Funmilayo N. Osuolale

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Nigerian Content and Industry Collaboration Department, Petroleum Technology Development Fund (PTDF), Memorial Drive, Abuja

ooagbede@lautech.edu.ng

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A REVIEW OF THERMODYNAMIC ANALYSIS OF DISTILLATION COLUMN

Funmilayo N. Osuolale[1,2], *Oluseye O. Agbede[1,2] , Solomon O. Alagbe[1,2] and Ambrose N. Anozie[3]

[1]Department of Chemical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria

[2]Energy and Sustainability Research Group, Ladoke Akintola University of Technology, Ogbomoso, P.M.B. 4000, Ogbomoso, Oyo State, Nigeria

[3]Department of Chemical Engineering, Obafemi Awolowo University, Ile-Ife, Osun State.

* Corresponding Author: ooagbede@lautech.edu.ng

ABSTRACT

Separation technique with distillation column is an energy intensive process even though it is one of the most extensively used separation process in the petrochemical, chemical and agro-allied industries. Studies have proved that some other schemes of distillation columns other than the conventional columns could be more energy efficient. This has led to a number of different configurations of the columns. This study presents a review of second law of thermodynamics in determining and enhancing the effectiveness of energy usage in the distillation columns. The review covers binary, multicomponent and crude distillation columns and it is not limited to the conventional columns. It can be concluded that exergy analysis of the columns while providing a true analysis of the column efficiency can be used to improve the column's energy efficiency. It is therefore imperative that process engineers should be armed with this tool to design and operate energy efficient columns.

Keywords: Distillation; Exergy analysis; Efficiency; Thermodynamics,

INTRODUCTION

Chemical industries requires a lot of energy for its daily operations. The fact that most frequently used sources of energy for the chemical industries are finite and energy requirement increases directly proportional to population growth in addition with the attendant ecological and environmental implications of indiscriminate use of energy has made efficient energy usage by energy consuming processes of high priority for all stakeholders in the industry. The ultimate goal of every engineering process is therefore efficacy of the process as well as energy efficiency. This demands improvement in energy utilization system and equipment to reduce the waste in energy.

Distillation column consumes $2.87 \times 10^{18} J$ a year which is equivalent to a continuous power consumption of 91GW or to a 54million tonnes of crude oil (Soave and Feliu, 2002). A recovering of as little as 1% will definitely translate to a tremendous amount. Therefore, it can be conveniently concluded that improvement in the efficiency of the distillation units in the refinery will greatly improve the overall efficiency of the refinery; culminating in a reduction in total cost of production, an increase in throughput and a reduction in the consumption of energy.

Distillation system has always been of special interest to researchers because it plays a key role in the petrochemical and chemical industries as one of the most popular separation techniques. However, the separation is known to consume a lot of energy. A number of people have worked on improving the performance of distillation columns and have come out with differs suggestions that are of great importance.

The use of intermediate reboiler and condenser has been suggested for significant reduction in the operating cost of a distillation column (Agrawal and Fidkowski, 1996). The most thermodynamically efficient arrangement for adding or removing heat from an intermediate location was presented by (Agrawal and Herron, 1998). Distillation with intermediate heat pump was the focus in another study (Wang et al., 2021). The feed condition is an area that has received attention in the recent past. Feed preheat has been considered in the study of the optimization of distillation schemes (Asadollahi et al., 2017). Soave and Feliu (2002) however opined that feed splitting before preheating can bring about further savings in energy.

Some other authors (Anozie et al., 2009, Al-Muslim et al., 2005) have looked into methods of determining and improving the efficiency of the distillation process. One of such is through the application of thermodynamic analysis also known as second law analysis or exergy analysis to distillation processes (Demirel, 2004).

Exergy analysis evolves from a combination of both first and second laws of thermodynamics to distinguish between quantity and quality of process energy usage, quantifies sources of inefficiency in the process and indicates available options that can be harnessed in the process to improve its energy efficiency (Rosen and Dincer, 1997). It encompasses the total energy of the system and therefore gives accurate and adequate analysis of the energy balance of the system.

