SCIENTIFIC RESEARCH JOURNAL

RESEARCH MANAGEMENT INSTITUTE

© UiTM Press, UiTM 2012

Scientific Research Journal is jointly published by Research Management Institute (RMI) and UiTM Press, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

Scientific Research

Journal

Saving Primary Energy Consumption Through Exergy Analysis of Combine Distillation and Power Plant

Alhassan Salami Tijani[1], Nazri Mohammed and Werner Witt[2]

[1]Faculty of Mechanical Engineering
Universiti Teknologi MARA
40450 Shah Alam, Selangor, Malaysia
[2]Chair of Process Engineering, Plant Design and Safety Technology
Brandenburg University of Technology (BTU)
Burger Chaussee 2, 03046 Cottbus, Germany
Email[1]: alhassan@salam.uitm.edu.my

ABSTRACT

Industrial heat pumps are heat-recovery systems that allow the temperature of waste-heat stream to be increased to a higher, more efficient temperature. Consequently, heat pumps can improve energy efficiency in industrial processes as well as energy savings when conventional passive-heat recovery is not possible. In this paper, possible ways of saving energy in the chemical industry are considered, the objective is to reduce the primary energy (such as coal) consumption of power plant. Particularly the thermodynamic analyses of integrating backpressure turbine of a power plant with distillation units have been considered. Some practical examples such as conventional distillation unit and heat pump are used as a means of reducing primary energy consumption with tangible indications of energy savings. The heat pump distillation is operated via electrical power from the power plant. The exergy efficiency of the primary fuel is calculated for different operating range of the heat pump distillation. This is then compared with a conventional distillation unit that depends on saturated steam from a power plant as the source of energy. The results obtained show that heat pump distillation is an economic way to save energy if the temperature difference between the overhead and the bottom is small. Based on the result, the energy saved by the application of a heat pump distillation is improved compared to conventional distillation unit.

Keywords: Distillation units; Heat integration; Exergy/energy system modelling

INTRODUCTION

Distillation remains the most commonly used separation technique in the petrochemical and chemical process industries in the separation of fluid mixtures, but it has a low thermodynamic efficiency in a stand-alone operation. Therefore energy saving in distillations is important in integrated process design. Process industries in the United States consume approximately 24.3×10^{15} kJ of energy annually at a cost of almost \$80 billion. A significant portion, almost 7.4×10^{15} kJ, of this energy input is eventually discarded as waste heat (heat discarded in an effluent stream and serves no value to the process) (U.S. Department of Energy 1991 [1]).

Generation of heat can be done in different ways; the importance of using a particular method can be established by comparing different options. Morosyuk [2] suggested that different options can be compared in the following order: comparison of energy performance parameters under theoretical conditions (such as Carnot efficiency); comparison of such parameters against those obtained under real practical process condition, with non-recoverable energy losses, losses due to friction, losses due to irreversibility in the process, mechanical and gear losses etc. Distillation is an energy-intensive process for which heat pumping may be well-suited. Industrial heat pumps are a class of active heat-recovery equipment that allows the temperature of a waste-heat stream to be increased to a higher, more useful temperature. Consequently, heat pumps can facilitate energy savings when conventional passive-heat recovery is not possible. There are many types of heat pumps used in the chemical industry, such as electrically driven heat pump [3-5]. Null [6] has discussed the different configurations of electrically driven heat pump-assisted distillation. Combination of a heat-and-power station with a heat pump is called a heat-cold-and-power station (HCPS) [7, 8]. According to Morosyuk [2] combined heat and power production by gas-turbine and steam power stations of different design increases the energy efficiency of primary fuel energy. Gholam *et al.* [9] said that heat integrated distillation sequences can provide significant energy savings. Whiles Patricia *et al.* [10] did

studied the thermodynamic performance of integrating concentrating solar power (CSP) with desalination plants. The integration of power plant and distillation processes have been considered extensively in these literatures [11-13], for example Patricia *et al.* [11] did evaluate the integration of a low-temperature multi-effect distillation (LT-MED) plant fed by the steam at the outlet of the turbine replacing the condenser of the power cycle, this method reduced capital investment cost. In this paper, some techniques that can be applied to improve the energetic efficiency of distillation systems by integration of the power plant and distillation are presented. Both electrical power and process steam is needed to operate the process plant, in this case the primary energy is a function of both the electrical power and the steam produced. The process design alternatives where simulated using the process simulator Aspen Plus™.

FUNDAMENTALS

Heat Pump

Heat pumping is an economic way to conserve energy when the temperature difference between the overhead and bottom of the column is small and the heat load is high [14]. Industrial heat pumps (IHPs) also offer the opportunity to capture the waste heat, upgrade it to useable temperatures, and reuse it in the industrial process [15]. Figure 1 is heat pump distillation unit that is operated by means of electrical power supplied to a compressor. The process temperature T_p of the heat pump distillation becomes useful by increasing the outlet pressure of the compressor.
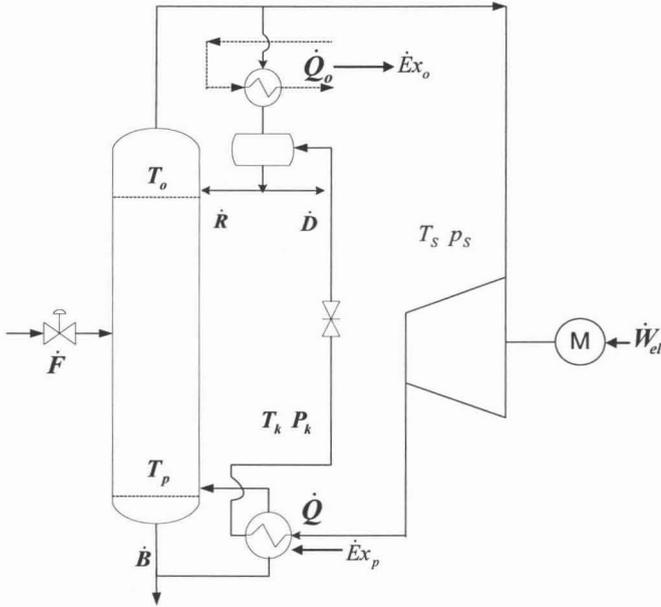
Figure 1: Electrically Driven Heat Pump Assisted Distillation

