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BREWERY HEAT EXCHANGER NETWORKS DESIGN AND OPTIMIZATION BASED ON PINCH ANALYSIS AT A SINGLE ΔT_{MIN}

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ABSTRACT

Pinch analysis was applied to design and optimize at a single ∆Tmin of 10 oC, a heat exchanger network for maximum energy recovery to reduce the energy consumption of a brewery. At ∆Tmin of 10 oC, the minimum heating and cooling requirements of the brewery were 5,185 kW and 3,039 kW, respectively. Above pinch, 120 possible design configurations were identified but only 8 are feasible. Below pinch, only 7 design configurations are feasible out of 52 possible. The optimum heat exchanger network obtained for the brewery is 1 process-to-process heat exchanger and 8 process-to-utility heat exchangers as a consequence of combining the configurations of the least cost feasible designs for both above and below pinch. The optimum heat exchanger network corresponds to a maximum of 22% heat recovery potential which accounts to 4.5% less than the existing operating cost equivalent to $432,133 per year at total annualized cost. Other values of ∆Tmin are recommended to be considered for future studies.

Keywords: brewery heat exchanger design, pinch analysis, heat exchanger optimization

I. INTRODUCTION

Energy consumption is an important issue in many industries because of its environmental and economic impact. A substantial method of decreasing energy consumption and its associated cost is by designing effective heat exchanger networks (HEN). Over the past decades, HEN has been widely utilized in the industry because of its potential to obtain substantial energy and economic savings [1, 2]. By using HEN, a large amount of utility costs can be saved. However, this

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would require additional investment; therefore, a trade-off between the capital and operation cost should be established [2].

The synthesis of HEN was first introduced and developed by Masso and Rudd [3]. Several papers presenting HEN methodologies are available [1, 4, 5]. The major contributions to HEN synthesis research present methodologies which can be classified into simultaneous and sequential approaches. The simultaneous approach typically solves the HEN synthesis problem through the mixed integer nonlinear programming [6]. This approach offers the advantage of accuracy, problem dimensionality and computational effectiveness. The techniques for this approach as well as setting up the problem models, however, are difficult to master [7]. Most importantly, there is a lack of active role of the designer in the process of decision-making [8].

The other approach, called sequential approach, divides the HEN design problem into two sub-problems: (i) targeting (i.e. determination of network targets such as minimum cooling requirement or Q_{cmin}, minimum heating requirement or Q_{hmin}, maximum energy recovery and minimum number of utilities) and (ii) designing HEN based on heuristics and certain guidelines (which are called Pinch rules) [9]. Pinch analysis techniques such as composite curves [10, 11], problem table algorithm [12] and pseudo-temperature enthalpy diagram method [13] belong in sequential approach.

Pinch design method is based on the first and second law of thermodynamics. This means that to ensure a feasible HEN design, the conservation of energy constraint is strictly considered and a positive difference between hot and cold streams is maintained during heat exchange. The concept of pinch design method was introduced by Umeda, Itoh and Shiroko [14], Linnhoff and Flower [15] and further refined by Linnhoff and Hindmarsh [16] and L. Sun and X. Luo [17]. The main disadvantage is that an optimal solution is not guaranteed. However, it allows the synthesis of HEN operating with the minimum energy consumption which is also a good approximation of the optimal network [18]. Pinch analysis has been a popular tool for the conservation of various resources over the years. It is widely used among industrial practitioners primarily because it provides them critical visualization insights and better control over the decision-making process. For these reasons, pinch analysis is preferred to mathematical programming approach [19].

Beer production is an energy intensive process; therefore, reducing the energy consumption of a brewery increases its competitiveness and efficiency. A recent study estimated that the energy intensity of producing 562 hectoliter (hl) of beer is around 262 MJ/hl, consisting of electrical (41%), thermal (58.8%) and manual (0.2%) of the total energy [20]. The actual [21] and projected annual beer production and energy consumption (assuming energy intensity of 262 MJ/hl [20]) of the top 40 countries accounting to 91.5% of the total beer produced is shown in Figure 1. The projected energy consumption for the next 10 years is enormous and that reducing it is imperative to be sustainable as population and economic growths are significantly increasing. Since thermal energy consumption accounts for the highest energy consumption, designing the HEN of the brewery plays a big role in decreasing its external energy demand [20, 22, 23]. Utility optimization in a brewery process based on energy integration methodology proposed 2 optimized configurations that include mechanical vapor recompression and heat pump systems [24]. Although there is a recent study mentioning pinch methodology as a way to improve the energy efficiency of a brewery, economic evaluations were not considered [25].

The objective of this study aims to obtain the optimum HEN using pinch methodology at a single ΔT_{min} of 10 ^oC by considering all possible configurations for maximum energy recovery (MER) to reduce the energy consumption of a brewery. The existing hot and cold utilities of the brewery were considered in the design. Technical evaluation based on network feasibility and performance of all possible configurations was implemented. In addition, economic evaluation was considered by calculating the corresponding capital cost, operating cost, and total annualized cost (*TAC*).

This study implements typical pinch analysis on a brewery which does not take into account the thermal losses during heat transfer. However, an actual brewery had been studied. Furthermore, in order to obtain relatively simple and practical network configurations, stream splitting was not employed during the synthesis of HEN. By default, the utilities are placed at the end of the network to avoid combinatorial exploration [26].

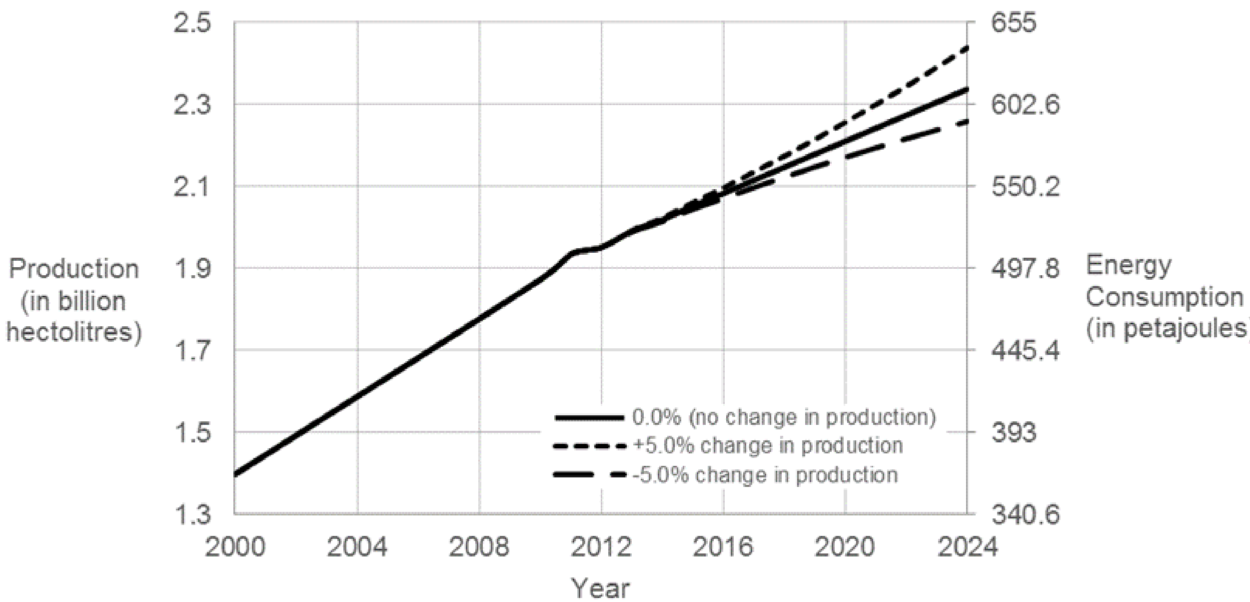


Figure 1. Annual beer production and corresponding energy consumption

II. METHODOLOGY

The parameters, as shown in the nomenclature presented in Table 1, necessary for evaluating the energy consumption during heating and cooling such as heat capacity flow rate (*MCp*), supply temperature (T_{supply}) and target temperature (T_{target}) levels was calculated using equation 1. The heat transfer coefficients were also determined using equations 2 to 5.

