Integration of Multiple Effect Evaporators with Background Process

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In multiple effect evaporators (MEE), evaporation takes place in stages; vapour coming from a stage loses its latent heat of vaporisation and acts as a heat source for the next stage. This process goes on till the last stage of evaporator where the desired concentration is achieved. MEE can be represented as a set process streams at different pressure/ temperature levels and its grand composite curve (GCC) can be generated. These process streams can be integrated with the background process to minimise the total energy consumption of the entire plant, rather than minimising the energy consumption of MEE and background process individually. An analytical methodology is developed to integrate (MEE) with the background process, such that the energy consumption for the entire pant can be minimised. A mathematical theorem is proposed to determine variation in overall energy requirement during integration of MEE with the background process. Proposed methodology is illustrated with the help of an example and up to 15.5 % of energy can be saved if the systems are integrated properly.

1. Introduction

Evaporation in multiple effect evaporators (MEE) takes place in stages. The vapour coming out from first stage acts as a heat source for second stage, similarly vapour coming from second stage acts as a heat source for the third one and this process continues till the desired concentration is achieved. External heat is required to supply thermal energy in the first stage. MEE are applied in various food processing, desalination industries etc. MEE is an energy intensive process, for pulp and paper industry MEE consumes 25-30 % of total energy consumed by the plant (Khanam and Mohanty, 2010). Therefore it becomes essential to optimise energy consumption of MEE, to reduce its energy costs. Mathematical modelling serves as an excellent tool for modelling of MEE. Kaya and Sarac (2007) developed a linear model of MEE, by initially assuming effect temperature. Often the focus is on minimizing the energy consumption of MEE as standalone system instead of minimizing the energy consumption of entire plant. Hillenbrand and Westerberg (1988) first developed a method for integrating MEE with background process. They used problem table algorithm to calculate the sensible heat transfer for each effect. Urbaniec et al. (2000) used process integration technique to integrate process streams and evaporators. Westphalen and Maciel (2000), for the given evaporator temperatures, calculated the possible energy integration with the background process. Accordingly they calculated the maximum vapour bleeding for each effect. Higa et al. (2009) showed how number of effect and vapour extraction for process demand effects total steam consumption using process integration techniques. Mesfun and Toffolo (2013) developed a method for integrating MEE, background process and heat and power cycle. They showed that bark liquor consumption can be reduced to half if total site integration is done for same thermal demand and power requirement. Ensinas et.al. (2013) carried out process integration and used multi-objective optimization for designing sugarcane ethanol plant.

The objective of the current work is to develop an analytical methodology for integrating MEE with background process for given effect temperatures to minimize the energy consumption of the entire plant.

2. Grand composite curve of MEE

In MEE there are number of streams entering and leaving the evaporator and undergo energy and mass transfer. These streams can be represented as process streams for integration with the background. Figure 1 shows n^{th} effect of a MEE with different streams.

Energy is required in every effect for vaporisation of water at constant effect temperature (Y) and may be represented as a cold stream. Its heat capacity (mCp_{energy}) is given as:

$$mCp_{energy} = V_n H_n + l_n h_n - l_{n-1} h_{n-1} \tag{1}$$

where, V is mass flow rate of vapour, H is enthalpy of vapour, l is liquor flow rate, and h is liquor enthalpy. The vapour generated from an effect acts as a heat source for the other effect. The vapour loses its heat in three steps. First it gets de-superheated, then it condenses at constant pressure, and at last it is cooled to atmospheric temperature. Vapour coming out from any stage gets superheated because of rise in boiling point (BPR) due presence of solute in liquor. Heat capacity of the vapour, as it gets de-superheated from effect temperature to saturation temperature (T), given as:

$$mCp_{de\text{-}superheating} = \frac{V_{n-1}\left(H_{n-1,Y_{n-1}} - H_{n-1,T_n-1}\right)}{Y_{n-1} - T_{n-1}} \tag{2}$$

Heat capacity for condensation is given as:

$$mCp_{condensation} = V_{n-1}\lambda_{n-1} \tag{3}$$

where, λ is latent heat of vaporisation. Heat capacity of the condensate up to atmospheric temperature is given as:

$$mCp_{cooling} = V_{n-1}Cp_{water} \tag{4}$$

Liquor enters the MEE at a temperature different than the effect temperature. Similarly the product temperature might be different from last effect temperature. These streams are considered for heat integration. For standalone MEE, there are four streams for every intermediate effect and five streams for the first and the last effects. Once the stream data are known, the utility requirement can be calculated by using modified problem table algorithm (MPTA), proposed by Bandyopadhyay and Sahu (2010), and the grand composite curve (GCC) can be generated. A typical GCC for MEE with two effects is shown in Figure 2.