ENERGY EFFICIENCY

The energy efficiency of a heat pump distillation is expressed in terms of coefficient of performance which is indicated by the symbol (ε). The coefficient of performance as expressed by Stockburger *et al.* [14], is the ratio of steam output ($\dot{Q}$) from compressor and the electrical power ($\dot{W}_{el}$) input to a compressor and is given by:

$$\varepsilon = \frac{\dot{Q}}{\dot{W}_{el}}$$

(1)

From equation 1 the theoretical maximum coefficient of performance (ε_c) of a Carnot process is given by:

$$\varepsilon_C = \frac{\dot{Q}}{\dot{Q} - \dot{Q}_o} = \frac{T_K \cdot \Delta S}{T_K \cdot \Delta S - T_S \cdot \Delta S} = \frac{T_K}{T_K - T_S}$$

(2)

As shown in figure 2, steam at T_s is compressed from point 1 to point 2 with the compressor outlet temperature of T_k, this process is the ideal Carnot process. Comparably compression from point 3 to point 4 is an isentropic process, whiles point 3 to point 5 shows the compression for a real process and this will be discussed in the next section.
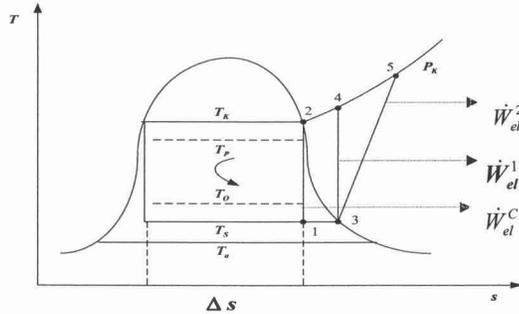
Figure 2: T-S diagram of a Standard Cycle (CARNOT) Process and Real Process
Point 1→ Point 2 (Carnot process) Point 3→ Point 4 (Isentropic process), Point 3→ Point 5 (Real process)

PERFORMANCE FACTORS OF A REAL PROCESS

There are other losses that occur in the case of real compression of the steam in a compressor, however these external losses have no effect on the working fluid. The mechanism of energy transfer from the source to the compressor is shown in figure 3. Electrical power of magnitude $\dot{W}^5_{el,motor}$ is supplied to the motor of the compressor. The motor (with electrical power of $\dot{W}^4_{el,gear}$) transfers its rotational motion through a gear system to the shaft connecting the compressor, the shaft (with electrical power of $\dot{W}^3_{el,shaft}$) finally transfer its power to the compressor. $\dot{W}^2_{el}$ is the electrical power available for the compressor from Point 3→ Point 5 (Real process).The detail of the losses as discussed by Stockburger *et al.* [14] is given as follows:

69
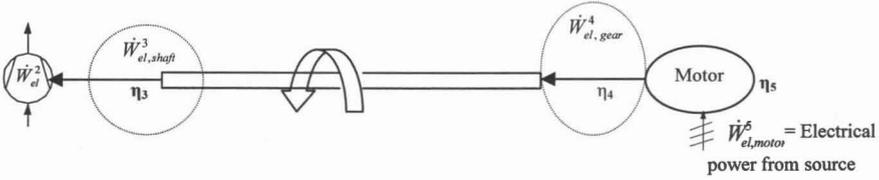
Figure 3: Mechanism of Electrical Power Transfer to the Compressor

Generally, the efficiency of the compressor is a product of several efficiencies

$$\eta_\Sigma = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \cdot \eta_5 \tag{3}$$

Where: $\eta_1 \equiv \dfrac{\dot{W}_{el}^{C}}{\dot{W}_{el}^{1}}$ is the performance factor η_1 of the two process i.e. Carnot process and isentropic process (refer to figure 2), detail discussion of this expression can be found in Stockburger *et al.* [14], where

$$\eta_1 = \left[\frac{h^{\cdot}(T_S) - h'(T_K)}{\dfrac{\chi}{\chi-1} \cdot \dfrac{R}{\tilde{M}} \cdot \left\{ \left(\dfrac{P_K}{P_S} \right)^{\frac{\chi-1}{\chi}} - 1 \right\}} + T_S \right] \cdot \left[\frac{1}{T_S} - \frac{1}{T_K} \right]$$

The other efficiencies associated with the compressor are (refer to figure 3):

$\eta_2 = \dfrac{\dot{W}_{el}^{1}}{\dot{W}_{el}^{2}}$ (Inner efficiency)

$\eta_{3,\,shaft\,mech.} = \dfrac{\dot{W}_{el}^{2}}{\dot{W}_{el,shaft}^{3}}$ (Shaft efficiency)

$\eta_{4,\,gear} = \dfrac{\dot{W}_{el}^{3}}{\dot{W}_{el,gear}^{4}}$ (Gear systems efficiency)

$\eta_{5,\,motor} = \dfrac{\dot{W}_{el}^{4}}{\dot{W}_{el,motor}^{5}}$ (Motor efficiency)

