Research Article

Thermodynamic Analysis and Optimization of Distillation Column: A Guide to Improved Energy Utilization

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Abstract
Energy consumption no doubt contributes a lot to the cost of production. To maximize profit, energy loss due to lost work must be minimized during production. Thus in this research, thermodynamic analysis was used to determine the energy efficiency of a propane-propylene splitter. In addition, the thermodynamic analysis was used to identify scope for possible modification and to set target for the column modification. The result indicated that the thermodynamic efficiency of the system was increased by 2.2% and the lost work in the column was reduced by 21.7Kw/hr. This was achieved by sacrificing only 2Kw/hr increase in the column minimum work.

1 Introduction

The excessive cost of separation systems results partly because of energy dissipation or lost work, hence the present trends explore the use of thermodynamics analysis in reducing the cost of separation systems, particularly in distillation operations. Thermodynamic analysis emphasizes the use of first and second law of thermodynamics and may be applied through pinch analysis and the exergy analysis to identify and quantify the energy dissipation and define targets for energy consumption [1].

The minimum thermodynamic condition for a distillation column is zero thermodynamic loss or reversible operation within the column, the stage-enthalpy or temperature-enthalpy profile of these conditions is called the Column Grand Composite Curve (CGCC). The CGCC can be used to identify scope for modification and set target for column modification or to integrate it most efficiently within the process train. It is a technique to enable designers apply the principle of pinch to distillation column design and modification to give a clearer picture of the thermodynamic consequences of the design alteration. Despite the benefit of CGCC, Dholel and Linnhoff [2] observed that one of the reasons CGCCs have not been used more often is the difficulty of constructing them due to the fact that at minimum thermodynamic condition, the column needs infinite stages and infinite numbers of side condensers and reboilers. In addition, to identify and quantify unused parts of available energy and determine the thermodynamic efficiency of distillation systems, exergy analysis is used [1]. Exergy is a measure of the quality and efficient use of energy [3] and is therefore a useful tool for optimization of energy system consumption.

The aim of this paper is to illustrate the application of thermodynamic analysis in optimization of distillation column energy utilization. In this study,

thermodynamic analysis of propane-propylene splitter case study was carried out to optimize its energy consumption and reduce operational cost. The propylene-propane splitter unit in this case study shown in Figure 1, is a part of a polypropylene plant which comprises propylene purification, polymerization, additive and extrusion units. The plant was designed to produce 35,000 metric tonnes of polypropylene resin per year [4]. The purification area upgrades 73 mole percent propylene from a Fluid Catalytic Cracking (FCC) unit to a minimum of 94 moles percent in the propylene-propane splitter.

2 Theory

2.1 *Column Grand Composite Curve (CGCC)*

The construction of the CGCC starts from a converged simulation [2], where the mole fraction of liquid (X^*), vapor (Y^*) for both light and heavy key components, vapor enthalpy (H_G^*), liquid enthalpy (H_L^*), molar flows of equilibrium vapor (G^*) and liquid stream (L^*) are obtained for each stage. The minimum vapor (G_{min}) and liquid (L_{min}) flows are obtained at each stage temperature by simultaneously solving equation (1) and (2)

$$G_{min}Y_L^* - L_{min}X_L^* = D_L \qquad (1)$$

$$G_{min}Y_H^* - L_{min}X_H^* = D_H \qquad (2)$$

To get the temperature-enthalpy picture for the minimum thermodynamic condition, the minimum vapor and liquid flows are expressed in terms of enthalpies. The enthalpies of the minimum vapor and liquid flows are obtained using direct molar proportionality, equations (3) and (4).

$$H_{Gmin} = H_G^*\left(G_{min}/G^*\right) \qquad (3)$$

$$H_{Lmin} = H_L^*\left(L_{min}/L^*\right) \qquad (4)$$

Enthalpy balance is carried out in each stage to calculate the enthalpy deficit (H_{def}) at each stage temperature, using equation (5) for stages before the feed stage and equation (6) for stage at and after the
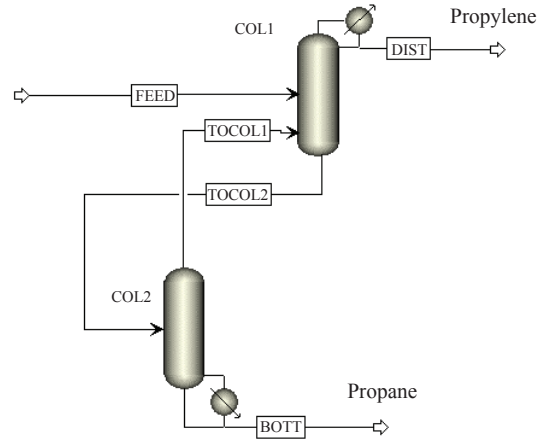