3. Mathematical results

Using mass and energy balance equations vapour evaporated in every stage (V) can be calculated for three effect MEE for forward feed flow by using Eq (5).

$$\begin{bmatrix} (\lambda_1 + h_2 - h_1) & -(H_2 - h_2) & 0 \\ -(h_2 - h_3) & (\lambda_2 + h_3 - h_2) & -(H_3 - h_3) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} F(h_2 - h_1) + E_1 - E_2 \\ F(h_3 - h_2) + E_2 - E_3 \\ W \end{bmatrix} \tag{5}$$

where, V is mass of vapour, W is total amount of vapour to be evaporated, F is the feed flow rate, and E is the distance by which individual effect are shifted away from Y axis in GCC. The mathematical results about MEE are established in this section.

Lemma: When ΔE_n amount of energy shift is taken place between n^{th} and $(n+1)^{th}$ effect in GCC of an MEE, the change in utility requirement for the first effect (ΔS_n) is approximately given as:

$$\Delta S_n = \left(\frac{K - n}{K}\right)\Delta E_n \tag{6}$$

where, n is the effect under consideration and K is total number of effects. ΔE_n is defined as:

$$\Delta E_n = \Delta E_{n+1} - \Delta E_n \tag{7}$$

Due to brevity, only outline of the proof is given here. It can be seen from Figure 2 that Effect 1 and 2 are separated from each other by E_1. Assuming that both effects are pinched initially and its hot utility requirement is H. The hot utility requirement for first effect is increased by ($E_1/2$). So the evaporation taking place in effect one increases by ($E_1/2$) as a result its cooling duty also increases by same amount. The

heat duty for second effect approximately decreases by $(E_1/2)$, as this much amount of evaporation has already taken place in first effect. So net energy shift between Effect 1 and 2 is given as:

$$\left(E_1/2\right) - \left(-E_1/2\right) = E_1. \tag{8}$$
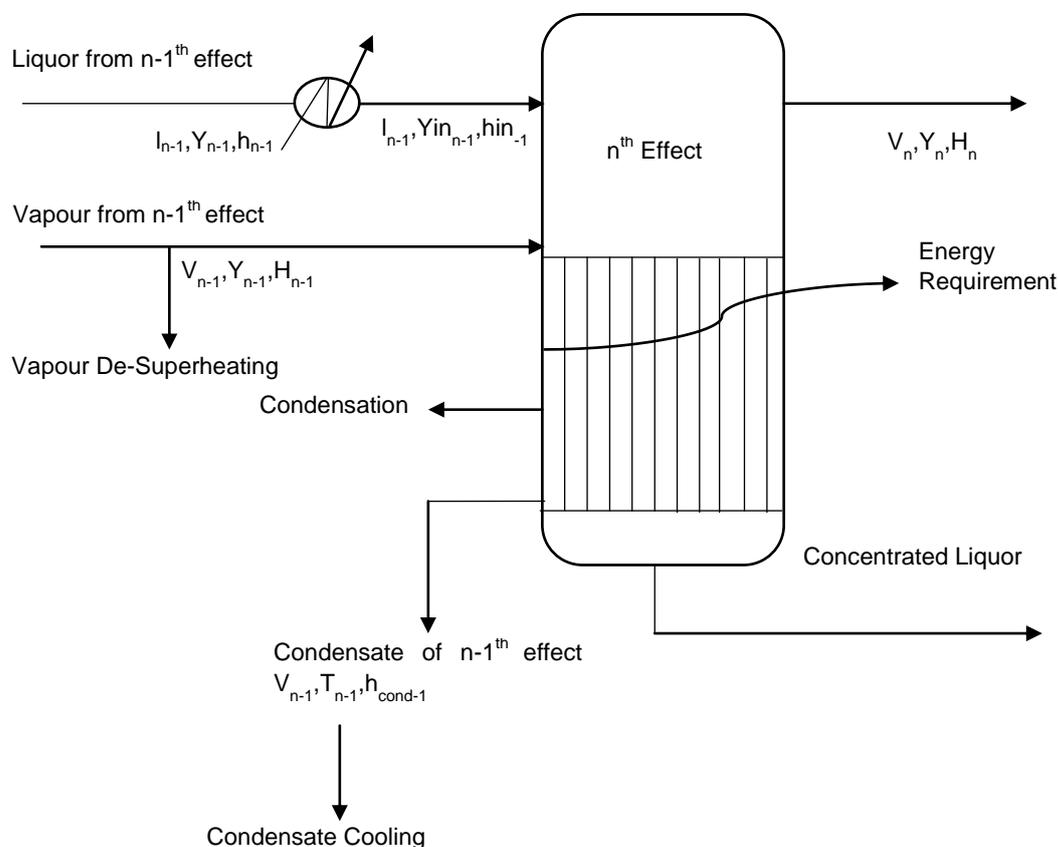
Figure 1: n^{th} effect evaporator
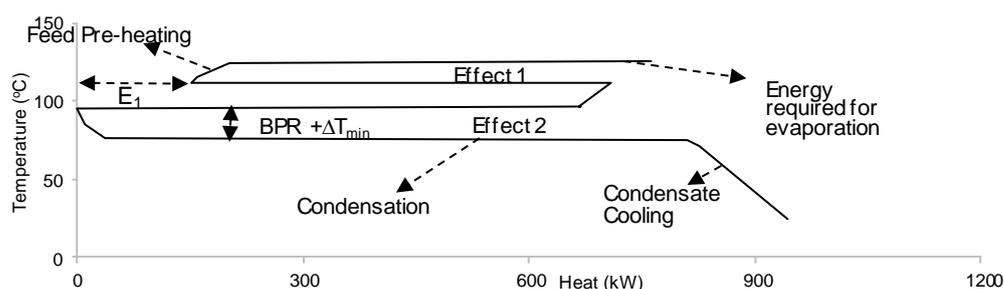
Figure 2: GCC for two effect MEE

The same concept can be used for generalising it for K effects. Change in utility requirement for effect 1, i.e., ΔS_n can be calculated from Eq(6). Net change in utility requirement for effect 1 (S) is given as:

$$S = -\left(\frac{K-1}{K}\right)E_1 + \frac{E_2 + E_3 + E_4.......E_K}{K} \tag{9}$$

Because of shifting of effect one away from pinch, external utility might be required by other effects (second effect requires external utility in Figure 2). Net change in utility requirement for MEE is given as:

$$Z = \frac{E_1 + E_2 + E_3 + E_4 \dots\dots E_K}{K} \qquad (10)$$

This proves the following theorem.

Theorem: If the effects are shifted away from the temperature axis by E_n, the net change in utility requirement for MEE is given as $\sum_{n=1}^{K} E_n / K$.

Form this theorem, it can be said that whenever there is shift between two effects, the utility requirement for MEE increases. Therefore, $E_n = 0$ for all effects, i.e., all effects should be pinched.

Corollary: In a standalone MEE, the minimum energy requirement corresponds to $E_n = 0$ for all stages.

Based on these results, integration of MEE with background is presented as a flowchart (Figure 3).

4. Illustrative example.

An example of concentrating sugar juice is considered for the purpose of illustration. In this example, a triple-effect forward feed MEE is considered. Feed of 1 kg/s with 15 % concentration is supplied at 80 °C. Product concentration is 60 % and must leave the battery limit at 80 °C. Effect temperatures are assumed to be 115, 80, and 60 °C with ΔT_{min} of 10 °C. Background streams are listed in Table 1. GCC for the background process is shown in Figure 4 (one with the thin line). GCC drawn is reflected about temperature axis and its hot utility requirement comes out to be 190 kW.

