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Pinch Analysis of Cumene Process using Aspen Energy Analyzer

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Abstract

This article is divided into two parts. In the first part a process flow diagram for the production of cumene is designed with Aspen HYSYS. Cumene obtained is 98.78% pure and the designed plant is safe to environment with less emissions. In the second part heat exchanger networks (HEN) was developed for the process plant by performing pinch analysis using Aspen Energy Analyzer. Retrofit analysis was applied to find an alternate HEN which saves the energy of the process by minimizing the operating costs. In retrofit mode seven new heat exchangers are added to the base case HEN which reduced the operating cost with the payback period of 0.1797 years. A design alternative for base case design is also proposed with a payback period of 0.2312 years.

Keywords: *Pinch analysis, HYSYS, heat exchanger networks (HEN), aspen energy analyzer, retrofitanalysis*

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INTRODUCTION

For efficient plant operations process modifications are necessary[1–3].Automation of plants with distributed control systems design is the new development in chemical process industries[4–6].For that it is desirable to develop rigorous models for realistic and large-scale processes with recycle streams, energy integration and non-ideal systems, and use them for evaluating plant-wide control schemes[1–3,7].

Linnhoff *et al.*,[8,9] introduced the pinch technology concept. This concept pinch method was developed to design energy efficient systems[10]. Heat Exchanger Networks (HEN) design is the well-known criteria in Pinch technology applications[8,9,11,12]. It is proved in the case of new plant designs that industrial energy cost can be saved up to 30% in combination with capital cost[13] and payback times in retrofit applications were reported to be less than one year[14]. Pinch analysis was derived from combined first and second law analysis, as a technique ensuring a better thermal integration, aiming the minimization of entropy production or equivalently energy destruction by heat exchangers networks[15].

Role of heat integration in improving the economics of companies and in reducing industrial emissions plays a vital role[16]. To reduce the drawbacks in pinch analysis different techniques are proposed for example total entropy generation minimization techniques[17–19].

Pinch analysis concept can be understood in terms of composite curves, grand composite curves, grid diagram, grid diagram for retrofit analysis etc.

The principles already applied in the process industries are first one is heat flow across the pinch should be zero, second principle is utilities consumption both hot and cold can be minimized by integrating streams above and below the pinch separately and the third one is excess energy flows tend to incur high capital costs due to the extra heat transfer capacity needed for both utility heating and cooling. Improved energy recovery may lead to capital savings[20]. The above established principles allow us to set energy targets prior to design, to design minimum energy networks by keeping the portion of the process above and below the pinch separate and to avoid black box i.e., giving decision power to engineers[20].

The present study aims at designing a process plant for the production of cumene using Aspen HYSYS v8.0 and applies the established pinch principles in designing an alternative energy efficient HEN by applying retrofit analysis by using Aspen Energy Analyzer.

METHODOLOGY

Optimization of operating conditions and retrofit of HEN are the two methods frequently used energy saving methods in designing the process plants[11]. In optimization of operating conditions, set points of the process were determined. In retrofit method, the pinch techniques had to be applied to improve the project performance. Retrofit had its advantages compared to optimization *i.e.*, in optimization approach, HEN is fixed but in the case of retrofit, it is possible to incorporate real plant information in the design step. Based on this reason only, retrofit is preferred for most of the industrial plants to improve the process efficiency by saving the energy. The fundamental steps followed in the retrofit analysis were:

1. Extracting the process data from the process plant
2. HEN design for the base case process and retrofit analysis
3. Design improvement
4. Economic analysis was performed for the base case and retrofit design
5. If the economic analysis of retrofit was satisfactory compared to base case then the modified design was implemented.

The extracted data from the step one contained hot and cold stream temperatures heat duties of all streams were calculated by using heat capacity data of each stream. Generally hot streams contained more energy, this energy was recovered by matching the cold streams with hot streams and this matching could be achieved by several combinations of hot and cold streams. Once the quantity of the energy was known, heat exchange area calculation was very easy. Segmentation streams were useful in the case of large temperature range of the process streams to calculate accurately the heat capacity of a phase changing stream. From stream data HEN grid diagram was designed. Next step was to improve the HEN it was done by knowing the gap between ideal energy consumption and current energy consumption of the HEN. If there was no gap between ideal and retrofit then retrofit project ended there. This is the situation where energy savings were poor. Ideal energy consumption could be achieved by recovering heat in the process by several ways.

