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PROCESS HEAT INTEGRATION AND PINCH ANALYSIS OF A VEGETABLE OIL EXTRACTION PLANT

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ABSTRACT

The pinch analysis of a vegetable oil extraction plant was conducted to establish a better energy saving methodology. This methodology identified energy-cost reduction, based on the thermodynamic characteristics of the process. The location of the pinch point and design of a Heat Exchanger Network (HEN) which satisfies minimum utility requirement were also analysed. The results obtained by improving the HEN design for the Vegetable Oil Extraction Plant using pinch analysis identified huge reduction in capital investment thus, lowering annual energy consumption by 764.8 kW with an associated annual cost reduction from $1.617 million to $1.263 million, an equivalent 22% annual cost savings. Hence, the developed procedure is a better heat integration mechanism and capable of reducing overall energy consumption of the plant.

Keywords: Energy, Heat-Exchanger, Pinch-Technology, Thermodynamic

INTRODUCTION

The basic requirement of any effective design is energy conservation. This is achieved by several means practiced today in some chemical plants. These processes include reactor off gases, combustion of low grade fuels, use of waste heat boilers, etc. [1]. One of the most important techniques used to identify energy optimization opportunities is *pinch technology*. A complete pinch analysis (or pinch technology) is a two stage methodology [2]. The first phase, pinch targeting, identifies scope for energy reduction based on the process thermodynamic characteristics. The second phase identifies specific process and heat recovery network modifications required to meet the targets. In any industrial process, there will be many hot and cold streams and an optimum arrangement of the streams for energy recovery by process-process heat exchange. For instance, a process of four cold and three hot streams is identified to have 2×10^8 feasible permutations [3]. The solution to design problem is therefore to develop the least cost Heat Exchanger Network (HEN) that accomplishes the required heating and cooling. Pinch analysis presents a systematic approach to process energy analysis that reduces external energy requirement and cost, thus improving process efficiency. The uniqueness of this approach is its simplicity to structural design techniques that achieves best use of energy and cost requirements.

Mathur and Alok [4] proposed that the pinch technique optimizes process design, yielding superior results compared to the traditional methods. This new technique permits the designer to track the energy flows in a manufacturing process more clearly and modify the process to reduce consumption. They further state that in employing pinch analysis technique, the system design problems are considered for identification of existing plant or for designing a new plant.

Linnhoff and Hinhmarsh [5] stated results from analysis of the Eni S.P.A Refining and Marketing Company, Rome, citing the pinch analysis as a rigorous structured approach that determines the minimum practical energy consumption of a process and guide the user in designing a Heat Exchanger Network, achieves this target. The procedure of pinch analysis should start with energy and enthalpy balance expressions for the process followed by identification of appropriate changes in process core condition that have an impact on energy savings. In this way, pinch technology becomes a consistent method for achieving savings from the basic heat and material balance to total site utility. Their result identified an additional advantage of pinch analysis to the refinery hydrogen system and water application. Furthermore, the pinch analysis technique led to reduction in operating cost, debottlenecking process; improved efficiency and reduced capital investment. Kleemann [6] identified other methods like mathematical modelling, computer programs as knowledge based and heuristic. He approached the design of a heat exchanger network in two stages. One, the energy analysis of the recovery problem, (which involves the heat balance of the system) and two a structural design of the heat exchanger network. He also identified that the design of the heat exchanger network requires a set of rules which are postulated according to results of the analysis. The application of rules leads to HEN with Minimum Energy Requirement (MER) and minimum use of hot and cold composites. Pinch analysis is also used to identify energy cost and HEN for a process and recognizing the pinch point. The procedure first predict ahead of design, the minimum requirement of external energy network area, and the number of units for a given process at the pinch point. Design considerations therefore include choice of optimum ΔT_m that generates a HEN with minimum energy requirements and achieves optimum efficiency. After recognizing the pinch, extraction of thermal data like supply and target temperatures, heat capacity flow rates and enthalpy are used to construct composite curves and Problem Table Algorithm.

Finally, a feasible HEN that achieves necessary heating and cooling is synthesized and capital cost estimated.

