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Energy analysis study of coal tar distillation process by feed splitting method

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ABSTRACT

Coal tar is a high viscosity liquid and has a black color which formed as a by-product of the production process of coke and gas from coal. Coal tar compounds have high economic value because they can be resold and valuable. One valuable compound is naphthalene. The coal tar evaluation process of its constituent components is carried out by distillation, with a high level of naphthalene purity achieved up to 96%. The coal tar distillation process normally requires high energy, which leads to expensive operational costs. In order to achieve low energy consumption during the distillation process, a study of energy analysis in the coal tar distillation process needs to be done. This study aims to analyze the energy consumption of the distillation process by using simulator software. Process simulations will be performed using the Aspen HYSYS simulator, where the variable in the form of the ratio of the feed flow rate into the distillation tower is divided into two streams, namely cold stream and hot stream. The location of the changed input feed is also a changing variable in this study. The fixed variables in this study were the operating conditions of the distillation process and the incoming feed flow rate, which was 2 m3/hour. The simulations suggest that the amount of energy saved in the condenser unit is 4.40 percent and 5.28 percent in the reboiler unit.

ABSTRAK

Tar batubara adalah cairan dengan viskositas tinggi dan berwarna hitam, hasil samping dari proses produksi kokas dan gas dari batubara. Senyawa tar ini memiliki nilai ekonomi yang tinggi karena komponen-komponen penyusunannya dapat dijual kembali dan bernilai, salah satunya adalah naftalena. Proses pemisahan tar batubara dari komponen-komponen penyusunnya dilakukan dengan cara destilasi, dengan tingkat kemurnian naftalena yang tinggi yaitu 96%. Proses destilasi tar batubara ini seringkali membutuhkan energi yang besar, sehingga kajian mengenai analisa konsumsi energi pada proses destilasi tar batubara perlu dilakukan. Studi analisa energi pada proses destilasi tar batubara dilakukan dengan menggunakan metode simulasi proses. Simulasi proses destilasi dilakukan dengan menggunakan perangkat lunak berupa Aspen HYSYS, dimana variabel yang berupa ratio laju alir umpan masuk ke dalam menara destilasi dibagi menjadi 2 aliran, yaitu aliran dingin dan aliran panas. Letak umpan masuk yag dirubah juga merupakan variabel berubah pada penelitian ini. Variable tetap pada penelitian ini adalah kondisi operasi proses destilasi dan laju alir umpan masuk, yaitu 2 m^3/jam. Hasil dari simulasi yang telah dilakukan didapatkan besarnya energi yang dapat dihemat sebesar 4.40% pada unit condenser dan 5.28% pada unit reboiler.

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1. Introduction

Distillation is a process that is often found in the petrochemical industry and is used to separate a compound from its components. Distillation is a unit operation that wastes energy or consumes much energy. Energy costs are the most significant hydrocarbon plant operating expenses[1]. Many studies on optimizing energy use from the distillation process have been carried out, both in scientific and industrial environments. Many techniques are used to achieve this, according to the operating conditions that exist in each place where the distillation process is carried out by considering various factors. An imbalance in the distillation process, such as the reflux and boil-up ratios employed or the feed being situated in the distillation column differently than anticipated owing to changes in the feed's composition, may result in high energy consumption. The location of the feed on the tray must have good accuracy so that the balance of the liquid and vapor phases can occur properly. Determination of the location of this incoming feed can be estimated at three predicted location points[2]. In another study conducted by Soun Ho Lee (2011) titled optimize the design for distillation feed, he discusses the effect of feed conditions and how the location of the feed entering the distillation column is a critical point for the distillation column's performance [3].

Many parameters of the distillation process, such as feed temperature, feed positioning on the tray, inter condenser and reboiler, and column efficiency enhancement, may be regulated to decrease energy usage [1]. Energy-saving initiatives in distillation towers may be divided into four categories: [4] integration process, side condenser and reboiler, and heat pump. In addition to several techniques and strategies for saving energy in the distillation column, techniques are developed to save energy, namely the feed splitting technique. In contrast to the energy-saving technique in the distillation tower using a change technique with vapor phase re-compression or with a heat pump change that requires a high additional investment (capital cost), the feed splitting technique only requires a heat exchanger in its application [5]. Feed splitting in cryogenic distillation has been carried out by [6], presented the results of the research study on energy saving analysis that the author has done on coal tar distillation using the feed splitting technique. The feed splitting technique has been applied to several types of distillation and gives the amount of energy saved varies depending on each type of distillation and the process. In hot distillation, feed splitting is used to pre-heat feed entering the distillation tower using fluid heated from the distillation tower's bottom product. In contrast, feed splitting is used to pre-cool some of the feed entering the distillation tower [6]. The energy requirement in cryogenic distillation is related to the energy load consumed by the refrigeration unit. The upper product of the distillation tower requires cooling below room temperature to convert the distillate vapor into a liquid phase.

