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MAXIMISING UTILITY SAVINGS THROUGH APPROPRIATE IMPLEMENTATION OF COMBINED HEAT AND POWER SCHEME

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Abstract. Combined Heat and Power (CHP) scheme, also known as cogeneration is widely accepted as a highly efficient energy saving measure, particularly in medium to large scale chemical process plants. The advantages of a CHP scheme for a chemical plant are two-fold: (i) to drastically reduce electricity bill from on-site power generation (ii) to save on fuel bills through recovery of the quality waste heat from power generation for process heating. In order to be effective, a CHP scheme must be placed at the right temperature level, in the context of an overall process system. Failure to do so might render a CHP venture worthless. This paper describes the procedure for an effective implementation of a CHP scheme using an ethyl benzene process as a case study. A key visualisation tool in Pinch Analysis technique known as the grand composite curve is used to guide CHP integration, and allows it to be optimally placed within the overall process scenario. The study shows that appropriate CHP integration with the ethyl benzene process above the pinch can potentially result in significant savings on electricity cost of up to 87%.

Keywords: Pinch analysis, composite curves, grand composite curves, cogeneration

Abstrak. Skema gabungan haba-kuasa yang juga dikenali sebagai kogenerasi telah diterima secara meluas sebagai salah satu daripada kaedah penjimatan tenaga yang amat berkesan, khususnya bagi loji proses kimia dari kategori industri sederhana dan besar. Terdapat dua kebaikan utama daripada skema gabungan haba-kuasa bagi sesebuah loji kimia: (i) bagi mengurangkan bil elektrik secara mendadak melalui penjanaan kuasa di dalam loji (ii) bagi menjimatkan bil bahan api melalui perolehan semula tenaga haba berkualiti yang terbazir daripada penjanaan kuasa untuk tujuan pemanasan proses. Untuk memastikan keberkesanannya, skema gabungan haba-kuasa perlu diintegrasi pada tahap suhu yang bersesuaian dalam konteks keseluruhan sistem proses. Kegagalan berbuat demikian akan menghasilkan skema gabungan haba-kuasa yang tidak akan mendatangkan sebarang manfaat. Kertas kerja ini menghuraikan kaedah implementasi yang berkesan untuk sebuah skema gabungan haba-kuasa berdasarkan satu kajian kes ke atas proses etil benzena. Sebuah teknik gambaran yang penting daripada kaedah analisis *Pinch* yang dikenali sebagai lengkuk rencam perdana telah digunakan sebagai panduan utama untuk integrasi optimum skema gabungan haba-kuasa dengan proses. Kajian ini menunjukkan bahawa integrasi bersesuaian di bahagian atas *Pinch* bagi skema gabungan haba-kuasa dengan proses etil benzena berpotensi menghasilkan penjimatan maksimum sebanyak 87% kos elektrik.

Kata kunci: Analisis *Pinch*, lengkuk rencam, lengkuk rencam perdana, kogenerasi

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1.0 INTRODUCTION

A combined heat and power (CHP) or cogeneration system is based on the fundamental concept of heat engine system from classical thermodynamics [1]. A CHP system utilises a heat source at high temperature to generate power, and in the process of doing so, rejects low quality heat to a low temperature heat sink. CHP has been widely accepted as a highly efficient energy saving measure, particularly in the medium and large scale process plants. The idea is that, while a plant generates power on-site to satisfy its own electricity needs, it also recovers waste heat from the exhaust of a power-generating turbine for process heating. The system allows a plant to be self-sufficient in terms of power, as well as heating needs. A CHP scheme functions as a supplier of the plant's utility heating through integration with selected process equipment. A key implementation issue that is very often overlooked is how to optimally integrate a CHP with a process. Inappropriate placement (integration) of a CHP can lead to capital and energy wastage, instead of savings [2]. In this paper, the procedure to achieve the optimal integration of CHP with a process based on Pinch Analysis concept is described. An ethyl benzene process is used as a case study to demonstrate the thermodynamic, as well as the economic impact of the appropriate implementation of a CHP scheme. An ethyl benzene process is well-suited for the CHP study since it is a major consumer of heat, as well as electrical power, due to the need to operate at high temperature (maximum design temperature: 400°C), and rather high pressure (maximum design pressure: 20 atm) in major equipment sections, including the reactor, separators, and recycle sections.