DEVELOPMENT OF HEAT EXCHANGER NETWORK

The design of a Heat Exchanger Network (HEN) for the process is carried out on the grid diagram. This systematic application of the Pinch Design Method allows the design of a good network that achieves the energy targets within practical limits. Two basic rules for a HEN design are the "Heat Capacity (C_p) Inequality Rule" and "Stream Splitting Rule". The C_p Inequality Rule is a guideline for matching streams. Above the pinch, the heat capacity of the hot stream should be equal or less than that of the cold stream and vice versa. Also, no cooling is used above the pinch. That is:

$C_{pHot} \leq C_{pCold}$ Above the pinch

$C_{pHot} \geq C_{pCold}$ Below the pinch

Stream splitting must be done in accordance with the stream count theory which criterion is generalized as:

$N_{Hot} \leq N_{Cold}$ Above the pinch

$N_{Hot} \geq N_{Cold}$ Below the pinch

The economics of applying pinch technology is reduced energy consumption by 15–20% with good paybacks. Economic comparison is carried out here by evaluating the cost of energy consumption per annum.

$$Total\ Energy\ Cost = \sum_{u=1}^{u}(Q_u * C_u)$$

Where

Q_u = Duty of utility, kW

C_u = Unit cost of utility $kW, yr

u = Total number of utilities used.

THE EXTRACTION PLANT SCHEMATIC

The schematic flow diagram of the plant is shown in Fig. 1. The plant consists of hot streams (need cooling) and cold streams (need heating) considered as sources and sinks of heat energy respectively. Streams considered for heat recovery are the solvent vapour flow, the miscella flow, Crude Palm Kernel Oil flow (CPKO) and mineral oil flow. These streams constitute the various hot and cold composites of the plant. The solvent vapour flows through pipes connections at the top of the distillation column, flasher, and heaters. The solvent vapour with a temperature of 190^0C and high pressure from the DTDC passes through the scrubbers and exchanges heat with miscella in the economizer. The miscella is pumped back to the economizer after passing through a recuperator with some part sent to the distillation column. The solvent vapour terminates at two huge condensers arranged in series. The oil from the distillation column is sent to a series of heaters, where water-solvent content vaporizes and final heating occurs in the lasher where the oil falls turbulently on a hot wire mesh and water evaporated. The mineral oil, pumped from P180 is sent to the absorber where it is, contacted with hot vapour. Absorption of soluble vapour component raises the temperature of the mineral oil to about 92^{0}C. The hot mineral oil flowing out the absorber is cooled by passing through two heat exchangers arranged in series, each exchanging heat with cold process water.