EXERGY EFFICIENCY

The exergy efficiency is given by:

$$\xi \equiv \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \qquad (4)$$

Referring to figure 1, the exergy efficiency of a Carnot process can be expressed as:

$$\xi_C = \frac{\dot{E}x_p}{\dot{E}x_o + \dot{W}_{el}^C} \qquad (5)$$

where

ξ_c = Exergy efficiency of Carnot process

$\dot{W}_{el}^C$ = electrical power input for Carnot cycle

$\dot{E}x_p$ = Exergy content of the outlet cold stream of reboiler (reboiler heat duty)

$\dot{E}x_o$ = Exergy content of the outlet cold stream of condenser (condenser heat duty)

The exergy transfers associated with the reboiler heat duty and condenser heat duty are as follows:

$$\dot{E}x_p = \dot{Q} \cdot \left(1 - \frac{T_a}{T_p}\right) \qquad (6)$$

$$\dot{E}x_o = \dot{Q}_o \cdot \left(1 - \frac{T_a}{T_o}\right) \qquad (7)$$

The exergy balance of the heat pump (refer to figure 1) is given by:

$$\dot{E}x_p + \dot{E}x_L = \dot{E}x_o + \dot{W}_{el}^C \qquad (8)$$

where $\dot{Ex}_L$ = exergy loss, equation 5 becomes:

$$\xi_c = \frac{\dot{Ex}_p}{\dot{Ex}_p + \dot{Ex}_L} \tag{9}$$

The total exergy loss during the heat transfer by the hot streams $\dot{Q}$ (reboiler) and $\dot{Q}_o$ (condenser) is given by:

$$\dot{Ex}_L = \dot{Ex}_{L,k} + \dot{Ex}_{L,o} \tag{10}$$

where

$$\dot{Ex}_{L,k} = \dot{Q} \cdot T_a \cdot \left(\frac{T_k - T_p}{T_k \cdot T_p} \right) \tag{11}$$

where $\dot{Ex}_{L,k}$ = Exergy loss by reboiler

$$\dot{Ex}_{L,o} = \dot{Q}_o \cdot T_a \cdot \left(\frac{T_o - T_s}{T_o \cdot T_s} \right) \tag{12}$$

$\dot{Ex}_{L,0}$ = Exergy loss by condenser

The difference in the heating and cooling processes (refer to figure 1) is equal to the electrical energy supplied to the compressor as shown below:

$$\dot{W}_{el}^c = \dot{Q} - \dot{Q}_o \tag{13}$$

Inserting equation (13) into (12) gives:

$$\dot{Ex}_{L,o} = (\dot{Q} - \dot{W}_{el}^c) \cdot T_a \cdot \left(\frac{T_o - T_s}{T_o \cdot T_s} \right) \tag{14}$$

The exergy loss due to heat transfer by the reboiler (see figure 1) is given by:

$$\dot{Ex}_k = \dot{Ex}_p + \dot{Ex}_{L,k} \tag{15}$$

$$\dot{Q} \cdot \left(1 - \frac{T_a}{T_K} \right) = \dot{Q} \cdot \left(1 - \frac{T_a}{T_P} \right) + \dot{Ex}_{L,K} \tag{16}$$

$$\dot{Ex}_{L,K} = \dot{Q} \cdot \left(\frac{T_K - T_a}{T_K} - \frac{T_P - T_a}{T_P} \right) \tag{17}$$

Inserting equations (12), (18) into equation (10) and inserting the result of equation (6) into (9) gives the expressed of Carnot efficiency as follows:

$$\dot{E}x_{L,K} = \dot{Q} \cdot T_a \cdot \left(-\frac{1}{T_K} + \frac{1}{T_P} \right) = \dot{Q} \cdot T_a \cdot \left(\frac{T_K - T_P}{T_K \cdot T_P} \right) \tag{18}$$

$$\xi_c = \frac{\dot{Q} \cdot \left(1 - \dfrac{T_a}{T_p} \right)}{\dot{Q} \cdot \left(1 - \dfrac{T_a}{T_p} \right) + \dot{Q} \cdot T_a \cdot \left(\dfrac{T_k - T_p}{T_k \cdot T_p} \right) + (\dot{Q} - \dot{W}_{el}^c) \cdot T_a \cdot \left(\dfrac{T_o - T_s}{T_o \cdot T_s} \right)} \tag{19}$$

$$\xi_c = \frac{\left(1 - \dfrac{T_a}{T_p} \right)}{\left(1 - \dfrac{T_a}{T_p} \right) + T_a \cdot \left(\dfrac{T_k - T_p}{T_k \cdot T_p} \right) + (1 - \dfrac{\dot{W}_{el}^c}{\dot{Q}}) \cdot \left(\dfrac{T_o - T_s}{T_o \cdot T_s} \right)} \tag{20}$$

If the temperature difference i.e. $T_k = T_p$ and $T_0 = T_s$, then exergy loss $\dot{E}x_L = 0$ (refer to equation (10)), this means that under Carnot cycle condition, there are no losses at both bottom (reboiler) and top (condenser) of the distillation unit. This also confirms that, the Carnot efficiency is 100% under the above condition (refer to equation (20)).