Table 1: Stream data for the background process

Stream	Tin (^{o}C)	Tout (^{o}C)	MCp (kW/ ^{o}C)
H1	100	99	250
H2	100	60	2
H3	85	60	2.5
C1	60	120	5
C2	70	100	4

Assuming equal vaporisation, $C_1^{initial}$ $C_2^{initial}$ and $C_3^{initial}$ values are calculated to be 0.2, 0.3, and 0.6. Mass of vapours for three effects are 0.222 kg/s, 0.259 kg/s, and 0.269 kg/s. Concentrations after second iteration, are calculated to be 0.193, 0.289, and 0.6 respectively. Corresponding mass of vapour are 0.222, 0.258, and 0.27 kg/s. Process streams data are extracted after second iteration and GCC is generated using MPTA (thick line in Figure 4). Minimum hot utility requirement is targeted to be 605.4 kW. Values of X_1, X_2, and X_3 are calculated to be 184.85 kW, 126.3 kW, and 130.47 kW, respectively. Therefore, X_o is 184.85 kW. Values of E_1, E_2, and E_3 are 0, 58.55 kW, and 54.38 kW, respectively. Using the proposed theorem net change in utility requirement for MEE, i.e. Z is determined to be 37.64 kW. GCC of the integrated systems is shown in Figure 5. Total hot utility requirement for the overall system is 648.19 kW. Related design data for the integrated MEE are given in Table 2. If the system is designed independently with same MEE temperature then total utility requirement for the system is 767.4 kW. So by proper integration 15.5 % energy can be saved.

Table 2: Final design parameter for integrated MEE

Concentration of liquor from stage one (%)	19.70	Liquor flow from stage 1 (kg/s)	0.761
Concentration of liquor from stage one (%)	29.30	Liquor flow from stage 2 (kg/s)	0.512
Vapour flow from stage 1 (kg/s)	0.239	Liquor flow from stage 3 (kg/s)	0.25
Vapour flow from stage 2 (kg/s)	0.249	Vapour flow from stage 3 (kg/s)	0.262

5. Conclusion

MEE is an energy intensive equipment for many process industries. Often the focus is on minimizing the energy consumption of MEE as a standalone system rather than minimizing the energy consumption of entire plant. In this paper an analytical methodology for integrating background process with MEE is proposed, proved mathematically, and demonstrated through an illustrative example. GCCs for MEE and the background process are matched appropriately to target the minimum overall hot utility requirement.