Exergy analysis assesses the quality of energy usage in a process (Szargut et al., 1998) and has been used to demonstrate standard for the effectiveness and efficiency of engineering devices (Asada and Boelman, 2004).

Unlike energy, exergy is not conserved but could be wasted and exhausted as a result of irreversibilities in the process system. Quantitative measurement of the irreversibilites in a process gives the effectivenss of the process and the extent of further improvement that could be ideally possible. It also gives indication of entropy generation in the system and the deviation of the system from ideality. The challenge therefore is to minimise irreversibilities in processes and hence increase its efficiency. Real processes always have elements of irreversiblities in them. Application of exergy analysis to process systems identify the points of energy losses and proportion of the losses in the system . It gives indication of the effectiveness as well as the efficiency of a system (Demirel, 2006, Dhole and Linnhoff, 1993).

This review focuses reducing the energy loss in a distillation column by the application of the second law analysis. The highlights of the review include the theory of the thermodynamic efficiency, applications in the recent past to distillation column and prospects for future processes.

The First law of thermodynamics

The first law of thermodynamics is about the conservation of energy. It states energy can change from one form to the other but the total energy of the system remains constant. The pictorial representation of the 1st law is given in Figure 1 for an open system (Perry, 2008)

$$input - output = accumulation \quad (1)$$

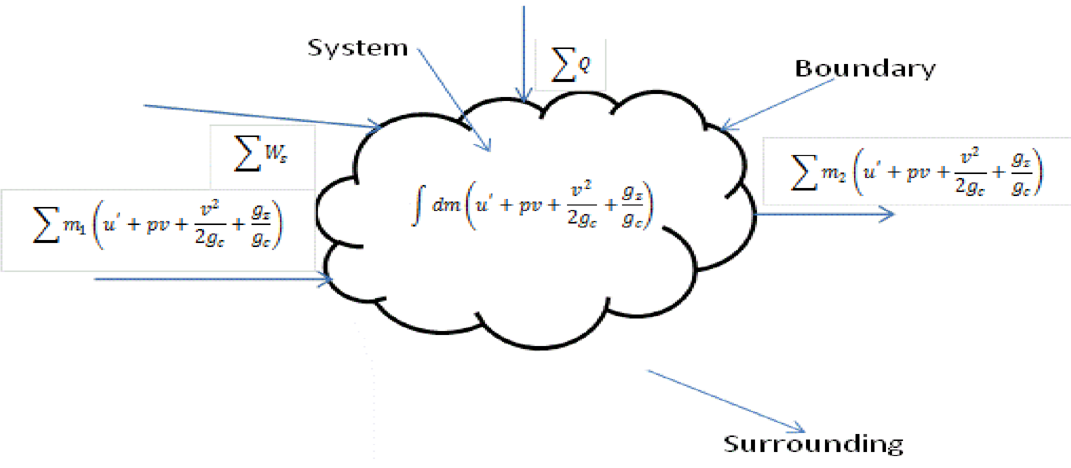

Figure 1: 1st law analysis of process

Using Figure 1,

Energy input into the system is

$$\sum Q + \sum W_s + \sum m_1\left(u' + pv + \frac{v^2}{2g_c} + \frac{g_z}{g_c}\right)_1$$

Where $\sum Q$ is the total heat energy into the system; $\sum W_S$ is total extenal work into the system; u', pv, $\frac{\upsilon^2}{2g_c}$, $\frac{g_z}{g_c}$ are the internal energy, the energy due to flow, the kinetic energy, and the gravitational or potential energy per unit mass respectively. All are defined relative to the environment.

m is the mass flow per unit time.

Energy out of the system is giving as

$$\sum m_2\left(u' + pv + \frac{v^2}{2g_c} + \frac{g_z}{g_c}\right)_2$$

The energy accumulated in the system is given as

$$\int dm\left(u' + pv + \frac{v^2}{2g_c} + \frac{g_z}{g_c}\right)$$

Subscripts 1 and 2 denotes inlet and outlet conditions.