EXERGY EFFICIENCY OF REAL PROCESS

The exergy efficiency of the real process including all losses can be shown as follows:

$$\xi_{real,HP} \equiv \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = \frac{\dot{E}x_P}{\dot{E}x_P + \dot{E}x_L} = \frac{\dot{E}x_P}{\dot{E}x_P + \dot{E}x_{L,k} + \dot{E}x_{L,o} + \dot{E}x_{L,motor,real}}$$

$\xi_{real,HP}$ = exergy efficiency of the real process $\tag{21}$

where: $\dot{E}x_{L,o} = (\dot{Q} - \dfrac{\dot{W}_{el}^{C}}{\eta_{12}}) \cdot T_a \cdot \left(\dfrac{T_o - T_s}{T_o \cdot T_s}\right)$, $\eta_{12} = \eta_1 \cdot \eta_2$ (refer to Stockburger et. al.[14]for details)

Exergy loss ($\dot{E}x_{L,motor,real}$) associated with the motor can be expressed as follows: $\dot{W}_{el,motor}^{s} \equiv \dot{W}_{el}^{C} + \dot{E}x_{L,motor,real}$, $\dot{W}_{el,motor}^{s} = \dfrac{\dot{W}_{el}^{C}}{\eta_{\Sigma}}$, $\dot{E}x_{L,motor,real} = (\dfrac{1}{\eta_{\Sigma}} - 1) \cdot \dot{W}_{el}^{C}$ $\dot{E}x_{L,motor,real} = \dfrac{1-\eta_{\Sigma}}{\eta_{\Sigma}} \cdot \dot{W}_{el}^{C}$, for further substitution of the above equation, equation (21) becomes:

$$\xi_{real,HP} = \dfrac{\dot{Q} \cdot \left(1 - \dfrac{T_a}{T_p}\right)}{\dot{Q} \cdot \left(1 - \dfrac{T_a}{T_p}\right) + T_a \cdot \dot{Q} \cdot \left(\dfrac{T_k - T_p}{T_k \cdot T_p}\right) + (\dot{Q} - \dfrac{\dot{W}_{el}^{C}}{\eta_{12}}) \cdot T_a \cdot \left(\dfrac{T_o - T_s}{T_o \cdot T_s}\right) + \dot{W}_{el}^{C} \cdot \dfrac{1-\eta_{\Sigma}}{\eta_{\Sigma}}}$$

(22)

$$\xi_{real,HP} = \dfrac{\left(1 - \dfrac{T_a}{T_p}\right)}{\left(1 - \dfrac{T_a}{T_p}\right) + T_a \cdot \left(\dfrac{T_k - T_p}{T_k \cdot T_p}\right) + (1 - \dfrac{1}{\eta_{12} \cdot \varepsilon_C}) \cdot T_a \cdot \left(\dfrac{T_o - T_s}{T_o \cdot T_s}\right) + \dfrac{1}{\varepsilon_C} \cdot \dfrac{1-\eta_{\Sigma}}{\eta_{\Sigma}}}$$

(23)

$$\xi_{real,HP} = \dfrac{1 - \dfrac{T_a}{T_p}}{1 - \dfrac{T_s \cdot T_a}{\eta_{12} \cdot T_k \cdot T_o} + T_a \cdot \dfrac{1-\eta_{12}}{\eta_{12}}\left(\dfrac{1}{T_k} - \dfrac{1}{T_s} + \dfrac{1}{T_p}\right) + \dfrac{1-\eta_{\Sigma}}{\eta_{\Sigma}} \cdot \dfrac{T_k - T_s}{T_k}}$$

(24)

Thus equation (24) shows that the exergy efficiency of the real heat pump process is a function of the following parameters $\xi_{real,HP} = f\left(T_k, T_p, T_T, T_s, T_a, \eta_{12}; \eta_{\Sigma}\right)$, the temperature relation is as follows:

T_k	>	T_p	>	T_o	>	T_s	>
steam temp.(hot side)		bottom prod.temp.		top temp.(column)		compressor inlet temp.	

T_a

ambient temp.

This is clearly a descriptive of a distillation column.

PROCESS DESCRIPTION OF CASE STUDY

This paper concentrates on the stripping column which is part of a Hydrocarbon Recovery (HCR) unit (see figure 4).
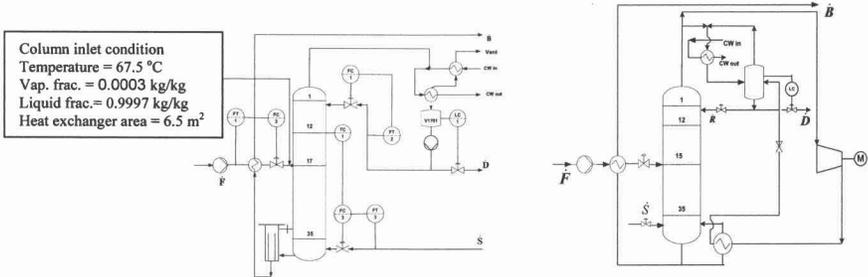
Figure 4: Energy Integration Alternatives:
(a) Base Case (d) Heat Pump Distillation

Figure 4 (a) provides a simple schematic illustration of the distillation unit (steam stripping column) unit from a real chemical plant. The main components of the feed stream are water, acetone, methanol, and acetic acid etc. The feed stream, which is close to its bubbling point enters the stripping column normally on tray 15. The column has a diameter of 0.728 m and 35 trays, where the rectifying section includes trays 1-15 and the stripping section 16-35. The column is operated with steam (700 kg/hr, 140°C and 3.75 bars) injection into the base below stage 35. The top pressure is 1.01 bar, reflux ratio 0.7 (operating plant) and the feed flow rate 4000 kg/hr. Figures 4 b shows the alternatives studied in this work. The operating targets are as shown below (mass %):

Distillate: $x_{Water} < 10\ \%$, $x_{Acetone} > 50\ \%$,
Base: $\quad x_{Acidity} < 3\ \%$, $x_{Acetone} < 0.22\ \%$, $x_{Methanol} < 2\ \%$

The acidity is the sum of the mass fraction of the acids i.e. acetic acid, formic acid and propionic acid. Acetone is the key component for the base and head qualities. In the next section a discussion of the integrating power plant to the design alternative is presented.