1.1 Process Description [2]

Ethyl benzene is produced via vapor phase ethylation of benzene to high purity ethyl benzene. Figure 1 is a simplified flow diagram of the process. Ethylene (S3) and benzene (S1) join two recycle streams as feeds to mixer M-1 operate at 5 atm. An optimum molar ratio of benzene to ethylene of 5:1 required in reactor R-6 is maintained in M-1. The mixed stream is preheated from 61 to 300°C in heat exchanger X-4, before being compressed from 4 atm to R-6 pressure at 14 atm. R-6 is a fixed-bed reactor with Zeolite ZSM-5 solid catalyst. The following exothermic reaction system occurs in R-6 at 330°C, 14 atm:

Primary reaction:

(1) C_6H_6 (benzene) + C_2H_4 (ethylene) $\rightarrow$ C_8H_{10} (ethyl benzene)

Side reactions:

(1) C_8H_{10} (ethyl benzene) + C_2H_4 (ethylene) $\rightarrow$ $C_{10}H_{14}$ (diethyl benzene)

(2) $C_{10}H_{14}$ (diethyl benzene) + C_6H_6 (benzene) $\rightarrow$ $2C_8H_{10}$ (ethyl benzene)

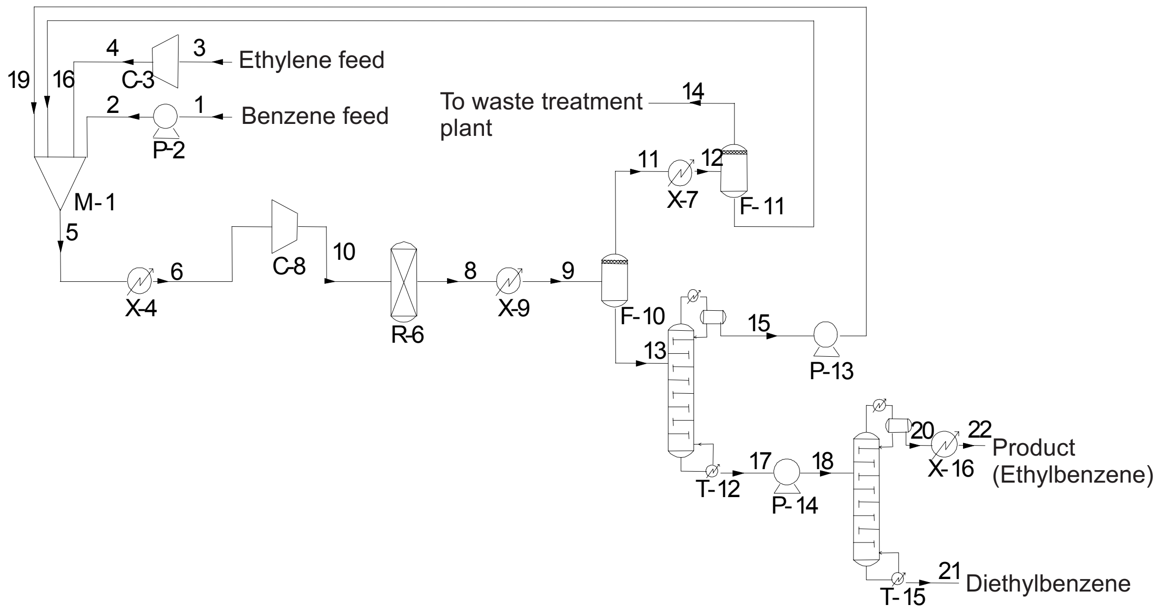

Figure 1 Process flow diagram for the ethyl benzene process

R-6 effluent (stream 8) is cooled from 332 to 153°C in heat exchanger X-9, before entering flash drum (F-10, at 5.7 atm, 151°C). F-10 overhead product (stream 11) which contains some impurities, a very small amount of ethyl benzene, and 4% benzene is cooled to 145°C, before being sent to the benzene recovery flash drum (F-11), operating at 5.4 atm, and 126°C. F-10 bottom stream (stream 13 at 151°C, 5.7 atm) that contains ethyl benzene products and some excess benzene is fed to the benzene recovery column (T-12), where most of the excess benzene is recovered. The distillate (stream 15) at 64°C, 1.1 atm containing benzene at 99.3% purity is recycled to the mixer (M-1) via stream 19. The bottom product (stream 17, 143°C, and 1.2 atm) enters distillation column (T-15), where ethyl benzene is separated from diethyl benzene. T-15 distillate (stream 20) contains the final product ethyl benzene at 99.9% purity. The liquid product is finally cooled from 139 to 30°C. The bottom product (stream 21) that contains a small amount of diethyl benzene, and some heavy end products is used as fuel in other parts of the plant.

