

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

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### **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.

**Key words:** *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  $24.3 \times 10^{15}$  kJ of energy annually at a cost of almost \$80 billion. A significant portion, almost  $7.4 \times 10^{15}$  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 [3,4,5]. 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 [11,12,13], 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 were 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

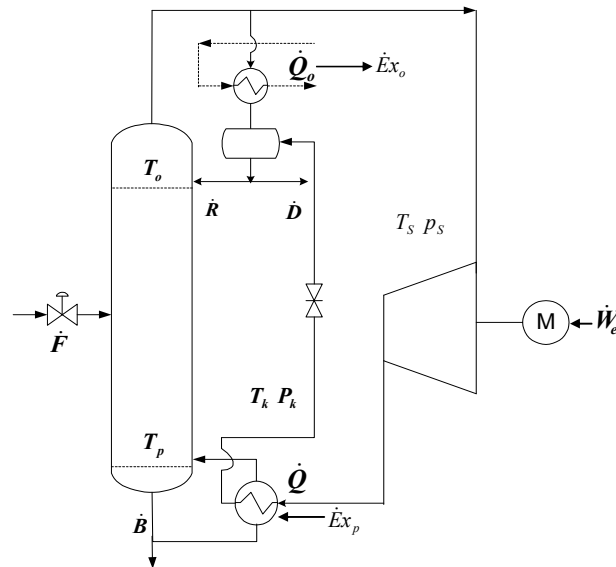


Figure 1: Electrically driven heat pump assisted distillation

**Energy efficiency**

The energy efficiency of a heat pump distillation is expressed in terms of coefficient of performance which is indicated by the symbol ( $\epsilon$ ). 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:

$$\epsilon = \frac{\dot{Q}}{\dot{W}_{el}} \tag{1}$$

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

$$\epsilon_c = \frac{\dot{Q}}{\dot{Q} - \dot{Q}_o} = \frac{T_K \cdot \Delta S}{T_K \cdot \Delta S - T_S \cdot \Delta S} = \frac{T_K}{T_K - T_S} \tag{2}$$

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, while point 3 to point 5 shows the compression for a real process and this will be discussed in the next section.

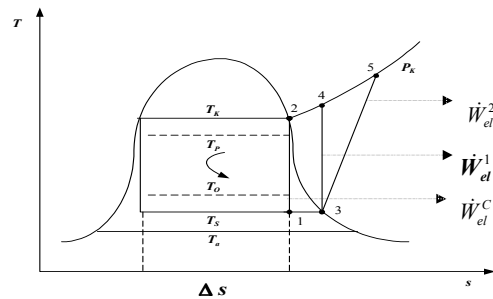


Figure 2: T-S diagram of a standard cycle (CARNOT) process and real process  
 Point 1→ Point 2 (Carnot process) Point 3→ Point 4 (Isentropic process),  
 Point 3→ Point 5 (Real process)

**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  $\dot{W}_{el,motor}^5$  is supplied to the motor of the compressor. The motor (with electrical power of  $\dot{W}_{el,gear}^4$ ) transfers its rotational motion through a gear system to the shaft connecting the compressor, the shaft (with electrical power of  $\dot{W}_{el,shaft}^3$ ) finally transfer its power to the compressor.  $\dot{W}_{el}^2$  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:

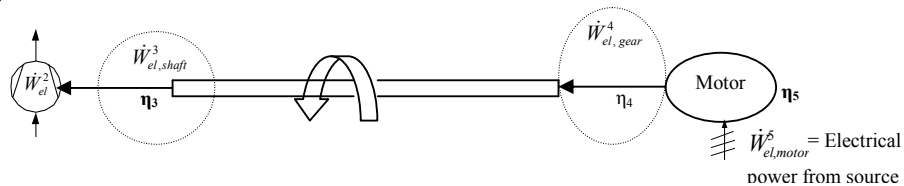


Figure 3: Mechanism of electrical power transfer to the compressor

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

$$\eta_{\Sigma} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \cdot \eta_5 \quad (3)$$

Where:  $\eta_1 \equiv \frac{\dot{W}_{el}^C}{\dot{W}_{el}^1}$  is the performance factor  $\eta_1$  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

$$\eta_1 = \left[ \frac{h^*(T_s) - h^*(T_k)}{\frac{\chi}{\chi-1} \cdot \frac{R}{M} \cdot \left\{ \left( \frac{P_k}{P_s} \right)^{\frac{\chi-1}{\chi}} - 1 \right\}} + T_s \right] \cdot \left[ \frac{1}{T_s} - \frac{1}{T_k} \right]$$