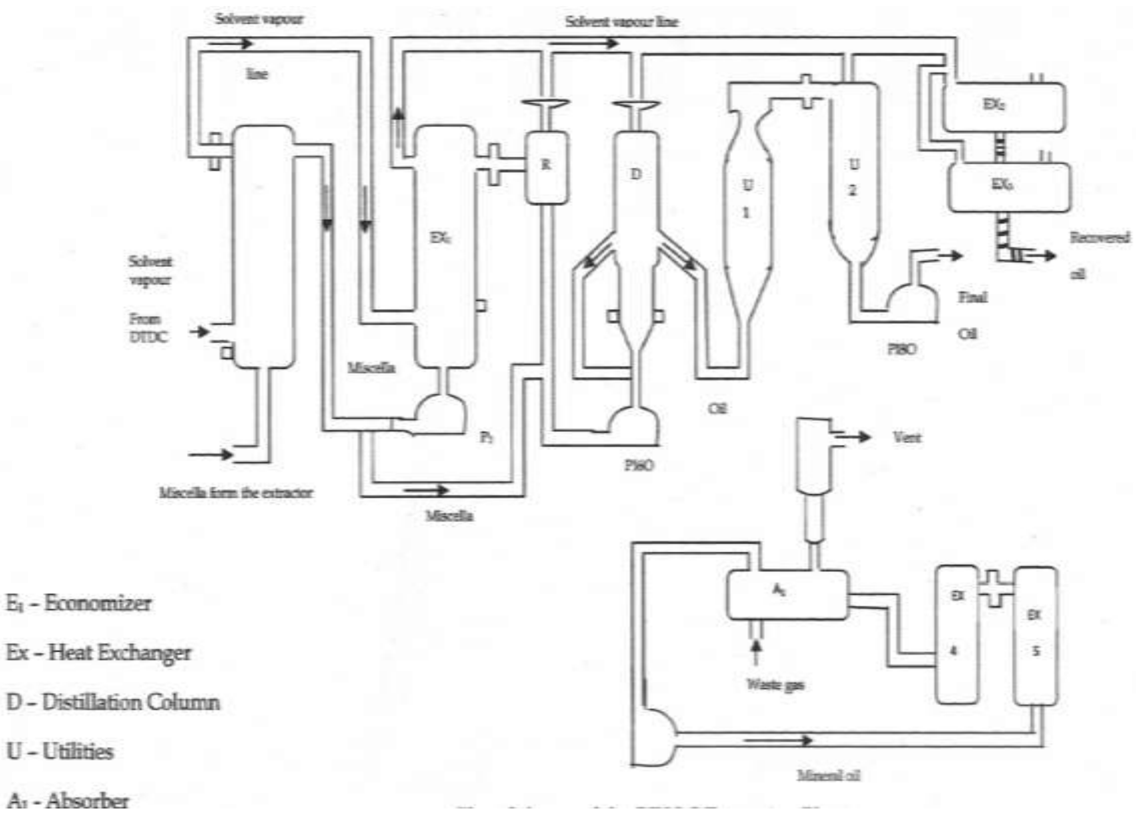

Fig. 1: Flow Scheme of the Vegetable Oil Extraction Plant [7]

PROBLEM DEFINITION

Heat Exchanger Network (HEN) streams data for extraction plant were obtained from [7]. These data consist of hot process streams and cold process streams. The streams are defined by fixed supply temperature, T_s and a fixed target temperature, T_t and temperature/enthalpy data that adequately set the heating and cooling requirements of the streams. Table 1 shows the process hot and cold streams data.

Table 1: Process Hot and Cold Streams Data [7]

S/No	Name	T_s ^{0}C	T_t ^{0}C	Heat Capacity kW/^{0}C	Heat Load, kW
1	Mineral Oil	92	40	8.1	421.2
2	Solvent Vapour	190	35	6.5	422.5
3	Oil Flow	80	135	3.9	214.5
4	Miscella	40	130	16	1440

The task here is to find the best arrangement of heat exchanger to achieve the target temperature.

PINCH ANALYSIS

A recommended pinch value of 16^{0}C in line with experienced ΔT_m values shown in Table 2 was adopted for the analysis. This reveals hot and cold utilities requirements of 491.9 kW and 266.1 kW respectively.

Table 2: Experienced ΔT_m Values for various Process [8]

No	Industrial Sector	Experienced ΔT_m values
1	Oil Refinery	20 – 40^{0}C
2	Petrochemicals	10 – 20^{0}C
3	Chemical	10 – 20^{0}C
4	Low Temperature Process	3 – 5^{0}C

Thus, this case study will be analysed with a pinch of 16^{0}C.