2.0 METHODOLOGY FOR CHP IMPLEMENTATION BASED ON PINCH ANALYSIS CONCEPT

2.1 Process Stream Data

The first step in a process integration study based on Pinch Analysis is to identify the process streams having potential for heat exchange. These may include hot streams

Table 1 Hot and cold streams for integration for the ethyl benzene process [4]

Stream number	Stream name	Type	T_S (°C)	T_T (°C)	ΔH (MW)	Heat capacity flowrate (FCp) (MW/°C)
1	Exh-4	Cold	61.44	300.00	5.745	24.08
2	T-15, Reb	Cold	190.06	191.06	1.485	1485.00
3	T-12, Reb	Cold	141.98	142.98	8.217	8216.67
4	X-7	Hot	151.00	145.00	0.037	6.11
5	X-9	Hot	331.97	153.00	4.909	27.43
6	X-16	Hot	139.23	75.00	0.228	3.55
7	T-12, Cond	Hot	83.66	63.8	9.161	461.28
8	T-15, Cond	Hot	139.24	138.24	1.496	1495.56

$\Delta H = FCP \times (\Delta T)$, so $1/FCP = \Delta H/\Delta T$.

(streams having surplus heat and need cooling) and cold streams (streams with heat deficits and need heating). Next, the heat contents or the enthalpy (ΔH) of the candidate process streams are calculated. Table 1 shows the process streams in terms of the supply temperature, T_S (beginning temperature), and target temperature, T_T (ending temperature). ΔH gives a stream's heat availability and requirement.

2.2 The Composite Curves

The composite curves are the profiles of the "resultant" or the cumulative hot, and cold process streams on a temperature versus enthalpy diagram. Constructed from process stream data, they provide a useful graphical representation of the quality and quantity of heat available, and required for the process streams under study. The composite curves are the most established of Pinch Analysis tools. It was first introduced by Hohmann [3]. Detailed steps for the curves' construction are available elsewhere [4]. For a given minimum approach temperature for heat exchange, ΔT_{min}, the composite curves give the minimum amount of hot and cold utility requirements for the process, and the maximum amount of heat recoverable. The point where ΔT_{min} occurs is called the heat recovery "pinch". The pinch, which limits the amount of recoverable heat, is identifiable from the temperatures of the hot and cold curves.