Figure 1: Schematic of propylene-propane splitter.

feed stage [2]. However, Bandyopadhyay [5] and Demirel [6] opined that at the feed stage, mass and energy balances differ from a stage without feed and finite changes of composition and temperature disturb the reversible operation. Thus we have the modified feed enthalpy deficit as equation (7). The CGCC is obtained by plotting temperature or stage number versus enthalpy deficit.

$$H_{def} = H_{Lmin} - H_{Gmin} + H_D \qquad (5)$$

$$H_{def} = H_{Lmin} - H_{Gmin} + \left(H_D - H_{feed}\right) \qquad (6)$$

$$H_{def,F} = Q_c + D\left[H_D + \frac{H_L\left(X_D - Y_L^*\right)}{Y_F^* - X_L^*} - \frac{H_V\left(X_D - X_F^*\right)}{\left(Y_F^* - X_F^*\right)}\right] \qquad (7)$$

2.2 *Exergy loss profiles*

The expressions for exergy, entropy and energy balances were derived by Demirel [1], [6]. The energy balance in a distillation column is expressed as in equation (8)

$$\frac{d(mU)_{sys}}{dt} + \Delta(\dot{m}H)_i - \dot{Q}_0 - \sum_j \dot{Q}_j + \sum_k \dot{W}_k \qquad (8)$$

where the first term is the change in internal energy, the second is the net change of enthalpy of an input or output stream i within the control volume, $\dot{Q}_0$ is the heat input rate from the surroundings, $\dot{Q}_j$ is the heat input rate from a reservoir and $\dot{W}_k$ shows the work done by the system. Also, the entropy balance is expressed

in equation (9)

$$\frac{d(mS)_{sys}}{dt} + \Delta(\dot{m}S)_i - \frac{\dot{Q}_0}{T_0} - \sum_j \frac{\dot{Q}_j}{T_j} = \sigma \qquad (9)$$

The term σ shows the rate of entropy production due to irreversibility, which is zero when processes and heat flows between the system and its surrounding are reversible. To eliminate $\dot{Q}_0$ from equations (8) and (9), equation (9) is multiplied by the temperature of the environment T_0 and the result is subtracted from Equation (8). The resulting equation (10) is the exergy balance for a distillation column [7].

$$\frac{d\left[\dot{m}\left(H - T_0 S - PV\right)\right]_{sys}}{dt} + \Delta\left[\dot{m}\left(H - T_0 S\right)\right]_i -$$

$$\sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j + \sum_k \dot{W}_k + T_0\sigma = 0 \qquad (10)$$

The term $H - T_0 S$ in equation (10) is called the availability (A) and the term $T_0\sigma$ is called the lost work (LW) or exergy lost if $T_0\sigma \geq 0$. The lost work is that portion of the total work that is necessary to overcome thermodynamic inefficiency due to driving forces within the system; it identifies and quantifies the power lost due to various irreversibilities and relates the evolution of a system to the environmental conditions. Applying equation (10) on a system at steady state in the absence of the work, the lost work in the system obtained as shown in equation (11)

$$LW = \sum(\dot{m}A)_{in} - \sum(\dot{m}A)_{out} +$$

$$\sum\left[\left(1 - \frac{T_0}{T}\right)q\right]_{in} + \sum\left[\left(1 - \frac{T_0}{T}\right)q\right]_{out} \qquad (11)$$

Similarly, applying equation (10) in an adiabatic system at a steady state in which the lost work is negligible, the minimum work in the system is obtained as shown in equation (12)

$$W_{min} = \sum(\dot{m}A)_{out} - \sum(\dot{m}A)_{in} \qquad (12)$$

The thermodynamic efficiency of the system, equation (13) is computed using the lost work and the

minimum work, when $W_{min} > 0$.

$$\eta = \frac{W_{min}}{LW + W_{min}} \qquad (13)$$

3 Methodology

Thermal analysis of the propylene-propane splitter was carried out using the Aspen Plus simulator Version 11.1 through its column targeting tool for rigorous column calculations. The column grand composite curve obtained from Aspen Plus RadFrac was used in this study. For each of the simulations, the Peng-Robinson (PR) property package was used. The Initial Plant Operating Data are as shown in Table 1.