COMBINATION OF DISTILLATION AND POWER PLANT

Via Electrical Power

Given that $\dot{W}^5_{el,motor}$ is the available electrical power from the source to drive the compressor motor for the real heat pump distillation process (refer to figure 3). $\dot{W}^5_{el,motor}$ is a function of the primary fuel consumed, i.e. $\dot{W}^5_{el,motor} = f(\dot{Ex}_{fuel})$. If T_o is used as the process reference temperature, a relationship can be developed between the useful exergy and the primary exergy input. For a power plant with a condensing turbine (only electrical power is produced, no steam production), the exergy efficiency is given by:

$$\xi_{real,fuel,HP} = \frac{\dot{Ex}_p(T_o)}{\dot{Ex}_{fuel}} = \frac{\dot{Ex}_p(T_o)}{\dot{W}^5_{el,motor}} \cdot \frac{\dot{W}^5_{el,motor}}{\dot{Ex}_{fuel}} = \frac{\dot{Ex}_p(T_o)}{\dot{W}^5_{el,motor}} \cdot \eta_{pp} \qquad (25)$$

Where η_p = efficiency of power plant

$$\dot{Ex}_{fuel} \approx \dot{m}_{fuel} \cdot H_l$$

The steam produced via the reboiler and the exergy losses are equal to the electrical power input and this is given by:

$$\dot{Ex}_p(T_o) + \dot{Ex}_L(T_o) = \dot{W}^5_{el,motor} \qquad (26)$$

Inserting equation (26) into (25) gives

$$\xi_{real,fuel,HP} = \frac{\dot{Ex}_p(T_o)}{\dot{Ex}_p(T_o) + \dot{Ex}_L(T_o)} \cdot \eta_{pp} \qquad (27)$$

If T_o is used as the reference temperature instead of T_a equation (25) can be expressed as:

$$\xi_{real,fuel,HP} = \frac{1 - \dfrac{T_o}{T_p}}{1 - \dfrac{T_s}{\eta_{12} \cdot T_k} + T_o \cdot \dfrac{1-\eta_{12}}{\eta_{12}}\left(\dfrac{1}{T_k} - \dfrac{1}{T_s} + \dfrac{1}{T_o}\right) + \dfrac{1-\eta_\Sigma}{\eta_\Sigma} \cdot \dfrac{T_k - T_s}{T_k}} \cdot \eta_{pp} \qquad (28)$$

Equation (28) is considered for the case when the total amount of electrical power produced by the power plant is used to directly operate the heat pump distillation unit. If however there is excess production of electrical power, then sale of electrical power has to be considered, in that case, the numerator and denominator of equation (28) is extended by the factor: $\dfrac{W_{el}^{sale}}{\dot{Q}} = \dfrac{\dot{m}_{stm} \cdot n(p_{stm})}{\dot{m}_{stm} \cdot \Delta h(p_{stm})}$ and this gives:

$$\xi_{real,fuel,HP} = \frac{1 - \dfrac{T_o}{T_P} + \dfrac{n(p_{stm})}{\Delta h(p_{stm})}}{1 - \dfrac{T_S}{\eta_{12} \cdot T_K} + T_o \cdot \dfrac{1-\eta_{12}}{\eta_{12}} \left(\dfrac{1}{T_K} - \dfrac{1}{T_S} + \dfrac{1}{T_o} \right) + \dfrac{1-\eta_{\Sigma}}{\eta_{\Sigma}} \cdot \dfrac{T_K - T_S}{T_K} + \dfrac{n(p_{stm})}{\Delta h(p_{stm})}} \cdot \eta_{pp}$$

(29)

where $n(p_{stm})$ = Specific electrical power output (MWh/t)
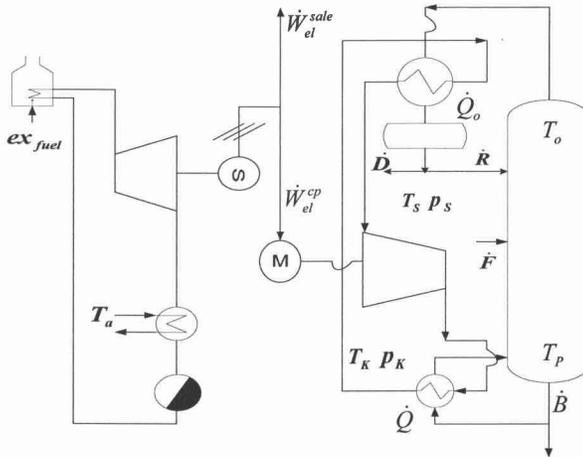
Figure 5: Integration of Heat Pump Distillation Unit with Condensing Power Plant

In this section, heat pump is used as a means of saving primary energy. The heat pump is operated via electrical power from the power plant (see figure 5). The exergy efficiency of the fuel is calculated for different operating range of the heat pump. The detail numerical calculations are given below (refer to table 1). The following numerical values are defined for equation (29), Given that $T_s = T_0 - 10K$, $T_k = T_p + 10K$; $x = 1.3$; $\tilde{M} =$

20kg/kmol; $\eta_2 = 0.72$; $\eta_{12} = 0.72 \cdot \eta_1$; $\eta_3 = 0.90$ $\eta_4 = 0.95$; $\eta_5 = 0.90$; $\eta_\Sigma = 0.554 \cdot \eta_1$; $\eta_{pp} = 0.35$.