Procedure for optimally integrating the background process with MEE for given effect temperature is also discussed. It is proved that to minimize the energy consumption of a standalone MEE as well as of a MEE
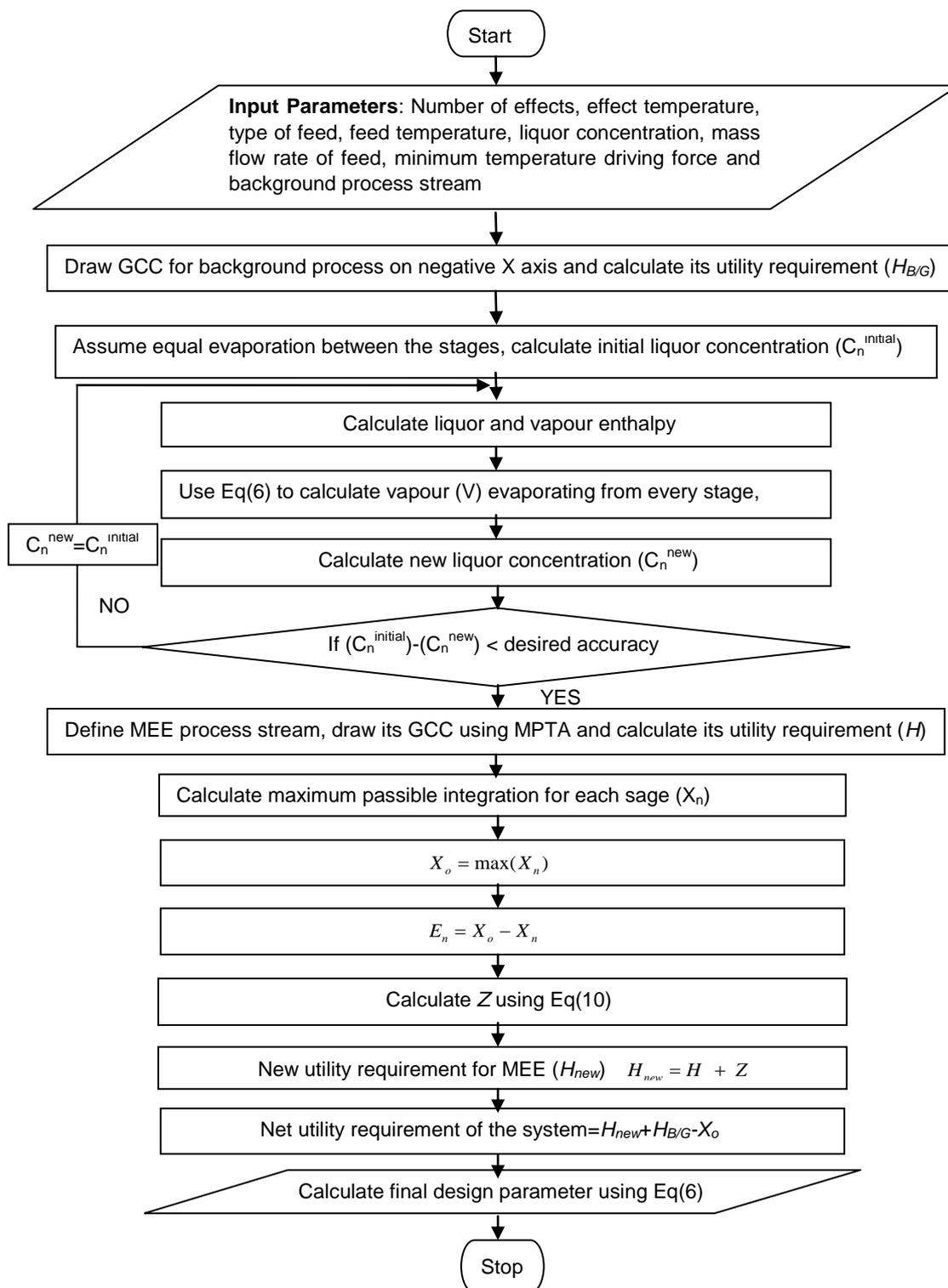
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                              ┌─────────┐
                              │  Start  │
                              └─────────┘
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   ╱──────────────────────────────────────────────────────────────────╲
   │  Input Parameters: Number of effects, effect temperature,         │
   │  type of feed, feed temperature, liquor concentration, mass       │
   │  flow rate of feed, minimum temperature driving force and         │
   │  background process stream                                        │
   ╲──────────────────────────────────────────────────────────────────╱
                                   │
                                   ▼
   ┌──────────────────────────────────────────────────────────────────┐
   │ Draw GCC for background process on negative X axis and calculate  │
   │ its utility requirement (H_{B/G})                                 │
   └──────────────────────────────────────────────────────────────────┘
                                   │
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   ┌──────────────────────────────────────────────────────────────────┐
   │ Assume equal evaporation between the stages, calculate initial    │
   │ liquor concentration (C_n^{initial})                              │
   └──────────────────────────────────────────────────────────────────┘
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              ┌──────────────────────────────────────────┐
              │ Calculate liquor and vapour enthalpy      │
              └──────────────────────────────────────────┘
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                                   ▼
              ┌──────────────────────────────────────────┐
              │ Use Eq(6) to calculate vapour (V)         │
              │ evaporating from every stage,             │
              └──────────────────────────────────────────┘
                                   │
   ┌──────────────┐                ▼
   │ C_n^{new}=   │   ┌──────────────────────────────────────────┐
   │ C_n^{initial}│   │ Calculate new liquor concentration       │
   └──────────────┘   │ (C_n^{new})                              │
                      └──────────────────────────────────────────┘
        NO                         │
                                   ▼
          ╱────────────────────────────────────────────────╲
          │ If (C_n^{initial})-(C_n^{new}) < desired accuracy │
          ╲────────────────────────────────────────────────╱
                                   │  YES
                                   ▼
   ┌──────────────────────────────────────────────────────────────────┐
   │ Define MEE process stream, draw its GCC using MPTA and calculate  │
   │ its utility requirement (H)                                       │
   └──────────────────────────────────────────────────────────────────┘
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   ┌──────────────────────────────────────────────────────────────────┐
   │ Calculate maximum passible integration for each sage (X_n)        │
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   │                    X_o = max(X_n)                                 │
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   │                    E_n = X_o - X_n                                │
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   ┌──────────────────────────────────────────────────────────────────┐
   │                    Calculate Z using Eq(10)                       │
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   ┌──────────────────────────────────────────────────────────────────┐
   │ New utility requirement for MEE (H_{new})   H_{new} = H + Z       │
   └──────────────────────────────────────────────────────────────────┘
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   ┌──────────────────────────────────────────────────────────────────┐
   │ Net utility requirement of the system=H_{new}+H_{B/G}-X_o         │
   └──────────────────────────────────────────────────────────────────┘
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   │       Calculate final design parameter using Eq(6)                │
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                                   │
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                              ┌─────────┐
                              │  Stop   │
                              └─────────┘
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The flowchart contains the following elements rendered as equations:

- Initial liquor concentration: $C_n^{initial}$
- Background process utility requirement: $H_{B/G}$
- New liquor concentration: C_n^{new}
- Assignment: $C_n^{new} = C_n^{initial}$
- Decision: If $(C_n^{initial}) - (C_n^{new}) <$ desired accuracy
- MEE utility requirement: H
- Maximum possible integration for each stage: X_n
- $X_o = \max(X_n)$
- $E_n = X_o - X_n$
- $H_{new} = H + Z$
- Net utility requirement of the system $= H_{new} + H_{B/G} - X_o$

Figure 3: Flowchart describing the procedure for integrating MEE with background process

integrated with the background process, all effects must be pinched. Example shows if the systems are integrated properly then 15.5 % energy can be saved.
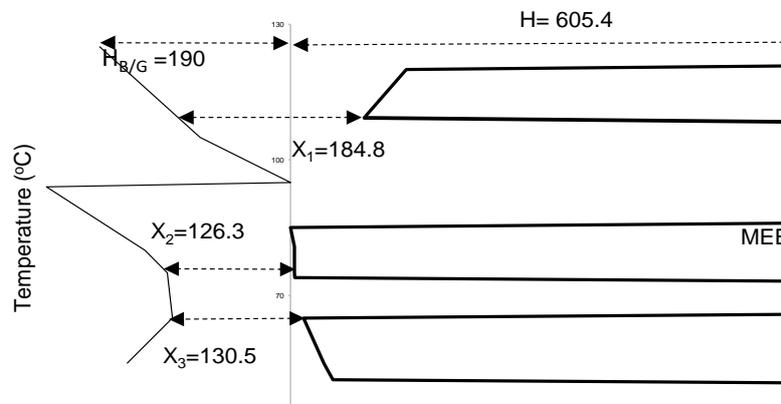
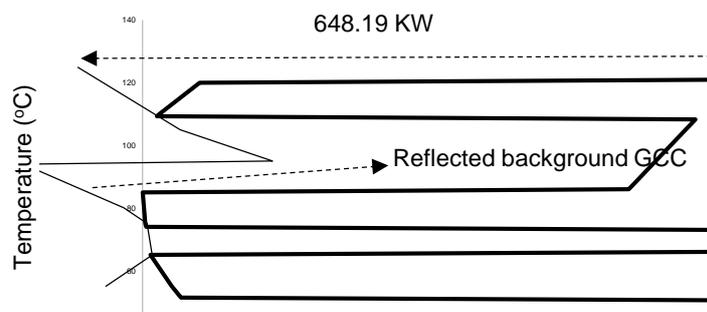Figure 4: GCCs of MEE and background process

Figure 5: Integrated GCCs for MEE and background process

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