Substituting all these terms into equation 1 gives

$$\sum Q + \sum W_s + \sum m_1 \left(u' + pv + \frac{v^2}{2g_c} + \frac{g_z}{g_c}\right)_1 - \sum m_2 \left(u' + pv + \frac{v^2}{2g_c} + \frac{g_z}{g_c}\right)_2 = \int dm \left(u' + pv + \frac{v^2}{2g_c} + \frac{g_z}{g_c}\right)$$

Equation 2

Assuming steady state operation for an open system, and neglecting the kinetic and potential energy, equation 2 becomes

$$\sum Q + \sum W_S = \sum m_2 h_2 - \sum m_1 h_1 \qquad (2)$$

Where the term $u' + pv$ is replaced by the specific enthalpy

The second law of thermodynamics

While the first law of thermodynamics gives the dimension of quantitative measure of the energy conversion in a process, the second law of thermodynamics gives the qualitative side of these conversions. The second law of thermodynamics establishes the difference in quality between different forms of energy as opposed to the quantity of energy transformation given by the first (Smith et al., 2005).

The second law is often defined in terms of entropy generated and accumulated within the system. A process is said to be ideal when the total entropy entering and leaving the process are equal. In reality however, there is entropy generation within the process system which makes the net entropy leaving a process greater than the entropy entering the process. This entropy rise in a real process makes it deviates from the ideal version. An efficient process therefore will minimize the entropy generation and hence convert the useful energy of the system to work, reduce the irreversibility and make the process tend more to its ideal state. (Jin et al., 1997)

Clausius in 1865 introduced the concept of entropy. Understanding of the concept of entropy led to a more general statement that the entropy production in any system must be greater than or equal to zero. For an open system, the statement can be written mathematically as (Holman, 1980):

$$Entropy\ production = Entropy\ outflow - Entropy\ inflow + Entropy\ accumulation \qquad (3)$$

$$Entropy\ outflow = m_2 s_2$$

where s_2 is the entropy per unit mass flow at the outlet

$$Entropy\ inflow = m_1 s_1 + \sum \frac{Q}{T_0}$$

This represent entropy from mass transport and entropy as a result of heat transfer at boundary of the control volume.

Substituting all terms into equation 4, gives

$$\sum m_2 s_2 - \left(\sum m_1 s_1 + \sum \frac{Q}{T_0} \right) + \int d(ms) > 0 \qquad (4)$$

Rearranging and solving for $\sum Q$*, assuming steady state operation and quantifying the entropy production by the identity* σ

$$\sum Q = \sum T_0 m_2 s_2 - \sum T_0 m_1 s_1 - T_0 \sigma \qquad (5)$$

Derivation of exergy function

The exergy function is derived from a combination of the first and second laws of thermodynamics. Szargut et al., (1988) defined exergy as "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above mentioned components of nature".

The first and second laws of thermodynamics mathematically presented in equations 3 and 6 are combined to obtain

$$\sum T_0 m_2 s_2 - \sum T_0 m_1 s_1 - T_0 \sigma + \sum W_S = \sum m_2 h_2 - \sum m_1 h_1 \qquad (6)$$

Rearranging further for a reversible process where $T_0 \sigma = 0$ and a steady state flow operation where $\sum m_1 = \sum m_2$ equation 7 becomes

$$W_{S\,rev} = m(\Delta h - T_0 \Delta s) = m(\Delta ex) = \Delta Ex = \Delta H - T_0 \Delta S \qquad (7)$$

Equation 8 gives a thermodynamic function called exergy. It looks similar to the Gibbs function but it is the minimum work required or the maximum work obtainable in bringing a system to equilibrium with its environment.