A composite curves for the ethyl benzene process for an approach temperature of 10°C is shown in Figure 2. The curves yield the following utility targets:

The minimum heating requirement, $Q_{H,min}$ = 8895 kW

The minimum cooling requirement, $Q_{C,min}$ = 9250 kW

Hot pinch temperature, $T_{pinch,\ hot}$ = 140°C

Cold pinch temperature, $T_{pinch,\ cold}$ = 130°C

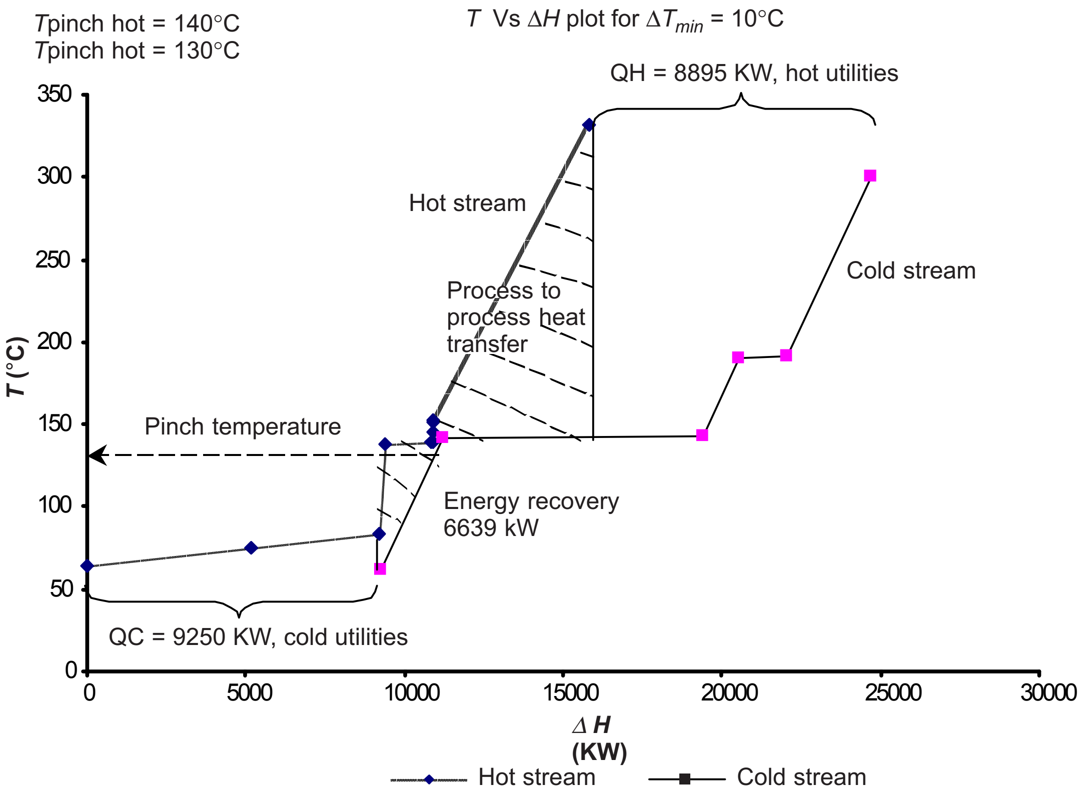

Figure 2 Temperature versus enthalpy (ΔH) plot, or the composite curves for the ethyl benzene process

2.3 The Grand Composite Curve (GCC)

In general, a grand composite curve can be plotted from the enthalpy difference (the horizontal gap) between the hot and cold composite curves, within the range of temperature for a process under study (see the generic representation of a GCC in Figures 3 and 4). The GCC is a profile of the process heat sources and sinks, as shown generically in Figure 4. Note that the heat sink, is separated from the heat source by the process pinch. The GCC allows a designer to place the right amount of utilities at appropriate temperature levels in a process, thereby providing an optimum interface between the process, and utility system.

2.4 Placement of A Combined Heat and Power Scheme (CHP)

As a heat engine, a CHP scheme generates power from a source of high quality heat. The lower quality heat derived from turbine exhaust may be used for process heating. Depending on the temperature levels that exist in a process, a CHP scheme that is to be integrated with a process can function either as a heat sink which accepts