$$Q = MCp\Delta T \quad \text{eq. 1}$$

$$\frac{hD}{k} = 0.36\ Re^{0.55} Pr^{\frac{1}{3}} \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad \text{eq. 2}$$

$$\frac{hD}{k} = 0.023\ Re^{0.80} Pr^{\frac{1}{3}} \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad \text{eq. 3}$$

$$Re = \frac{Dv\rho}{\mu} \quad \text{eq. 4}$$

$$Pr = \frac{Cp\mu}{k} \quad \text{eq. 5}$$

Table 1. Nomenclature

Symbol	Definition	Units
A	heat exchange area	[m²]
a	installation cost of the HE	[US$]
b	duty-related cost set coefficients of the HE	[-]
c	area-related cost set coefficients of the HE	[-]
C_{cu}	utility cost for cold utility	[US$/kW-yr]
C_{hu}	utility cost for hot utility	[US$/kW-yr]
Cp	heat capacity	[kJ/kg-°C]
D	flow area diameter	[m]
F	LMTD correction factor	[-]
h	heat transfer coefficient	[kJ/h-m²-°C]
HE	heat exchanger	[-]
HEN	heat exchanger network	[-]
k	thermal conductivity	[W/m-K]
$LMTD$	logarithmic mean temperature difference	[-]
MCp	heat capacity flowrate, (MCp_c is for cold stream and MCp_h is for hot stream)	[W/ °C]
MER	maximum energy recovery	[kW]
N_{shell}	number of shells in the heat exchanger	[-]
PHE	process-to-process heat exchanger	[-]
PL	plant life	[years]
Q	heat load at a given interval (Q_c is cooling load and Q_h is heating load)	[kW]
Q_{cmin}	minimum cooling requirement	[kW]
Q_{hmin}	minimum heating requirement	[kW]
Pr	Prandtl number	[-]
ROR	rate of return	[%]
Re	Reynolds number	[-]
T_c	temperature of cold stream ($T_{c,in}$ is inlet and $T_{c,out}$ is outlet)	[°C]
T_h	temperature of hot stream ($T_{h,in}$ is inlet and $T_{h,out}$ is outlet)	[°C]
T_{supply}	supply temperature (inlet)	[°C]
T_{target}	target temperature (outlet)	[°C]
TAC	total annualized cost	[-]
U	overall heat transfer coefficient	[kJ/h-m²-°C]
v	velocity	[m/s]
ΔT_{min}	minimum temperature difference	[°C]
λ	annualization factor	[1/yr]
μ	viscosity	[cP]
μ_w	viscosity of water	[cP]
ρ	density	[kg/m³]

Considering heat exchange between two streams as shown in Figure 2, the heat load, that is the heat transferred between the two streams, is a function of the inlet temperature and *MCp* of the streams is calculated using equations 6 and 7. The outlet temperatures of the hot and cold streams are calculated using equations 8 and 9, respectively. The ΔTs are determined using equations 10 and 11.

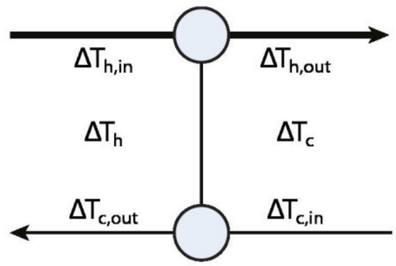


Figure 2. Stream matching via heat exchanger

$$Q = MCp_h(T_{h,in} - T_{h,out}) \quad \text{eq. 6}$$

$$Q = MCp_c(T_{c,in} - T_{c,out}) \quad \text{eq. 7}$$

$$T_{h,out} = T_{h,in} - \frac{Q}{MCp_h} \quad \text{eq. 8}$$

$$T_{c,out} = T_{c,in} + \frac{Q}{MCp_c} \quad \text{eq. 9}$$

$$\Delta T_h = T_{h,in} - T_{c,out} \quad \text{eq. 10}$$

$$\Delta T_c = T_{h,out} - T_{c,in} \quad \text{eq. 11}$$

The heat exchanger (HE) area per match is calculated using equations 12 to 14.

$$A = \frac{Q}{U\ x\ F\ x\ LMTD} \quad \text{eq. 12}$$

where

$$LMTD = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \quad \text{eq. 13}$$

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} \quad \text{eq. 14}$$

The next step is targeting for Q_{cmin}, Q_{hmin} and MER. The composite curve and grid diagram were generated considering that ΔT_{min} was set at 10 °C. A comprehensive discussion of the targeting procedure is provided by Kemp [27].

The existing utilities in the brewery were considered. The cold utilities available were cooling water and propylene glycol. Only one hot utility, which is the low pressure steam, is utilized in the brewery. All possible configurations were then synthesized by first dividing the network into above and below the pinch region. The sub-network below the pinch region was first solved. Each possible configuration in this region was first tested for feasibility. The same procedure was done for the region above the pinch. For HEN designs utilizing process-to-process heat transfer, sensitivity analyses were implemented to determine the temperature interval where the network would be feasible. Based on Figure 2, the feasibility criteria were expressed as follows:

1. All ΔT_h and ΔT_c should be greater than ΔT_{min} to ensure efficient heat transfer
2. The load Q and HE area should be a positive value
3. The temperatures of the HE should be within the range of the supply and target temperature of the streams exchanging heat.

After all the possible configurations were designed and tested for feasibility, the feasible networks were then evaluated in terms of network performance and cost individually for above and below the pinch region. The network performance was determined by the Q_h, Q_c and energy recovered. The network cost, on the other hand, was evaluated in terms of capital cost, operating cost and TAC using equations 15 to 18. The optimal design corresponds to design with the minimal TAC [28].

$$C_{capital} = a + b\left(\frac{A}{N_{shell}}\right)^{c} x\, N_{shell} \qquad \text{eq. 15}$$

$$OC = \sum\left(C_{hu} x Q_{hu,\min}\right) + \sum\left(C_{hu} x Q_{cu,\min}\right) \qquad \text{eq. 16}$$

$$TAC = \Lambda\, x\, C_{capital} + OC \qquad \text{eq. 17}$$

where

$$\Lambda = \frac{\left(1 + \frac{ROR}{100}\right)^{PL}}{PL} \qquad \text{eq. 18}$$

The assumptions used for equations 15 to 18 are shown in Table 2.

Table 2. Assumptions for Network Cost Calculation

Variable	Assumption
a (\$)	10,000
b	800
c	0.8
ROR (%)	10
PL (yr)	15

III. RESULTS AND DISCUSSION

The actual operation of a typical brewing process as shown in Figure 3 is divided into two stages:

Hot stage: The malt is processed in the mill to separate the husks from kernel and then ground prior to mashing. Water is then added to the milled malt. The malt/water mixture is combined with rice/water mixture in the mash converter. The mash is heated from 63 °C to 78 °C before it goes to the lauter tun. The clarified wort goes to the wort kettle where it is boiled up to 100 °C. The wort is further clarified in the whirlpool and then cooled to 13 °C before it undergoes fermentation.

Cold Stage: The sugar is converted to alcohol in the fermentation tank by using yeast at 14 °C. The beer is cooled down to 7 °C before it undergoes treatment to precipitate protein via silica gel. It is then chilled to -2 °C, filtered and stored in bright beer tank where it ends its maturation.

