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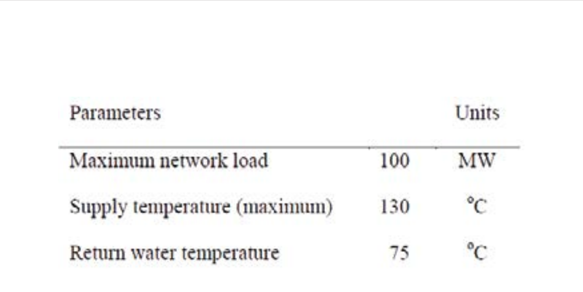
Abstract

This paper discusses a case study in which the waste heat from a refinery is used to heat up district heating water for a local district heating (DH) network. The potential of using heat pumps in order to recover heat from low temperature process water streams for DH is to be analyzed. The heat pump will have to extract heat from a source at 37°C and add it to the DH water to increase its temperature as much as possible with reasonable values of the coefficient of performance (COP). The process water is presently cooled down using cooling towers. Extracting heat from the process water serves two purposes – waste heat recovery for DH and reduction in the load sent to the cooling towers.

1. Introduction

The modern society faces a variety of challenges to meet the energy requirements of a growing population. Considering that process industry is among the most energy demandingsectors, chemical engineers have embarked on a quest for shaping a sustainable future. Due to the limitation of fossil fuels, the need for energy independence, as well as the environmental problem of the greenhouse gas effect, there is a large increasing interest in the research and development of chemical processes that require less capital investment, reduced operating costs, and lead to high eco-efficiency. The use of heat pumps is a hot topic due to many advantages, such as low energy requirements as well as an increasing number of industrial applications. Although the research and development carried out



Parameters		Units
Maximum network load	100	MW
Supply temperature (maximum)	130	°C
Return water temperature	75	°C

Table 10.1 Operating conditions of district heating system

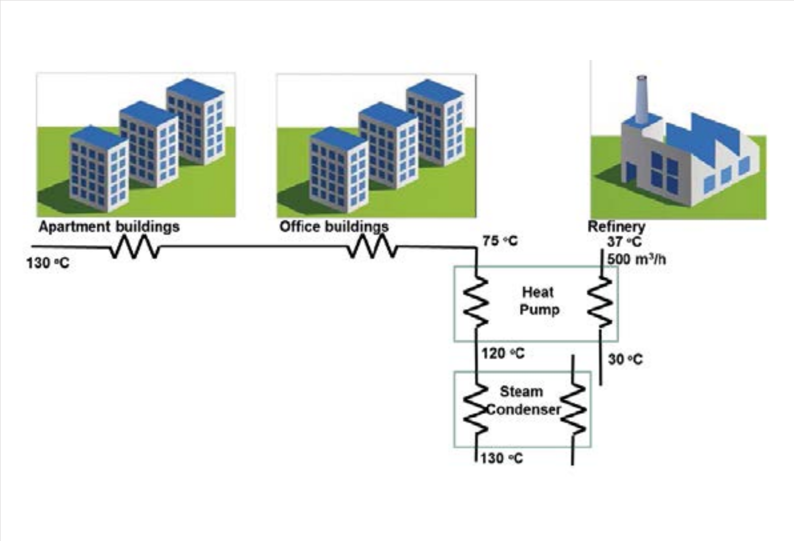


Figure 10.1 Waste heat stream of refinery to deliver heat to district heating system

in academia and industry in this field are expanding quickly, there is still no book currently available focusing on the use of heat pumps in the chemical industry.

The authors of this paper have recently published a book (Kiss and Infante Ferreira, 2017) which provides an overview of heat pumps technology applied in the process industry, covering both theoretical and practical aspects: working principle, applied thermodynamics, theoretical background, numerical examples and case studies, as well as practical applications in the chemical process industry. The worked out examples instruct the students, engineers and process designers about how to design various heat pumps used in the process industry. The reader will benefit from learning more about heat pumps, what they are, when and how to use them properly; getting more information about the theoretical and practical background of HP; understanding how to identify the need, select, design and apply heat pumps; discovering the existing and potential applications of heat pumps in a process; and finding the specifics of heat pump applications in the process industry.

