

## Development of an integrated structure of CHP and heavy hydrocarbons liquids using Fischer-Tropsch Synthesis

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### Abstract

Recent developments in gas-to-liquid conversion industry lead to reduction in initial investment, and it is expected by growth in demand for refined products in countries and the need to import these products in the countries. Implementing such projects can prevent currency outflow. In this article an integrated structure is developed for producing liquid fuels from natural gas through Fischer-Tropsch synthesis. This integrated structure consists of steam and gas turbines and HRSG heat exchanger for power and heat recovery. Auto thermal reforming method, due to its high efficiency and exothermic nature is developed here for producing the synthesized gas. The exergy analysis indicates that the highest destruction rate of the equipment is related to the Fischer-Tropsch synthesis unit by 37.34% and the lowest to the gas turbine by 0.3%. The amounts of exergy destruction in compressors and pumps, gas turbine and steam turbine are 2.51%, 0.29% and 3.26%, respectively. The more the rate of exergy destruction in compressors, pumps and turbines, the more the rate of consumed power in the aforementioned equipment; consequently, the exergy destruction in these equipment should be minimized. The overall thermal efficiency (HHV base) of this Integrated structure is 65.55%, which yields 9 MW power for industrial and residential consumption, and heat with the amount of 21 MW for utilizing in reboilers.

### Keywords

*Integration, Gas-to-liquid, Fischer-Tropsch, Exergy*

## 1. Introduction

The enforcement of global pressures on reducing greenhouse gas emissions together with, legislative frameworks in Europe and the USA are force manufacturers of liquid transportation fuels to meet the stricter emission standards. The fact that Fischer-Tropsch technology is considered as a manner in achieving environmental compliance is inevitable. As crude oil production declines and its price rises, the Fischer-Tropsch as a progressively striking technology in the energy mix empowers the synthetic hydrocarbons production from coal or natural gas feedstocks. Fischer-Tropsch products are ultraclean fuels containing no aromatics, sulfur, or nitrogen compounds. The Fischer-Tropsch synthesis is impeccable, emerging option for environmentally sound production of fuels from both biomass and fossil fuels. According to large fossil fuels

reserves such as coal, declining petroleum reserves, and significant, projected increases in demand for liquid fuels, it is projected to play a promising role in the future. Fischer-Tropsch synthesis is based on several gas feedstock syntheses including coal gasification, natural gas, and biomass. Scientifically, Fischer-Tropsch synthesis is a catalyzed chemical reaction, where syngas, a mixture of carbon monoxide and hydrogen, is converted into gaseous, liquid, and solid hydrocarbons and a considerable amount of oxygenates (Speight, 2014).

Biomass is a great contributor in energy sector. It is the only natural, renewable carbon resource and a considerable substitute for fossil fuels. There exist a wide range of biomass based materials like crop residue, agro-crops, and several tree species. These materials can be burnt directly for energy and can be

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processed further to be converted into liquid fuels like ethanol and diesel (Ail & Dasappa, 2016). There exist many studies in optimizing gas-to-liquid processes in oil and gas industry (Ghorbani, Hamed, Shirmohammadi, Mehrpooya, & Hamed, 2016). Various approaches are introduced for optimizing energy in a GTL unit with a capacity of 10,000 BPD at different levels of the process by applying optimizer software (Majid Amidpour, Panjeshahi, & SHARIATI, 2009). Certain residues, like that of palm oil, either have a disposal problem for the processing industry or are not used and thus, there is a considerable potential for improvement. These factors indicate a strong driving force for the development of innovative polygeneration plants based on solid residues (Salomón, Gomez, & Martin, 2013). Status of trending biomass to liquid conversion processes and emphases on the technological developments in Fischer Tropsch process is explored (Ail & Dasappa, 2016). Exergy analyses are run to assess and optimize different processes (Ghorbani, Maleki, Salehi, Salehi, & Amidpour, 2013; Petrakopoulou, Tsatsaronis, & Morosuk, 2013; Sheikhi, Ghorbani, Shirmohammadi, & Hamed, 2015; Shirmohammadi, Ghorbani, Hamed, Hamed, & Romeo, 2015), (i.e Exergy analysis is run to assess a biogas production from a municipal solid waste landfill (Xydis, Nanaki, & Koroneos, 2013)). A production process of Fischer–Tropsch fuels from biomass is optimized through Exergy analysis. The greatest volume of exergy loss occurs in biomass gasification and in generation of electricity from the Fischer–Tropsch tail gas (Prins, Ptasinski, & Janssen, 2005). Economic assessment is run for a biomass-fired cogeneration plant supplied with an Organic Rankine Cycle as a heat source for small scale heat distribution system (Tańczuk & Ulbrich, 2013). Energy and environmental assessments are run for a small-scale biomass gasification CHP utilization in the industry (Adams & McManus, 2014). Economic and CO<sub>2</sub> emissions reduction analyses of wastewater treatment plant are run for biogas recovery and its consumption in a small power plant in Brazil (dos Santos et al., 2016). A biomass-to-synthetic natural gas process is analyzed through the second law of thermodynamic i.e. exergy analysis. Biomass gasifier, CH<sub>4</sub> synthesis part and CO<sub>2</sub> capture unit have the greatest volume of exergy loss, respectively. The range of about 69.5–71.8% can be obtained for the overall exergetic efficiency of the biomass-to-SNG process (Juraščík, Sues, & Ptasinski, 2010). A techno-economic comparison of Fischer-Tropsch and fast