Table 1: Simulation Results of Exergy Efficiency
of Heat Pump Combine with Power Plant

T_o	[K]	$328 \rightarrow$							
$T_P - T_o$	[K]	10	20	30	40	50	60	70	80
T_P	[K]	338	348	358	368	378	388	398	408
T_s	[K]	318							
T_k	[K]	348	358	368	378	388	398	408	418
P_s	[bar]	$0.1 \rightarrow$							
P_k	[bar]	0.39	0.58	0.85	1.21	1.69	2.32	3.13	4.15
$h''(T_s) - h'(T_k)$ [kJ/kg]		2269	2227	2185	2143	2100	2058	2015	1972
η_1		1.01	0.98	0.95	0.922	0.899	0.882	0.863	0.847
η_{12}		0.728	0.709	0.692	0.664	0.647	0.635	0.621	0.61
η_Σ		0.56	0.541	0.531	0.511	0.498	0.488	0.478	0.469
$n(p_{stm})/\Delta h_{stm}$		$0.461 \rightarrow$				$0.37 \rightarrow$			
$\zeta_{real, fuel, HP}$		0.325	0.272	0.262	0.259	0.241	0.236	0.231	0.225
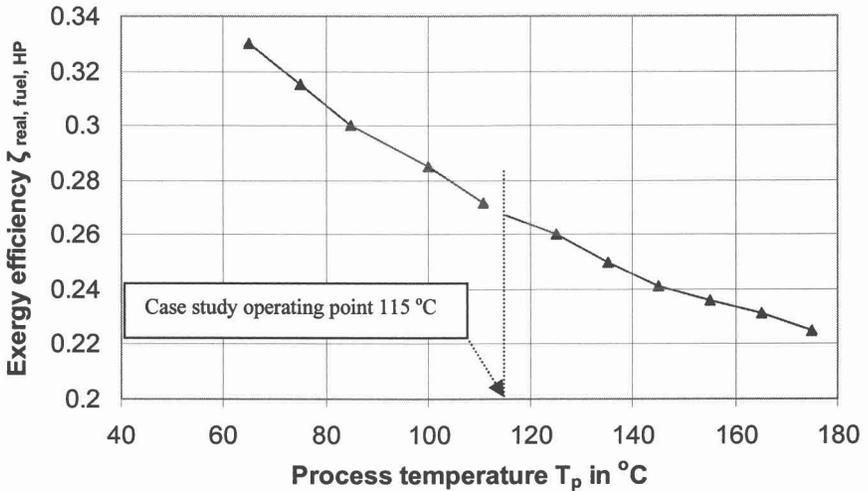
**Figure 6: Exergy Efficiency of Power Plant
and Heat Pump Distillation, T$_o$=55 °C**

Figure 6 show that as the process temperature of the heat pump increases, the exergy efficiency also decreases. This result shows that heat pump is an economic way to save energy if the temperature difference between the overhead and the bottom is small. This indicates that heat pump combination is best operated at a smaller process temperature difference. For this case study the heat pump is operated at 115 °C which corresponds to exergy efficiency of 27%.

Via Steam

In this section, a conventional distillation unit (see figure 7) that depends on saturated steam from a power plant as source of energy is analysed. Considering the steam from the power plant with the following properties, P_{stm}, T_{stm} and Δh_{stm}, the mass flow rate of the steam from the turbine can be calculated as follows:
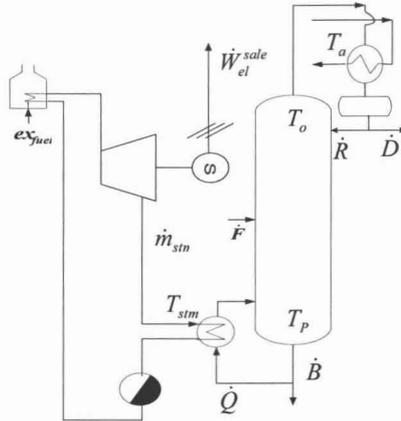
**Figure 7: Steam and Electrical Power
from Power Plant (Back Pressure Turbine)**

$$\dot{m}_{stm} = \frac{\dot{Q}}{\Delta h_{stm}(p_{stm})}$$

(30)

The exergy transfer to the distillation process can be calculated as follows:

$$\dot{Ex}_{stm}(T_o) = \dot{m}_{stm} \cdot \Delta h_{stm}(p_{stm}) \cdot \left(1 - \frac{T_o}{T_{stm}}\right)$$

(31a)

The exergy input is necessary to operate the distillation unit is:

$$\dot{Ex}_p(T_o) = \dot{m}_{stm} \cdot \Delta h_{stm}(p_{stm}) \cdot \left(1 - \frac{T_o}{T_p}\right)$$

(31b)

For any given steam flow rate from the power plant (see figure 7), there is a corresponding electrical power generation and the ratio of these two parameters are given by:

$$n(p_{stm}) = \frac{\dot{W}_{el}^{sale}}{\dot{m}_{stm}} \Rightarrow \dot{W}_{el}^{sale} = n(p_{stm}) \cdot \dot{m}_{stm}$$

(32)

where $n(p_{stm})$ indicates the amount of electrical power produced per ton of net steam from the power plant (steam turbine). Given that the exergy of fuel input to power plant is $\dot{E}x_{fuel}$, considering the distillation process operating on steam from the power plant as well as the electrical power from power plant, the exergy efficiency is:

$$\xi_{real,fuel,stm} = \frac{\dot{E}x_p(T_o) + \dot{W}_{el}^{sale}}{\dot{E}x_{fuel}}$$

(33)

Combination of equations (31b), (32) and (33) gives:

$$\xi_{real,fuel,stm} = \left[\Delta h_{stm}(p_{stm}) \cdot \left(1 - \frac{T_o}{T_p}\right) + n(p_{stm})\right] \cdot \frac{1}{\dfrac{\dot{E}x_{fuel}}{\dot{m}_{stm}}}$$

$\dfrac{\dot{E}x_{fuel}}{\dot{m}_{stm}} = ex_{bpp}=$ the specific exergy input to the power plant (back pressure turbine) per ton of steam produced. The main idea of this section is to study how the outlet steam of the turbine can be used to operate the distillation column. From equation (34) if p_{stm} and $n(p_{stm})$ are predefined, the efficiency $\xi_{real, fuel, stm}$ increases with increasing process temperature T_p. This means that when using steam from a power plant to heat a process stream, it is better to maintain a smaller temperature difference $(T_{stm} - T_p)$ between the power plant and the process plant. But sufficient temperature difference $(T_{stm} - T_p)$ is required to achieve heat transfer. The simulation results are shown in figure 8 and table 2. Exergy efficiency calculations as function of T_p is illustrated in table 2 for steam quality of 4 bar and 10 bar and a graphical illustrative example of the calculation is shown in figure 8.