The book starts with an introduction to heat pumps that provides an overview of heat pumps, and the possible sources of heat and cold usable by HPs in the chemical process industry (CPI). Then, it continues with some theoretical background related to the thermodynamics of heat pump cycles (e.g. fundamentals, enthalpy, entropy, equations of state, chemical / phase equilibrium), entropy production minimization and exergy analysis, as well as Pinch analysis and process integration (e.g. minimize energy use, maximize heat recovery). After that, the selection of heat pumps is explained, including the required steps during development, demonstration and deployment of heat pumps in industry. The next chapters cover more in-depth several types of heat pumps such as: mechanically driven heat pumps (e.g. vapor recompression, vapor compression, compression resorption, trans-critical, and Stirling heat pumps), thermally driven heat pumps (e.g. liquid-vapor absorption, solid-vapor adsorption, ejector based heat pumps), and solid state heat pumps (e.g. magnetic refrigeration, thermoelectric, and thermos-acoustic heat pumps). Heat pump applications and several case studies (e.g. application to distillation, evaporation and refrigeration) are included in the final chapters.

In this paper one of the case studies discussed: “a vapor compression heat pump for heat recovery” is reproduced as an example of the contents of the book.

2. Vapor compression heat pump for heat recovery

Waste heat from a refinery is to be used to heat up district heating water for a local district heating network. This case has been investigated by Ravi (2010). The details of the existing district heating (DH) network may be found in Table 10.2.

Purpose is to investigate the possibility of extracting waste heat from the refinery and constructing a district heating substation. The potential of using heat pumps in order to recover heat from low temperature process water streams for DH is to be analyzed. The heat pump will have to extract heat from a source at 37°C and add it to the DH water to increase its temperature as much as possible with reasonable values of the coefficient of performance

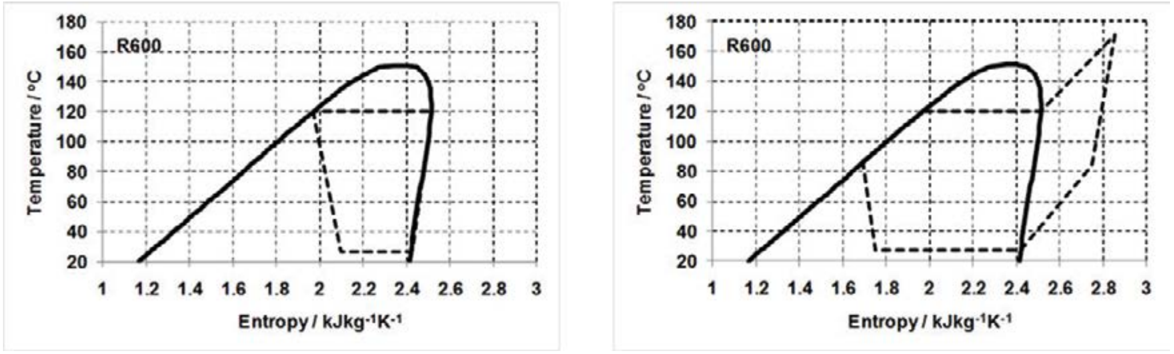


Figure 10.2 Single stage heat pump cycle of butane (R600). Left without internal heat exchanger and right with internal heat exchanger

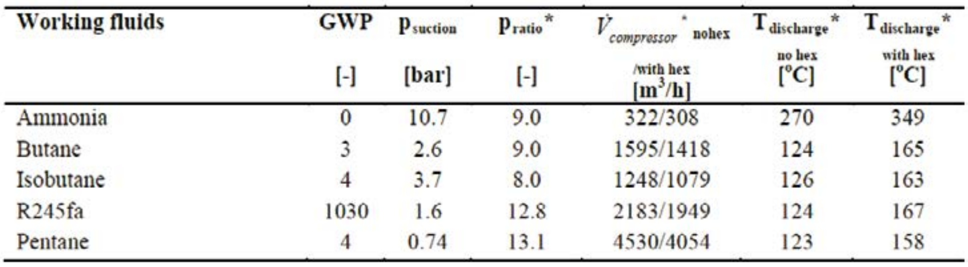
(COP). The process water is presently cooled down using cooling towers. Extracting heat from the process water serves two purposes – waste heat recovery for DH and reduction in the load sent to the cooling towers. The available volumetric flow rate of process water is 500m3/h.

Vapor compression heat pumps are the most widely used type of heat pumps. Current maximum temperatures are limited to 120°C and, since this is the technology closest to market applications, it is the most interesting technology for this refinery case.

Current industrial heat pumps refer to 90°C as high temperature applications. However, in the case of the considered heating network, the temperatures of interest are higher than 100°C. In order to study the potential of using high temperature heat pumps, first a market study should be conducted to investigate if machines operating within these temperature ranges are available. Thereafter, a study is conducted to analyze the use of different refrigerants for the heat pump.