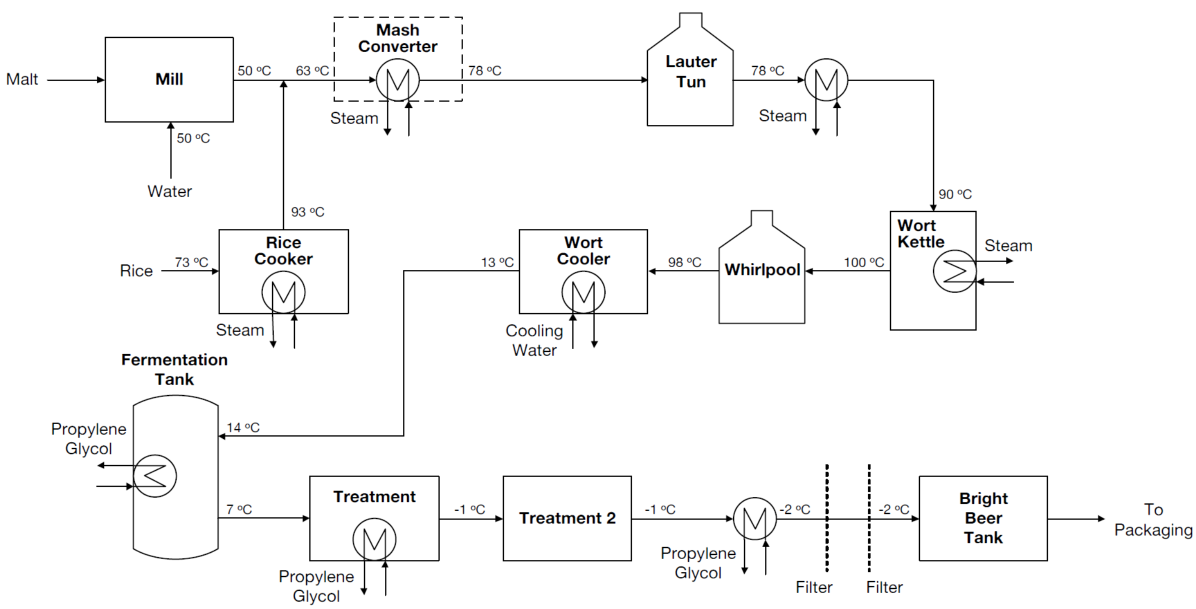


Figure 3. The brewing process

The stream table, based on the production data obtained from the brewery, is presented in Table 3.

Table 3. Stream Table

Process	Stream no.	Type	T_{supply} (°C)	T_{target} (°C)	MCp (W/°C)	ΔH (kW)	h (kJ/h-m²-°C)
Rice cooking	1	Cold	73	93	10,152	203	203
Mash conversion	2	Cold	63	78	137,686	2,065	19,211
Wort heating	3	Cold	78	90	39,021	468	21,985
Wort boiling	4	Cold	90	100	357,712	3,577	23,326
Wort cooling	5	Hot	98	13	45,167	3,839	22,057
Fermentation	6	Hot	14	7	4,548	32	14,837
Treatment	7	Hot	7	-1	33,024	264	14,240
Beer cooling	8	Hot	-1	-2	33,024	33	13,364

Since the current system of the brewery does not take advantage of process-to-process heat transfer, the total heating load and cooling load is calculated by adding the enthalpy of the cold streams and hot streams, respectively. The total heating load is 6,314 kW whereas the total cooling load is 4,168 kW.

At $\Delta T_{min} = 0$, the composite curve is known as the shifted composite curve as shown in Figure 4a. From this plot, the range of potential ΔT_{min} was identified. The pinch point occurs at the lowest temperature of the cold stream which is 63 °C. This implies that below the pinch point no process-to-process heat transfer can occur since only hot streams exist. The possible ΔT_{min} range is $0 < \Delta T_{min} < 35$°C. Based on Figure 4b, the Q_{hmin} and Q_{cmin} at ΔT_{min} of 10 °C are around 5,185 kW and 3,039 kW, respectively. The MER for both hot and cold streams is determined to be 1,129 kW each. The Grand Composite Curve as shown in Figure 4c allows understanding of how energy flows in the system in designing for MER. The zero value of the enthalpy coincides with the pinch point temperature at shifted temperature, in this case at 68 °C. Figure 4d shows the Balanced Composite Curve which resulted to re-plotting the composite curve including the utility streams (at their target heat loads).