The work of the refrigeration unit is very calculated in this distillation process to get the liquid distillate product with the expected quantity. The feed splitting technique is applied to cryogenic distillation with the principle that the feed into the distillation tower is divided into two streams, where only one stream will be cooled using the distillate product stream in a heat exchanger. In contrast, one of the other feed streams enters with hotter conditions. The effects of separating the feed into two streams into the distillation tower are the cooled stream (colder feed) will maintain a lower reflux ratio, and the uncooled heat stream reduces the heat requirements of the reboiler unit. The optimum condition of the feed splitting technique in the cryogenic distillation process using two simulation models is the cooled vapor phase ratio of 89%. In this ratio, the amount of energy consumed in the condenser unit is 82.58 MJ/hour, and the reboiler unit is 281.5 MJ/hour. The split feed ratio significantly impacts the energy consumed in the feed splitting technique. The feed splitting technique for azeotrope distillation of water-ethanol was conducted by Tavan and Shahhosseini (2016). An azeotropic mixture between water and ethanol has specific characteristics in the separation process. Boiling points close together will certainly give a more significant effort to achieve a product with the desired purity level. This separation process has drawbacks, which require high capital investment and external energy input [5]. The feed splitting method divides into two streams for azeotrope ethanol-water distillation. One of the inlet feed streams is heated by the stream from the bottom product of the 2nd distillation process of the entire process chain. Simulation of feed splitting in azeotropic ethanol-water distillation, the amount of energy saved is 27.5% of the overall energy used in the condenser and reboiler units.

Applying the feed splitting technique to another type of distillation, namely reactive distillation, also impacts the amount of energy consumed. Although not many journals discuss the feed splitting technique in reactive distillation [7]. Research [7] outlines synthesizing butyl propionate from n-butanol and propionic acid using a sulfuric acid solution catalyst or a cation resin. In butyl propionate distillation, this feed splitting technique reduces the total annual cost by 10.4%, from $358,700 to $321,400. In comparison, it also reduces the total annual capital cost by 10.2% from $207,400 to 186,200 and reduces operating costs by 11.9% from %128,100 to $112,800. There is also a study conducted by Mohammad Asodallahi (2017) using the feed splitting technique in ethane-ethylene separation, which can reduce energy consumption by 22% in the condenser and 24% in the reboiler [8]. The Feed Splitting technique can be an alternative to save energy in a distillation tower while still paying attention to important points in a distillation process. In several types of distillation according to the process and product, the application of this feed splitting technique gives different results. Before the feed splitting technique is applied to a distillation process, the procedure steps carried out are a concern that must be reviewed and reviewed to maintain product purity targets following specifications and minimum annual total costs. The feed splitting technique may be used to investigate the energy demands that can be saved in the process during the initial design of a distillation tower or while the distillation tower is in operation. Compared to other energy-saving techniques, the feed splitting method is an alternative energy-saving option worth considering since it has reduced capital expenditures for modification or enhancement. The feed splitting method is an alternative energy-saving approach worth considering since it has lower capital expenses for modification or improvement when compared to other energy-saving strategies.

Coal tar is a complex compound containing hydrocarbon and phenolic compounds with large molecular weight, black color, and high viscosity [9]. As a byproduct of coal pyrolisis, coal tar is seen as a liquid fuel feedstock [10]. Coal tar production is not a primary process goal: the primary goal is to produce metallurgical coke for use in blast furnaces, with approximately 90% of total world coke production used for this purpose. In comparison, the remaining 10% is primarily used in cupola furnaces and for other industrial purposes [11]. One of the components of coal tar is a compound Naphthalene (Naphthalene) with a composition in coal tar ranging from 10-13%.). However, what needs to be observed in the production of naphthalene from coal tar is the number of impurities in coal tar which has a boiling point close to this naphthalene compound [12]. The composition of coal tar is generally described as in Figure 1. Distillation of coal tar is carried out using several distillation towers. The top and bottom products from each distillation tower will be directly converted into semi-finished products and then processed in another distillation tower. The existing coal tar distillation process uses four distillation towers in the process. The first unit in the coal tar distillation process involves two towers, whose function is to remove moisture and obtain light oil products (BTX mixture), semi-finished products (middle crude oil), and soft pitch. Then in the 2nd unit, the coal tar distillation process also involves two distillation towers, whose function is to obtain indene, naphthalene, and wash oil products. In general, the following is the composition of coal tar in Figure 2.