The reference pressure and temperature commonly used are 101.325 kPa and 298.15 K respectively. (Szargut et al., 1988)

Exergy is a key aspect of providing better understanding of the process; quantifying sources of inefficiency and distinguishing quality of energy used (Dincer and Al-Muslim, 2001). For a real process, the exergy input always exceeds the exergy output; this imbalance is due to irreversibilities, which some have referred to as exergy loss or recoverable exergy. A pictorial representation is given in Figure 2 (Dincer and Rosen, 2012; Rosen and Dincer, 1997)

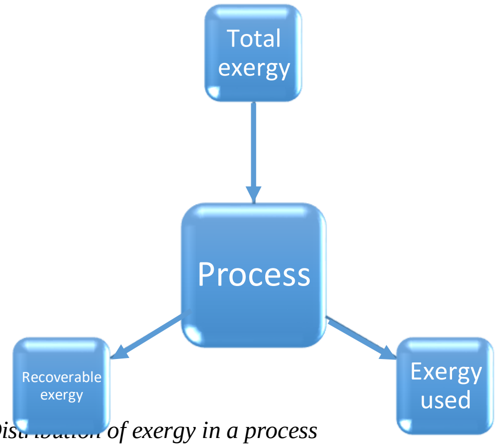

Figure 2: Distribution of exergy in a process

THERMODYNAMIC ANALYSIS OF BINARY AND MULTICOMPONENT SYSTEMS

Optimal thermodynamic feed conditions have been identified through thermodynamic efficiency analysis of distillation columns (Agrawal and Herron, 1997). It was suggested that a binary mixture of same compositions one being saturated vapour and the other saturated liquid gives a substantial improvement in distillation column efficiency.

The fact that irreversibility in a column is high and its fluxes are distributed in non-uniform manner in the column is reiterated in another research effort. They are found to be more significant in the condenser, reboiler and feed tray. The target therefore is to minimise the temperature pinch by inserting a heat pump to function in between two successive trays.

Column grand composite curve (CGCC) and exergy loss profile were used in thermodynamically retrofit of distillation column (Demirel, 2006). The retrofit suggestions were based on the reduction in exergy loss of the process and subsequent increase in exergy efficiency. It includes feed preheating, inclusion of side reboilers and condensers.

Exergy analysis has been used in determining distillation column feasible operating conditions, (Anozie et al., 2009), in determining binary plate distillation column reflux ratio (Anozie, 2010a) and in optimizing binary plate distillation column operations (Anozie et al., 2010b).

Exergy analysis was implemented in the control of binary distillation column using relative exergy array (REA) in place of relative gain array (RGA) (Osuolale and Zhang, 2015a). In another study artificial neural network (ANN) was used in the modelling, control and optimisation of energy efficient column (Osuolale and Zhang, 2014).

In all these cases, the criteria focused on increase in thermodynamic efficiency at thermodynamically feasible conditions. The method, in all these cases, has been proved on binary systems.

A comprehensive list on review of thermodynamic analysis of distillation process was presented by (Demirel, 2004). The focus is on conventional column emphasising reduction of ecological cost energy cost and thermodynamic cost. Exergy analysis of an ideal heat integrated distillation column was performed and compared with the conventional distillation column (Huang et al., 2006). The heat integrated column gives potential for internal heat integration between the rectifying and the stripping section.

Exergy analysis was used to determine the stage for heat to be added in a dividing wall heat distillation column (Suphanit et al., 2007). This method was successful in improving the efficiency of the columns with multiple feeds and products.

A five column scheme for purifying methanol was shown to have an exergy loss decrease of about 21.% compared to the four column scheme (Sun et al., 2012). The purity and the yield of methanol in both schemes are the same.

Feyzi and Beheshti (2017)computed the exergy efficiency of a reactive distillation column under different operating conditions. Response surface method (RSM) was then applied to model and optimize the efficiency. Exergy efficiency of the column was increased by 12 % and the exergy loss was reduced by 28%.