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

$$\begin{aligned} \eta_2 &= \frac{\dot{W}_{el}^1}{\dot{W}_{el}^2} \quad (\text{Inner efficiency}) \\ \eta_{3, \text{shaft}} &= \frac{\dot{W}_{el}^2}{\dot{W}_{el}^3} \quad (\text{Shaft efficiency}) \\ \eta_{4, \text{gear}} &= \frac{\dot{W}_{el}^3}{\dot{W}_{el}^4} \quad (\text{Gear systems efficiency}) \\ \eta_{5, \text{motor}} &= \frac{\dot{W}_{el}^4}{\dot{W}_{el}^5} \quad (\text{Motor efficiency}) \end{aligned}$$

### Exergy efficiency

The exergy efficiency is given by:

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

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

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

Where:

$\xi_C$  = 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:

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

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

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

$$\dot{E}x_p + \dot{E}x_L = \dot{E}x_o + \dot{W}_d^c \quad (8)$$

Where  $\dot{E}x_L$  = exergy loss, equation 5 becomes:

$$\xi_c = \frac{\dot{E}x_p}{\dot{E}x_p + \dot{E}x_L} \quad (9)$$

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

$$\dot{E}x_L = \dot{E}x_{L,k} + \dot{E}x_{L,o} \quad (10)$$

Where:

$$\dot{E}x_{L,k} = \dot{Q} \cdot T_a \cdot \left( \frac{T_k - T_p}{T_k \cdot T_p} \right) \quad (11)$$

$$\dot{E}x_{L,o} = \dot{Q}_o \cdot T_a \cdot \left( \frac{T_o - T_s}{T_o \cdot T_s} \right) \quad (12)$$

Where  $\dot{E}x_{L,k}$  = Exergy loss by reboiler

$\dot{E}x_{L,o}$  = 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:

$$\dot{W}_d^c = \dot{Q} - \dot{Q}_o \quad (13)$$

Inserting equation 13 into 12 gives:

$$\dot{E}x_{L,o} = (\dot{Q} - \dot{W}_d^c) \cdot T_a \cdot \left( \frac{T_o - T_s}{T_o \cdot T_s} \right) \quad (14)$$

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

$$\dot{E}x_k = \dot{E}x_p + \dot{E}x_{L,k} \quad (15)$$

$$\dot{Q} \cdot \left( 1 - \frac{T_a}{T_k} \right) = \dot{Q} \cdot \left( 1 - \frac{T_a}{T_p} \right) + \dot{E}x_{L,k} \quad (16)$$

$$\dot{E}x_{L,k} = \dot{Q} \cdot \left( \frac{T_k - T_a}{T_k} - \frac{T_p - T_a}{T_p} \right) \quad (17)$$

$$\dot{E}x_{L,k} = \dot{Q} \cdot T_a \cdot \left( -\frac{1}{T_k} + \frac{1}{T_p} \right) = \dot{Q} \cdot T_a \cdot \left( \frac{T_k - T_p}{T_k \cdot T_p} \right) \quad (18)$$

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

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

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

If the temperature difference i.e.  $T_k = T_p$  and  $T_o = T_s$ , 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:

$$\xi_{real,HP} \equiv \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = \frac{\dot{E}x_p}{\dot{E}x_p + \dot{E}x_L} = \frac{\dot{E}x_p}{\dot{E}x_p + \dot{E}x_{L,k} + \dot{E}x_{L,o} + \dot{E}x_{L,motor,real}} \quad (21)$$

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

Where:  $\dot{E}x_{L,o} = \left(\dot{Q} - \frac{\dot{W}_{el}^c}{\eta_{12}}\right) \cdot T_a \cdot \left(\frac{T_o - T_s}{T_o \cdot T_s}\right)$ ,  $\eta_{12} = \eta_1 \cdot \eta_2$  (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:

$$\dot{W}_{el,motor}^s \equiv \dot{W}_{el}^c + \dot{E}x_{L,motor,real}, \dot{W}_{el,motor}^s = \frac{\dot{W}_{el}^c}{\eta_{\Sigma}}, \dot{E}x_{L,motor,real} = \left(\frac{1}{\eta_{\Sigma}} - 1\right) \cdot \dot{W}_{el}^c, \dot{E}x_{L,motor,real} = \frac{1 - \eta_{\Sigma}}{\eta_{\Sigma}} \cdot \dot{W}_{el}^c, \text{ for further}$$