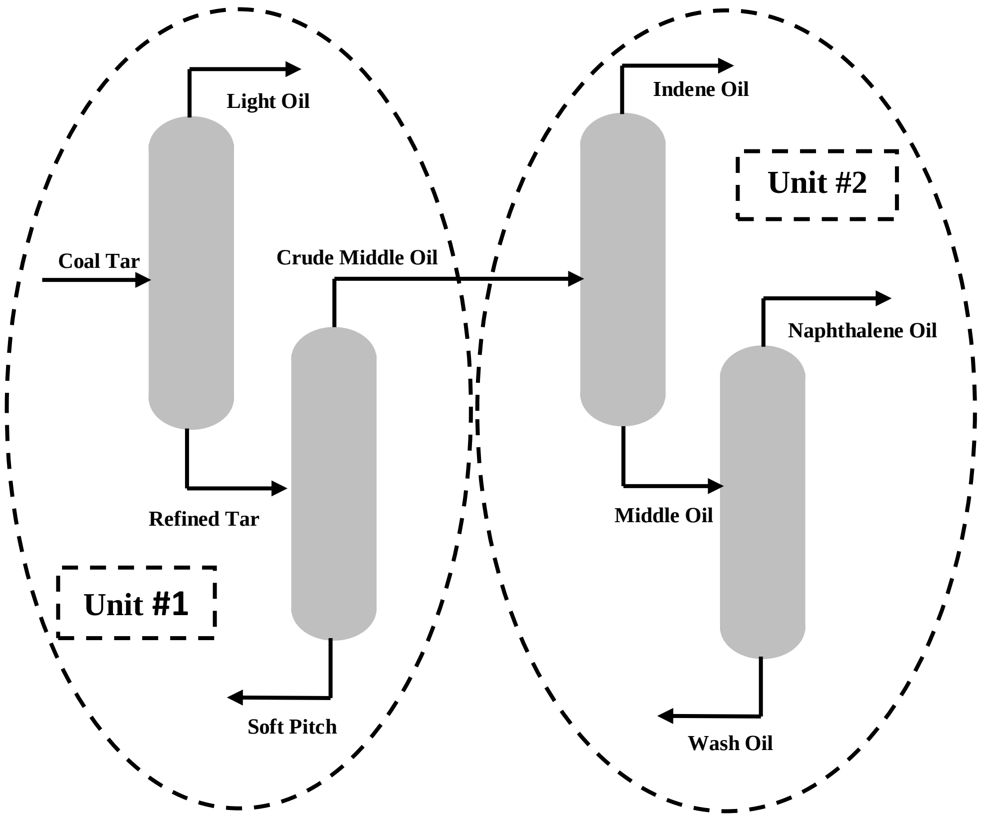
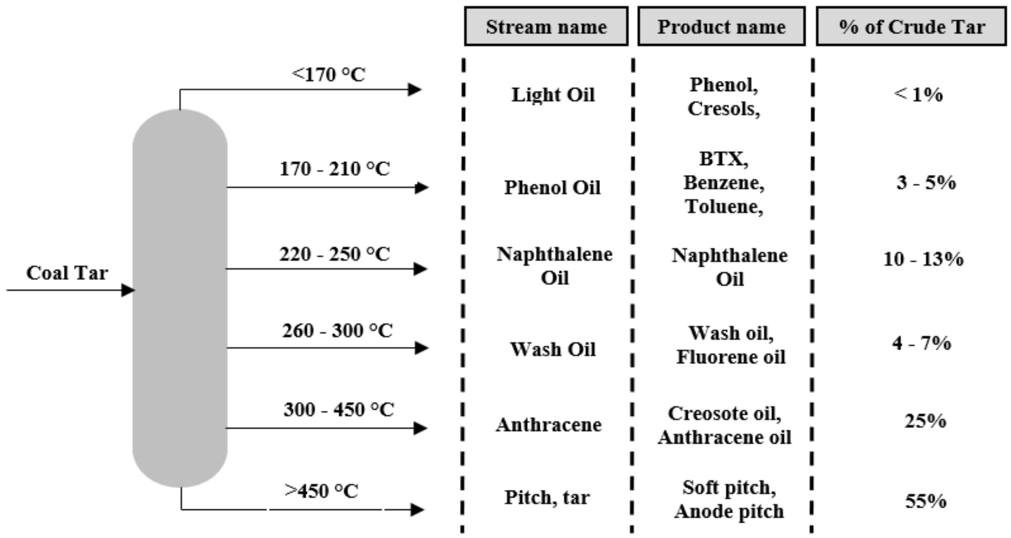


Figure 1. General description of coal tar distillation process.



	Stream name	Product name	% of Crude Tar
<170 °C	Light Oil	Phenol, Cresols,	< 1%
170 - 210 °C	Phenol Oil	BTX, Benzene, Toluene,	3 - 5%
220 - 250 °C	Naphthalene Oil	Naphthalene Oil	10 - 13%
260 - 300 °C	Wash Oil	Wash oil, Fluorene oil	4 - 7%
300 - 450 °C	Anthracene	Creosote oil, Anthracene oil	25%
>450 °C	Pitch, tar	Soft pitch, Anode pitch	55%

Figure 2. General composition of coal tar.