Composite curves were used to analyze the gap between the ideal and current HEN. If it was not possible to get ideal energy consumption by current HEN then the HEN was subjected to redesign by the pinch design method.

After designing the HEN the next step was the economic analysis. In economic analysis, capital investment and hot and cold utility load energy consumption costs were evaluated. The same economic procedure was applied to retrofit of the HEN. Retrofit was a trade-off problem between the energy saving and the capital investment[20]. If the new HEN developed by retrofit satisfied the desired economy of the process then the next step to be followed was detail engineering step. If the proposed HEN does not satisfy the economic criteria, search for a new HEN design step was necessary for the design improvement.

The present study explained the production of cumene by Aspen HYSYS v8.0 and the pinch analysis of the process was done by using Aspen Energy Analyzer.

PROCESS DESCRIPTION

The present process contained a mixer, compressor, two heat exchangers, plug flow reactor and two distillation columns. Process was designed by using Aspen HYSYS v8.0. Process flow diagram is shown in Figure 1. Raw materials for the process were propene and benzene both reacted in high pressure, high temperature preheated gas phase reactor to give cumene as product. There was also a sequential reaction occurring for the formation of isopropyl benzene. Reaction kinetics is shown in Eqs. (1) and (2):

$C_6H_6 + C_3H_6 \rightarrow C_9H_{12}$ ------- (1)

k= 2.8×10^7; E = 104174 kJ/kmol

$C_9H_{12} + C_3H_6 \rightarrow C_{12}H_{18}$ ------- (2)

k= 2.32×10^9; E = 146742 kJ/kmol

Before sending to the plug flow reactor, three unit operations were applied. In the first step, reactants were mixed; in the second step, compressed; in the third step preheated and in the next step reactants were passed to the reactor. The product mixture contained cumene, isopropyl benzene and unconverted propylene, benzene. The products were cooled before sending to the two distillation columns. In the two distillation columns, the first column separated benzene and in the second column, cumene and isopropyl benzene was separated. The final product cumene purity obtained was 98.9% pure. Steady state process data are shown in Tables 1 and 2.

After that, HEN was developed and retrofit analysis was applied for alternative efficient HEN design using Aspen Energy Analyzer.

DATA EXTRACTION FROM THE PROCESS

Energy data were extracted from the designed process Aspen Energy Analyzer. The extracted data consisted of temperatures, heat duty, and heat capacity of each stream, utility data and the cost data which was helpful in determining the energy cost and capital investment. The present design and retrofit analysis applied to the data of the cumene process plant and the data contained the extracted values of temperature and flow data of the process streams. Heat duty for each stream was calculated by Aspen Energy Analyzer. The extracted data of the process are shown in Tables 1–6. The process contains three hot streams and three cold streams. Three cold streams, two hot streams were segmented to satisfy the condition of phase change followed by large temperature change in a single phase. Utilities present in the process were two heating utilities and two heating and two cooling utilities. Heating utilities were fired heat, HP (high pressure) steam. Cooling utilities are Air, LP (low pressure) steam generation. Figure 1 shows the process flow diagram of cumene production process.

Retrofit is a trade-off problem between energy saving and capital investment[20]. Results are evaluated by the relative amount of the cost saved and investment needed. Utility cost index for the present process is 0.00169 and base operating time 8765.76 h are needed to calculate the energy cost saving and the heat exchanger cost is needed to estimate the investment cost[11].

