Heat Exchanger Process Optimization in a Typical Brewery Plant

Shadrack Mathew Uzoma, Tamzor Lebari Aban

Abstract—The research attempts to improve upon the performance efficiency of the heat exchanger network system of Pabod Brewery, Port Harcourt, Rivers State, Nigeria. It swaps the heat system of the plant by the use of Pinch Technology to recover waste heat and integrating the recovered energy for process application. The application software is Microsoft Excel and Problem Table Method was employed in the numerical analysis of data. The gross energy expenditure by the plant is 10.44MW at production capacity of 400,000 liters of beer per day. On quantitative aggregate 6.157MW goes for heating and 4.267MW for cooling. A temperature pinch or minimum approach temperature (ΔTmin) of 100°C was used in the pinch analysis of the heat exchangers performance. The research findings confirmed minimum heating utility of 5.04MW and cooling utility of 3.09MW, with energy upturn of 1.08MW and 1.23MW for the hot and cold flows respectively. This correlates to energy conservation of 18% for hot utility and 21% for the cold utility. The hot stream pinch temperature is 710°C while that of the cold stream is 610°C. Heat exchangers network configuration design were performed above and below the pinch. The network designs were produced and integrated to produce improved heat exchanger network system for the Brewery plant.

Index Terms—Above and Below Pinch, Improved Heat Exchanger Network System, Minimum Approach Temperature, Minimum Heating and Cooling Utility.

I. INTRODUCTION

Pinch technology and heat process integration, provides a procedural approach for reduced energy consumption in processes. The line of attack is founded on thermodynamic rules; precisely the first and secondly laws of thermodynamics, the change in the enthalpy of the streams is taken care of by the first law whereas, the second law is used for the determination of the course of heat transfer, that is, heat energy is transferred due to potential difference, that is, from hot spots to cold areas. The process analysis starts on the balance in the material and heat [1, 11]. Pinch technology enabled processes identify the right changes in the process conditions that can impact positively on energy economy [4, 12].

Targets can be established for energy cutback early before designing the heat exchange system, after putting in place the bits and pieces of the material and heat balance. It is common with this approach that these targets are achieved during the design at the utility levels [11]. Summarily, Pinch technology is a dependable method that saves energy from heat, material balance and even up to entire location utility arrangement [10]. Energy efficiency is awfully essential for production plants, because it is one of the deciding factors for final product price and increasing of incomes. There is more or less a stream that contains heat and need heating. Heat integration among all the streams in a process plant more or less doubles energy value of plants and decreases utility need. Energy swap and recovery introduced by Linnhoff among all the streams in process plant is referred to as heat integration [2].

Global instability and fluctuation in oil prices and the ultimate drive for energy conservation and recovery in the industrial sectors more so the process industries such as oil and gas refining, petrochemical, chemical, breweries and cryogenic processes initiate this research, the research work is focused on process and energy optimization of brewery plants. More importantly the soaring rate of energy utilization globally [3, 5] predication on ecological issues and economic implications has awaken serious concern about the use of energy. Energy conversion effectiveness and the performance efficiency of the associated system are object of serious consideration on the other hand. In this regard, the overarching issue is the optimal approach to the use of energy and integration of efficient energy recovery system. It is believed this approach would trim down energy consumption for any process application to the optimal minimal level. Low operating temperature limits could also be encouraged by virtue of energy consumption at optimal minimal capacity. Inadvertently emissions could also be contained at a measure stipulated by international standards [5].

This study is tailored to optimization and recovery of energy in the heat exchanger network of Pabod brewery, Port Harcourt, Rivers State, Nigeria. The process diagram of the brewery is as shown in Fig. 1.

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A typical application process invented by Linnhoff and Vredeveld known as Pinch Technology would be applied in reorganizing the energy need of this establishment even redesigning and changing the configuration of the existing network system. Pinch Technology reproduced a new set of thermodynamically based methods that generate minimal energy levels in design of heat exchanger networks (HEN). It is an analysis based tool and algorithm for studying industrial processes.

The Pinch Technology as a process tool application to Pabod Brewery is design for energy cutback in the heat exchanger network system of this facility [7, 8, 9, 11]. Applying the rigorous thermodynamics based equations developed by Linnhoff to the hot and cold utilities of the case study brewery plant, with appropriate mass and heat load balance viz-a-viz material requirement, optimal minimal heat load requirement could be specified for the company in terms of optimal minimal heating and cooling energy requirements.