Figure 2 shows the composition of compounds present in coal tar with different boiling points. Requires several distillation tower units to separate these compounds from coal tar. As explained earlier, the coal tar distillation process requires four distillation towers; the first and second towers produce light oil, phenol oil, and a mixture of coal tar pitch with anthracene compounds. Meanwhile, the third and fourth distillation towers will produce naphthalene oil and wash oil products. The subject of study in this research is the second unit of the coal tar distillation process, namely the unit to obtain indene oil, naphthalene oil, and wash oil products. In this 2nd unit, the energy consumption required is quite significant because the required distillation tower bottom temperature is relatively high. The purity of the top product in the second unit's distillation process is also a major problem. The intended purity of the top product of naphthalene is better than 96 percent, and the tolerance of the naphthalene component in the bottom product wash oil is not more than 3 percent. The unwise use of energy in the operation of the distillation tower is the focus of attention in this study. The reflux flow rate returned to the distillation tower to obtain high purity naphthalene products is a burden on this distillation tower reboiler unit. Teknik feed splitting kemudian menjadi salah satu alternatif strategi efisiensi energi yang diterapkan dalam proses distilasi ini, dengan pertimbangan yang telah dikemukakan pada pendahuluan bahwa teknik feed splitting tidak memerlukan nilai investasi yang besar dalam penerapannya.

With the concept that a feed stream has a specific enthalpy value that will enter the distillation column, this enthalpy value will reference the cooling and reboiling needs of the process. With this feed splitting technique, the equilibrium in the column will change due to the location of the incoming feed stream on a different tray. A feed that enters with certain temperature conditions will contact the hot flow from the reboiler and the cold flow from the condenser (reflux). If the flow that enters the distillation column on the tray is lower, the reflux requirement will be less so that the condenser duty will be small. However, the need for reheating in the reboiler unit will be significant. Then it will be investigated as research material to achieve a distillation process with optimal energy consumption and expected product purity. In general, the energy balance of a distillation column can be written as follows:

$$Q_R = Q_C - Fh_F + Dh_D + Bh_B \tag{1}$$

Where,

Q_R = Reboiler Duty Q_C = Condenser Duty
F = Feed flowrate, h_F = Entalphy of feed
D = Distillate flowrate, h_D = Entalphy of distillate
B = Bottom flowrate, h_B = Entalphi of bottom

By using the minimum reflux ratio as in the McCabe-Thiele method, it can be explained that the minimum reflux ratio will be influenced by the conditions of the feed entering the distillation column. The condition of the colder feed or low FhF will reduce the minimum reflux ratio so that the duty on the condenser will decrease and will directly increase the duty on the reboiler. And if the minimum reflux ratio is increased, then the duty on the reboiler will increase. So from the above equation, it can be illustrated that the value of Q_C will greatly influence the Q_R value. Regarding the use of the minimum reflux ratio, as in the McCabe-Thiele method, it can be explained that the minimum reflux ratio will also be influenced by the condition of the feed entering the distillation column. The condition of the colder feed or low Fh_F will reduce the minimum reflux ratio so that the duty on the condenser will decrease and will directly increase the duty on the reboiler. Furthermore, if the minimum reflux ratio increases, then the reboiler's duty will increase. So, from the above equation, it can be illustrated that the value of Q_C will significantly influence the Q_R value. The relationship between the incoming feed temperature conditions and the minimum required reflux ratio can be seen in the following figure.

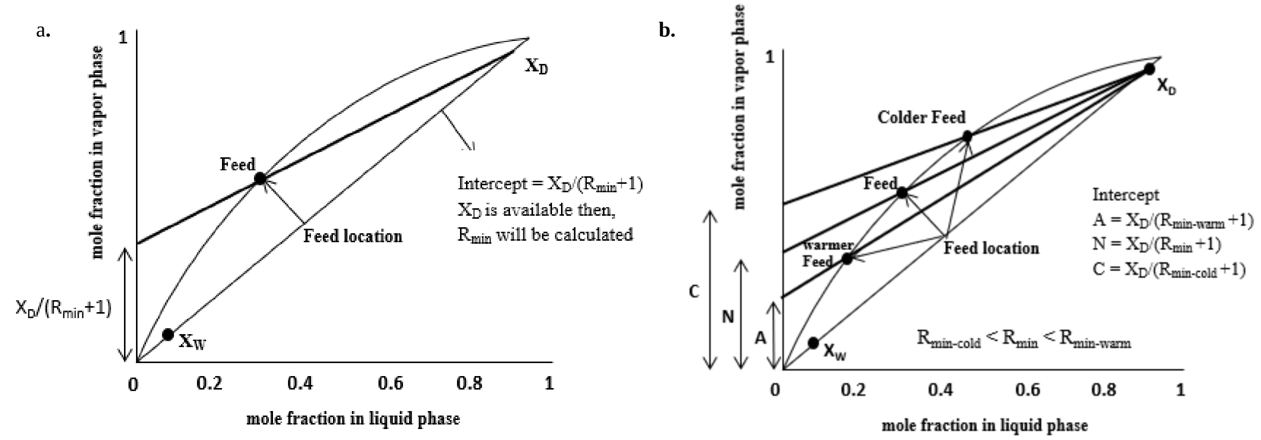


Figure 3. (a) Conventional feed (b) Preheated and pre-cooled feed stream.

2. Research Methodology

The research conducted is research with laboratory tests and field tests. Laboratory testing consists of testing soil properties, compaction, and CBR. The test carried out is a test of the physical and mechanical properties of the soil. Field testing was carried out, namely the dynamic cone penetrometer (DCP) test, to determine the bearing capacity of the soil at the research site, located at Munjul Highway, Pasir Tenjo Village Pandeglang Regency. The combined substance was apus bamboo leaf ash (Gingantocchloa apus).