substitution of the above equation, equation 21 becomes:

$$\xi_{real,HP} = \frac{\dot{Q} \cdot \left(1 - \frac{T_a}{T_p}\right)}{\dot{Q} \cdot \left(1 - \frac{T_a}{T_p}\right) + T_a \cdot \dot{Q} \cdot \left(\frac{T_k - T_p}{T_k \cdot T_p}\right) + \left(\dot{Q} - \frac{\dot{W}_{el}^c}{\eta_{12}}\right) \cdot T_a \cdot \left(\frac{T_o - T_s}{T_o \cdot T_s}\right) + \dot{W}_{el}^c \cdot \frac{1 - \eta_{\Sigma}}{\eta_{\Sigma}}} \quad (22)$$

$$\xi_{real,HP} = \frac{\left(1 - \frac{T_a}{T_p}\right)}{\left(1 - \frac{T_a}{T_p}\right) + T_a \cdot \left(\frac{T_k - T_p}{T_k \cdot T_p}\right) + \left(1 - \frac{1}{\eta_{12} \cdot \epsilon_c}\right) \cdot T_a \cdot \left(\frac{T_o - T_s}{T_o \cdot T_s}\right) + \frac{1}{\epsilon_c} \cdot \frac{1 - \eta_{\Sigma}}{\eta_{\Sigma}}} \quad (23)$$

$$\xi_{real,HP} = \frac{1 - \frac{T_a}{T_p}}{1 - \frac{T_s \cdot T_a}{\eta_{12} \cdot T_k \cdot T_o} + T_a \cdot \frac{1 - \eta_{12}}{\eta_{12}} \left(\frac{1}{T_k} - \frac{1}{T_s} + \frac{1}{T_p}\right) + \frac{1 - \eta_{\Sigma}}{\eta_{\Sigma}} \cdot \frac{T_k - T_s}{T_k}} \quad (24)$$

Thus equation 24 shows that the exergy efficiency of the real heat pump process is a function of the following parameters  $\xi_{real,HP} = f(T_k, T_p, T_T, T_s, T_a, \eta_{12}, \eta_{\Sigma})$ , the temperature relation is as follows:  $T_k > T_p > T_o > T_s > T_a$   
 steam temp.(hot side) bottom prod. temp. top temp.(column) compressor inlet temp. 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).

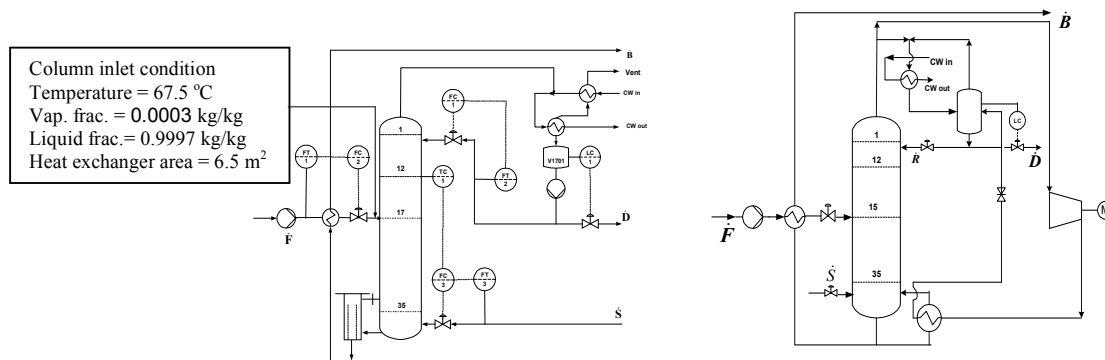


Figure 4: Energy integration alternatives: (a) base case (d) heat pump distillation

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:  $x_{Acidity} < 3 \%$ ,  $x_{Acetone} < 0.22 \%$ ,  $x_{Methanol} < 2 \%$



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  $\dot{W}_{el,motor}^5$  is the available electrical power from the source to drive the compressor motor for the real heat pump distillation process (refer to figure 3).  $\dot{W}_{el,motor}^5$  is a function of the primary fuel consumed, i.e.  $\dot{W}_{el,motor}^5 = f(\dot{E}x_{fuel})$ . 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:

$$\xi_{real, fuel, HP} = \frac{\dot{E}x_p(T_o)}{\dot{E}x_{fuel}} = \frac{\dot{E}x_p(T_o)}{\dot{W}_{el,motor}^5} \cdot \frac{\dot{W}_{el,motor}^5}{\dot{E}x_{fuel}} = \frac{\dot{E}x_p(T_o)}{\dot{W}_{el,motor}^5} \cdot \eta_{pp} \quad (25)$$