Ranking the interval temperatures in order of magnitude

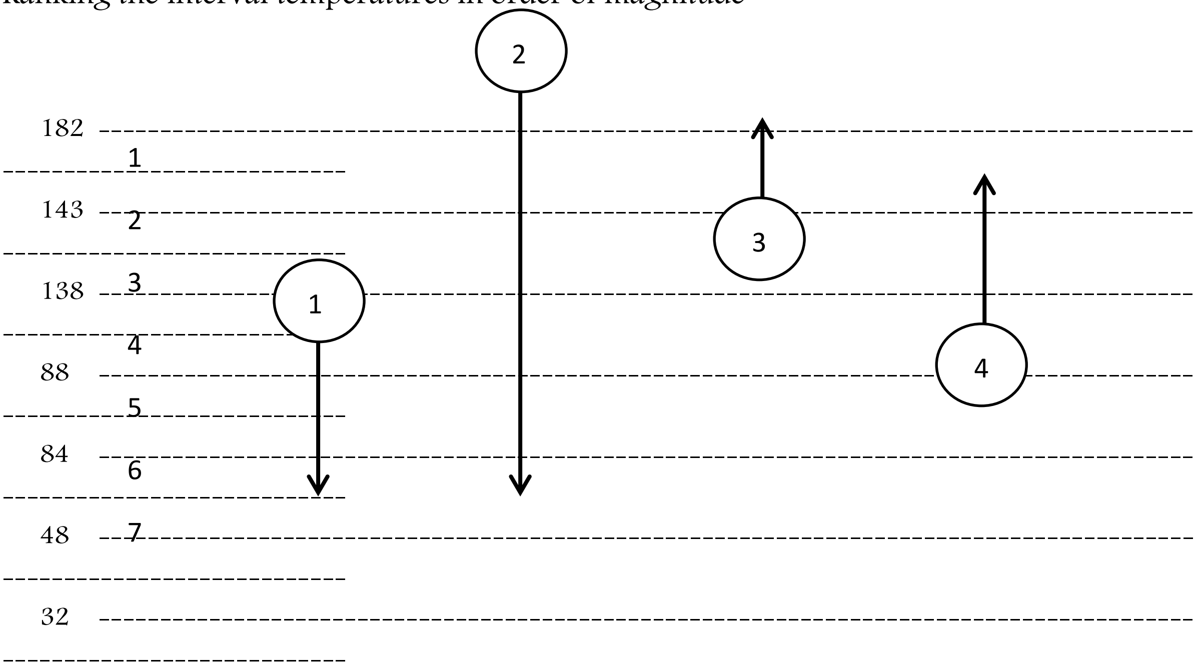

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Fig. 2: Temperature Interval Analysis with ΔT_m = 16

Carrying out heat balance in each interval using:

$$\Delta H_n = \left[\sum C_{pc} - \sum C_{pH}\right] * \Delta T_m$$

Rewriting,

$$\Delta H_n = \Delta \sum C * \Delta T_m$$

For interval 1,

$$\Delta H_1 = (0 - 6.5) * (182 - 143)$$

$$\Delta H_1 = -253.5\ kW$$

Since ΔH is negative, it indicates that the interval is deficient of heat (otherwise surplus or availability of heat).

Similarly, the results of other intervals are shown in Table 3.

Table 3: Heat Contents of various Intervals

Interval	ΔT_i	$\sum C_{pc}$	$\sum C_{pH}$	$\Delta \sum C$	ΔH	Comment
1	39	0	6.5	−6.5	−253.5	Deficit
2	5	3.9	6.5	−2.6	−13	Deficit
3	50	19.9	6.5	13.4	670	Surplus
4	4	16	6.5	9.5	38	Surplus
5	36	16	14.6	1.4	50.8	Surplus
6	16	0	14.6	−14.6	−233.4	Deficit
7	5	0	6.5	−6.5	−32.5	Deficit

Interpreting the above result in an energy cascade diagram gives:

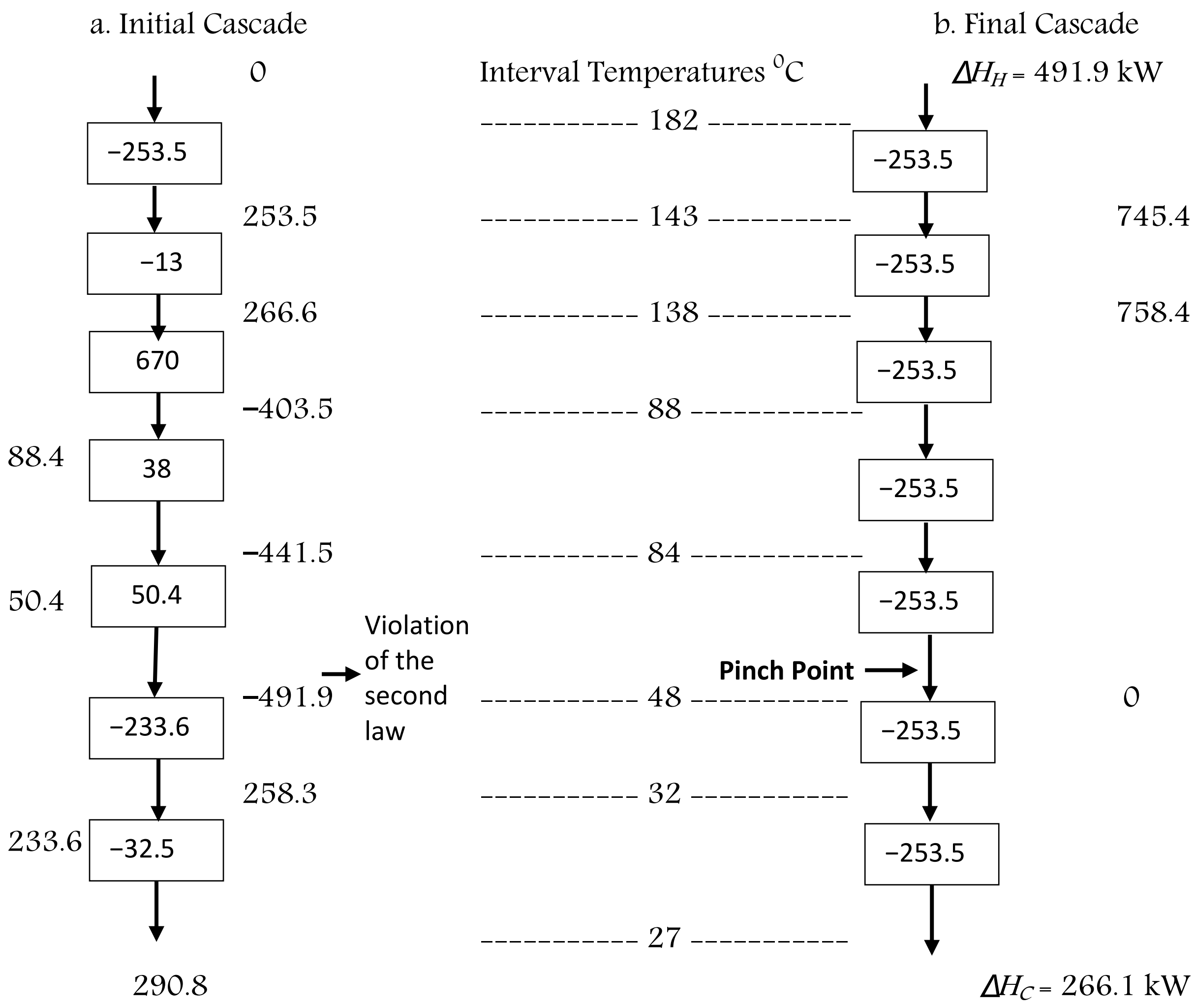

Fig. 3: Energy Cascade Diagram

From Fig. 3 it is clearly seen that:

i. The pinch occurs at a temperature of 56^{0}C for hot streams and 40^{0}C for cold streams

ii. Process pinch occurs at interval temperature of 48^{0}C

iii. Process requirements of 491.9 kW for External hot utility and 266.1 kW External cold utility.

DESIGN OF HEAT EXCHANGER NETWORK (HEN)

The grid representation of the streams is shown in Fig.4, with vertical dotted lines representing the pinch. This separates the grid into two thermal regions; regions above and below the pinch. Heat exchangers connecting streams are represented by two circles joined by a straight line.