By referring to some research literature that has been carried out, the feed splitting technique is applied to coal tar distillation. Simulation of feed splitting on coal tar distillation was performed using the simulator with data validation using initial design data and daily operational data so that the simulated conditions matched the actual conditions in the field. Coal tar compounds contain many heavy aromatic compounds and phenolic compounds, so that in the simulations, it is essential to select the fluid package to be used. The following are some of the steps carried out in the feed splitting simulation of coal tar distillation:

1. Collection of distillation tower design data along with other supporting equipment
2. Collect numerical data in daily operation data for the distillation process. Such as pressure, temperature, feed and product flow rate, as well as the purity of the resulting product
3. The collection of properties data from each component involved in the distillation process will be used as a reference for finding compounds or components available in the simulator; if the components or compounds are not available, a characteristic equation of properties that corresponds to the compound will be sought.
4. Input the acquired data and begin the simulation with recommended fluid package modifications. The most appropriate operating conditions will be utilized as a reference for the fluid package used in the following simulation.
5. Determine the initial conditions of the simulation that have been validated with daily data on coal tar distillation operations with steady-state conditions.
6. Simulation of feed splitting with variations in the ratio of cold and hot feeds entering the distillation tower and also variations in the location of two different incoming feeds into the distillation tower
7. Determine the most optimum conditions from the simulation carried out.

It can be described in a flow chart schematic, as shown in Figure 4 dan 5.

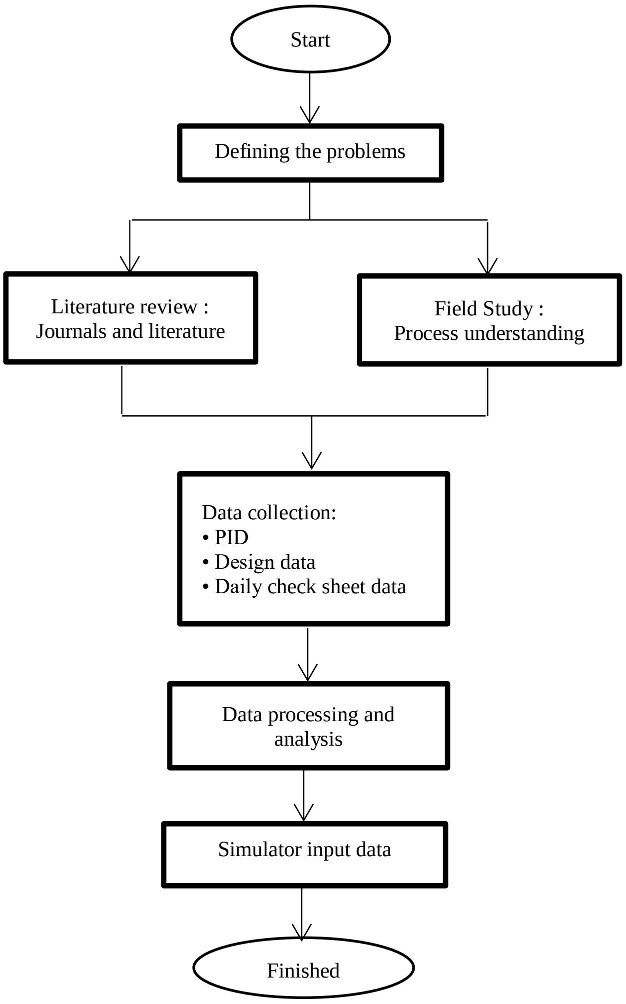


Figure 4. Literature study research flowchart.

