated in the high pressure (HP) refrigerant drum. The feed gas to the investigated plant is cooled through the chiller E-3 and the chilled liquid is fed to the Stabilizer V-100. About 46% of the butane in the plant feed gases are retained in the stabilizer. The stabilizer is designed to recover 96% of its feed butane and all lighter components in the overhead gas product and produce stabilized condensate with RVP less than 12 psia. The stabilized condensate product leaves the stabilizer, cools with the Stabilizer Condensate Cooler (not shown in Figure 1), and routed to storage before being injected in GPC crude pipeline going to El-Hamra terminal within the accepted specifications.

3. Results and discussion

3.1. Optimization of the current operating conditions

The most important factors to be optimized are refrigerant propane flowrate and the intermediate pressure of the compressor. The influence of these two variables on the considered refrigeration system is discussed in the following subsections.

3.1.1. Effect of the refrigerant propane flowrate

Propane flowrate can affect the temperature of the chilled stream, condensate production and electrical consumption of the refrigeration cycle. The influence of propane flowrate on temperature, condensate production is described in Figures 2 while the obtained linear equation that relate between the propane flowrate and electrical power consumption is as follow:

$$\text{Power consumption (kW)} = 10 + 0.0212 * \text{propane flowrate (kg/hr)}$$

It is noticed as expected that by increasing the propane mass flowrate, condensate production as well as the power consumption increase, while the cooling temperature decreases.

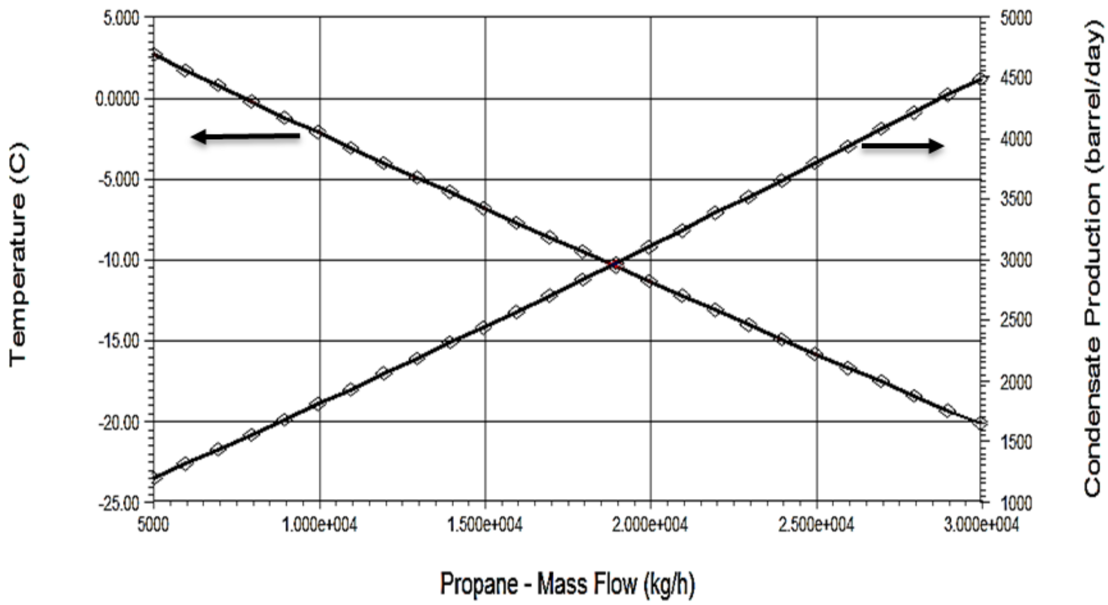

Figure 2. Effect of propane flowrate on condensate production and cooling temperature

HYSYS software was used to optimize the propane flowrate, which depends on both condensate production and power consumption. The optimization results showed that the optimum propane flowrate is 16500 kg/hr compared to 13440 kg/hr for the original case study. Additionally, according to this modification, the amount of condensate production is increased from 2320 bbl /day to 2749 bbl /day while the power consumption is raised by 417 kW. Regarding the current modification, the capital cost remains the same as in the original case, as no new assets or equipment are added to the cycle. However, the operating cost increases due to the additional consumption of electricity as well as an expected increment in losses. The operating cost includes the power consumption, the utilized propane and the expected losses of the cycle costs. The propane flowrate optimization leads to an increment of the compressor power consumption from 503 to 620 kW. In addition, the electrical consumption of the air cooler increases by 300 kW. The additional cost of the total power increment of 417 kW can be calculated as follows:

Electrical power cost = 1.23 ($/kW. day)* power consumption (kW)= 1.23 * 417= 513 $/day

The propane flow rate is increased from 13440 kg/day to 16500 kg/day with an increment of 3060 kg/day. The additional propane cost can be determined taking into consideration that the purchased price of propane is 450 $/ton.