Table 1: Initial Plant Operating Data [8]

Item	Feed	Product	Bottom
Material Stream			
Vapour Fraction	1.00	0.00	0.00
Temperature [C]	53.00	41.75	54.24
Pressure [bar]	18.23	17.22	19.25
Molar Flow [kgmole/h]	290.70	246.96	43.74
Mass Flow [kg/h]	12344.37	10419.80	1924.57
Liquid Volume Flow [m³/h]	23.82	20.03	3.79
Heat Flow [kcal/h]	-227856.96	-43.83	-1156869.77
Component Mole Fraction			
Propylene	0.81	0.946	0.043
Propane	0.19	0.054	0.957
Reflux ratio = 10.2			

Energy Stream	Qc	Qr
Heat Flow [kcal/h]	8455410.08	7530102.71

The thermal analysis was used in identifying design targets for improvements in energy consumption and efficiency based on the concept of Minimum Thermodynamic Condition (MTC) for a distillation column. Sensitivity analysis was carried out to study the interactive effect of those process variables involved in the operation of the propane-propylene splitter case study. The analysis provided a tool that was used in the optimization of the operating condition of the propane-propylene splitter. The efficient operating

criterion considered was the mole fraction of propylene in the distillate, which should be a minimum of 0.94. Thermal analysis of the optimized splitter was also carried out to determine the extent of improvement achieved.

4   Results and Discussions

4.1   *Exergy analysis for operating condition modification*

The propane-propylene splitter in our case study is operated with its feed stage located at tray 38. However, it was designed to operate at a feed stage of 90. Exergy analysis of the column, Table 2 was used to show the thermodynamic implication of the decision to change the feed stage location by the plant operators.

**Table 2**: Exergy analysis for feed stage location in the propane-propylene splitter

	Column Minimum Work (watt)	Column Lost Work (watt)	Thermo-dynamic Efficiency (%)	Propylene in Distillate (%)
Feed Stage at Stage 90	9786	137536	6.6	95.2
Feed Stage at Stage 38	3743	134631	2.7	94.6

The change of feed stage location from stage 90 to stage 38 shows the reduction of the thermodynamic efficiency of the column by 3.9%. However, while the effect of this change on the purity of the distillate at the same distillate rate is almost insignificant (i.e. 0.6% reduction in purity of the distillate), exergy analysis reveals that the decision to change the feed tray location by the plant operators has saved the company 6.04Kw/hr of energy due to the reduction in the minimum work required in the column.

4.2   *Identifying target for possible modification*

The Column Grand Composite Curve (CGCC) presents the results of the thermodynamic analysis of the column for possible modification towards achieving the best energy performance. The common considerations for column modification that may be identified in the CGCC are scope for the reflux, feed preheating/cooling and side condenser/reboiler modification. These were based on the condition that the feed condition has been chosen appropriately beforehand [2].