pyrolysis as the means of utilizing sugar cane bagasse in transportation fuels production is made by (Michailos, Parker, & Webb, 2017). The Fischer–Tropsch technology dominates both large-scale and small-scale projects in middle distillate liquid transportation fuel markets. The large technology providers follow strategies to scale-up plants to provide commercial economies of scale, which to date are more costly than originally forecasted. Some small-scale technology providers are now focusing on GTL with efforts to eliminate associated gas flaring in remote producing oil fields. There exists the potential on various scales of GTL to supply liquid fuels in land-locked gas-rich regions (Wood, Nwaoha, & Towler, 2012).

In this article, an integrated structure of CHP and liquid fuels from natural gas developed through Fischer-Tropsch synthesis. In the GTL process, conversion of natural gas from liquid to gaseous phase considerable amount of energy is revealed. This energy is utilized for cogeneration of power and heat with HRSG heat exchange, steam turbine and gas turbine. From reviewing some studies it is deduced that Peng-Robinson equation of state is applied for phase equilibrium analysis, and Lee-Kesler equation of state is applied for calculating enthalpy and entropy are applicable (Ahmed, 2013; Reid, Prausnitz, & Poling, 1987). In this article Peng-Robinson equation of state for phase equilibrium analysis, and Lee-Kesler equation of state to calculate enthalpy and entropy are applied in thermodynamic model. These equations provide appropriate results when calculating thermodynamic properties of nitrogen and hydrocarbons mixture. The liquid and vapor equilibrium phases are calculated through Aspen Hysys better in comparison with Aspen Plus and Pro, in estimating the temperature of dew point has less precision (M Amidpour et al., 2015; Ghorbani, Hamed, Shirmohammadi, Hamed, & Mehrpooya, 2016; Ghorbani, Mafi, Shirmohammadi, Hamed, & Amidpour, 2014).

## 2. Thermo Physical Properties of Natural Gas Hydrocarbons

Natural gas hydrocarbons consist of methane, ethane, propane, and butane, and non-hydrocarbon gases like carbon dioxide, nitrogen, or helium. The difficulties in thermo physical properties of natural gas hydrocarbons are mainly of two sources. One is the complex nature of the thermodynamic and physical properties of mixtures and the other, the small temperature approach between the hot and cold composite curves in multi-stream heat exchangers and wide temperature range. This

phenomenon not only increases the difficulty of the modelling for the problem, but also adds to the non-linearity nature of the components when running the optimization procedure. Consequently, the accurate forecast of phase equilibrium for vapour-liquid ratios and values of enthalpy and entropy is essential for the mixtures/blends.

## 2.1. Vapour - Liquid Equilibrium Calculations

The equilibrium condition for every component of a two-phase mixture is expressed by the equality of fugacity. The equilibrium criterion is presented by:

$$f_i^V = f_i^L \quad i = 1, 2, \dots, n \quad (1)$$

where,

$f_i^V$  = fugacity of component  $i$  in vapour phase mixture  
 $f_i^L$  = fugacity of component  $i$  in liquid phase mixture and

$n$  = number of components in mixture

The fugacity coefficient, defined as the fugacity to pressure ratio, of each component in any phase is to pressure, temperature and volume by the following generalized thermodynamic Eq.(7):

$$\ln \phi_i = \frac{1}{RT} \int_V^{\infty} \left[ \left( \frac{\partial P}{\partial n_i} \right)_{T,V,n_{j \neq i}} - \frac{RT}{V} \right] dV - \ln Z \quad i = 1, 2, \dots, n \quad (2)$$

Where,  $V$  = total volume of  $n$  moles of the mixture,  $n_i$  = number of moles of component  $i$