Additional propane cost = 450* 3.060= 1377 $/day

The expected propane losses are expected to be increased by the same factor of flow propane rate increment, which is 22.77%. Thus, the cost of the extra losses was calculated to be 2766.555 $/year (8.384 $/day).

Due to the considered modification, the condensate production increases by 430 bbl/day. However, by comparing the vapor pressure of the produced condensate from the modified cycle to the original cycle, an amount of 80 bbl/day of condensate should be recovered in the stabilization section to meet the desired specification of condensate. Therefore, the net outcome of this modification is the increase in condensate production by 350 bbl/day. The average selling price of the condensate is approximately 65 $/bbl. The profit of increasing the condensate production was estimated to be 20851.616$/day. According to the previous calculation, due to increasing the propane flowrate by 22.77% of its original flow rate, the yearly profit of the modified cycle is increased with about 6,881,033 $/year.

3.1.2. Effect of intermediate pressure

In the current refrigeration cycle, suction pressure of the first stage, intermediate pressure (suction pressure of the second stage), and discharge pressure of the second stage are 2.3, 8 and 15 bars respectively for the existing compressor. This intermediate pressure can be controlled by adjusting the valve LV 13-7 as illustrated in Figure 1. The pressure drop across this valve affect the vapor fraction of propane entering the economizer V-12, and this consequently affects the propane flowrate entering the chiller, which is a key factor in the achieved degree of cooling. Table 2 illustrates the effect of intermediate pressure on both the vapor fraction of the propane stream entering the economizer and the propane flowrate entering the chiller.

Table 2. Influence of compressor intermediate pressure on the input stream vapor fraction of the economizer and input propane flowrate of chiller

Intermediate pressure, bar	Propane vapor fraction entering the economizer	Propane flowrate entering the chiller, kg/hr
7.5	0.2232	13170
8	0.2070	13440
8.5	0.1911	13710
9	0.1754	13970

Table 2 displays that the intermediate pressure increase leads to a reduction in the vapor fraction of stream entering the economizer and an increment in the propane flowrate entering the chiller. This increase in propane flowrate enhances the heat transfer between the refrigerant and process streams in the chiller, which in turn increases the efficiency of the current refrigeration cycle. The intermediate pressure has insignificant effect on the total electrical consumption of the 2-stages compressor, as the suction and discharge pressures of the compressor in all cases are fixed at 2.3 and 15 bar respectively. The effect of intermediate pressure on the degree of cooling as well as the amount of condensate are depicted in Figure 3.

Practically, when the intermediate pressure is increased from 8 bar to 9 bar, the temperature of chilled stream reduces to -5.77^{o}C instead of – 5.2^{o}C and this raises the condensate production from 2320 bbl/day to 2395 bbl/day. Furthermore, the electrical daily consumption is increased from 503 kw to 523 kw. The extra electrical cost was estimated to be 24.6 $/day. Accordingly, due to raising the condensate production by 75 bbl/day, there is an additional profit of about 150,000 $ per month.