The horizontal distance between the CGCC pinch point and the vertical axis represents the scope for reflux ratio as shown in the propane-propylene splitter case study CGCC with feed stage at tray 90, Figure 2.
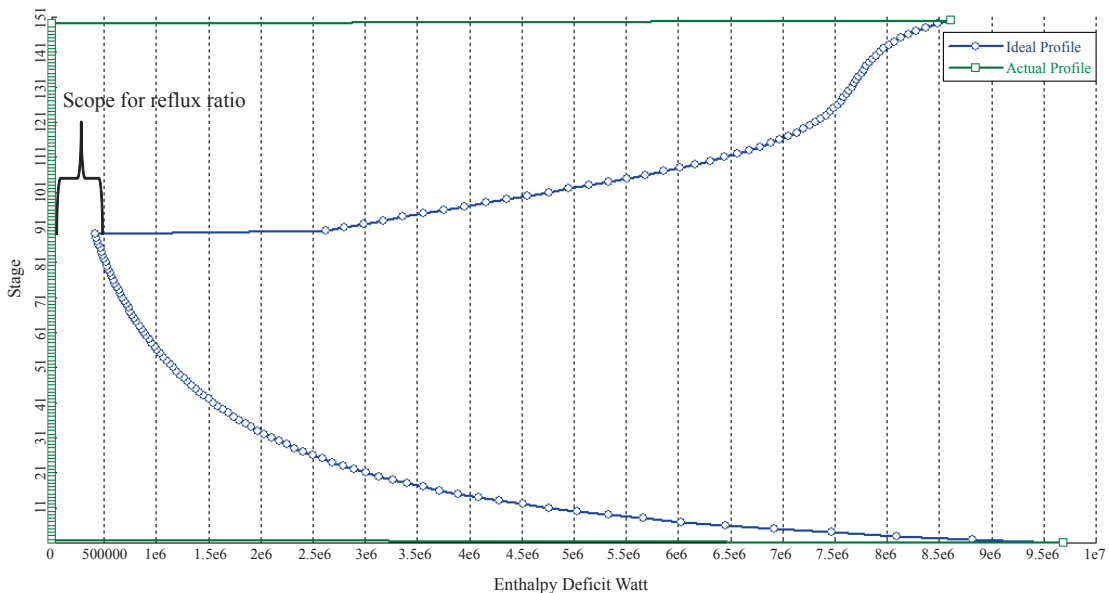
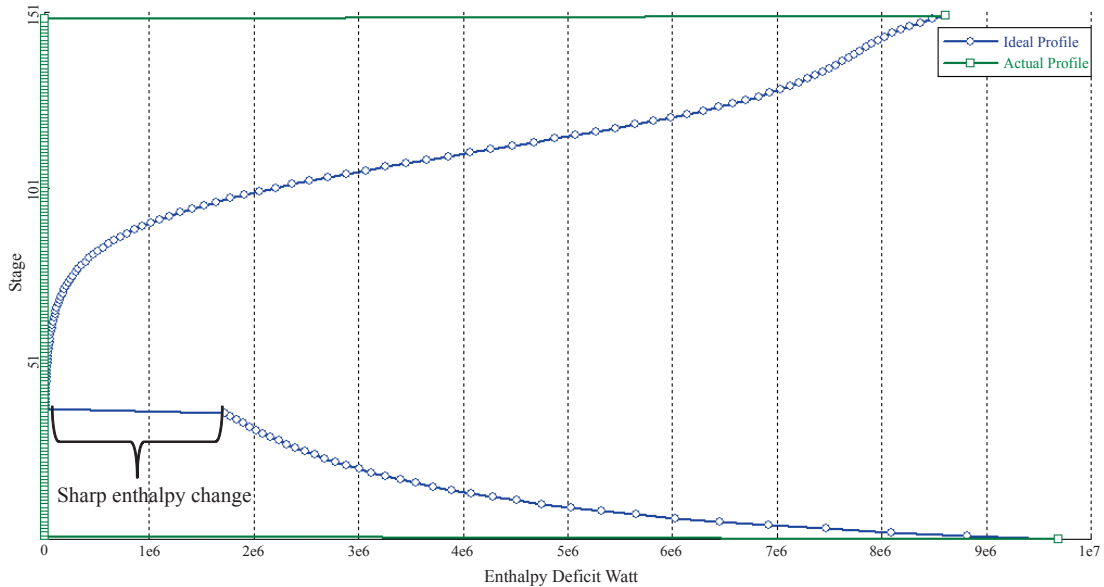**Figure 2**: CGCC for feed stage at tray 90.

Figure 3: CGCC for feed stage at tray 38.

The minimum work in the splitter was reduced by changing the feed stage to tray 38, at this condition, the CGCC Figure 3 indicates that there is no scope for reflux ratio reduction in the splitter. Thus to optimize the energy consumption of the splitter, it was necessary to identify other conditions for possible modification. The next consideration is to identify a sharp change in enthalpy. A sharp enthalpy change in a CGCC indicates excessive subcooling/heating of the stream. This sharp enthalpy change increases the condenser and reboiler load. To reduce this load,Dohle and Linnoff [2] suggested the use of either feed preheating/cooling or the use of side condenser/reboiler. They prefered feed preheating/cooling to side condensing/reboiler. Their reason being that Feed conditioning offers a more moderate temperature level and is external to the column unlike side condensing/reboiling. However, in this study, the adjustment of feed stage and pressure of the column is used to reduce the condenser and reboiler load. This approach is chosen because it enables the effective utilization of energy in the distillation column without additional capital cost as only adjustments of operating condition are involved.

4.3 *Optimization of column energy utilization*

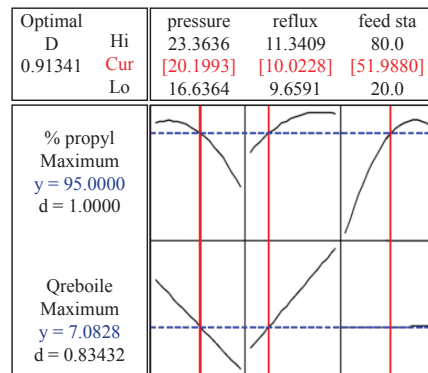The operating condition; reflux ratio, column pressure

Figure 4: Optimization of the splitter [8].

and feed stage are variables which were chosen to optimize the energy efficiency of the distillation column using response surface optimization as shown in Figure 4.