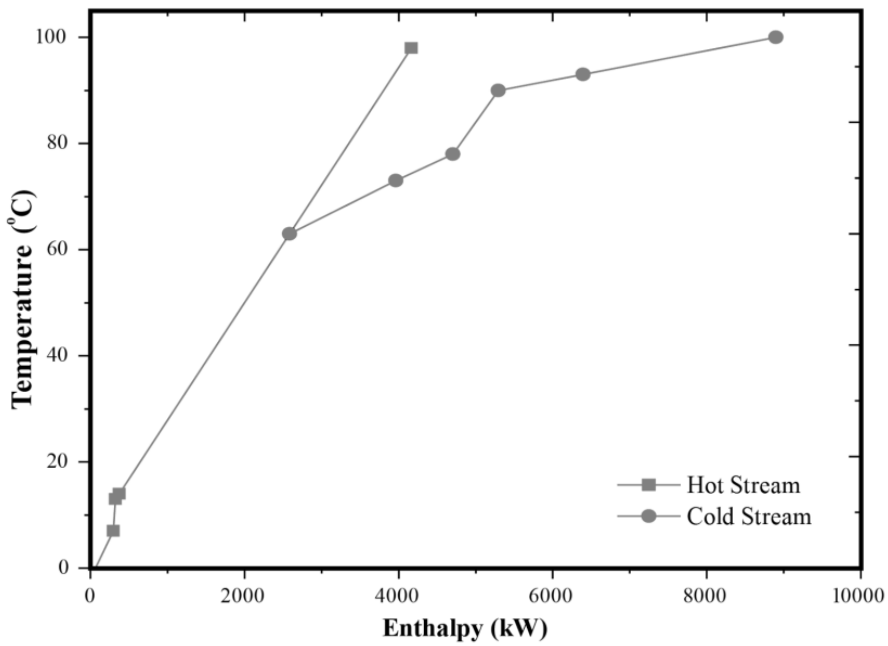


Figure 4a. Shifted composite curves

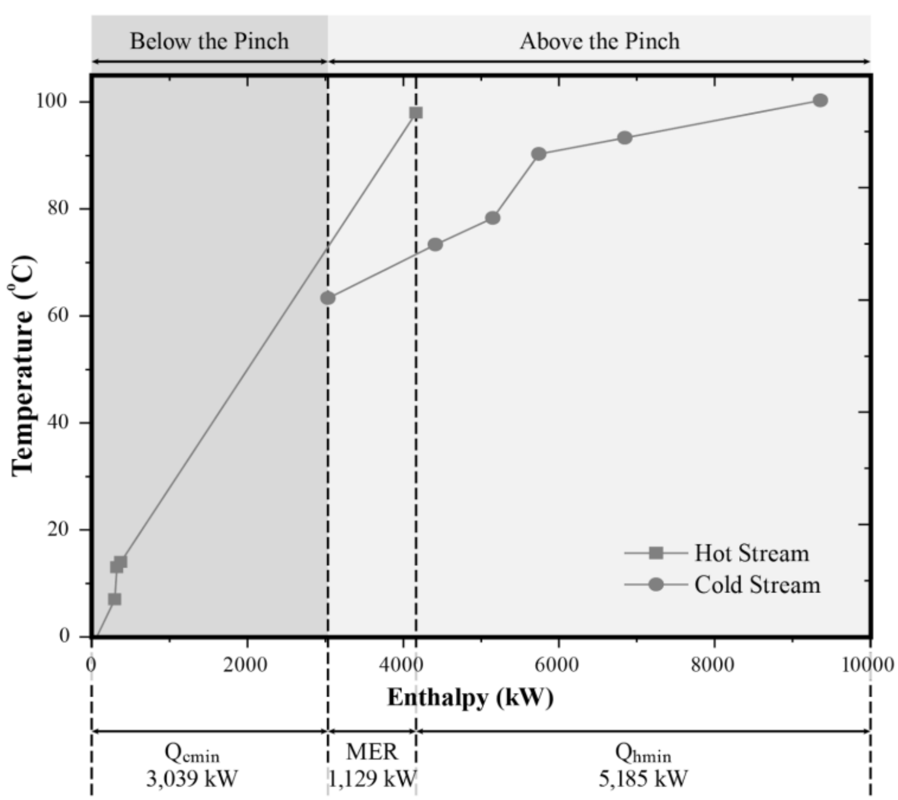


Figure 4b. True composite curves

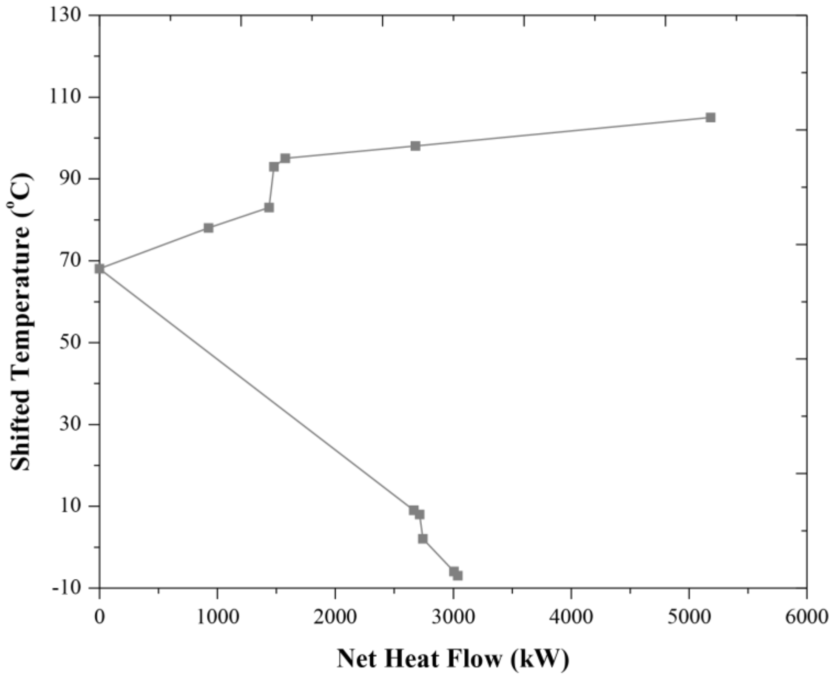


Figure 4c. Grand composite curve

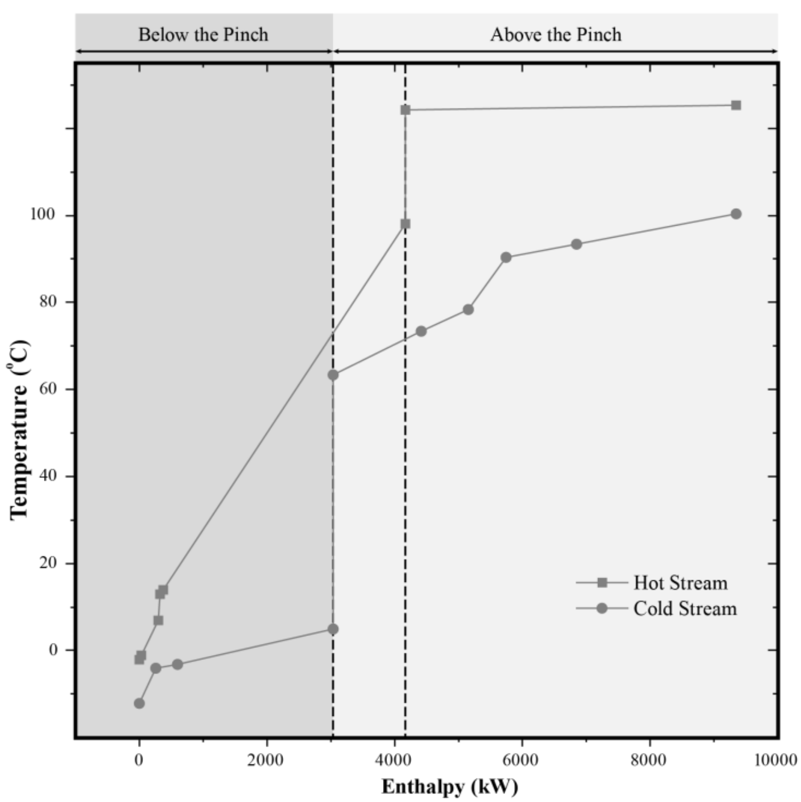


Figure 4d. Balanced composite curves

Table 4 shows that at ΔT_{min}= 10 °C the heating and energy demand for the utility are both reduced by 1,129 kW which corresponds to a total of 22% energy savings.

Table 4. Potential Heating and Cooling Savings

	Present Demand (kW)	Minimum Demand (kW)	MER (kW)	Maximum Potential Energy Recovery (%)
Heating	6,314	5,185	1,129	
Cooling	4,168	3,039	1,129	
Total	10,482	8,224	2,258	22

3.1 Allocation of Utility

The existing utilities of the brewery were considered in this study but adjustments were done to T_{supply} and T_{target}. Table 5 summarizes the characteristics of the utility streams.

Table 5. Utility Streams

Name	Type	T_{supply} (°C)	T_{target} (°C)	Cost index ($/kJ)	Target load (kW)	*Cp* (kJ/kg-°C)
Propylene glycol (PG)	Cold	-12	-11	4.64E-06[a]	297	2.5
Cooling water (CW)	Cold	3	4	2.12E-07[b]	2,742	4.183
LP steam (LPS)	Hot	125	124	1.90E-06[b]	5,185	2196