Costs of the heat exchangers are calculated by the following equations i.e. Eqs. (3–7) [21]. Each type of heat exchange equipment's had its own equation for calculating the capital cost:

For shell and tube:

$CC = a + b(Area/N_{shell})^c \times N_{shell}$ …Eq. (3)

Fired heater:

$CC = a + b(Duty)^c$ …Eq. (4)

CC is the installed capital cost of a heat exchanger, a is installation cost of the heat exchanger, b, c are the duty or area related cost set coefficients of the exchanger, Area is the heat transfer area of the exchanger, N_{shell} is the number of heat exchanger shells in the heat exchanger, Duty is the amount of energy being transferred in the heat exchanger. Operating cost is a time dependent cost that represents the energy cost to run the equipment. For Aspen Energy Analyzer, the operating cost is dependent on the calculated energy targets in the HEN:

$OC = \Sigma(C_{hu} \times Q_{hu,min}) + \Sigma(C_{cu} \times Q_{cu,min})$ …Eq. (5)

OC is the operating cost, $C_{hu}$is utility cost for the hot utility, $Q_{hu,min}$ is energy target of hot utility(kW), C_{cu} is utility cost for the cold utility($/kW yr) $Q_{cu,min}$ is energy target of hot utility (kW). Total annualized cost (TAC) accounts for both the capital cost and operating cost associated with the heat exchangers in the HEN. The equation used to calculate the TAC is

$TAC = \Lambda \times \Sigma CC + OC$ …Eq. (6)

CC is the installed capital cost of a heat exchanger ($), OC is the operating cost ($/ yr), Λ is the annualization factor (1/ yr).

The annualization factor accounts for the depreciation of capital cost in the plant. It must be considered since the capital cost and operating cost of a heat exchanger network do not have the same units. The following equation is used to calculate the annualization factor:

$\Lambda=(1+ ROR/100)PL/PL,$ …Eq. (7)

ROR is the rate of return (percent of capital), PL is the plant life (year).

BASE CASE HEN ANALYSIS FOR RETROFIT

Heat integration studies were performed for the process flow diagram shown in Figure 1. In the first step of the analysis, data were extracted from the steady state process and the grid diagram was developed and is shown in Figure 2. In the next step, an alternative design for the base case design was developed and it is shown in Figure 3. Results are explained with composite curve as shown in Figure 4. Grand composite curve are shown in Figure 5. HEN for the current process is represented as grid diagram and is shown in Figure 2. Hot streams are represented by thick red color lines in the upper portion of the grid diagram and the cold streams are represented by blue thick lines in the lower portion. The base case has six exchangers between process streams. Hot and cold composite curves are combined and are shown as composite curve in Figure 6. Composite curve represents heating and cooling demand of the process corresponding to the temperature range. Quantity of maximum energy recovery can be calculated from the composite curve. The close gap in the diagram shows the ΔT min, it means the minimum driving force for heat exchange. Pinch point is the point where the two curves approach closest and the temperature difference of two composite curves is ΔT min. Economic efficiency and is decided by ΔT min and it affects heat exchange area. For the present study ΔT min is identified as 9.5ºC.