Where  $\eta_{pp}$  = efficiency of power plant

$$\dot{E}x_{fuel} \approx \dot{m}_{fuel} \cdot H_l$$

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

$$\dot{E}x_p(T_o) + \dot{E}x_L(T_o) = \dot{W}_{el,motor}^5 \quad (26)$$

Inserting equation 26 into 25 gives

$$\xi_{real, fuel, HP} = \frac{\dot{E}x_p(T_o)}{\dot{E}x_p(T_o) + \dot{E}x_L(T_o)} \cdot \eta_{pp} \quad (27)$$

If  $T_o$  is used as the reference temperature instead of  $T_a$  equations 25 can be expressed as:

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

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:

$$\frac{W_{el}^{sale}}{\dot{Q}} = \frac{\dot{m}_{stm} \cdot n(p_{stm})}{\dot{m}_{stm} \cdot \Delta h(p_{stm})} \text{ and this gives:}$$

$$\xi_{real, fuel, HP} = \frac{1 - \frac{T_o}{T_p} + \frac{n(p_{stm})}{\Delta h(p_{stm})}}{1 - \frac{T_s}{\eta_{12} \cdot T_k} + T_o \cdot \frac{1 - \eta_{12}}{\eta_{12}} \left( \frac{1}{T_k} - \frac{1}{T_s} + \frac{1}{T_o} \right) + \frac{1 - \eta_{\Sigma}}{\eta_{\Sigma}} \cdot \frac{T_k - T_s}{T_k} + \frac{n(p_{stm})}{\Delta h(p_{stm})}} \cdot \eta_{pp} \quad (29)$$

Where  $n(p_{stm})$  = Specific electrical power output (MWh/t)

**Application**

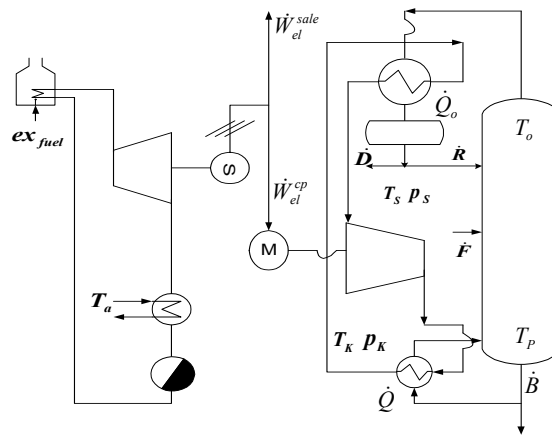


Figure 5: Integration of heat pump distillation unit with condensing power plant

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  $T_s = T_o - 10K$ ,  $T_k = T_p + 10K$ ;  $\chi = 1.3$ ;  $\tilde{M} = 20\text{kg/kmol}$ ;  $\eta_2 = 0.72$ ;  $\eta_{12} = 0.72 \cdot \eta_1$ ;  $\eta_3 = 0.90$ ;  $\eta_4 = 0.95$ ;  $\eta_5 = 0.90$ ;  $\eta_{\Sigma} = 0.554 \cdot \eta_1$ ;  $\eta_{pp} = 0.35$ ,

Table 1: Simulation results of exergy efficiency of heat pump combine with power plant

$T_o$	[K]	328	→						
$T_p - T_o$	[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							
$P_k$	[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
$\eta_1$		1.01	0.98	0.95	0.922	0.899	0.882	0.863	0.847
$\eta_{12}$		0.728	0.709	0.692	0.664	0.647	0.635	0.621	0.61
$\eta_\Sigma$		0.56	0.541	0.531	0.511	0.498	0.488	0.478	0.469
$n(p_{stm})/\Delta h_{stm}$		0.461				0.37			
$\zeta_{real, fuel, HP}$		0.325	0.272	0.262	0.259	0.241	0.236	0.231	0.225