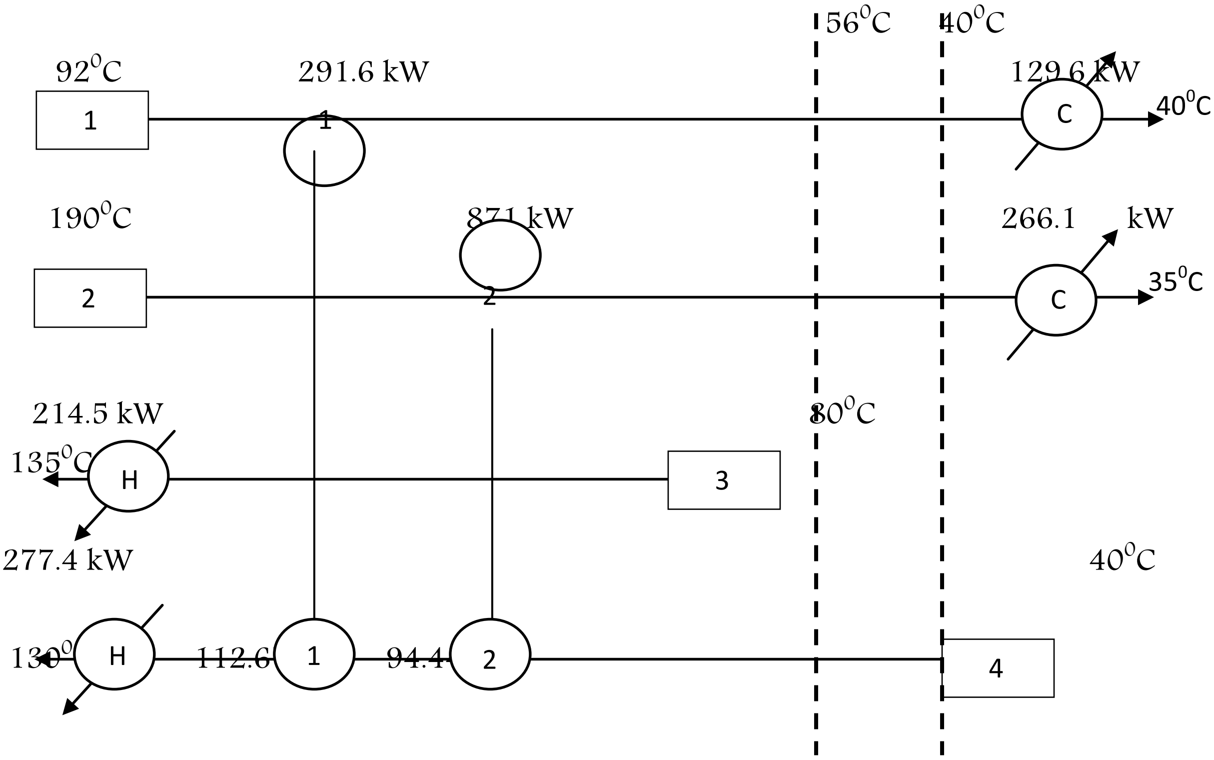

Fig. 4: Designed Heat Exchanger Network

RESULTS AND DISCUSSION

ECONOMIC EVALUATION

The cost of heat energy is estimated for the present design and retrofit design proposed by pinch analysis of the case study. Comparison is made by estimating the cost heat per unit of utility used on both design. The cost per unit is estimated from Ricci and Baling [9] as \$0.38 per kCal/hr heat consumption per unit.

$$1.162 * 10^3 kCal/hr = 1kW$$

Therefore, cost of heat is estimated at:

$$C_u = \$615.6\ per\ kW\ of\ heat\ consumption$$

CAPITAL INVESTMENT ESTIMATION

The annual cost per unit in HEN design of the case study shown in Fig. 1 is estimated using the total energy cost equation as presented in Table 4.

Table 4: Annual Heat Cost of Vegetable Oil Extraction Plant [7]

Symbol	Name	Capital, Q (kW)	Cost per yr (Q_i*C_u) $million
E_1	Economizer	810	0.499
Ex_1	Condenser	620	0.382
U_1	Heater	150	0.092
U_2	Heater	105	0.065
Ex_2	Condenser	175	0.108
Ex_3	Condenser	395	0.243
Ex_4	Heat Exchanger	185	0.114
Ex_5	Heat Exchanger	185	0.114
$Total = \sum_{u=1}^{u}(Q_u * C_u)$		2815	1.617

The annual heat energy consumption cost for the HEN generated by pinch analysis is presented in Table 5.

Table 5: Annual Heat Cost for the Proposed HEN

Symbol	Name	Capital, Q (kW)	Cost per yr (Q_i*C_u) $million
Hex_1	Heat Exchanger	291.6	0.180
Hex_2	Heat Exchanger	871	0.536
Hu_1	Hot utility	214.5	0.132
Hu_2	Hot utility	277.4	0.171
Cu_1	Cold Utility	129.6	0.080
Cu_2	Cold utility	266.1	0.164
$Total = \sum_{u=1}^{u}(Q_u * C_u)$		2050.2	1.263

The pinch analysis of the Vegetable Oil Extraction Plant revealed a possible energy recovery design that can be generated with capital/cost reductions. With respect to the streams considered for heat recovery, source and target temperatures were attained with product specifications met. Based on the results obtained, opportunities for reducing energy consumption were identified during the pinch analysis for the plant. The reduction of the total utility used in the retrofit design being reduced from 8 to 6. This is due to the introduction of new matching of the mineral oil and solvent vapour. This new stream matching also led to a reduction in the number of condenser used to recover the solvent. By improving the HEN design using pinch analysis, possibilities of reducing the plant capital investment were identified by lowering energy consumption by 764.8 kW with an associated cost reduction from $1.617 million per year to $1.263 million per year, an equivalent 21.89% annual cost savings.

CONCLUSIONS

This paper has shown the opportunities to use steam at lower pressure and to use less expensive external utilities. Hot and cold utility consumption could be reduced by modifying the heat recovery network to eliminate cross pinch heat transfer. The greatest source of pinch transfer identified is the huge condenser arranged in series in the solvent vapour flow line. Thus, this paper presents an opportunity to eliminate the cross pinch heat transfer by replacing the steam (used for heating) and external cold utilities via a process-process heat recovery. These streams are currently rejecting their heat to process water. The results obtained by improving the Heat Exchanger Network (HEN) design for the Vegetable Oil Extraction Plant using pinch analysis identified huge reduction in capital investment through lowering annual energy consumption by 764.8 kW with an associated annual cost reduction from $1.617 million to $1.263 million, an equivalent 21.89% annual cost savings.

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