Table 2: Simulation Results

P_{stm}	bar	4	10
T_{stm}	°C	143	180
$\dot{m}_{stm}$	kg/hr	1000	1000
$n(p_{stm})$	MWh/t	0.273	0.20
$\Delta h_{stm}(p_{stm})$	MWh/t	0.592	0.54
T_o	°C	55.34	55.34
T_P	°C	101	135
$T_P - T_o$	°C	45.6	80
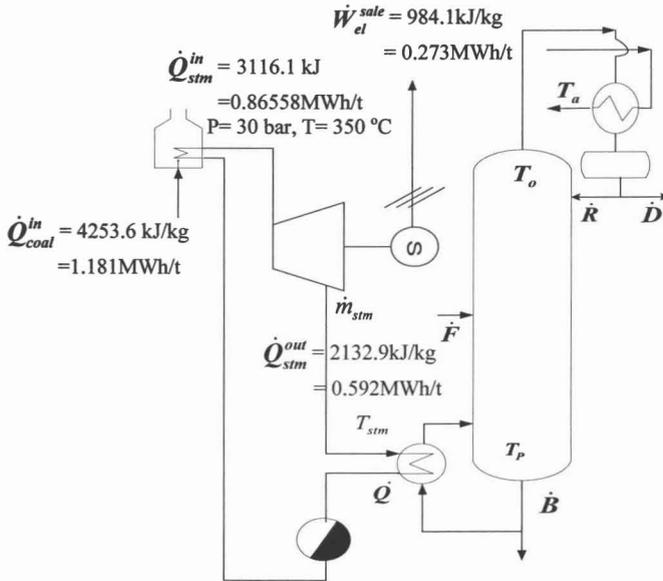
**Figure 8: Integration of Conventional Distillation Unit
with Back Pressure Power Plant**

From figure 9 it can be observed that if T_p is increased, $\xi_{real,\,fuel,\,stm}$ increases. This condition gives lower values of $(T_{stm} - T_p)$. If the outlet pressure P_{stm} of the turbine is increased, the specific electrical energy $n\,(P_{stm})$ decreases. This effect is shown in figure 9 via the difference of the 4 bar and 10 bar pressures. As shown in figure 9, the graph with the steam at 4 bar shows a higher and better efficiency than steam at 10 bar. The reason being, at 4 bar, the electrical power produced by the backpressure turbine is higher than that of 10 bar, also the change in specific enthalpy at 4 bar is higher than that at 10 bar.
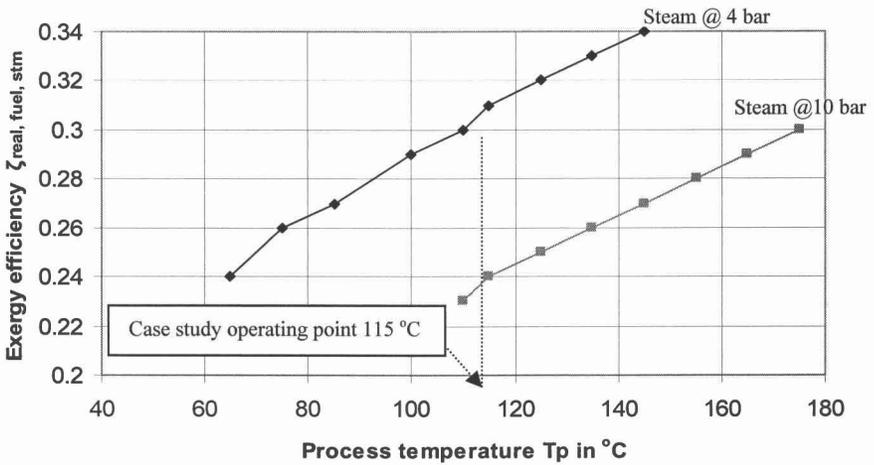
Figure 9: Exergy Efficiency as a Function of the Process

The result shows that a power plant can best be operated together with chemical plant when the outlet pressure of the turbine is small and this favours higher efficiency of primary energy consumption.

COMPARISON OF THE TWO ALTERNATIVES

In order to compare the two processes (i.e. conventional distillation and heat pump-see figure 10), it is also necessary to consider the exergy efficiency of the heat pump which is operated via electrical power output of the power plant (see figure 11).
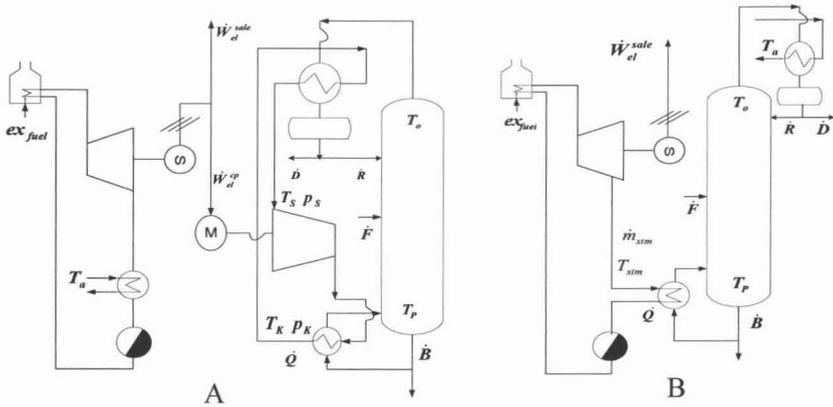
Figure 10: A: Combine Power Pplant and Heat Pump (Operated via Electrical Power)
B: Combine Power Plant and Distillation Unit (Operated via Steam)