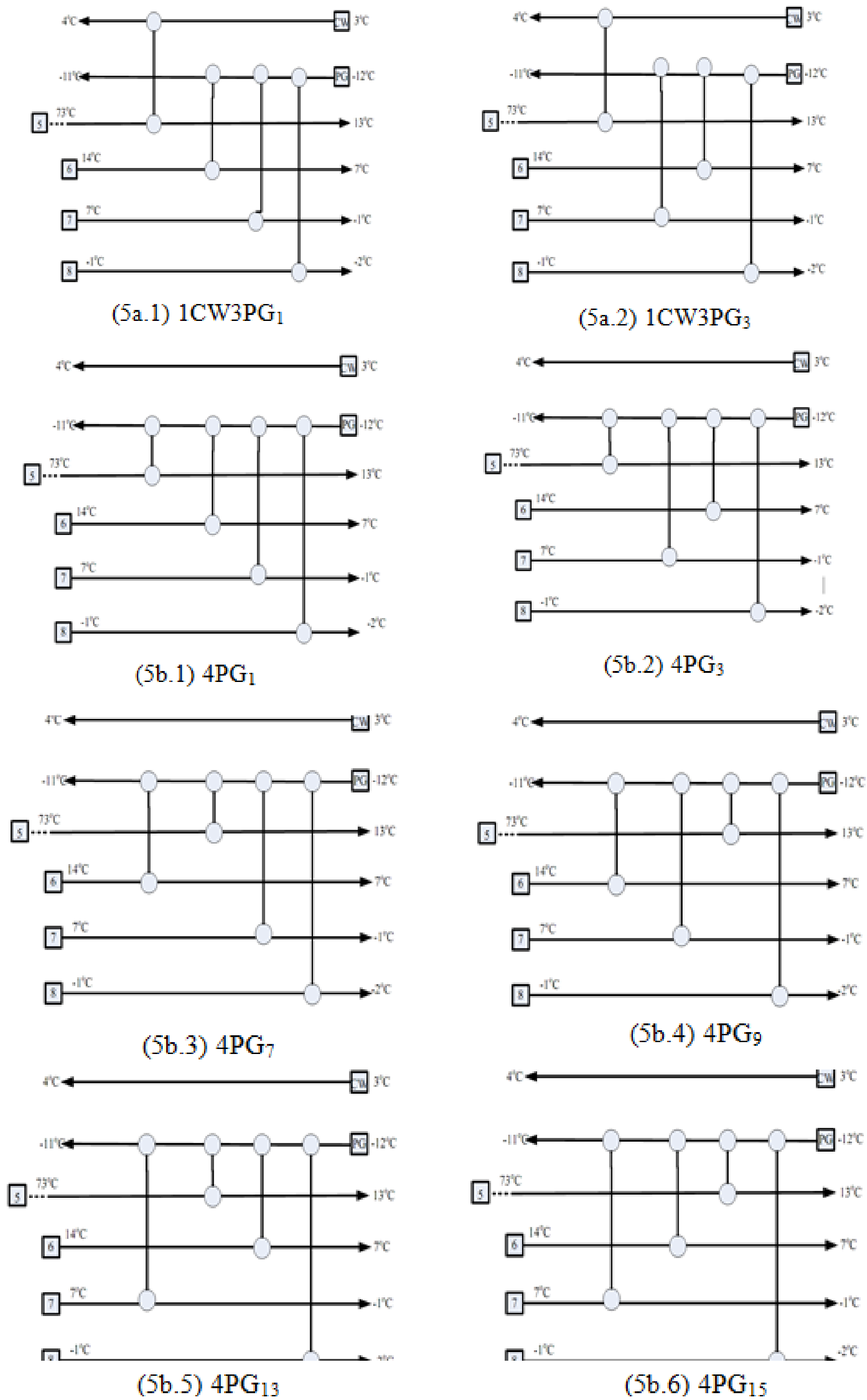
Note: [a]=calculated manually based on 2008 price; [b]=obtained from Aspen Energy Analyzer database based on 2008 price

3.2 Feasible Network Configurations

The feasible network configurations were determined for the two sub-networks (below and above the pinch). By doing this, the problem becomes simpler and can be treated in much easier fashion than the original single-task problem [29].

3.2.1. Below the Pinch

There are 4 hot streams and 2 cold utility streams below the pinch. Since no process-to-process can occur, all the hot streams were connected to the utilities. Figure 5 presents the feasible networks for the region above the pinch. There are 120 possible configurations for HEN above the pinch as shown in Table 6. Only 8 design configurations complied with the feasibility criteria. The names of the designs indicate the number of process streams connected to cooling water and propylene glycol, the subscripts differentiate the similarly configured designs from each other (i.e., $1CW3PG_1$, as shown in Figure 5a.1, means 1 process stream is connected to cooling water and 3 with propylene glycol, the subscript indicates that it is the 1st out of the 120 possible designs).



(5a.1) $1CW3PG_1$ (5a.2) $1CW3PG_3$

(5b.1) $4PG_1$ (5b.2) $4PG_3$

(5b.3) $4PG_7$ (5b.4) $4PG_9$

(5b.5) $4PG_{13}$ (5b.6) $4PG_{15}$

Figure 5. Feasible HEN below pinch for (5a) 1CW and 3PG and (5b) 4PG connected hot stream

Table 6. Network Configuration Below Pinch Region

No. of streams connected to CW	No. of streams connected to PG	No. of possible configurations	No. of feasible designs
4	0	24	0
3	1	24	0
2	2	24	0
1	3	24	2
0	4	24	6
Total		120	8

The feasible HEN configurations indicate that cooling water is not enough to supply all the cooling requirement of the system. At least two streams should be connected to propylene glycol for the network to be feasible. It is evident that the stream connection of stream 8 is a key determinant whether the design would be feasible, i.e., stream 8 should be connected to propylene glycol and its corresponding HE should be the farthest from the pinch or HE^4. This is because of the low target temperature of stream 8 of -2 ^oC. Connecting it with cooling water will result in a temperature difference of at most 6 ^oC only.

Table 7. Network Performance and Cost of Feasible HEN Below the Pinch

HEN design name	Cold utility load (kW)	Area (m^2)	No. of HE	No. of shells	Capital cost ($)	Operating cost ($/yr)	*TAC* ($/yr)
$1CW3PG_1$	3,039	40.4	49	49	60,786	66,311	85,890
$1CW3PG_3$	3,039	40.3	49	49	60,786	66,475	86,103
$4PG_1$	3,039	27.8	28	28	53,753	444,993	462,307
$4PG_3$	3,039	27.8	28	28	53,753	444,993	462,307
$4PG_7$	3,039	27.8	28	28	53,753	444,993	462,307
$4PG_9$	3,039	27.8	28	28	53,753	444,993	462,307
$4PG_{13}$	3,039	27.8	28	28	53,753	444,993	462,307
$4PG_{15}$	3,039	27.8	28	28	53,753	444,993	462,307

Table 7 summarizes the network performance and cost of feasible HEN configurations below the pinch. For 1CW and 3PG, although the *TAC* of $1CW3PG_1$ is lower than that of $1CW3PG_3$, the difference is very minimal. This can be accounted to their similarity in stream matches. For 4PG configurations, with the exception of stream 8 being connected farthest from the pinch, the order of heat exchangers connecting streams 5, 6 and 7 can be interchanged. The costs also are of the same value for all designs using 4PG. It can also be observed in Table 7 that as the number of propylene glycol-hot stream connections increases, the HE area decreases. This is accounted to both MCp and temperature range (causing a higher ΔT once connected with the hot stream) of propylene glycol being lower than the cooling water. Among these configurations, the least cost are $1CW3PG_1$ and $1CW3PG_3$.

3.2.2 Above the Pinch

In the above the pinch region, the primary focus is to set-up the process-to-process heat exchangers (PHE) for maximum recovery. Different configurations, depending on the number of PHE, were tested. To test whether the network could be feasible, different scenarios were simulated by varying the temperature of HE. There are 52 possible configurations for HEN above the pinch by considering at most 3 PHEs as shown in Table 8. The name of the design indicates the number of PHE, the subscripts differentiate the similarly configured designs from each other (i.e., $1PHE_1$, as shown in Figure 6a, utilizes only 1heat exchanger connecting 2 process streams; the subscript indicates that it is 1^{st} design out of 52).

Table 8
Stream Match of Feasible HEN Below the Pinch

No. of PHE	No. of possible configurations	No. of feasible designs
1	4	1
2	12	2
3	36	4
Total	52	7

Figure 6 presents that only 7 configurations can generate a feasible network. The HE closest to the pinch or HE^1 is strictly for matching stream 2 and 5. Cold stream 2 (MCp = 138 kW/^oC) and hot stream 5 (MCp = 45 kW/^oC) is feasible (near the pinch) because it satisfies the requirement above the pinch that $MCp_h \leq MCp_c$ [30].

Aside from stream 2, only streams 1 and 3 can be connected with stream 5. Although cold stream 4 has a large MCp (358 kW/^oC), even larger than that of stream 2, it has a very high temperature interval of 90-100 ^oC which generates negative values of ΔT_h and ΔT_c once connected with hot stream 5.