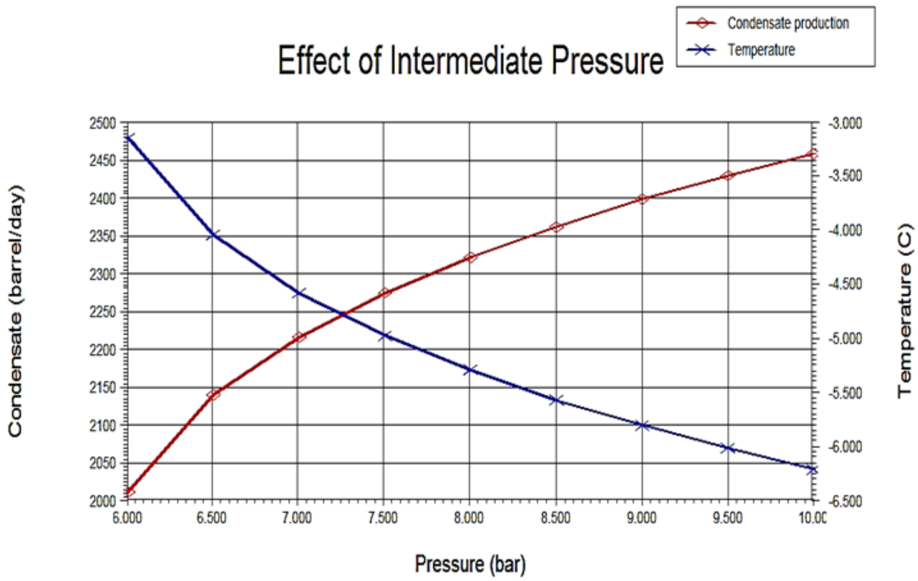

Figure 3. Effect of intermediate pressure on degree of cooling and condensate production

Regarding Table 2, the propane flow rate is increased by 530 kg/day (from 13440 to 13970 kg/day). The additional cost due to propane increment was calculated to be 238.5 $/day.

As stated before, the expected losses of the modified refrigeration cycle increases by the same factor of increasing the propane flowrate (3.94%). The additional cost of extra losses, additional gain, and net profit were calculated to be 1.45 $/day, 4875 $/day and 4610.45 $/day respectively.

According to the above calculations, increasing the intermediate pressure by 1 bar leads to an increase of the condensate production with insignificant effect on the power consumption with a yearly profit increase of 1,521,448.5 $.

3.2. Using ammonia as a refrigerant instead of propane

The second approach of modifications considers the replacement of propane with ammonia as a refrigerant using the original existing vapor compression cycle; this modified cycle was simulated applying the HYSYS Software version 8.6. The ammonia flowrate was estimated to achieve the same degree of cooling given by the current propane cycle. The variation between ammonia and propane flowrates requirements can be attributed to depend on the variation in latent heat of vaporization between them.

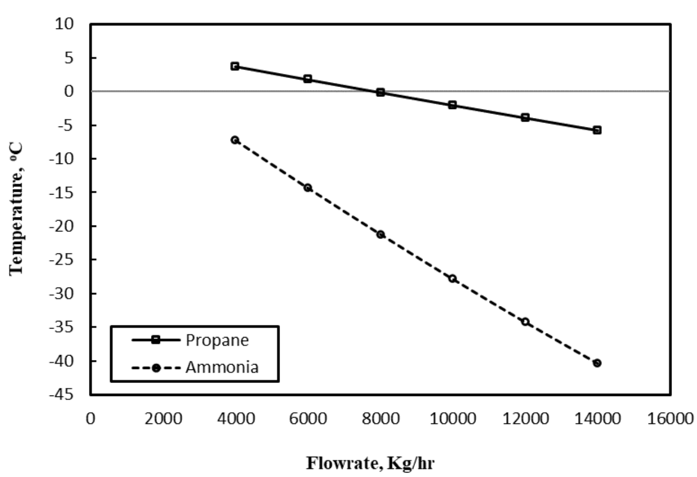

Figure 4. Effect of flowrate on chilled temperature for propane and ammonia systems

Using HYSYS software version 8.6, the estimated ammonia flowrate is 4000 kg/hr, which is small compared to propane flowrate of 13440 kg/hr. This can be attributed to the big difference between the latent heat of vaporization of ammonia (1371 kJ/kg) and that of propane (428 kJ/kg). Additionally, it is noticed that the power consumption of the compressor in the suggested ammonia cycle is lower than that of the same compressor in the original propane cycle. This power saving in case of ammonia system can be ascribed to the low molecular weight of ammonia (17 g/mol) compared to propane (44 g/mol). Furthermore, the cost of ammonia (310 $/ton) is lower than propane cost (450$/ton). Therefore, it is clear that the application of ammonia instead of propane in the considered refrigeration system is more economically attractive. It should be also noticed that the ammonia system is more economically attractive even when compared to the original propane cycle with the optimized flowrate or optimized intermediate pressure. Figure 4 shows the comparison between the ammonia and propane flowrates influence on the chilled feed temperature. It is clear that the increasing of flowrate is more effective in reducing the temperature in case of ammonia due to its lower latent heat of vaporization.