Figure 11 show that the higher the process temperature the greater is the exergy efficiency of alternative operated via steam from power plant whiles the exergy efficiency of the heat pump combination decreases, this means that heat pump combination is best operated at a smaller process temperature difference. Whiles the alternative distillation attains a higher efficiency at higher process temperature.
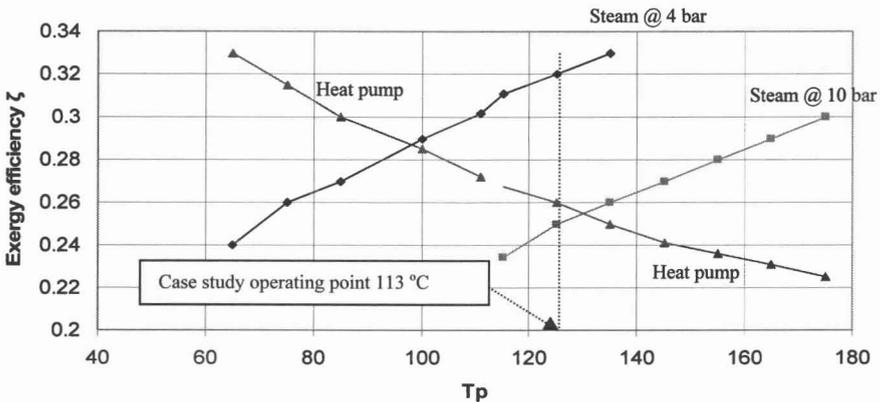
Figure 11: Comparison of Exergy Efficiency of the Two Processes, T_o=55 °C

CONCLUSION

In this paper, possible ways of saving energy in the chemical industry have been considered from theoretical point of view, the objective is to reduce the primary energy (such as coal) consumption of power plant. Some practical examples such as conventional distillation unit and heat pump are used as a means of reducing primary energy consumption with actual indications of energy savings. The results obtain shows that heat pump distillation is an economic way to save energy if the temperature difference between the overhead and the bottom is small. It was observed from this study that the efficiency of the combination of power plant and conventional distillation unit increases as the operating temperature increases. It was also concluded that steam at 4bar coming from a back pressure turbine could best be used to operate the distillation unit when compared with steam at 10 bar.

REFERENCES

[1]   U.S. Department of Energy, 1991. Heat Pumps For Industry, prepared for the U.S. Department of Energy, Office of Industrial Technologies, National Renewable Energy Laboratory, Golden, Colorado, pp.114.

[2]   T. V. Morosyuk, 1994. The conceptual selection model of a household heat pump, No. 200Uk-94, Deposited in Ukrainian State Scientific and Technical Library.

[3]   F. Moser and H. Schnitzer. 1985. *Heat Pumps in Industry*. Elsevier, Amsterdam.

[4]   F. Ziegler and P.Riesch. 1993. Absorption cycles. A review with regard to energetic Efficiency, *Heat Recovery Systems* CHP 13, pp.147-159.

[5]   W. Davidson and W. Campagne, 1987. Save energy by absorption heat pumping, Hydrocarbon Processing.

[6]   H. P. Null, 1976. Heat pumps in distillation, *Chem. Eng. Prog.* Vol. 73, pp. 58-64

[7]   T. V. Morosyuk, 1999. Modeling selection of a heat pump integrated with a power unit. *Chemical and Petroleum Engineering*, Vol. 35, Nos. 3-4,

[8]   T. V. Morosyuk, B. A. Minkus, L. I. Morosyuk, and R. K. Nikulchin. 1996. Absorption heat pumps built in small power aggregates, *Proceedings of Conference International surles pomps a chaleur a absorption*. Montreal, Canada, pp. 747-751

[9]   Gholam Reza Salehia, Majid Amidpoura, Kazem Hassanzadeha, Mohammad Reza Omidkhahb. 2012. Controllability analysis of heat integrated distillation systems for a multicomponent stream, *Computers & Chemical Engineering*, Vol. 36, pp. 282–293.

[10]   Patricia Palenzuelaa, Guillermo Zaragozab, Diego Alarcónb, Julián Blancob, 2011. Simulation and evaluation of the coupling of desalination units to parabolic-trough solar power plants in the Mediterranean region, *Desalination*, Vol. 281, pp. 379–387.

[11]   Patricia Palenzuela, Guillermo Zaragoza, Diego C. Alarcón-Padilla, Elena Guillén, Mercedes Ibarra, Julián Blanco, 2011. Assessment of different configurations for combined parabolic-trough (PT) solar power and desalination plants in arid regions, *Energy*. Vol. 36, Issue 8, pp. 4950–4958.

[12]   L.V. van der Ham, 2012, Improving the exergy efficiency of a cryogenic air separation unit as part of an integrated gasification combined cycle, *Energy Conversion and Management*, Vol. 61, pp. 31–42.

[13]   Liqiang Duan, Mingde Zhao, Yongping Yang. 2012, Integration and optimization study on the coal-fired power plant with CO_2 capture using MEA, *Energy*, 45 (2012). pp.107-116

[14]   D. Stockburger, and L. Bartmann, 1978, Chem.-1ng.-Tech. Verlag Chemie, GmbH, D-6940 Weinheim, pp. 497-502.

[15]   A. McConkey, and T. D. Eastop, 1993. Applied Thermodynamics for Engineering Technologist, Longman Group UK Ltd.