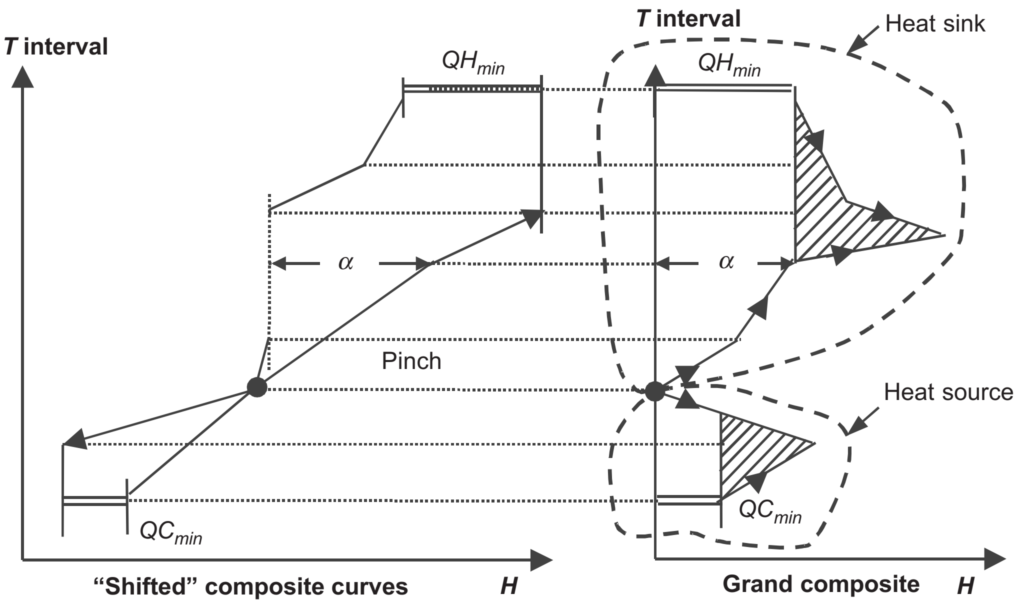

Figure 3 Construction of the grand composite curve

heat from a process for power generation, or as a source of utility heat to be supplied for process heating.

If the temperature levels of a process are high enough (e.g., in excess of 500°C, as found in cement plants), it may be possible for the process to supply waste heat, and

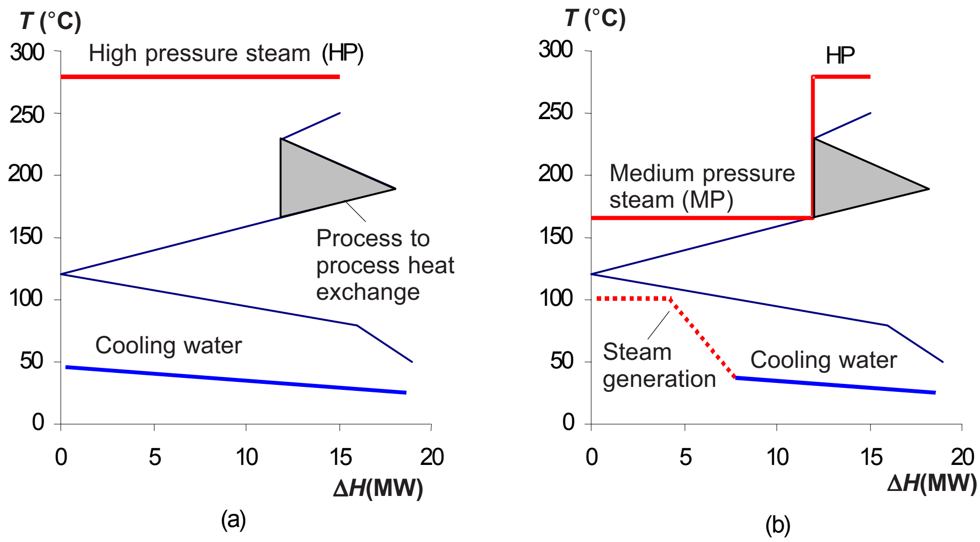

Figure 4 The grand composite curve provides an interface for the optimum selection of multiple utility levels (a) one hot and one cold utility scenario (b) multiple utilities

generate high-pressure (HP) steam for power generation. In this case, the process functions as a heat source, and the CHP, a heat sink. Recall that, in the context of a GCC, the heat source comes from the process below the pinch. In this instance, integrating a CHP with a process below the pinch allows power to be generated from waste heat, while reducing the overall cold utility requirement.