From Figure 4, it is obvious that the flowrate effect is high in case of ammonia system and this consequently make ammonia system more effective in refrigeration process compared with the original propane system. Similarly, Figure 5 reveals the influence of propane and ammonia flow rates on condensate production. It is clear that the ammonia refrigeration cycle can produce larger amount of condensate than propane at the same flowrates. The difference between condensate throughput corresponding to ammonia and propane systems increases and becomes more significant with increasing flowrate. For example at a flowrate of 8000 kg/hr, the condensate production for the ammonia system is 5500 bbl/day compared to 1700 bbl/day in case of propane cycle. Accordingly, the above results indicate that the application of the ammonia refrigeration system could be more profitable, especially when the cycle operates at the optimum flowrate. Thus, the ammonia flowrate should be optimized to gain more profit for the unit under consideration.

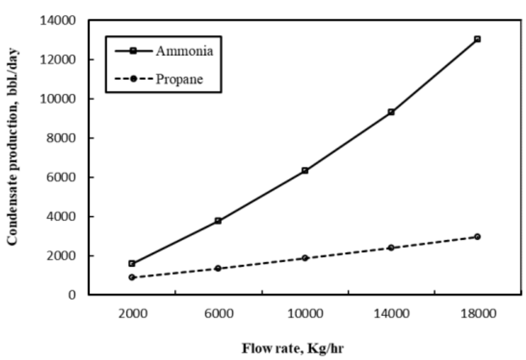

Figure 5. Effect of ammonia and propane flowrates on condensate production

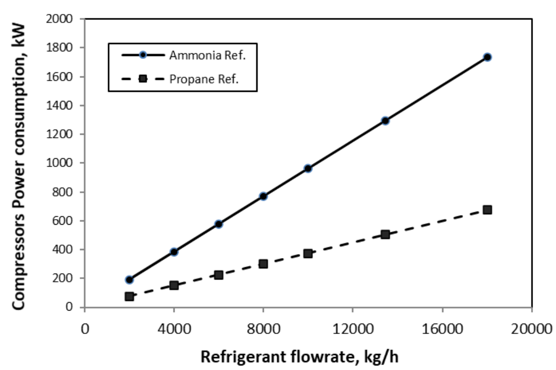

Figure 6. Effect of flow rate of ammonia and propane on power cost

However, the power consumption is another important factor that should be taken into account when comparing between the effectiveness of both refrigeration cycles. Figure 6 shows the flowrate versus power consumption at the compressor relationship for propane and ammonia refrigeration cycles. From this figure, it is obvious that ammonia approach consumes more power than propane refrigeration system at all studied flowrates and the gap between them increases with increasing flowrate. For example, flowrate of 8000 kg/hr of ammonia consumes 771.36 kW, but for the same flow of propane it consumes only 299.4 kW. The increase in power consumption in case of ammonia cycle may be ascribed to the higher discharge temperature. Nevertheless, this cycle can operates at small flowrate compared to the propane cycle to achieve the same efficiency as it is discussed before. This may lead to saying that the power consumption of the ammonia cycle will be lower than that corresponding to the propane cycle at the same operating conditions. Thus, it is needed to study the process economics for ammonia and propane cycles which is a vital parameter in selecting the appropriate refrigeration system. The economic study using HYSYS software shows that by using ammonia instead of propane for the considered refrigeration system to achieve the same degree of cooling and the same amount of condensate, the additional monthly saving is about 22,000$. This high saving can be attributed to the lower power consumption and reduced losses during maintenance. The forgoing results confirms that the ammonia refrigeration system is more profitable than the existing propane system.

However, the main drawbacks of ammonia are its corrosive and poisonous nature. Ammonia is corrosive for some metals such as copper and brass. Therefore, it is preferable to use ammonia in units that does not include copper and brass in its construction especially copper pipes. Regarding the investigated case study, the refrigeration system was constructed from carbon steel and this in turn encourage the use of ammonia without significant corrosion problems. With applying ammonia as a refrigerant, safety precaution should be taken into account to avoid the hazards related to the poisonous nature of ammonia. Additionally, the operators in this unit should be aware of these hazards. For example, ammonia concentrations higher than 700 ppm can cause serious harm to eyes while danger of death is expected on direct exposure of 30 min if the ammonia concentration reaches 2500 ppm.