In this work, it was necessary to carry out exergy analysis to determine the implication of applying the result of the optimization process on the thermodynamic efficiency of the column. The work as shown in Table 3 indicts that the lost work in the column was reduced by 21.7Kw/hr. This was achieved by sacrificing only 2Kw/hr increase in the column minimum work. While the overal thermodynamic efficiency of the system has increased by 2.2%.
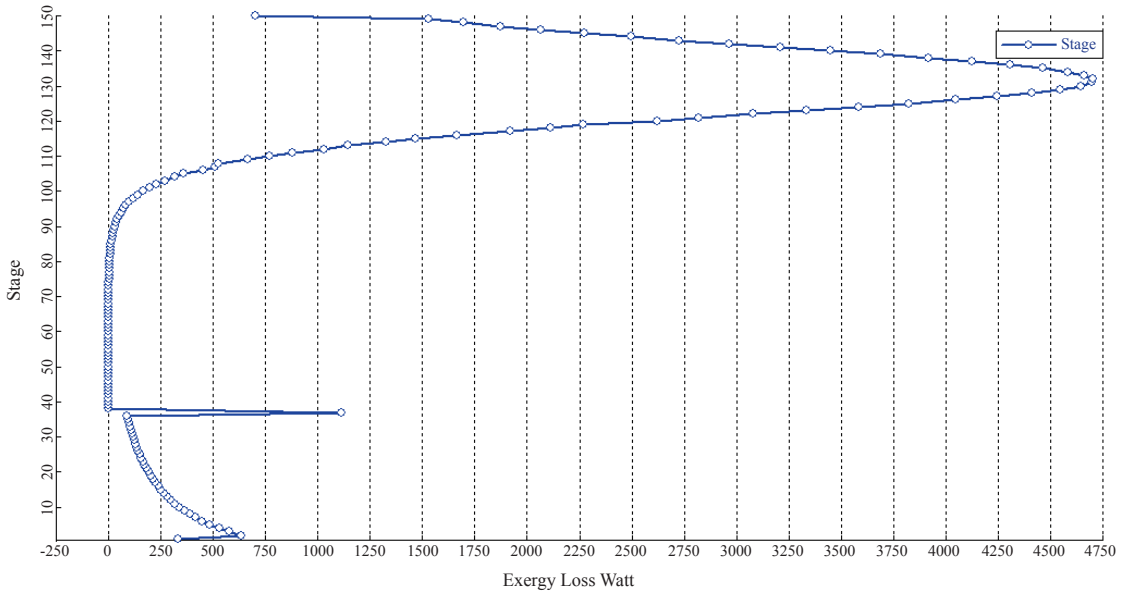
Figure 5: Exergy loss profilefor feed stage at tray 38.
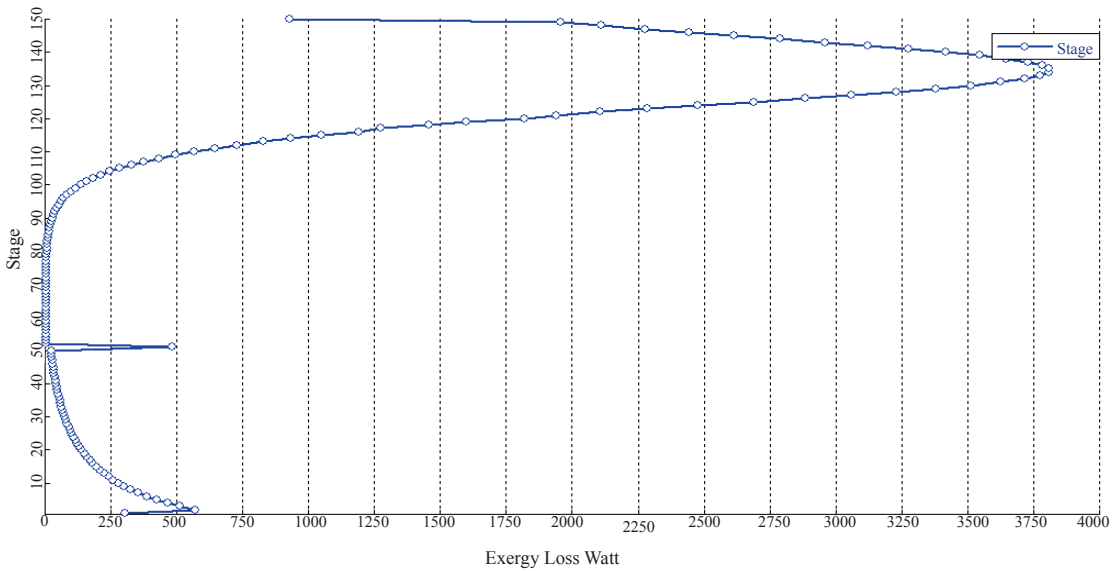
Figure 6: Exergy loss profile for the optimized operating conditions.