II. RESEARCH SIGNIFICANCE

The outcome of this research would be beneficial to the company in view but also to allied process industries. Improved process mixing would culminate in energy cutback and the cost of use of energy. Recouping the lost waste heat lends itself to productivity improvement. Savings in energy consumption will boost the financial capacity of the company while creating opportunities for new jobs. The company’s industrial activities become more profitable even at the same measurable energy input. Pinch Technology application to process had been assessed to result in 30%-50% financial breakthrough [6] in process industries.

III. MATERIALS AND METHOD

A. Preamble

Energy utilization during brewing operations, that is, heating and cooling are significantly influenced by certain controlling parameters. These parameters among others are: inlet temperature (source), outlet temperature (target) and heat capacity flow rate. The parameters are obtained from the operational data of the plant. The optimal minimal energy level for heating and cooling are then determined by these procedures:

(a) Recognition of hot and cold processes, utility Streams of a brewing plant.
(b) Extracting data from pertinent plant process utility and streams (heat capacity flow rate, Cp), that may be used in the analysis for the network design.
(c) Choice of a “suitable” ΔTmin value, in decided range, which is used as a parameter for design [3].
(d) In the brewing industries, ΔTmin falls within the range of 100C and 200C.
(e) Heat flow analysis above and below the pinch.
(f) Heat exchanger design above and heat exchanger design below pinch.
(g) Integrating the two network systems to developed the new improved (proposed) heat exchanger network system for the case study plant (Pabod Brewery).

B. Applicable Models

The applicable models for computational analysis in the design process of the proposed heat exchangers network system HENs are as follows:

The thermal load, Q, for utilities and streams is expressed as,

\[ Q = \int_{T_s}^{T_e} C_p \ dT = C_p \Delta T = C_p(T_e - T_s) \]  (1)

\[ \frac{dT}{\Delta T} = \frac{1}{C_p} \]

Where,

\( Q \), ΔH—thermal load or enthalpy change of the streams (W)

\( C_p \)—heat capacity flow rate (W/°C)

\( T_e \)—source temperature (°C)

\( T_s \)—target temperature (°C)

The hot stream thermal energy need is expressed as:

\[ Q_h = mC_{ph}(T_{h,in} - T_{h,out}) \]  (2)

The cold stream thermal energy need is expressed as:

\[ Q_c = mC_{pc}(T_{c,in} - T_{c,out}) \]  (3)

\( m \)—mass flow rate of streams (kg/s)

\( T_{h,in} \)—inlet or source temperature of the hot stream (°C)

\( T_{h,out} \)—outlet or target temperature of the hot stream (°C)

\( T_{c,in} \)—inlet or source temperature of the cold stream (°C)

\( T_{c,out} \)—outlet or target temperature of the cold stream (°C)

The exit temperatures of the hot and cold streams are determined by expressions in equations (4) and (5).

\[ T_{h,out} = T_{h,in} - \frac{Q}{mC_{ph}} \]  (4)

\[ T_{c,out} = T_{c,in} - \frac{Q}{mC_{pc}} \]

\[ \Delta T_h = T_{h,in} - T_{h,out} \]

\[ \Delta T_c = T_{c,out} - T_{c,in} \]

Heat exchanger surface area, A, per match is expressed as:

\[ A = \frac{Q}{U(\Delta T_{LMTD})} \]  (6)

\( U \), where \( \Delta T_{LMTD} \) is the logarithmic mean temperature difference expressed as:

\[ \Delta T_{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{ln\left(\frac{T_{h,in} - T_{c,ou}}{T_{h,out} - T_{c,in}}\right)} \]  (7)

\[ \frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} \]

\[ Q = UA\Delta T_{LMTD} \]  (8)

\( U \)—overall heat transfer coefficient (W/m² °C)

\( \Delta T_{LMTD} \)—logarithmic mean temperature difference (°C)

\( h_1 \), \( h_2 \)—convective heat transfer coefficients of the fluid at inner and outer walls of the
heat exchanger tubes (W/m²°C)

Heat transfer coefficient for shell heat exchanger is given as,

\[ \frac{hD}{k} = 0.36P_0^{0.55} \times P_T^{2/3} \left[ \frac{\mu}{\mu_B} \right]^{0.14} \] (9)