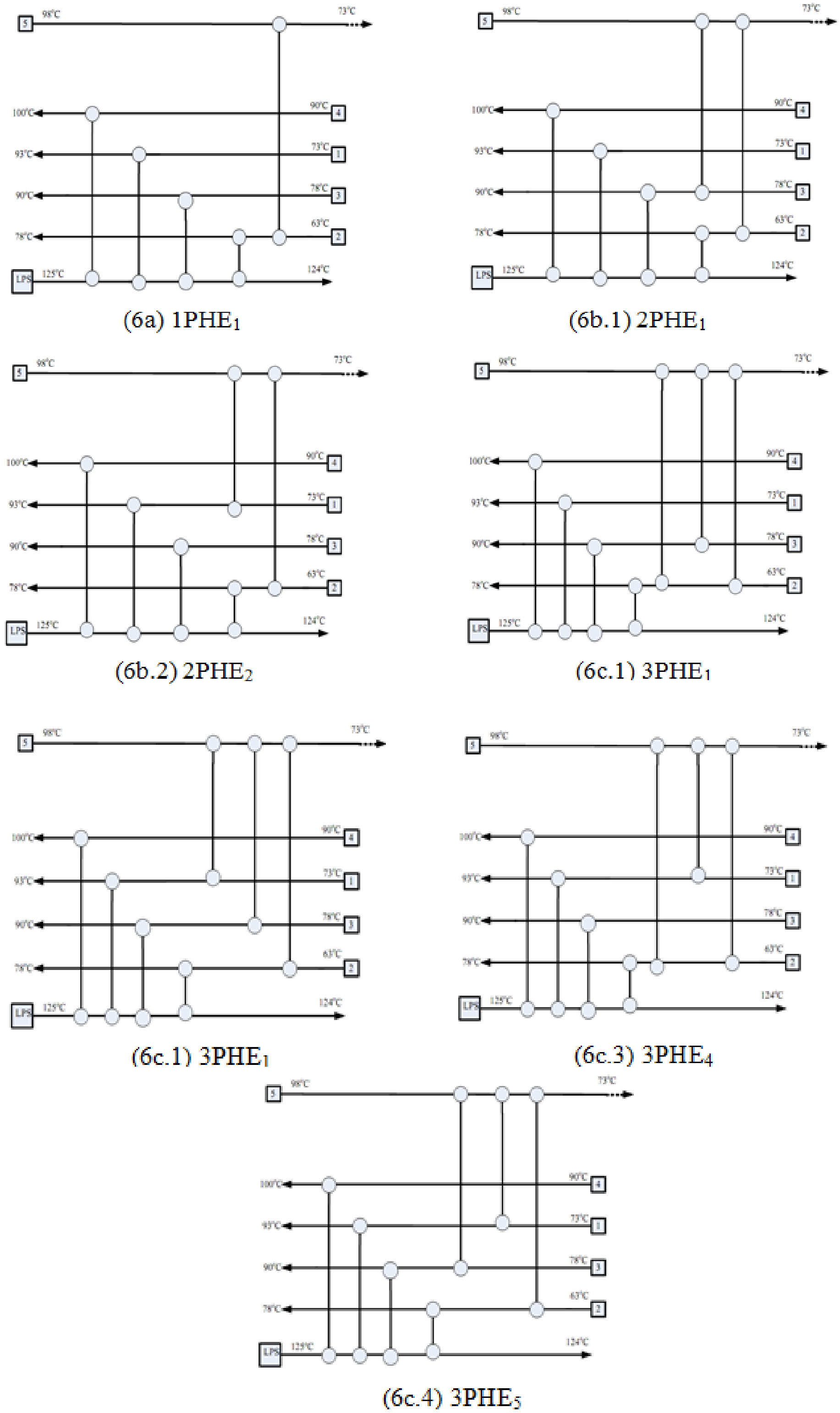


Figure 6. Feasible HEN above pinch for (6a) 1 PHE, (6b) 2PHE[1] and (6c) 3PHE[1]

[1] Conditional feasibility, subject to temperature constraints

For configurations involving more than 1PHE, the feasibility of the network depends on temperature profile of HE especially the one closest to the pinch. The feasibility conditions are summarized in Table 9. Table 10 summarizes the network performance and cost of feasible HEN configurations above the pinch. Different feasible temperatures for $T_{h,in}$ of HE^1 and HE^2 were used to determine the best combination for the system. Among these designs, $1PHE_1$ is the least cost, obviously because it has only 1PHE.

Table 9. Temperature Constraints for Feasible HEN Configurations Above the Pinch

HEN design name	HE^1	HE^2
$2PHE_1$	$89.4\ ^oC \le T_{h,in} < 98\ ^oC$	N/A
$2PHE_2$	$95\ ^oC \le T_{h,in} < 98\ ^oC$	N/A
$3PHE_1$	$88.5\ ^oC \le T_{h,in} < 98\ ^oC$	$88.5\ ^oC < T_{h,in} \le 91.67\ ^oC$ if $T_{h,in}$ of $HE^1 = 88.5\ ^oC$ $89\ ^oC < T_{h,in} \le 95.34\ ^oC$ if $T_{h,in}$ of $HE^1 = 89\ ^oC$ $89.4\ ^oC < T_{h,in} < 98\ ^oC$ if $T_{h,in}$ of HE^1 is within $89.4\ ^oC \le T_{h,in} < 98\ ^oC$ (Note: $T_{h,in}$ of $HE^1 < T_{h,in}$ of HE^2)
$3PHE_2$	$89\ ^oC \le T_{h,in} < 98\ ^oC$	$94.63\ ^oC < T_{h,in} \le 95.34\ ^oC$ if $T_{h,in}$ of $HE^1 = 89\ ^oC$ $94.63\ ^oC < T_{h,in} < 98\ ^oC$ if $T_{h,in}$ of HE^1 is within $89.2\ ^oC \le T_{h,in} < 98\ ^oC$ (Note: $T_{h,in}$ of $HE^1 < T_{h,in}$ of HE^2)
$3PHE_4$	$85\ ^oC \le T_{h,in} < 98\ ^oC$	$87.5\ ^oC < T_{h,in} \le 88.88\ ^oC$ if $T_{h,in}$ of $HE^1 = 85\ ^oC$ $90\ ^oC < T_{h,in} \le 92\ ^oC$ if $T_{h,in}$ of $HE^1 = 87.5\ ^oC$ $92.5\ ^oC < T_{h,in} \le 95.25\ ^oC$ if $T_{h,in}$ of $HE^1 = 92.5\ ^oC$ $95\ ^oC < T_{h,in} < 98\ ^oC$ if $T_{h,in}$ of HE^1 is within $95\ ^oC \le T_{h,in} < 98\ ^oC$ (Note: $T_{h,in}$ of $HE^1 < T_{h,in}$ of HE^2)
$3PHE_5$	$89\ ^oC \le T_{h,in} < 98\ ^oC$	$89\ ^oC < T_{h,in} \le 90.7\ ^oC$ if $T_{h,in}$ of $HE^1 = 89\ ^oC$ $90\ ^oC < T_{h,in} \le 92\ ^oC$ if $T_{h,in}$ of $HE^1 = 90\ ^oC$ $92.5\ ^oC < T_{h,in} \le 95.25\ ^oC$ if $T_{h,in}$ of $HE^1 = 92.5\ ^oC$ $95\ ^oC < T_{h,in} < 98\ ^oC$ if $T_{h,in}$ of HE^1 is within $95\ ^oC \le T_{h,in} < 98\ ^oC$ (Note: $T_{h,in}$ of $HE^1 < T_{h,in}$ of HE^2)