Exergy analysis of a triple-column extractive distillation(TCED)gf process that seperates ternary azeotropic mixture of ACN/EtOH/H2O yields a total exergy destruction of 1097.69kW. Exergy loss of 29.20% was caused by the coolers and condensers. From the thermodynamic analysis, a superstructure TCED with four-parallel evaporator organic Rankine cycles (FPE-ORC) system was proposed which result in a higher exergy efficiency of 12.27% and an economic benefit of $64300/year (Yuan et a., 2021)

In a more recent treatise of the distillation column, the exergy efficiency was found to increase when the gap between the operating line and equilibrium is reduced (Tumbalam Gooty et al., 2021). The driving force ΔT between the reboiler and condenser and other heat exchangers are factors that should be taking into special consideration in improving the efficiency of the column.

THERMODYNAMIC ANALYSIS OF CRUDE DISTILLATION UNITS

The crude distillation unit has a lot of component to be analysed thermodynamically. This includes preflash column, the atmospheric distillation column, the vacuum distillation column, the heat exchanger network and the heaters. In his treatise, application of the exergy concept in the petroleum refining and petrochemical industry (Rivero, 2002), Rivero asserted that one of the future applications of exergy in the industry will be in the area of developing methodologies that will incorporate exergy to the existing simulation, analysis and optimization tool with the aim of conducting exergoeconomic and exergoecological studies that will give real economic benefit of the process in terms of its efficiency and evaluate its environmental impacts.

A number of work have been published on the thermodynamic analysis of crude distillation unit. Cornelissen (Cornelissen, 1997) performed analysis on a crude distillation unit with an efficiency of 0.27 for the ADU, 0.373 for the VDU, 0.541 for the heater and 0.0518 for the overall process.

Al-Muslim and Dincer(2005) came out with a result of 0.433 for the ADU, 0.501 for the VDU, 0.821 for heater 1, 0.956 for heater 2 and 0.233 for the overall system in terms of exergy efficiency. The energy efficiency is 0.497 for the ADU, 0.579 for the VDU and 0.519 for the overall system. It was also asserted that the highest irreversibility losses occur in the ADU and 6.2% of these losses resulted from chemical exergy contribution, the rest are due to physical exergy as a result of the temperature difference. In another related work, the authors went further to study the effects of varying reference state on the efficiency of the column (Al-Muslim et al., 2005) and reported that increasing the reference temperature decreases the exergy efficiencies of the system.

In the exergy and exergoeconomic analysis of a crude oil combined unit (Rivero et al., 2004), the total exergy losses of the plant are 111.08 MW, of which 11.32% is effluent exergy and 88.68% is irreversible exergy losses. The ADU has the highest total exergy loss of 60.54%.

The exergy analysis of a whole crude distillation unit was conducted, locations and magnitude of the inefficiencies based on exergy loss distribution of the process led to improving the exergy of the process from 28.9% to 41.4% and reducing the total annual consumption of the process by 28.7% (Yan et al., 2019).

The highest exergy loss which was 86% of total exergy loss was detected in the furnace of a crude distillation system (Nur Izyan and Shuhaimi, 2014). From exergy composite curves, fuel reduction strategies were generated and implemented.

Exergy analysis of crude distillation units of two refineries in Nigeria were presented with the atmospheric units having 33.3% and 31.6% respectively. Modifications of the operating and feed conditions drastically increased the exergetic efficiencies of the units (Osuolale and Anozie, 2019). In another study, optimization of the crude distillation unit using exergy rate profile increased the efficiency of the column from 33% to 53% (Osuolale and Anozie, 2017).

Exergy analysis was used in control and optimization of atmospheric distillation unit and the crude distillation unit of the refinery. (Osuolale and Zhang, 2015b, Osuolale and Zhang, 2016, Osuolale and Zhang, 2017)

CONCLUSION

The exergy analysis of distillation columns has revealed things that could bring about the improvement of distillation columns. This include optimum feed conditioning, multiple feed column, use of intermediate heat exchangers and making use of energy efficient schemes of distillation processes other than the conventional distillation process. The study of distillation processes in higher institution of learning can focused more on these schemes in addition to conventional distillation column being taught. Exergy analysis of chemical processes should be incorporated in our education system. This review is focused on distillation columns but the truth is every other chemical processes can be made more efficient from application of second law of thermodynamics.

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