Heat transfer coefficient for tube heat exchangers is expressed as,

Reynolds’s Number, \( R_e = \frac{D_v \rho v}{\mu} \)

Prandtl’s Number, \( Pr = \frac{C_v \rho}{k} \)

The minimum number of heat exchangers units for maximum heat recovery, \( N_{\text{MIN}} \), is expressed as:

\[ N_{\text{MIN}} = \left[ N_h + N_c + N_u - 1 \right]_{\text{AP}} + \left[ N_h + N_c + N_u - 1 \right]_{\text{BP}} \] (10)

\( N_h \) — Number of hot streams
\( N_c \) — Number of cold streams
\( N_u \) — Number of utility stream

AP/BP — Above/Below pinch

C. Stream Matching Approach and Input Parameters

Stream matching is done based on the heat capacity flow rate equality restrictions. It is worthy to note that the inlet temperature, \( T_i \) and heat capacity flow rate \( C_p \) determines the quantity of heat transferred between the streams. These networks were first divided into above and below pinch for the blend of the feasible design. The heat capacity flow rate restrictions above and below the pinch must be strictly adhered to. Above the pinch, \( C_{\text{h}} \leq C_{\text{c}} \), while below Pinch \( C_{\text{c}} \geq C_{\text{h}} \). The stream data for the brewery plant is as shown on Table I.

| TABLE I: STREAM DATA FOR THE PLANT |
|-----------------------------------|

| Stream No | Process | Type     | Ts °C | Ti °C | mCp MW°C | \( \Delta H \) MW | \( h \) W/m²°C |
|-----------|---------|----------|-------|-------|-----------|----------------|---------------|
| 1         | Marsh   | Cold     | 61    | 76    | 0.138     | 2.07           | 420           |
| 2         | Wort    | Cold     | 77    | 90    | 0.039     | 0.507          | 390           |
| 3         | Wort    | Cold     | 90    | 10    | 0.358     | 3.58           | 620           |
| 4         | Wort    | Hot/H1   | 96    | 12    | 0.046     | 3.864          | 1560          |
| 5         | Ferment | Hot/H2   | 15    | 8     | 0.0045    | 0.031          | 5             |
| 6         | Treat   | Hot/H3   | 7     | -1    | 0.034     | 0.272          | 680           |
| 7         | Beer    | Hot/H4   | -1    | -2    | 0.033     | 0.099          | 150           |
|           | Utility | (HU)     | 12    | 12    | -         | -              | 890           |
|           | Cooling | (HU)     | 4     | 0     | -         | -              | 450           |
|           | Propyl | Glycol   | -12   | -11   | -         | -              | 180           |

D. Computational Numerical Results:

1) The Problem Table Method

This is a numerical step to finding the pinch in the network and the minimum utility needs, it was specified by [10], and it saves the pains and time of drawing composites curves, and manipulating the curve by marking points on paper to arrive at the preferred \( \Delta T_{\text{MIN}} \) on the graph. Thus, in this research the Problem table method is used rather than the composite or compound curves method.

2) Steps for The Problem Table Method

(a) The stream temperatures were first converted to interval or shifted temperature by dividing the \( \Delta T_{\text{MIN}} \) and adding half to the cold flow and subtracting half from the hot flow. Because using the shifted temperature instead of the real temperature captures the minimum temperature difference.

For hot streams, \( T_{\text{SHIFTED}} = T_{\text{ACTUAL}} - \frac{\Delta T_{\text{MIN}}}{2} \) (11)

For cold flow, \( T_{\text{SHIFTED}} = T_{\text{ACTUAL}} + \frac{\Delta T_{\text{MIN}}}{2} \) (12)

(b) Heat balance analysis is done on streams falling within temperature intervals

\( \Delta H_n = (\sum C_{ph} - \sum C_{pc}) \Delta T_n \) (13)

(c) The shifted temperatures for the hot and cold streams were obtained by applying equations (13) and (14). The results are as shown in Tables II and III

| TABLE II: SHIFTED TEMPERATURE FOR HOT STREAM USING \( \Delta T_{\text{MIN}} = 10^6 \)°C |
|-----------------------------------------------|

| Hot-H1 | 96   | 12   | 91   | 7    |
| Hot-H2 | 15   | 8    | 10   | 3    |
| Hot-H3 | 7    | -1   | 2    | -6   |
| Hot-H4 | -1   | -2   | -6   | -7   |

| TABLE III: SHIFTED TEMPERATURE FOR COLD STREAM USING \( \Delta T_{\text{MIN}} = 10^6 \)°C |
|-----------------------------------------------|

| Cold-C1 | 61   | 76   | 66   | 81    |
| Cold-C2 | 77   | 90   | 82   | 95    |
| Cold-C3 | 90   | 100  | 95   | 105   |