Table 10. **Network Performance and Cost of Feasible HEN Above the Pinch**

HEN design name	Hot utility load (kW)	Area (m^2)	No. of HE	No. of shells	Capital cost ($)	Operating cost ($/yr)	*TAC* ($/yr)
$1PHE_1$	5,185	165	5	5	110,996	310,852	346,604
$2PHE_{1.7}$	5,185	173	6	6	125,044	310,852	351,129
$2PHE_{1.8}$	5,185	172	6	6	124,461	310,852	350,941
$2PHE_{1.9}$	5,185	168	6	6	122,529	310,852	350,319
$2PHE_{1.10}$	5,185	168	6	6	121,988	310,852	350,145
$2PHE_{2.7}$	5,185	265	6	6	150,712	310,852	359,397
$2PHE_{2.8}$	5,185	177	6	6	127,426	310,852	351,896
$3PHE_{1-1.19}$	5,185	168	7	7	133,834	310,852	353,960
$3PHE_{1-1.20}$	5,185	167	7	7	133,350	310,852	353,805
$3PHE_{1-1.21}$	5,185	168	7	7	133,869	310,852	353,972
$3PHE_{1-1.22}$	5,185	171	7	7	134,396	310,852	354,141
$3PHE_{1-1.23}$	5,185	166	7	7	132,236	310,852	353,446
$3PHE_{1-1.24}$	5,185	170	7	7	134,038	310,852	354,026
$3PHE_{2-2.19}$	5,185	266	7	7	162,324	310,852	363,137
$3PHE_{2-2.20}$	5,185	179	7	7	139,604	310,852	355,819
$3PHE_{2-2.21}$	5,185	176	7	7	137,977	310,852	355,295
$3PHE_{4-4.16}$	5,185	170	7	7	135,695	310,852	354,560
$3PHE_{4-4.17}$	5,185	197	7	7	145,490	310,852	357,715
$3PHE_{4-4.21}$	5,185	182	7	7	140,633	310,852	356,150
$3PHE_{4-4.22}$	5,185	254	7	7	160,304	310,852	362,486
$3PHE_{4-4.25}$	5,185	178	7	7	138,467	310,852	355,453
$3PHE_{4-4.26}$	5,185	178	7	7	138,467	310,852	355,453
$3PHE_{4-4.27}$	5,185	240	7	7	155,679	310,852	360,997
$3PHE_{5-5.1}$	5,185	187	7	7	142,378	310,852	356,712
$3PHE_{5-5.2}$	5,185	257	7	7	161,361	310,852	362,827
$3PHE_{5-5.3}$	5,185	240	7	7	155,779	310,852	361,029

The optimum HEN design's total utility requirement is 8,224 kW (3,039 kW for cooling and 5,185 kW for heating). This means that both cooling and heating requirements were reduced by 1,129 kW because of the process-to-process heat transfer between streams 2 and 5. The optimum design indicates that below pinch streams 7 and 8 should be connected with propylene glycol whereas streams 5 and 6 with cooling water. On the other hand, above the pinch, only 1 process-to-process heat exchanger is required.

Regarding HE targets, it is worth noting that both the number of HE and total area are lower than the target. The target number of HE is 10 implying that the logical solution is to design HEN with two PHE. The results from the optimization, however, indicate that nine HE are enough for MER. In fact, increasing the number of PHE even resulted in higher *TAC*. This is one of the reasons why the designer should be involved in choosing HEN.

Table 11 compares the network performance and cost of the optimum HEN design with the existing design of the brewery. It should be noted that the *TAC* of the optimum HEN design is significantly lower than the operating cost of the existing design. Around 4.5% will be reduced from the annual cost of operation of the brewery. This 4.5% reduction already includes recovery of capital cost within the 15 year plant life.

Table 11. **Network Performance and Cost of Optimum HEN Design**

Name	Q_c (kW)	Q_h (kW)	Capital cost ($)	Operating cost ($/yr)	*TAC* ($/yr)
Existing design	4,168	6,314		452,430	
Optimum HEN	3,039	5,185	171,782	377,163	432,133

After obtaining the optimum configurations above and below the pinch, the designs were combined in a single grid diagram. Figure 7a shows the existing design and Figure 7b shows the optimum design.

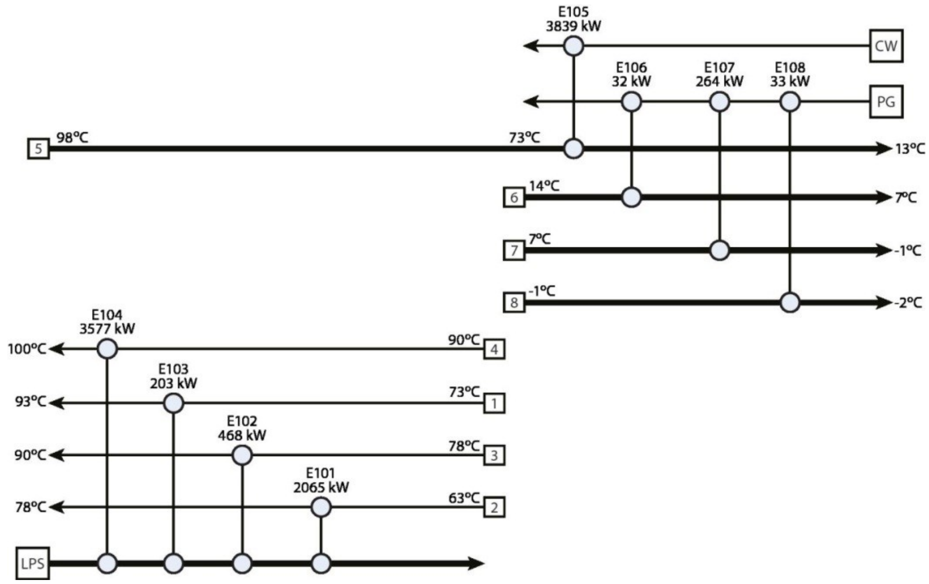


Figure 7a. Existing grid diagram

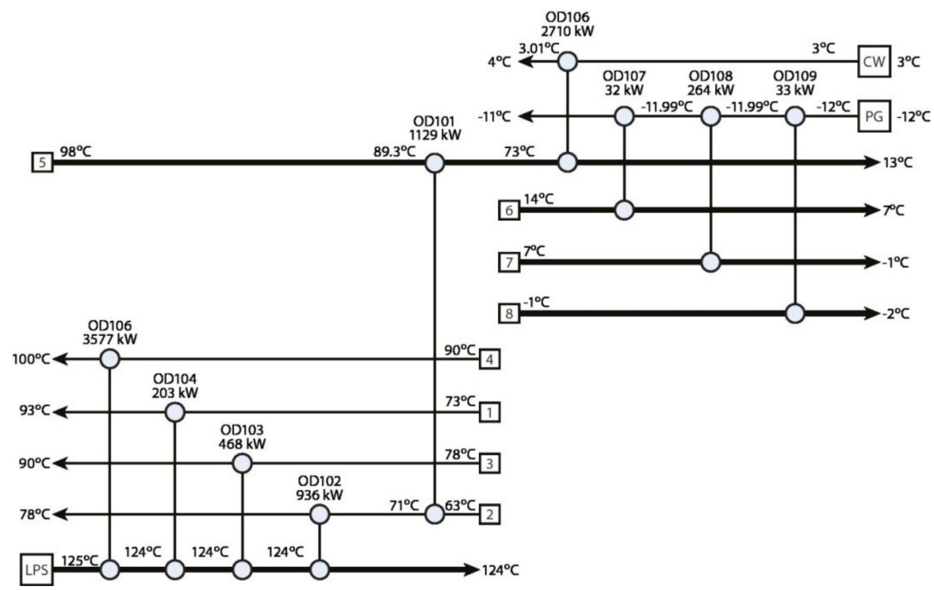


Figure 7b. Optimum grid diagram

IV. CONCLUSIONS AND RECOMMENDATIONS

Pinch method was applied to analyze and design HEN to reduce the energy consumption in a brewery. The case study involves 8 streams (4 hot and 4 cold), all of which relies on the energy supplied by the utilities. It is concluded that:

1. The existing energy consumption from utilities is 10,482 kW (4,168 kW for cooling and 6,314 kW for heating);
2. Using pinch analysis, at ΔT_{min} of 10 ^{o}C, the Q_{hmin}, Q_{cmin} and MER are determined to be 5,185 kW, 3,039 and 1,129 kW, respectively;
3. Below the pinch, where two cold utility streams and four hot streams exist, 120 configurations were identified but only 8 are feasible;
4. Above the pinch, where process-to-process heat transfer can occur, the configurations were varied by changing the number of PHE and only 7 designs are feasible out of 52 possible configurations for designs having one to three PHE;
5. The optimum HEN constitutes of 1PHE and 8 utility-processes heat exchangers.
6. The optimum HEN is designed to recover 22% potential (1,129 kW) energy savings; and
7. The total annualized cost is estimated to be $432,133 per year which is 4.5% less than the existing operating cost of the brewery.

The study found out that stream match is very vital in determining feasible network configurations. In addition, the feasibility may also be constrained by the temperature profile of the individual heat exchangers.

It is recommended that:

1. A mathematical model for stream matching be developed to reduce the task of identifying possible configurations;
2. Stream splitting should also be considered in the analysis;
3. The comparison with other methods and the practicality of installing and manufacturing the heat exchanger be examined;
4. The effect of various ΔT_{min} be evaluated; and

The method is applied in other industries.

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References

1. Allen, B., Savard-Goguen, M., and Gosselin, L., Optimizing heat exchanger networks with genetic algorithms for designing each heat exchanger including condensers, *Applied Thermal Engineering,* **29**, 3437–3444 (2009)
2. Castier, M., Pinch analysis revisited new rules for utility targeting, *Applied Thermal Engineering*, **27**, 1653–1656 (2007)
3. Masso, A.H., and Rudd, D.F., The synthesis of system designs. II. Heuristic structuring, *AlChE,* **15**, 10–17 (1969)
4. Bakhtiari, B., and Bedard, S., Retrofitting heat exchanger networks using a modified network pinch approach, *Applied Thermal Engineering,* **51**, 973-979 (2013)
5. Chen, D., Yang, S., Luo, X., Wen, Q., and Ma, H., An explicit solution for thermal calculation and synthesis of superstructure heat exchanger networks, *Chin. J. Chem. Eng.*, **15**, 296-301 (2007)
6. Tan, Y.L., Ng, D.K.S., El-Halwagi, M.M., Foo, D.C.Y., and Samyudia, Y., Floating Pinch Method for Utility Targeting in Heat Exchanger Network (HEN), Chemical Engineering Research and Design (2013).
7. Sun, K.N., Alwi, S.R.W., and Manan, Z.A., Heat exchanger network cost optimization considering multiple utilities and different types of heat exchangers, *Computers and Chemical Engineering,* **49**, 194-204 (2013)
8. Raskovic, P., and Stoiljkovic, S., Pinch design method in the case of a limited number of process streams, *Energy,* **34**, 593-612 (2009)
9. Pettersson, F., Synthesis of large-scale heat exchanger networks using a sequential match reduction approach, *Computers and Chemical Engineering,* **29**, 993–1007 (2005)
10. Anantharaman, R., Abbas, O.S., and Gundersen, T., Energy Level Composite Curves—a new graphical methodology for the integration of energy intensive processes, *Applied Thermal Engineering,* **26**, 1378–1384 (2006)
11. Nordman, R., and Berntsson, T., Use of advanced composite curves for assessing cost-effective HEN retrofit I: Theory and concepts, *Applied Thermal Engineering,* **29**, 275–281 (2009)
12. Alwi, S.R.W., Manan, Z.A., Misman, M., and Sze, C.W., SePTA-A new numerical tool for simultaneous targeting and design of heat exchanger networks, Computers and Chemical Engineering (2013).
13. Xiangkun, M., Pingjing, Y., Xing, L., and Wilfried, R., Synthesis of flexible multi-stream heat exchanger networks based on stream pseudo-temperature with genetic/simulated annealing algorithms, *Journal of the Chinese Institute of Chemical Engineers,* **38**, 321–331 (2007)
14. Umeda, T., Itoh, J., and Shiroko, K., Heat exchange system synthesis, *ChemEngProg*, **74**, 70–76 (1978)
15. Linnhoff, B., and Flower, J.R., Synthesis of heat exchanger networks. I. Systematic generation of energy optimal networks, *AIChE Journal*, **24**, 633–642 (1978)
16. Linnhoff, B., and Hindmarsh, E., The pinch design method for heat exchanger networks, *ChemEngSci,* **38**, 745-763 (1983)
17. Sun, L., and Luo, X., Synthesis of multipass heat exchanger networks based on pinch technology, *Computers and Chemical Engineering,* **35**, 1257-1264 (2011)
18. Martın, A., and Mato, F.A., Hint: An educational software for heat exchanger network design with the pinch method, *Education for Chemical Engineers*, **3**, 6–14 (2008)
19. Rozali, N.E.M., Alwi, S.R.W., Manana, Z.A., Klemes, J.J., and Hassan, M.Y., Process integration techniques for optimal design of hybrid power systems, *Applied Thermal Engineering,* 1-10 (2013)

20. Fadare, D.A., Nkpubre, D.O., Oni, A.O., Falana, A., Waheed, M.A., and Bamiro, O.A., Energy and exergy analyses of malt drink production in Nigeria, Energy, **35**, 5336-5346 (2010)
21. Barth-Haas Group & Germain Hansmaennel, Beer Production: Market Leaders and their Challengers in the Top 40 Countries in 2012 (2012), http://www.barthhaasgroup.com/johbarth/images/pdfs/report2013/Barth_Beilage_2013.pdf
22. Ahmad, M.I., Zhang, N., Jobson, M., and Chen, L., Multi-period design of heat exchanger networks, *Chemical Engineering Research and Design,* **90**, 1883–1895 (2012)
23. Sturma, B., Hugenschmidt, S., Joyce, S., Hofacker, W., and Roskilly, A.P., Opportunities and barriers for efficient energy use in a medium-sized brewery, *Applied Thermal Engineering,* **53**, 397-404 (2013)
24. Dumbliauskaite, M., Becker, H., and Marechal, F., 2010. Utility optimization in a brewery process based on energy integration methodology. Proceedings of ECOS, 91-98 (2010)
25. Muster-Slawitsch, B., Weiss, W., Schnitzer, H., and Brunner, C., The green brewery concept- Energy efficiency and the use of renewable energy sources in breweries, *Applied Thermal Engineering,* **31**, 2123-2134 (2011)
26. He, Q., and Cui, G., A principle of stream arrangement based on uniformity factor for heat exchanger networks synthesis, *Applied Thermal Engineering,* **61**, 93-100 (2013)
27. Kemp, I.C., "Pinch analysis and process integration", 2nd ed., Elsevier, Ltd., (2007)
28. Bogataj, M., and Kravanja, Z., An alternative strategy for global optimization of heat exchanger networks, *Applied Thermal Engineering,* **43**, 75-90 (2012)
29. Escobar, M., and Trierweiler, J.O., Optimal heat exchanger network synthesis: A case study comparison, *Applied Thermal Engineering,* **51**, 801-826 (2013)
30. Matijaseviæ, L., and Otmaeiæ, H., Energy recovery by pinch technology, *Applied Thermal Engineering,* **22**, 477–484 (2002)