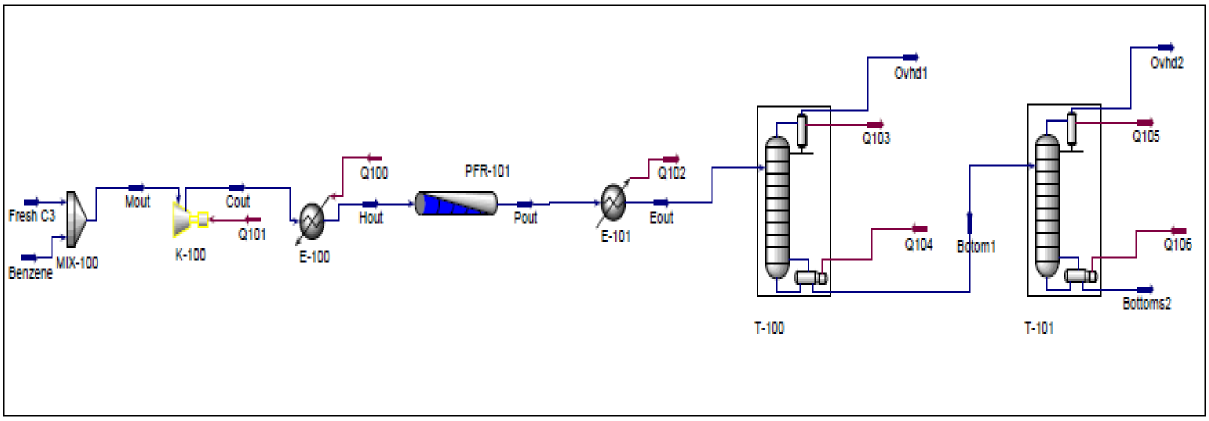

Fig. 1: *Process Flow Diagram for Acetone Production.*

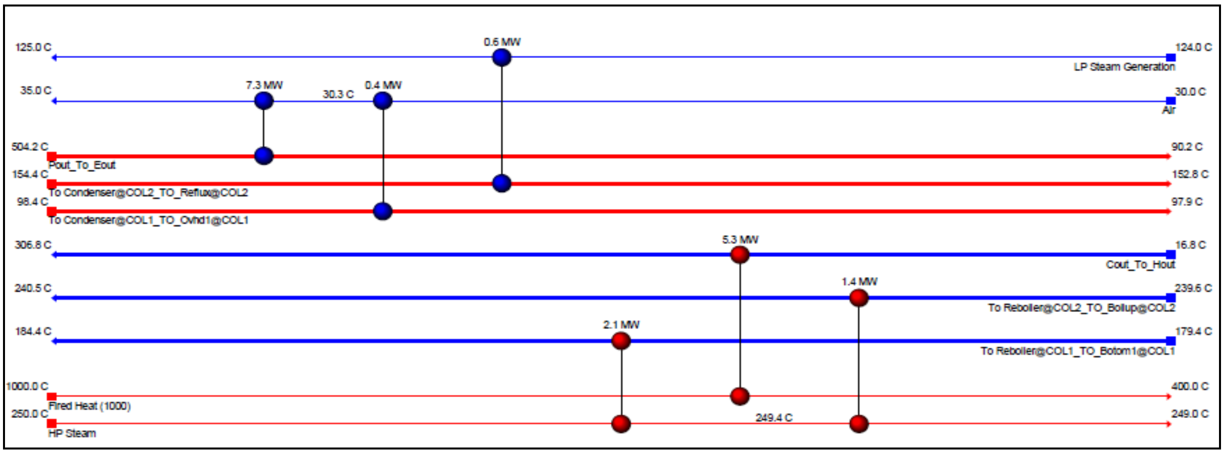

Fig. 2: *Heat Exchanger Network Design for the Current Configuration of the Cumene Process.*

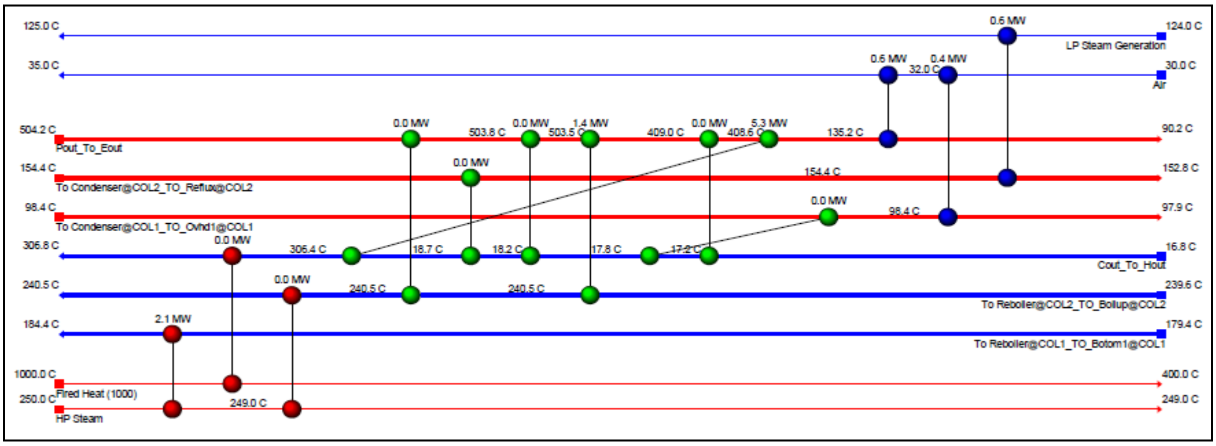

Fig. 3: *Retrofit Design for the Base Case Design.*

HEN IMPROVEMENT

From the process flow diagram, heat was exchanged in condenser@COL1, Condenser@COL2, Reboiler@COL1, E100@Main, E101@Main, Reboiler@COL2.