Commercially available high temperature heat pumps usually provide water at 90 °C. Very few manufacturers have the experience to supply large scale units (greater than 1 MW thermal capacity) in the 90 °C range. Friotherm (a Swiss firm) has extensive experience in waste heat recovery and has installed many heat pumps for district heating. Also Thermea and Combitherm (both from Germany) have experience with heat pumps that can be used to produce hot water at 90 °C for district heating. At the moment, the preferred working fluid is generally R134a (1,1,1,2-tetrafluoroethane). High temperature heat pumps are custom made and all three manufacturers had no previous experience in operation of a heat pump with sink temperature at 120 °C. For achieving the high temperature of 120°C on the sink side, Friotherm and Combitherm have proposed to use R245fa (pentafluoropropane) as the refrigerant whereas Thermea has proposed the use of CO2 refrigerant. A market survey has shown that there are no commercially available absorption heat pumps that can deliver water at 120 °C. Similarly, mechanical vapor recompression (MVR) heat pumps cannot be used in this case as the source is a liquid. The district heating water that has to be heated from 75°C is considered to be part of the refinery heat exchanger network. The pinch point for the refinery has then been calculated at 75 °C for the cold stream and 85 °C for the hot stream. Thus, using a heat pump for transfer ring heat from the stream below the pinch point (cooling water at 37 °C) to one above the pinch point (DH water at 75 °C) would be an efficient solution. DH water is to be heated from 75°C to 130°C. Some possible temperature levels for the implementation of heat pumps need to be considered. A solution that is proposed is to heat DH water from 75°C to at least 120°C using a heat pump and then to do the additional heating with medium pressure (MP) steam or waste heat recovered from flue gas. This way, the requirement for MP steam would go down and the heat pump will work with reasonable efficiency limits. The aim of the process is two-fold – cooling down process water and heating up water for district heating.

The process water can be cooled down to 30 °C. The operating conditions of the heat pump are schematically represented in Figure 10.5.



Working fluids	GWP [-]	$p_{suction}$ [bar]	p_{ratio}* [-]	$\dot{V}_{compressor}$* nohex /with hex [m^3/h]	$T_{discharge}$* no hex [°C]	$T_{discharge}$* with hex [°C]
Ammonia	0	10.7	9.0	322/308	270	349
Butane	3	2.6	9.0	1595/1418	124	165
Isobutane	4	3.7	8.0	1248/1079	126	163
R245fa	1030	1.6	12.8	2183/1949	124	167
Pentane	4	0.74	13.1	4530/4054	123	158

Table 10.2 Comparison of the working fluids in terms of performance indicators

The method introduced in Chapter 6 can be used in order to determine the performance of vapor compression heat pumps operating with diverse working fluids. The input variables used are:

- Source (process water) temperature at inlet and outlet (Tsource,in=37 °C, Tsource,out=30 °C),
- Source (process water) flow rate
- Sink (district heating water) temperature at inlet and outlet (Tsink,in=75 °C, Tsink,out=120 °C),
- Isentropic efficiency of compressor (i 0.70),
- Pinch temperature in condenser (Tmin 3 K)

The method proposed in Chapter 6, making use of REFPROP (Lemmon et al., 2013), gives thefollowing output variables:

- Pressure, temperature, enthalpy and entropy at all relevant states of the heat pump cycle,
- COP,
- Heating Capacity, Q
- Compressor Power, W

The calculation procedure aims to determine the best solution for each working fluid among feasible solutions. In order to eliminate incorrect solutions, during the course of calculations a few aspects should be verified. If the evaluated conditions do not fulfill one of the requirements, the values of the particular cycle should be discarded.

The following requirements should be met by the evaluated cycle:

- The compressor outlet temperature must be higher than the sum of the sink outlet temperature and the minimum pinch temperature
- The quality of vapor at the outlet of the compressor must be greater than 1
- The quality of the two phase vapor entering the evaporator must not exceed 0.9

The operating conditions of the condenser should prevent a temperature cross. A Q -T diagram for the condenser is used to verify this.

Three options have been considered for the cycle:

- Single stage heat pump cycle
- Single stage heat pump cycle with internal heat recovery
- Two-stage heat pump cycle

Figure 10.6 illustrates the cycles in T-s diagrams for butane. Without internal heat exchanger the discharge temperature of the compressor is close to saturation. This may lead to unacceptable operating conditions and damage of the compressor. The internal heat exchanger will generally improve the efficiency of the heat pump cycle. It always leads to an increase of the discharge temperature of the compressor. For butane the temperature reaches 165.3 °C when a hot water temperature of 120 °C is required. This is close to the limit of operation for the current compressor /lubricant designs. Notice that this only happens when an approach temperature of 3 K can be realized in the internal heat exchanger. With a less efficient heat exchanger the temperature can be limited but this will reduce the COP of the cycle.