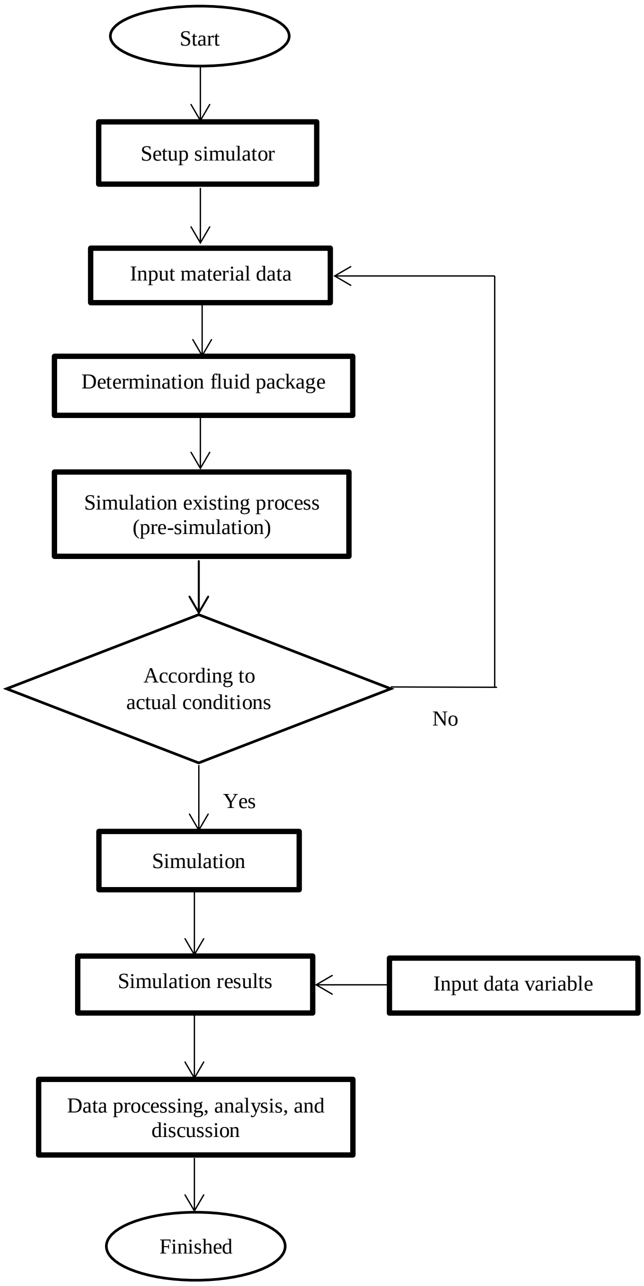


Figure 5. Research flowchart on the simulator.

The research variables were divided into 2, namely ;

1. Fixed variable. The fixed variables are pressure, temperature, feed flow rate. The operating conditions for the distillation towers in the 1st and 2nd towers as fixed variables, shown in Table 1.
2. Variables change. The changing variables include the ratio of the split feed flow rate and the feed's location entering the distillation tower. Simulations were carried out on the 2nd unit of the overall coal tar distillation process. The simulation was chosen only for the 2nd unit because the energy load used is significant in this unit, and the processes that occur are often unstable. Expected product purity is sometimes challenging to obtain. The output target of this 2nd unit distillation is shown in Table 3. The compounds involved in this simulation are shown in Table 3.

Table 1. Operating condition of 2nd unit coal tar distillation

Distillation tower	Operating condition				
	Feed flowrate	Pressure	Top temperature	Bottom temperature	Output product
1st tower	2 m^3/hour	1.2-1.3 Bar	180 ^oC	230 ^oC	Indene oil
2nd tower	1.6-1.7 m^3/hour	1.2-1.4 Bar	225 ^oC	270 ^oC	Naphthalene oil, wash oil

Table 2. Feed flow rate split ratio as variable change.

Feed flow rate split ratio		
Scenario	Cold stream	Hot stream
1	90%	10%
2	80%	20%
3	70%	30%
4	60%	40%
5	50%	50%
6	40%	60%
7	30%	70%
8	20%	80%
9	10	90%

Table 3. Product specification on 2nd unit coal tar distillation.

Product	Purity
Indene	7% content naphthalene
Naftalena	96% content naphthalene, 180 ppm quinoline
Wash Oil	3% content naphthalene

Table 4. Compounds involved in simulation.

Compounds in coal tar	
Light Oil	• Benzene
	• Toluene
	• O-Xylene
	• M-Xylene
	• P-Xylene
Crude Middle Oil	• Indene
	• Naphthalene
Creosote	• Anthracene
	• Acenaphthene
	• Fluorene
	• Dibenzothiohene
	• Phenanthrene
	• 2,6-dimethylnaphthalene
	• biphenyl
Wash Oil	• Phenol
	• Cresol
	• Xylenol
	• Quinoline
	• Iso Quinoline
	• 1-Methyl Naphthalene
	• 2-Methyl Naphthalene
	• Thianaphthene
	• Indole

3. Result and Discussion

The simulation begins by entering the data that has been obtained, such as initial design data, operation data, and properties data. In this simulation, the real state of the field serves as a reference. Several fluid packages are employed to create a simulation as near reality as possible. The fluid package utilized was based on the simulator's recommendations, namely NRTL, Wilson, and UNIQUAC. The activity coefficient models of Wilson, Nonrandom Two Liquid Theory (NRTL), and Universal Quasi-chemical Theory (UNIQUAC) are of the most applied chemical thermodynamic models in phase equilibria calculations and materials behavior prediction or correlation [13]. All three thermodynamic models have their benefits and drawbacks. They may be employed in binary and ternary vapor-liquid and liquid-liquid equilibrium systems [14]. A combination of nonelectrolyte components such as hydrocarbons, ketones, esters, amines, alcohols, nitriles, and water may be represented by the UNIQUAC equation [15]. There are differences in the simulation results from the three suggested fluid packages. The UNIQUAC fluid package was finally chosen as the basis for calculations in this simulation because the results obtained were closest to the actual conditions. The initial simulation is the state before the feed splitting technique is applied to the stream entering the 2nd distillation tower. The first distillation tower has 60 trays, and the feed enters on the 30th tray, while the second distillation tower has 70 trays, and the feed enters on the 35th tray. An overview of the initial simulation is shown in Figure 6.