If the temperature levels of a process are not high enough (e.g., between 100-200°C, as found in the ethyl benzene plant under study), it is necessary to have an independent heat source to raise HP steam for power generation. The exhaust from a turbine of such CHP scheme is usually low-pressure (LP) steam that can be used to supply heat to the part of a process that requires heat, or a heat sink. In the context of a GCC, the heat sink is the process above the pinch.

In conclusion,

(1) a CHP system should only supply heat to a heat sink, which is the process above the pinch,
(2) a CHP system may get its heat supply from a heat source, which is the process below the pinch, in order to generate power, and
(3) it is most important to avoid placing a CHP scheme across the pinch temperature. This essentially means that the CHP supplies heat to the part of a process that needs to reject heat, i.e. a process heat source, thereby resulting in the wastage of energy and capital.

The foregoing analysis proves that pinch analysis has a key role to play in the implementation of a CHP scheme. The general rule for an appropriate placement of CHP scheme is either above, or below, and not across the process pinch [5].

3.0 CASE STUDY RESULTS

3.1 CHP Scheme for the Ethyl Benzene Plant [6]

Superheated steam is generated in a boiler operating at 41 bar, at a temperature of 300°C. The grand composite curve for ethyl benzene process in Figure 5 shows that two different steam levels (low pressure and medium pressure steam), and one cooling level are required to satisfy the process heating, and cooling requirements. A two-stage steam turbine (isentropic efficiency of 85 percent was assumed) with saturated exhaust steam at 220 and 160°C was therefore selected to expand the superheated steam to meet the heating needs in terms of heat quality, and quantity, as shown by the grand composite curve. The electricity requirement for the major equipment in the process, which include pumps and compressors, is 1030.3 kW, as shown in Table 2. Detailed energy balance calculations for the input and output streams of the power generating turbine showed that the CHP scheme for the ethyl benzene process can only generate a maximum of 890 kW of electrical power [4]. This

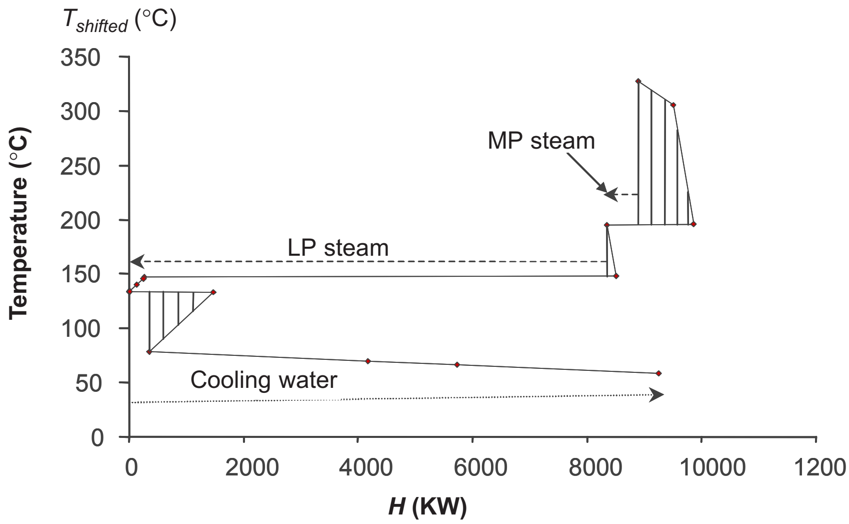

Figure 5 The grand composite curve for the ethyl benzene process

represents 87% of the process electricity requirement for the major equipment. Additional electricity is imported from the local authorities at RM 0.288/kW.hr. A total of 330 "on-stream" days (annual operating days) are assumed for this plant. Table 3 shows that installing a CHP scheme with a two-stage turbine can potentially