Figure 10.7 shows the heat pump COPs that can be attained with the most suitable refrigerants. Ammonia shows a lower performance when high hot water temperature is required. It also shows a decrease in performance when an internal heat exchanger is added to the ammonia system. What is not visible from Figure 10.7 is that the compressor discharge temperature becomes extremely high when ammonia would be selected. The performance of pentane, R245ca, R245fa and butane is very similar. Since pentane and butane are fluids which most probably are already available in the plant, these fluids are much cheaper than

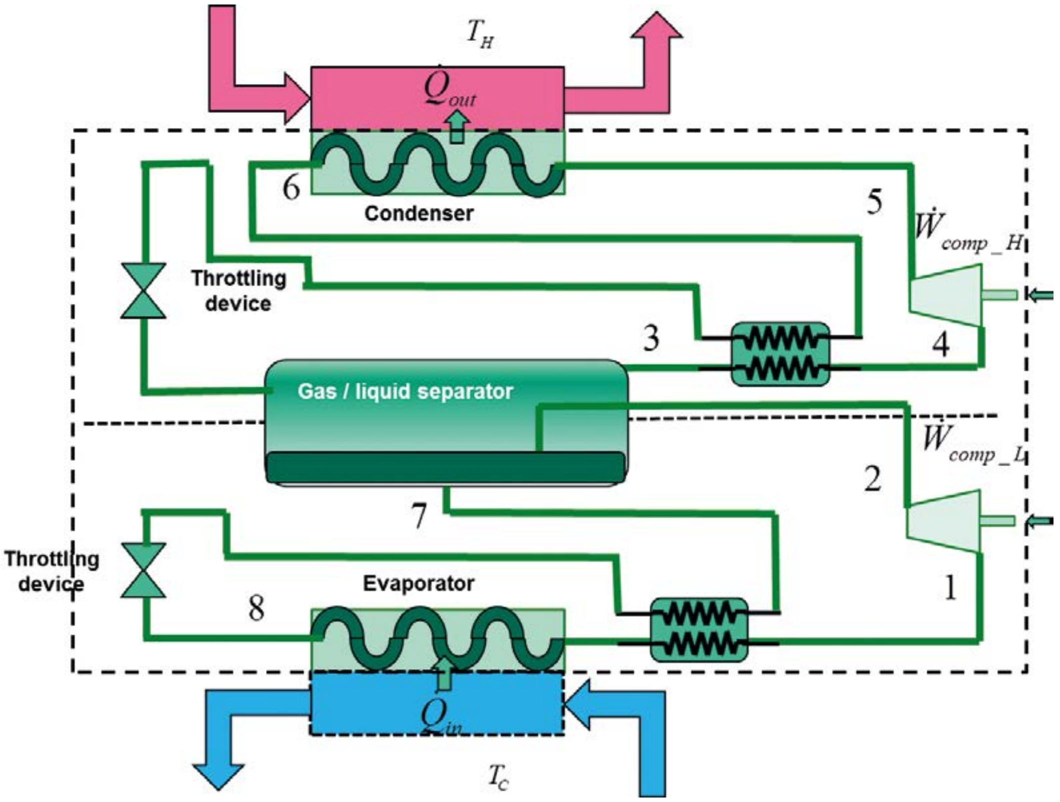


Figure 10.5 Schematic of the two stage heat pump with two internal heat exchangers.

the HFCs and the HFCs have high GWP factors, pentane and butane should be preferred as working fluids.

Figure 10.3 COP of single stage heat pump cycle of diverse refrigerants: without internal (left) and with internal heat exchanger (right)
Table 10.3 provides more details about the performance indicators of the different working fluids. The table makes clear that the operating conditions of butane are more favorable than those of pentane (operation always above atmospheric pressure and significantly lower pressure ratio). From the table is also clear that from the selected working fluids only ammonia shows extremely high discharge temperatures

* These values apply when the hot water outlet is 120 °C; the volume flow applies per MW heating capacity.
The volume flow at the compressor inlet gives an indication of the compressor size required. The smaller the volume flow, the smaller the compressor and its initial costs.
As indicated in Table 10.2 the water needs to be heated to 130 °C so that it can be delivered to the district heating network. It is always possible that part of the heating is done with the heat pump and that a fuel is further used to reach the required temperature. In this case it has been assumed that the thermal efficiency of the electrical grid is 0.42 and of a boiler 0.86. It has further been assumed that electricity costs 65 €/MWh and gas costs 32 €/MWh. Heating the water flow from 75 °C to 130 °C with a boiler would cost 10.1 M€/year. Depending on the share of the heat pump and on its COP, the heat pump will give the yearly savings shown in Figure 10.8. Obviously, using the heat pump as much as possible is always advantageous even if the COP decreases to values around 3.0 (see also Figure 10.7). The working fluid with the highest COP gives the largest yearly energy costs savings.