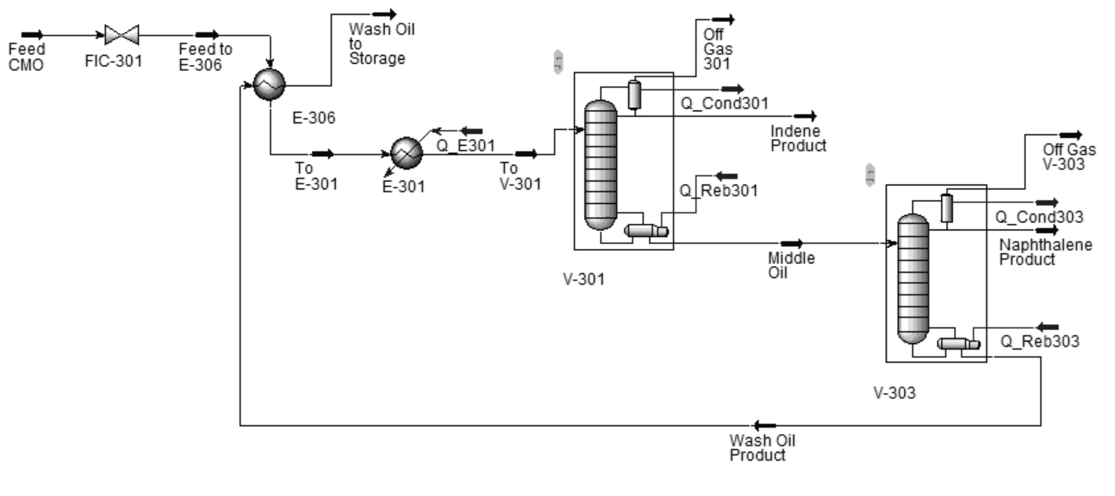


Figure 6. Simulation before feed splitting.

In the initial simulation, the product purity specifications were obtained as expected. In the first distillation tower, the product purity of indene oil is 37% with an impurity component, namely naphthalene, which is 3%. To achieve naphthalene purity of 96% and wash oil purity of 3%, the bottom stream from the first distillation tower was redistilled in the second. The energy load on the 2nd distillation tower is 6.048 x 105 kcal/hour on the condenser unit and 6.060 x 105 kcal/hour on the reboiler unit. The study in this research is the incoming feed split into two streams before entering the 2nd distillation tower to reduce the energy load on the condenser and reboiler units. The feed-in-feed ratio is split into variables to be observed to obtain optimum conditions. In addition to the split feed ratio, the variable studied in this study is the location of the incoming feed from the two split feed streams into the

2nd distillation tower. The simulation description after the feed splitting technique is applied to the 2nd distillation tower, shown in Figure 7. In the 35th and 53rd tray placements, the highest savings were found in a series of simulations. Table 5 shows the outcomes of the simulation.

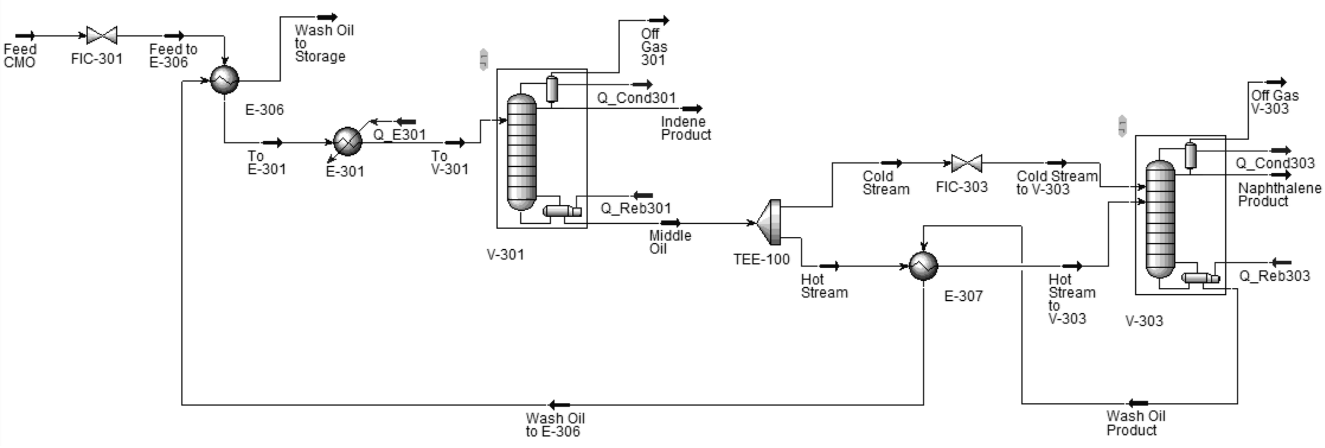


Figure 7. Simulation after feed splitting is applied.

Table 5. The results of the feed splitting simulation at the 35th and 53rd tray locations.