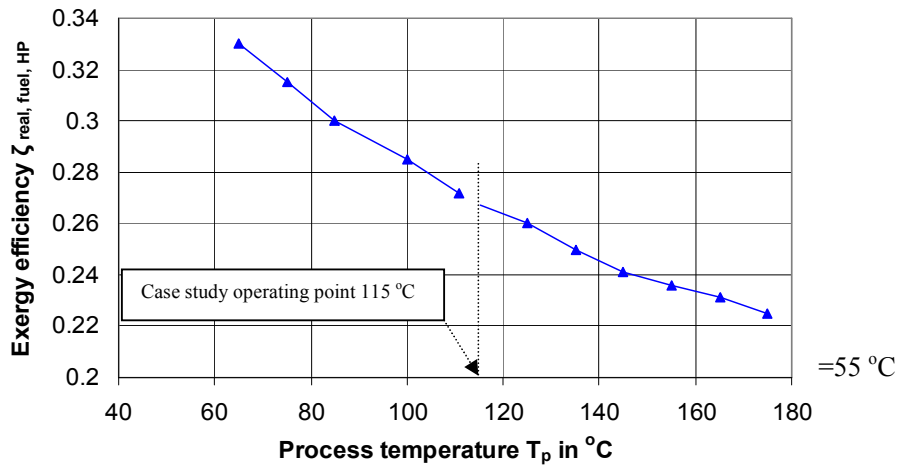


Figure 6: Exergy efficiency of power plant and heat pump distillation,  $T_o=55\text{ }^\circ\text{C}$

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  $\Delta h_{stm}$ , the mass flow rate of the steam from the turbine can be calculated as follows:

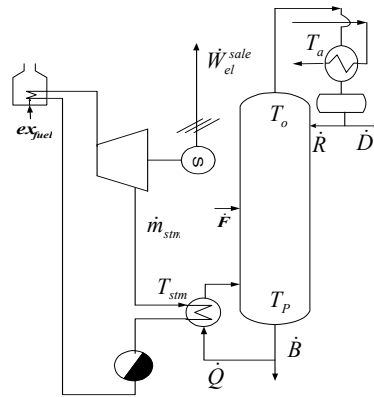


Figure 7: Steam and electrical power from Power plant (back pressure turbine)

$$\dot{m}_{stm} = \frac{\dot{Q}}{\Delta h_{stm}(p_{stm})} \tag{30}$$

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

$$\dot{Ex}_{stm}(T_o) = \dot{m}_{stm} \cdot \Delta h_{stm}(p_{stm}) \cdot \left(1 - \frac{T_o}{T_{stm}}\right) \tag{31a}$$

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

$$\dot{Ex}_p(T_o) = \dot{m}_{stm} \cdot \Delta h_{stm}(p_{stm}) \cdot \left(1 - \frac{T_o}{T_p}\right) \tag{31b}$$

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:

$$n(p_{stm}) = \frac{\dot{W}_{el}^{sale}}{\dot{m}_{stm}} \Rightarrow \dot{W}_{el}^{sale} = n(p_{stm}) \cdot \dot{m}_{stm} \tag{32}$$

$n(p_{stm})$  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  $\dot{Ex}_{fuel}$ , considering the distillation process operating on steam from the power plant as well as the electrical power from power plant, the exergy efficiency is:

$$\xi_{real, fuel, stm} = \frac{\dot{Ex}_p(T_o) + \dot{W}_{el}^{sale}}{\dot{Ex}_{fuel}} \tag{33}$$

Combination of equations 31b, 32 and 33 gives:

$$\xi_{real, fuel, stm} = \left[ \Delta h_{stm}(p_{stm}) \cdot \left( 1 - \frac{T_o}{T_p} \right) + n(p_{stm}) \right] \cdot \frac{1}{\frac{\dot{E}x_{fuel}}{\dot{m}_{stm}}} \tag{34}$$

$\frac{\dot{E}x_{fuel}}{\dot{m}_{stm}} = ex_{bpp}$  = 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

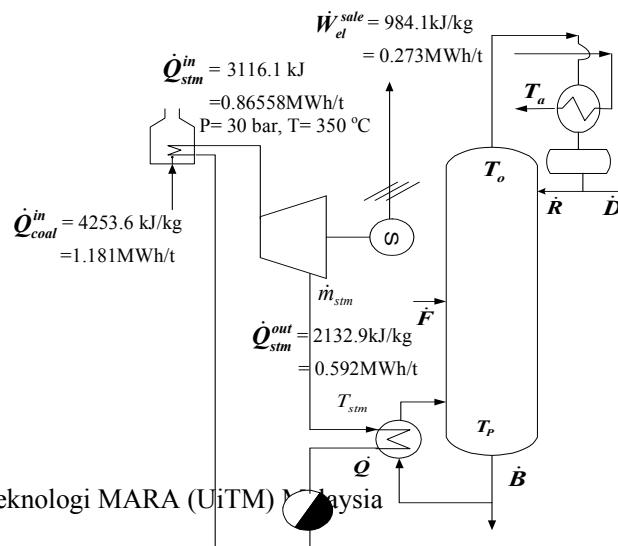


Figure 8: Integration of conventional distillation unit with back pressure power plant

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.