The process stream was heated from 62.25–584.3 F in exchanger E-100. The product stream from the reactor was cooled to 194.3 F in E-101 and their heating and cooling duties are 1.87×10^{7} Btu/h, 2.492×10^{7} Btu/h. All the heating and cooling requirements of the process were combined together; the result was the Grid diagram as shown in Figure 7. Simply the Grid diagram is an overview of all the heating/cooling requirements of the process.

Figure 4 shows the temperature versus enthalpy plot or composite curve. Composite curves set the energy targets prior to design. Energy targets from the composite curve are heating 0.5648 MW and cooling load 0.0049 MW. Figure 5 shows the Grand Composite Curve (GCC). GCC is a plot of shifted temperatures versus the cascaded heat between each temperature interval.

Figure 5 shows the grand composite curve (GCC). GCC is a plot of shifted temperatures versus the cascaded heat between each temperature interval.

Figure 6 shows the range targets plot. Range target gives the information corresponding to the optimization of the minimum approach temperature. It is calculated by minimizing the total annual cost. It means finding the best compromise between utility requirements, heat exchange area and unit shell number. As the minimum approach temperature is varied the total annual cost of the network is calculated. There will be a ΔT min which will yield a minimum total cost. Here the ΔT min calculated is 9.5 ºC.

Figure 7 show the grid diagram and it contains process streams, utility streams, heat exchangers, and split mixers. In the grid diagram, blue color represents cooler, red represents heater, grey shows the heat exchanger as a process-process exchanger and the heat exchanger is attached to two process streams, green shows that the heat exchanger has been added or modified by a retrofit action. The split/branches in the process stream will always converge back to a single arrow stream. The convergence of the branches indicates a mixer in the process stream.