$Z$  = compressibility factor of the mixture

The fugacity coefficient can be calculated by an equation where pressure, temperature, volume and compositions are of concern, that is, an equation of state. In general, any equation of state which provides reliable volumetric data over the full range of the above integral can be applied in describing the fluid phase behaviour. The simplest and the most applicable equation is the semi-empirical two-parameter cubic equation such as the Peng-Robinson and Soave-Redlich-Kwong equations. In this study, the Peng-Robinson equation of state is applied in the calculating the phase equilibrium. The Peng-Robinson equation of state is presented as follows:

$$P = \frac{RT}{v-b} - \frac{a\alpha}{v(v+b)+b(v-b)} \quad (3)$$

Imposing the classical critical point conditions on equation (3) and solving for parameters  $a$  and  $b$  yields:

$$a = \Omega_a \frac{R^2 T_c^2}{P_c}, \quad \Omega_a = 0.45724 \quad (4)$$

$$b = \Omega_b \frac{RT_c}{P_c}, \quad \Omega_b = 0.07780$$

where, the subscript  $c$ , is the values at the critical point and  $R$  is the gas constant.

The temperature dependent parameter  $\alpha$  is defined through

$$\alpha = \left[ 1 + (0.3796 + 1.5422\omega - 0.2699\omega^2) (1 - \sqrt{T_r}) \right]^2 \quad (5)$$

where,  $\omega$  is the acentric factor.

The random mixing rule is recommended for all two-constant cubic equations of state, which defines the constant and temperature dependent parameters of Peng-Robinson equation of state for mixtures as:

$$P = \frac{RT}{v-b_m} - \frac{(a\alpha)_m}{v(v+b_m)+b_m(v-b_m)} \quad (6)$$

$$(a\alpha)_m = \sum_i \sum_j [y_i y_j \sqrt{a_i a_j \alpha_i \alpha_j} (1 - k_{ij})]$$

$$b_m = \sum_i [y_i b_i]$$

where, the indices  $i$  and  $j$  are the components and  $k_{ij}$  is the binary interaction coefficient. Eq.

(6) can be rewritten as:

$$Z_m^3 + (B_m - 1)Z_m^2 + (A_m - 3B_m^2 - 2B_m)Z_m - (A_m B_m - B_m^2 - B_m^3) = 0$$

$$A_m = \frac{(a\alpha)_m P}{(RT)^2}$$

$$B_m = \frac{b_m P}{RT}$$

(7)

where,  $Z$  is a constraining factor,  $A$  and  $B$  are the coefficients related to the gas state parameters and  $m$  is the mixture.

## 2.2. Calculating the Thermodynamic Properties

The Lee-Kesler equation of state is applied for thermodynamic properties prediction of non-polar mixtures. In this article, natural gas hydrocarbons consists of methane, ethane, propane, and butane, together with non-hydrocarbon gases. Consequently, the Lee-Kesler equation of state is applied in the of the enthalpy and entropy calculation. This model is expressed as:

$$Z = Z^{(0)} + \frac{\omega}{\omega^{(r)}} (Z^{(r)} - Z^{(0)}) \quad (8)$$

where,  $\omega$  is an acentric factor, 0 and  $r$  is the relevant parameters of simple and reference liquids.

In this study the Peng Robinson equation of state is applied for calculating phase

equilibrium of vapor and natural gas hydrocarbons, and Lee kasler equation of state is applied in predicting entropy and enthalpy. The results indicate that Aspen Hysys outperforms to Aspen plus and Pro in terms of calculating phase equilibrium of vapor and liquid as well as accuracy, while the same is of less accuracy for estimating dew point and wet bulb temperatures. In comparison to result of error which is less than 0.5 percent, it can be neglect able. In this study, since separation is of high priority, Hysys software is applied for simulation.

### 3. Process Description

In today’s economy the energy crisis is considered as one of the most important problems. One way of consuming natural gas is its conversion into another valuable products. The Fischer-Tropsch synthesis is a proper manner in converting natural gas into more valuable products like liquid fuels. In the synthesis the gas (carbon monoxide - hydrogen) is eventually converted into linear aliphatic hydrocarbons and oxygenated products. The main reason for adopting this method are: 1). the rising trend of oil reserves 2) away from the consumer market and transportation problems and 3) environmental regulations and the need for clean fuel.

One factor that prevents the development of GTL technology is the cost of the product which makes it impossible to compete with other refined products. Recent developments in GTL industry lead to a reduction in initial investment. A rise in demand for refined products in the countries and the need to import these products is expected. Implementing such projects can prevent

currency outflow from the countries. GTL conversion process has three steps: 1). synthesis gas from natural gas, 2). conversion of synthesized gas into different hydrocarbons and 3). Hydrocracking to produce high quality fuel.

In GTL process, converting natural gas from the gaseous phase to some products in the liquid phase results in the release of a great quantities of energy and multiple hot and cold streams in this process makes it to have a significant temperature difference. Consequently, GTL process is intense energy producer and has the capability of producing considerable amounts of it, therefore, it is possible to build a power plant in its vicinity. This issue indicates that GTL process can not only provide its required energy but also produce power.