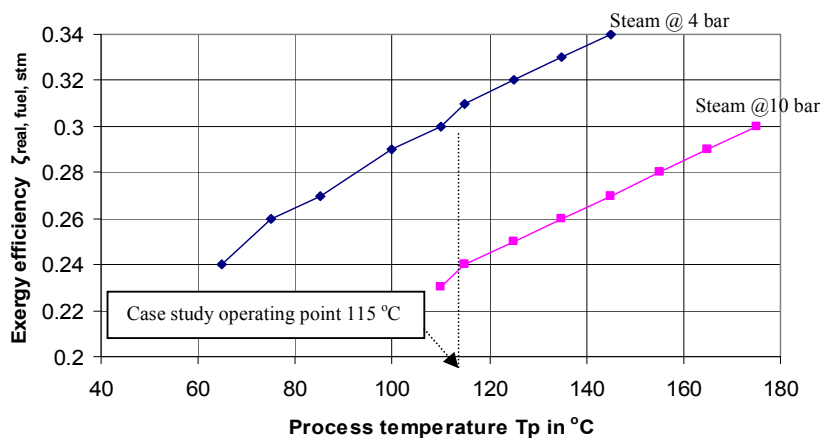


Figure 9: Exergy efficiency as a function of the process

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).

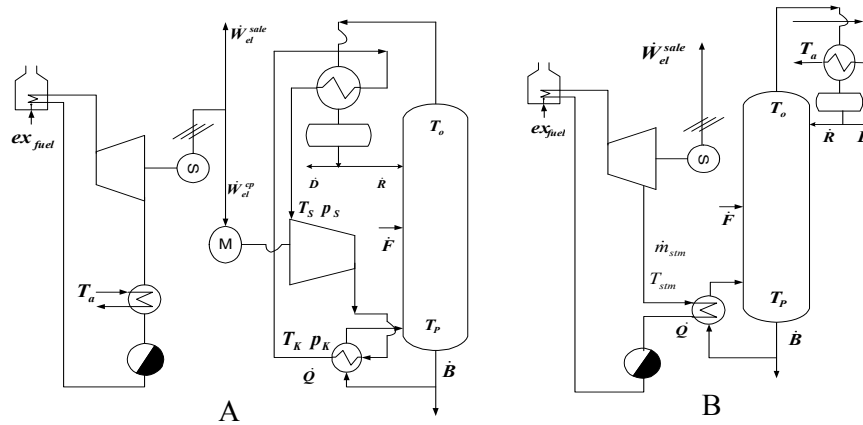


Figure 10: A: Combine power plant and heat pump (operated via electrical power)  
 B: Combine power plant and distillation unit (operated via steam)

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.

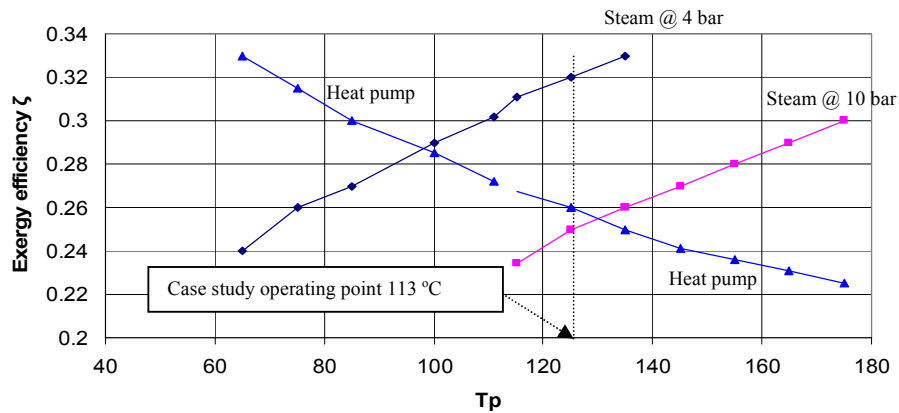


Figure 11: Comparison of exergy efficiency of the two processes, T<sub>0</sub>=55 °C

**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.

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