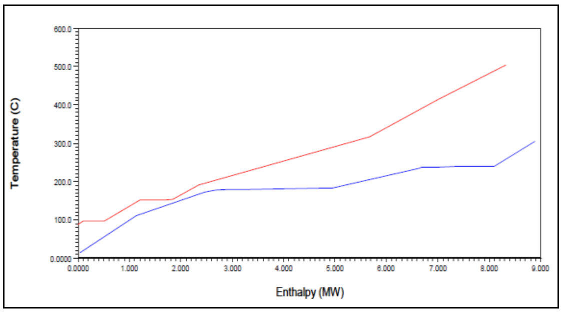

Fig. 4: *Composite Curve.*

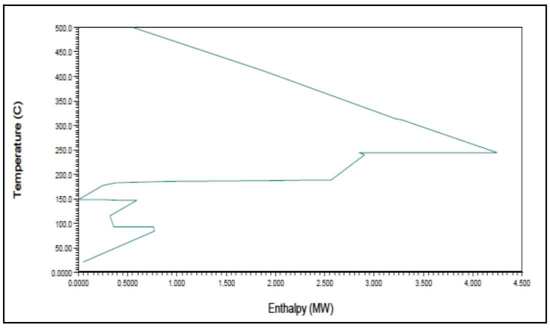

Fig. 5: *Grand Composite Curve.*

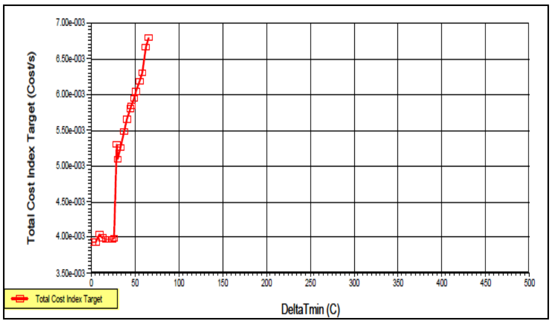

Fig. 6: *Range Target Plot.*

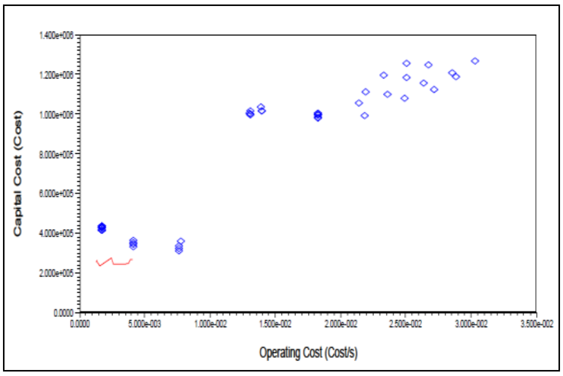

Fig. 7: *Retrofit Alpha Plot.*

It shows the heat available in various temperature intervals and the net heat flow in the process (which is zero at the pinch).

Table 1: Process Data of Cumene Process.

Name	Fresh C3	Benzene	Mout	Cout	Hout
Vapour	0.9354	0.00	0.3005	0.00	1.0
Temperature [F]	77.000	114.8	102.50	62.2	584.2
Pressure [psia]	29.007	362.5	29.007	377.09	376.3
Molar flow [lbmole/h]	242.50	456.3	698.85	698.85	698.8
Mass flow [lb/h]	11662	35645.6	47307.8	47307.8	47307.8
Stdideal liqvol flow [USGPM]	41.735	80.695	122.430	122.430	122.43
Molar enthalpy [Btu/lbmole]	5385.6	22561.3	16601.3	13240.1	39245.2
Molar entropy [Btu/lbmoleF]	26.456	–19.7820	–6.49858	–7.6351	20.5075
Heat flow [Btu/h]	1306061.6	10296016.7	11602078.3	9253084.1	27427133.41

Table 2: Process Data of Cumene Process.

Name	Pout	Eout	Ovhd1 @COL1	Botom1 @COL1	Ovhd2 @COL2	Bottoms2 @COL2
Vapour	1.0	0.0	1.00	0.0	1.0	0.0
Temperature [F]	939.4	194.2	208.4	364.0	306.9	464.8
Pressure [psia]	375.7	375.0	25.38	29.00	14.50	29.00
Molar flow [lbmole/h]	468.4	468.4	242.5	225.9	198.4	27.55
Mass flow [lb/h]	47307.8	47307.8	18976.9	28330.9	23864.8	4466.1
Std. ideal liq. vol flow [USGPM]	108.45	108.45	42.965	65.488	55.114	10.373
Molar enthalpy [Btu/lbmole]	58545.8	5350.0	38493.6	4623.9	11759.9	23834.8
Molar entropy [Btu/lbmoleF]	47.56	–0.4581	0.55	25.152	38.12	37.38
Heat flow [Btu/h]	27427336	2506374	9334966	–1044879	2333362	–656745

Table 3: Process Hot Stream Data.

Hot stream name	Hot T_{in}(°C)	Hot T_{out}(°C)
To Condenser@COL1_TO_Ovhd1@COL1	98.36	97.86
To Condenser@COL2_TO_Reflux@COL2	154.4	152.7
HP steam	250.0	249.4
Fired heat (1000)	1000.0	400.0
Pout_To_Eout	504.15	90.15
HP steam	249.40	249.0

Table 4: Process Cold Stream Data.