Figure 10.4 Yearly energy costs savings when the heat pump is applied to heat the waste heat stream from 75 °C to the indicated temperature. The remaining temperature increase up to 130 °C is obtained making use of fuel fired boiler. Left without internal heat exchanger; right with internal heat exchanger. The large pressure ratios in Table 10.3 suggest that two stage compression will possibly lead to more suitable operating conditions. For this reason the performance of two stage systems with open flash

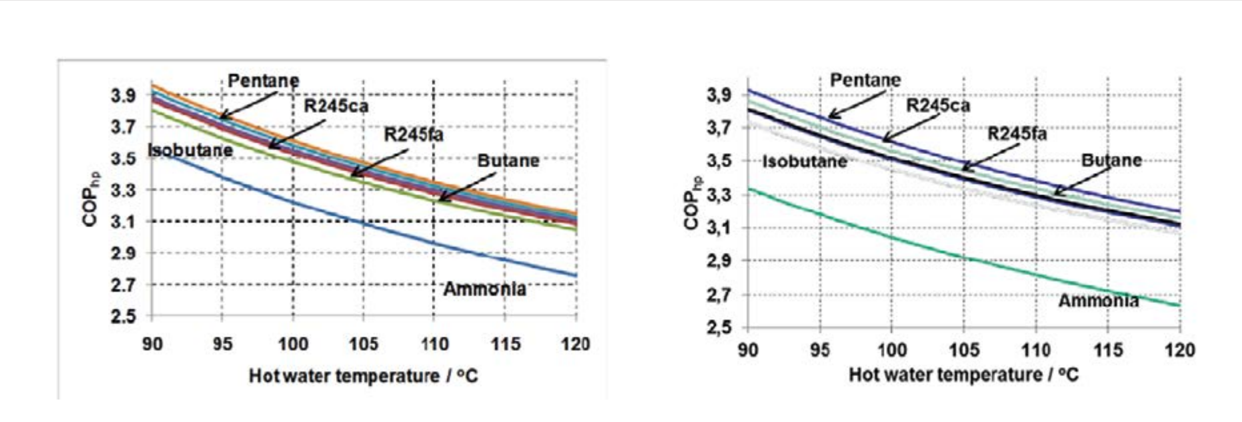


Figure 10.6 COP of two stage heat pump cycles of diverse refrigerants (left) and of single stage cycle with internal heat exchanger (right).

tanks has also been investigated. This design considers two internal heat exchangers between the liquid flow and the vapor flow before entering each of the compressors. The schematic of the process is illustrated in Figure 10.5.

An energy balance for the separator, considering it externally adiabatic, gives the ratio of the mass flows through both compressors so that the COP of the cycle can be calculated:

$$COP_{2-stage} = \frac{h_5 - h_6}{(h_2 - h_1) \times \dfrac{h_3 - h_7}{h_2 - h_9} + (h_5 - h_4)}$$

The indexes of the enthalpy correspond to the states indicated in Figure 10.9.
The ratio [(h3-h7) / (h2 -h9)] is based on the energy balance around the separator considering it externally adiabatic and gives the ratio between the mass flow through the low pressure compressor and the mass flow through the high pressure compressor. Figure 10.10 shows on the left side the predicted COP for the two stage heat pump system when diverse refrigerants are applied. To facilitate a comparison with the single stage performance (when an internal heat exchanger is applied), the results for the single stage are shown in the right hand side.

From the figure it is evident that the performance of the ammonia system significantly improves while the improvement of the other fluids is small (lower temperatures) to negligible (higher temperatures). The calculations have assumed the isentropic efficiency of the compressor to be maintained with the pressure ratio. In reality, at least for screw compressors, the efficiency will decrease with the pressure ratio so that the two-stage solution offers a better solution.

3. Conclusions

The book by Kiss & Infante Ferreira (2017) serves as a reference for scientists, researchers, engineering procurement and contracting (EPC) organizations, operators of chemical and biorefineries production facilities, R&D engineering departments, and other industry practitioners involved in heat pumps and energy efficient technologies. The example case study reproduced in this paper gives an indication of the contents of the book and illustrates the possible advantages of the implementation of heat pumps in the process industry.

References

Kiss, A.A., Infante Ferreira C.A. (2017) Heat Pumps in Chemical Process Industry. CRC Press. Taylor & Francis Group, Boca Raton, USA.