The shifted temperatures were ranked in descending order taking note of the fact that any repeated temperatures must be entered once. Table IV shows the entry for the shifted temperatures.

| TABLE IV: SHIFTED TEMPERATURE FOR THE HOT AND COLD STREAMS |
|-------------------------------------------------------------|

| Shifted Temperature °C |
|------------------------|
| 105 95 91 82 81 66 |
| 10 7 3 2 -6 -7 |
The net heat capacity flow rates for the different temperature intervals expressed as \( \sum C_{pc} - \sum C_{ph} \) and the interval temperature difference, \( \Delta T_{in} \) are as in Table V. For interval 1, \( \sum C_{pc} - \sum C_{ph} = 0.367 \text{MW/}^\circ\text{C} \); Interval 2, \( \sum C_{pc} - \sum C_{ph} = 0.038 \text{MW/}^\circ\text{C} \); Interval 3, \( \sum C_{pc} - \sum C_{ph} = 0.038 - 0.046 = -0.008 \text{MW/}^\circ\text{C} \); Interval 4, \( \sum C_{pc} - \sum C_{ph} = 0.046 - 0.046 \text{MW} \text{MW/}^\circ\text{C} \) and so to the twelfth interval.

### TABLE V: INTERVALS NET HEAT FLOW RATES AND TEMPERATURE DIFFERENCE

| Interval | 1  | 2  | 3  | 4  | 5  | 6  |
|----------|----|----|----|----|----|----|
| \( \sum C_{pc} - \sum C_{ph} \) (MW/\(^\circ\text{C}) | 0.367 | 0.038 | 0.008 | - | 0.046 | - |
| \( \Delta T_{in}(^\circ\text{C}) | 10 | 4 | 9 | 1 | 15 | 56 |
| Interval | 7 | 8 | 9 | 10 | 11 | 12 |
| \( \sum C_{pc} - \sum C_{ph} \) (MW/\(^\circ\text{C}) | 0.051 | 0.039 | 0.039 | 0.034 | 0.033 |
| \( \Delta T_{in}(^\circ\text{C}) | 3 | 4 | 1 | 8 | 1 |

3) **Construction of The Problem Table**

The shifted temperatures were listed in descending format as in Table 4. The streams population were displayed within the temperature gaps with their respective heat flow rate capacity \( C_p \) and \( C_p \). Knowing the values for \( \sum C_p \) and \( \sum C_p \) for respective intervals, the heat loads were calculated, see Table 5. The highest negative enthalpy value (deficit) was gotten at interval 5. This quantity of heat was added to the surplus/deficit column and everything equilibrates. The zero point on the hot utility add column becomes the pinch point as displayed in Table 6. The computational results confirmed that 5.08MW of heat available to be taken away by cold utility. That is, the hot utility demand is 5.08MW and that the cold utility demand is 3.09MW in the bottom of hot Utility Add Column. The pinch happens at the point where the heat transferred within the cascade is zero (0) MW, at interval no 5. Since no crosswise heat flow across the pinch, then the pinch temperature is 66 \(^\circ\text{C}\). The indication is that the temperature for hot streams is 66 \(^\circ\text{C} + 5^\circ\text{C} = 71 \(^\circ\text{C}\), while that of cold streams is 66 \(^\circ\text{C} - 5^\circ\text{C} = 61 \(^\circ\text{C}\).

IV. **ANALYSIS AND DISCUSSION OF RESULTS**

A. **Stream Grid Populations**

In this work, the pinch is at 71 oC and 61oC for the hot and cold streams, respectively, while the \( Cp \) values are listed alongside their streams. See Fig. 1.

![Fig. 2. Stream grid with pinch separating the process](image)

Fig. 2 presents the stream populations and their temperatures below and above the pinch. It harmonized hot flows with cold streams through heat recovery. This is carried out by identifying heat available with the hot flow. Each match takes a stream or flow to its needed temperature, since the pinch breaks up the heat swap system into two thermally autonomous parts, hence the HENs are separately designed for the respective regions. When the heat recuperation is fully exploited the residual thermal demands are supplied by hot utility. With reference to figure 1, all streams are represented in horizontal parallel lines, the arrow head of the cold flows are directed to the right. The bisecting vertical lines stand for the pinch point temperature and the square boxes represent heat exchangers.