Cold stream name	Cold T_{in}(°C)	Cold T_{out}(°C)
Air	30.00	30.26
LP steam generation	124.0	125.0
To Reboiler@COL1_TO_Botom1@COL1	179.4	184.4
Cout_To_Hout	16.80	306.8
Air	30.26	35.00
To Reboiler@COL2_TO_Boilup@COL2	239.5	240.4

Table 5: *Process Heat Exchanger Load and Area Data.*

Heat exchanger name	Load (MW)	Area(m^2)	ΔT min Hot	ΔT min Cold	Overall heat transfer coefficient (kJ/hm^2°C)
Condenser@COL1	0.40	57.71	68.09	67.86	373.22
Condenser@COL2	0.61	26.62	29.40	28.76	2862.2
Reboiler@COL1	2.10	16.23	65.55	69.97	6910.9
E-100@Main	5.32	121.8	693.1	383.1	351.54
E-101@Main	7.30	370.8	469.1	59.89	346.46
Reboiler@COL2	1.40	58.65	8.937	9.419	9566.6

Table 6: *Process Utility Stream Data.*

Utility Name	Load (MW)
Air	7.710
LP steam generation	0.611
HP steam	3.511
Fired heat (1000)	5.326

PERFORMANCE EVALUATION

The performance of the HEN designed from the process is compared is tested with the design obtained from the retrofit analysis. The parameters include the heating, cooling, operating, capital, and operating cost values relative to the target values, amount of energy being transferred for heating and cooling purpose in the design, number of exchangers, number of shells, and the total heat transfer area values relative to the target values. The individual utility cost and load for all the utilities in the design. The percentage values of the utility load relative to the target values.

The following plots as depicted in Figure 8–11, obtained for various retrofit analysis designs gives the selection of the best performance design with less operating cost and low payback period.