Further the exergy loss profile in Figure 5 and 6 indicates that the maximum exergy loss occurred in the stripping section of the column between stage 140 and 130. A comparison of Figure 5 and 6 shows that the maximum exergy loss has been reduced from 4.74Kw/hr to 3.74Kw/hr by implementing the optimization result. In addition, comparing the CGCC of the splitter before optimization, Figure 2 with the CGCC after optimization in Figure 7, it is observed that the enthalpy deficit due to sharp enthalpy change has been reduced from 1700Kw to 800Kw.
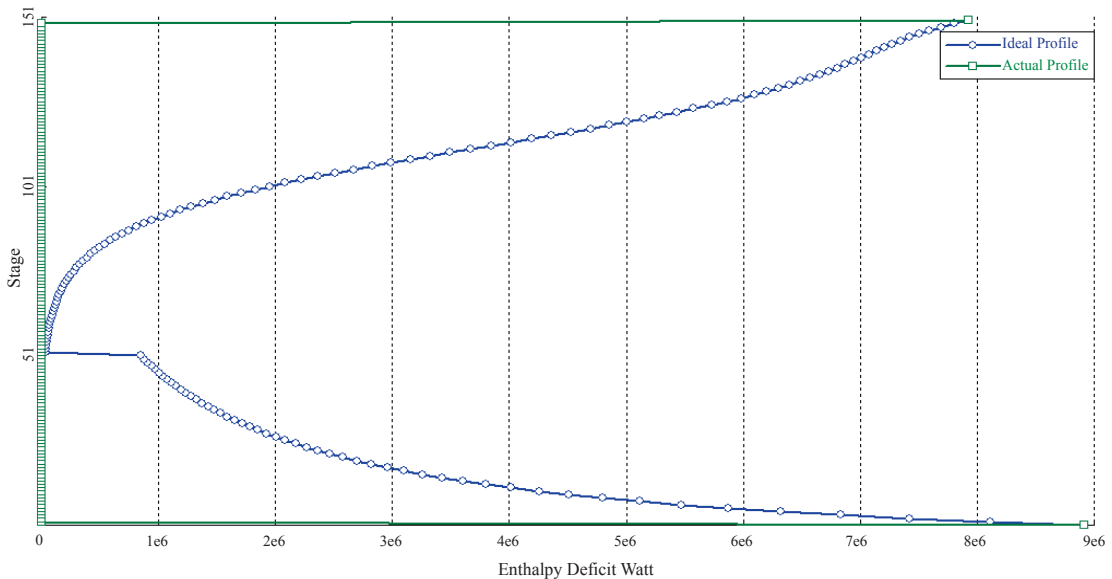
Figure 7: CGCC for the optimized operating conditions.

Table 3: Exergy analysis for column before and after optimization

Operating Condition	Column Minimum Work (watt)	Column Lost Work (watt)	Thermo-dynamic Efficiency (%)	Propylene in Distillate (%)
Before Optimization	3743	134631	2.7	94.6
After Optimization	5838	112926	4.9	95.0

5 Conclusions

In this research, thermodynamic analysis was carried out on the propane-propylene splitter unit to identify possible modification towards achieving the best energy performance. Amongst other considerations for column modification, adjustment of operating conditions (reflux ratio, column pressure and feed stage) was proffered followed by process optimization on the splitter. Additionally, thermodynamic analysis was used to ascertain the implication on the energy efficiency, of applying the optimization result in the system. The result indicated that the thermodynamic efficiency of the system was increased by 2.2% and

the lost work in the column was reduced by 21.7Kw/hr. This was achieved by sacrificing only 2Kw/hr increase in the column minimum work.

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