However the density of vapor ammonia is 0.86 kg/m^3 which are less than the density of the air, so it naturally goes upwards if any leakage occurs and reduce the potential of continuous accumulation of ammonia to reach dangerous concentration, which is an important advantage over propane with density of 2.01 kg/m^3.

The capital cost for the suggested approach is the same as the original propane refrigeration system because there are no new additional assets required for the cycle using ammonia refrigerant. As previously mentioned, the operating cost includes the compressor power consumption, the required refrigerant, and the expected losses costs. The daily power consumption of the compressor in original cycle with propane is 503 kW, while the estimated value for the proposed cycle with ammonia is 385 kW. Similarly, for air cooler in case of ammonia system, the power consumption is also reduced by an amount of 110 kw. Thus, the saving of electrical power consumption was estimated to be 280.44 $/day (92545.2 $/year).

For calculating the saving in refrigeration cost, the cost of refrigerants in the original and modified cycles should be estimated. As mentioned before, the required ammonia flowrate is 4000 kg/hr compared to 13440 kg/hr in case of propane system. The calculated costs of propane and ammonia were 145152 $/day (47,900,160 $/year) and 29760 $/day (9,820,800 $/year) respectively.

Regarding the above results, there is savings of 4808 $/hr for the proposed modification due to use ammonia instead of propane as refrigerant. Additionally, the cost of the expected losses for the ammonia and propane refrigeration systems should be estimated. It should be noticed that the losses is reduced to 8 ton/year for ammonia cycle in comparison with 27 ton/year in case of propane cycle. Therefore, the cost relating to the expected losses in both refrigeration systems are estimated calculated to be 12150 $/year and 2480 $/year for propane cycle and ammonia cycle respectively.

As expected, the cost of losses in case of the proposed ammonia refrigeration system is reduced by 9670 $/year. The condensate production of 2320 bbl/day is obtained from both cycles without any change because the degree of cooling in both cycles is the same. Thus, there is no difference in the operating cost regarding the condensate production in the both investigated cycles. The total annual savings for the proposed modification is 38,181,575 $/year when using ammonia as refrigerant instead of propane in the original refrigeration unit. However, due to the poisonous nature of ammonia, an ammonia gas detector should be added to detect any possible leakage of ammonia and to be sure that the working place is healthy and safe. From the previous results, it is clear that the proposed route of using ammonia refrigeration system is preferred over both the current propane system and the first proposal of operational conditions optimization because it is the highest profitable alternative for upgrading the considered refrigeration unit.

4. Conclusion

The aim of this work is to study and improve the refrigeration cycle performance used in an existing condensate recovery plant. To accomplish this target, two different scenarios were suggested for upgrading the present refrigeration cycle (vapor compression cycle) operated with propane as a refrigerant. The first upgrading technique focused on optimizing the operational conditions of the current cycle, namely refrigerant flowrate and intermediate pressure. The results showed that increasing propane flowrate from 13440 to 16500 kg/hr leads to an increase of the condensate production by 335 bbl/day, while the required power increases by 420 kW. The annual profit due to this refrigerant flowrate increment was estimated to be 6,881,033 $. On the other hand, the condensate production is increased by 80 bbl /day without any additional requirement of excess power when the intermediate pressure increases from 8 bar to 9 bar. The estimated annual profit related to the intermediate pressure influence is 1,521,448.5 $.

The second suggested scenario to improve the investigated unit is using ammonia as a refrigerant instead of propane in the current vapor compression refrigeration cycle. Ammonia has the advantage of higher efficiency and lower cost. The replacement of propane with ammonia for achieving the same degree of cooling showed a reduction in the required refrigerant flowrate to be 4000 kg/hr of ammonia cycle compared to 13440 kg/hr in case of propane cycle. Moreover, the power consumption in case of the suggested ammonia system is reduced by 228 kW. This consequently will save about 92545.2 $/year. Therefore, it is clear that the application of ammonia instead of propane in the considered refrigeration system is more economically attractive compared to the original refrigeration unit. It should be also noticed that the ammonia system is preferable and more economically attractive even when compared to the original propane cycle with the optimized flowrate or optimized intermediate pressure. Thus, the ammonia cycle is the best alternative for upgrading the current refrigeration system. This study can be taken as guidelines for improving both new and in operation condensate recovery plants through enhancing the performance of their refrigeration systems.

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