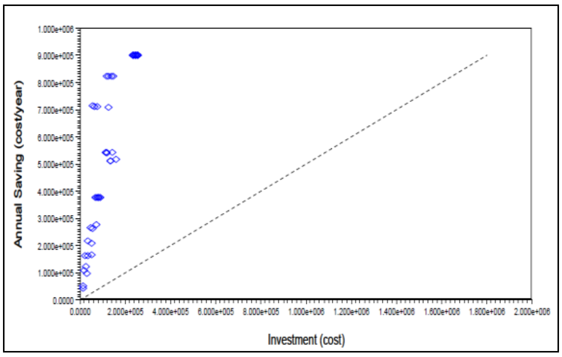

Fig. 8: *Investment Saving Curve.*

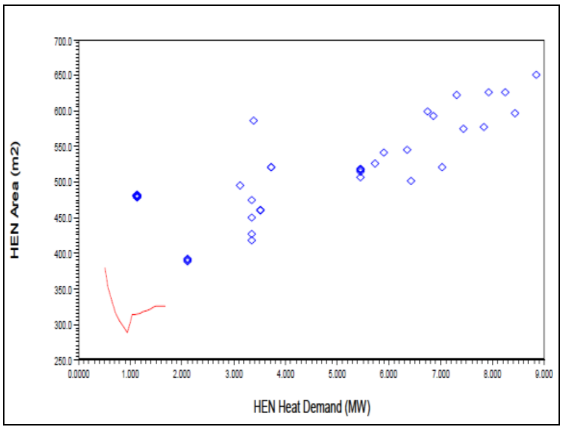

Fig. 9: *Area Heat Demand Curve.*

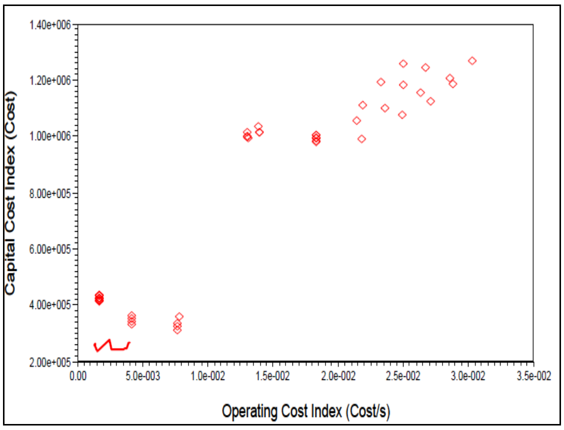

Fig. 10: *Capital Cost Index and Operating Cost Index.*

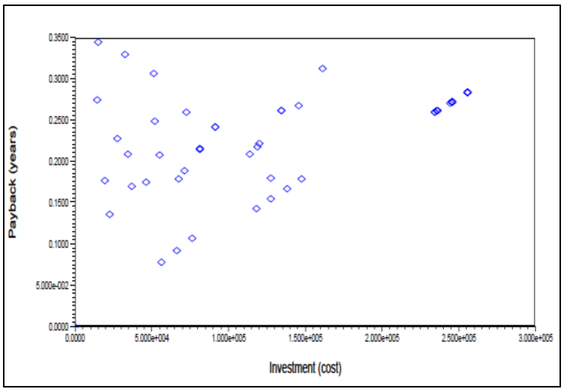

Fig. 11: *Payback Investment Curve.*

Possible recommended designs can be obtained from the Aspen Energy Analyzer and the suggested design alternatives reported are five. From the alternate designs best one with less payback period is selected and it is shown in Figure 12. In retrofit mode we can generate new HEN designs and they are compared with existing base case design. The comparisons are made in terms of additional investment and operating cost savings.

Cumene process HEN obtained is shown by a grid diagram in Figure 10. The process has three hot streams and three cold streams. The current HEN has six heat exchangers between process streams. Utilities are represented by thin lines and MP and LP are steam heaters. The grid diagram performance can be improved by recovering heat from heat energy from hot streams.

Seven new heat exchangers are added to the base case design. The improved HEN is efficient with low capital cost and less payback period of 0.2312 years which is less than a year.

Figure 3 shows the retrofit design for the base case while Figure 12 shows the recommended alternate design for the base case.

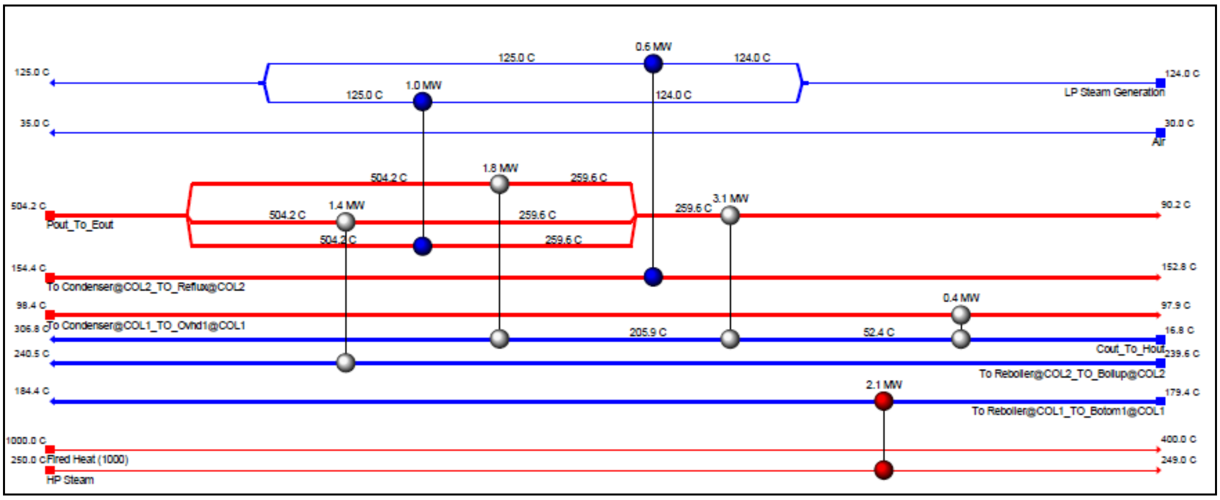

Fig. 12: *Design Alternative for Base Case Design.*

CONCLUSIONS

In this work a process isproposed for the production of cumene. The product purity is 98.78% and the plant is safe to operate with less emissions. After the development of the process HEN is developed for the base case process. The developed HEN is improved by designing the alternative HEN by retrofit analysis using AspenEnergy Analyzer. The base case HEN capitalindex is 1.272×10^6 and the improved HEN cost index is $2.664 \times 10^5$with a payback period of 0.1797 years.

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