Table 2 Electricity requirements for the major equipment in the process [4]

Equipment	Electricity usage (KW)
Pumps	10.007
Compressors	1020.3
Total requirements	1030.3

Table 3 Comparison of utility costs with and without CHP scheme [4]

Scheme	Fuel cost (RM)	Boiler feedwater (RM)	Electricity cost (RM)	Total utility cost (RM)
(a) With CHP scheme	3 064 320	170 334	316 800	3 551 454
(b) Without CHP scheme	2 753 625	170 334	2 357 699	5 281 658
% Savings ((b) – (a))/(b)			87%	33%

save a maximum of 87% of the electricity cost for the pumps and compressors. This is economically very attractive, as compared with a conventional plant that completely depends on electricity supply from the grid.

With a CHP scheme, the total savings in terms of heat and power was estimated at RM 1 730 200/yr. The installed capital cost correlation from Ulrich [7], and a simple payback period relation were used to predict the economics of the CHP scheme. The results of the economic analysis are presented as follows:

(1)	Steam boiler cost	= RM 1 937 100
(2)	Two-stage turbine cost	= RM 1 477 100
(3)	Total installation cost	= RM 3 414 200

$$\text{Payback period} = \frac{\text{Installation cost for CHP scheme (RM)}}{\text{Total Utility Savings (RM/yr)}} = \frac{\text{RM 1 3414 200}}{\text{RM 1 730 200/yr}}$$

$$= 1.97 \text{ years}$$

From the calculations, a CHP scheme for the ethyl benzene process is clearly attractive due to the high return on investment, and the reasonably short payback period of within 2 years.

4.0 CONCLUSION

The paper outlines the procedure for saving utilities (electricity and fuel bills) through the appropriate implementation of a combined heat and power scheme in an existing ethyl benzene plant. Starting with a ΔT_{min} = 10°C, the composite curves are drawn and the energy targets are established. Integrating CHP with the process above the pinch allows a maximum potentail savings on electricity of up to 87%. Finally, we conclude that implementing a CHP scheme using Pinch Analysis allows significant reductions in energy cost and is therefore, highly recommended as demonstrated by the case study on the ethyl benzene plant.

NOTATION

FCP	= Heat-capacity flow rate
ΔH_i	= Total enthalpy change of enthalpy interval i on the composite curve
ΔH	= Total enthalpy change of a given hot or cold process stream
Q	= Heat exchanger duty
Q_{Hmin}	= Minimum hot utility target
Q_{Cmin}	= Minimum cold utility target
T_{hot}	= Temperature of hot composite curve

T_{cold} = Temperature of cold composite curve
ΔT = Temperature difference
ΔT_{LM} = Logarithmic mean temperature difference (LMTD) for enthalpy interval i of the composite curve
ΔT_{min} = Minimum temperature difference on composite curve

REFERENCES

[1] Smith, J. M., H. C. Van Ness, and M. M. Abbott. 1996. *Introduction to Chemical Engineering Thermodynamics*. fifth edition. McGraw-Hill International Editions.

[2] Westwood, A. R., and B. Linnhoff. 1985. CHP and Process Integration. *The Institution of Gas Engineers, Communications 1272*, 51st Autumn Meeting, London. 1-26.

[3] Hohmann, E. C. 1971. Optimum Networks for Heat Exchange. *Ph.D. Thesis.* University of Southern California.

[4] Lim, F. Y., L. C. Eng, S. T. Tang, N. S. Wong, and J. Sayuti. 2002. Process Integration of an Ethyl Benzene Plant. *Project Report*. Universiti Teknologi Malaysia.

[5] Smith, R. 1995. *Chemical Process Design*. Mc Graw Hill.

[6] Manan, Z. A. 2003. Lecture Notes for A Three-Day Course on Maximising Energy Savings in The Process Industry Using Pinch Analysis. Kuala Lumpur. Malaysia.

[7] Ulrich, G. D. 1984. *Process Plant Design and Economics*. John Wiley.