Feed Tray Position	Split Scenario		Duty (10^5 kcal/hour)		Energy Saving (%)	
	Cold stream (tray 35th)	Hot stream (tray 53rd)	Condenser	Reboiler	Condenser	Reboiler
Tray 35th and 53rd	90	10	5.928	5.910	1.98	2.48
	80	20	5.928	5.911	1.98	2.46
	70	30	5.927	5.913	2.00	2.43
	60	40	5.926	5.903	2.02	2.59
	50	50	5.926	5.896	2.02	2.71
	40	60	5.924	5.893	2.05	2.76
	30	70	5.923	5.887	2.07	2.85
	20	80	5.921	5.881	2.10	2.95
	10	90	5.782	5.74	4.40	5.28

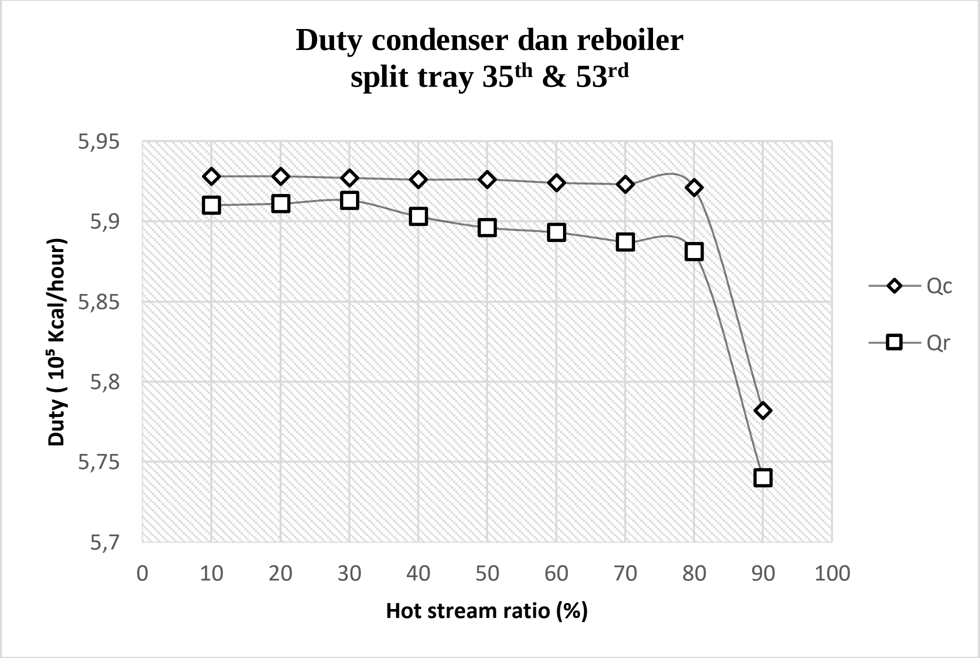


Figure 8. Graph of the decrease in energy consumption on the 35th and 53rd feed splitting tray simulation.

Figure 8 shows a significant decrease in energy consumption in the composition of the hot feed flow rate of 90%. At the hot feed flow rate of 90%, the cold feed flow rate is only 10%, causing a decrease in the reflux ratio in this distillation process. From the results of several simulations, the most optimum variation of the feed inlet ratio is the ratio of 10% for cold flow and 90% for hot flow. Furthermore, the location of the split feed in the distillation tower is on the 35th tray for the cold feed stream and the 53rd tray for the hot feed stream. The energy saved from the simulation results is 4.40% in the condenser unit and 5.28% in the reboiler unit, shown in Table 6. The result proves that the enthalpy value of a feed stream that enters the distillation tower can affect the heat requirement of the reboiler unit.

Table 6. Simulation result data.

Equipment unit	Before split	After split (optimum)	Percentage energy-saving (%)
Condenser	6.048×10^5 kcal/h	5.782×10^5 kcal/h	4.40%
Reboiler	6.060×10^5 kcal/h	5.740×10^5 kcal/h	5.28%

As a result of the low boiling point differences between the compounds in coal tar and other distillation types, the results of the feed splitting simulation on coal tar distillation provide a low energy saving value compared to other energy efficiency analysis studies in other distillation types. The temperature difference is not too far makes the heat exchange in the heat exchanger unit (E-307) not too large. Another thing that affects the energy saved is the feed flow rate factor included in this distillation system. The initial design of this coal tar distillation tower unit is only in the range of 2 m3/hour for the inlet feed flow rate; if it is greater than that, it will be challenging to obtain the desired product purity. However, overall aspects of this simulation, while still considering the purity of the naphthalene product as the main priority in the distillation process, the current feed splitting simulation conditions that the author has carried out are the most optimum. Energy analysis studies on coal tar distillation will continue to be developed in the future with other distillation units that have the potential to have high energy loads.

4. Conclusion

The UNIQUAC thermodynamic model is adequate and near the real circumstances in this simulation. By considering the compounds involved in this distillation process, the feed splitting simulation results in the coal tar distillation process of the naphthalene unit. It was found that the best feed inlet location was on the 35th and 53rd trays. The energy saved from the simulation is 4.4% in the condenser unit and 5.28 in the reboiler unit. Thus, the conclusions obtained from the overall research on the energy analysis study of the coal tar distillation process using the feed splitting method.

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