B. **Network Design Above Pinch**

Above pinch there is just one Hot stream (H1) and three cold streams C1, C2 and C3. The available heat with hot as well as the cold streams are calculated as in Tables VI and VII. Adding up with the above pinch region the following constraint are paramount:

Above pinch region constraints:
1. \( CP_h \leq CP_c \)
2. \( N_h \leq N_c \) implying the number of heat exchangers for the hot flows should be less or equal to that of cold streams

V. **Heat Available WITH THE STREAMS**

Table VI displays the quantity of heat available on the hot stream 1 to be matched with a cold stream that would need heat, to satisfy the heat demand of this hot stream.

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Table VI: Heat Available with Hot Stream

| Stream | Temperature [°C] | ΔT | ΔH [MW] |
|--------|------------------|----|---------|
| H1     | 84               | 0.046 | 3.864 |
| H2     | 7                | 0.0045 | 0.0315 |
| H3     | 8                | 0.034 | 0.272 |
| H4     | 3                | 0.033 | 0.099 |

Table VII: Heat Requirement of Cold Stream

| Stream | Cp [MW/°C] | ΔT | ΔH [MW] |
|--------|------------|----|---------|
| C1     | 0.138      | 15 | 2.04    |
| C2     | 0.038      | 13 | 0.49    |
| C3     | 0.367      | 10 | 3.67    |

A. Heat Exchanger Network design (Making matches) For above Pinch Region

The Cp inequality rule, is observed with respect to the constraint \( CP_h \leq CP_c \) or \( CP_c \geq CP_h \). The stream H1 is split into two segments, bigger branch with Cp value of 0.037 [MW/°C] and sub-branch with Cp value of 0.009 [MW/°C], to ease its coupling. The sub-branch of H1 is coupled by C1 (2.07MW) and C1 is completely satisfied, whereas H1 is left with heat load of 1.79MW that is satisfied by the heat requirement of C3 (3.67MW). The bigger-branch of H1 is coupled with C3 (3.67MW) but the heat demand of C3 is much more than the left over heat load on H1, so C3 is partially satisfied through the smaller-branch of H1 and C3 is left with 1.88MW that will be satisfied with external hot utility of 2.37MW. The heat exchangers network designs above and below the pinch are as in Fig. 3 and 4 respectively.

The hot streams below pinch are matched with propylene glycol and water reason being that just one cold stream C1 exists below pinch, and it is already at pinch temperature and could not be matched. Thus the total external cooling utility that will be needed is 3.05MW with water taking 2.749MW and P-Glycol matching the remaining 0.305MW.

B. The Proposed Heat Exchanger Network Design

Having completed the probable matches, the designs for both regions of pinch are put together and filtered to additionally reduce the capital cost; this now becomes the new system design match that is proposed by this research, as shown in Fig. 5.

VI. RECOMMENDATION

The detailed design concept of the proposed heat exchangers network system is recommended. Cost imperatives of heat exchangers used in process application is also been considered as a potent area of research endeavor. In the course of this work integrating Pinch Technology as a process tool application is strongly advised.
VII. CONCLUSION

Pinch Technology as a process tool applied to the heat exchanger network system of Pabod Brewery provides the solution to the required lowest amount of heat utilization. In this work, minimum approach temperature (ΔTmin) of 100°C was applied. Minimum heating and cooling utilities of 5.08MW and 3.09MW were confirmed. Energy upturn of 1.08MW and 1.23MW were achievable for the hot and cold flows. The performance efficiency of system was improved by 18% for the hot utility and 21% for the cold utility. At minimum approach temperature (ΔTmin) of 100°C, the temperature pinch for the hot was 710°C and that for the cold flow was 610°C. In view of the substantial energy savings in the system by pinch analysis it believed that emission due to high operating temperatures would be curtailed and level of effectiveness in energy utilization would be greatly enhanced. The overall effectiveness rated in terms of the efficiency of heat recovery and integration in the brewery plant is 39%. The measure of energy conservation was so staggering and tempting to recommend the finding of this work to the case study establishment. This is enable the implementation of the research results in operational procedures even if the need redesigning the heat exchangers network system of the process plant.

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