In this article, among the different methods of producing synthesis gas (Catalytic Partial Oxidation, Non-Catalytic Partial Oxidation, Combined Reforming Steam-Methane-Reforming and Auto thermal Reforming) auto thermal reforming (ATR) is of concern. Because of high efficiency and exothermic nature auto thermal reforming (ATR) is more appropriate when it comes to energy consumption. In (ATR) partial oxidation and adiabatic reforming with steam are applied together. Here, the synthesized gas production reactor (Gibbs reactor) converts mixture of natural gas, oxygen and steam to synthesis gas through auto thermal reforming.

The properties of feed and product streams for an integrated structure of CHP and liquid fuels from natural gas through Fischer-Tropsch synthesis are tabulated in Table 1.

**Table 1.** Process Properties of the integrated structure including Fischer-Tropsch Synthesis

| Stream no. | T (°C) | P (kPa) | Mass flow (kgmol/h) | Stream no.      | T (°C) | P (kPa) | Mass flow (kgmol/h) |
|------------|--------|---------|---------------------|-----------------|--------|---------|---------------------|
| Feed       | 35     | 3700    | 625                 | 601             | 847    | 9000    | 1831                |
| 101        | 165    | 3700    | 1251                | 602             | 717    | 9000    | 1831                |
| 102        | 300    | 3700    | 1251                | 603             | 363    | 450     | 1831                |
| 103        | 220    | 3200    | 1163                | 606             | 152    | 450     | 1831                |
| 104        | 220    | 3200    | 9                   | 611             | 25     | 450     | 1831                |
| 105        | 220    | 3200    | 1138                | HT-COND         | 145.5  | 3200    | 29.82               |
| 106        | 220    | 3200    | 305                 | HT-COND2        | 220    | 3200    | 27.67               |
| 107        | 220    | 3200    | 305                 | Liquid Products | 220    | 3200    | 33                  |
| 108        | 165    | 3200    | 305                 | Syngas          | 1121   | 3700    | 2005                |
| 109        | 220    | 3200    | 0.3                 | Water           | 246    | 3700    | 350                 |
| 110        | 241    | 3700    | 0.3                 | WAX             | 237    | 100     | 28.03               |
| O2         | 25     | 3700    | 350                 | Exhaust         | 3      | 200     | 305                 |

The hydrogen to carbon monoxide ratio for synthesis gas consumed in the GTL process is about 1.6 to 2.65. According to auto thermal method applied here, the appropriate ratio is about 1.981. In this process there is no need to

capture carbon dioxide and hydrogen separation units to adjust this ratio.

The schematic of the integrated structure of CHP and liquid fuels from natural gas through Fischer-Tropsch synthesis is shown in Fig. (1).

The unit of Fischer-Tropsch syngas is the core unit of GTL, consequently its reactor is deliberated as the heart of process. The vital process of Fischer-Tropsch is presented as:

| Rxn No. | Specification type | Stoichiometry                                                                       |
|---------|--------------------|-------------------------------------------------------------------------------------|
| 1       | CONVERSION         | 3 H <sub>2</sub> + CO --> CH <sub>4</sub> + H <sub>2</sub> O                        |
| 2       | CONVERSION         | 5 H <sub>2</sub> + 2 CO --> C <sub>2</sub> H <sub>6</sub> + 2 H <sub>2</sub> O      |
| 3       | CONVERSION         | 7 H <sub>2</sub> + 3 CO --> C <sub>3</sub> H <sub>8</sub> + 3 H <sub>2</sub> O      |
| 4       | CONVERSION         | 9 H <sub>2</sub> + 4 CO --> C <sub>4</sub> H <sub>10</sub> + 4 H <sub>2</sub> O     |
| 5       | CONVERSION         | 11 H <sub>2</sub> + 5 CO --> C <sub>5</sub> H <sub>12</sub> + 5 H <sub>2</sub> O    |
| 6       | CONVERSION         | 13 H <sub>2</sub> + 6 CO --> C <sub>6</sub> H <sub>14</sub> + 6 H <sub>2</sub> O    |
| 7       | CONVERSION         | 15 H <sub>2</sub> + 7 CO --> C <sub>7</sub> H <sub>16</sub> + 7 H <sub>2</sub> O    |
| 8       | CONVERSION         | 17 H <sub>2</sub> + 8 CO --> C <sub>8</sub> H <sub>18</sub> + 8 H <sub>2</sub> O    |
| 9       | CONVERSION         | 19 H <sub>2</sub> + 9 CO --> C <sub>9</sub> H <sub>20</sub> + 9 H <sub>2</sub> O    |
| 10      | CONVERSION         | 21 H <sub>2</sub> + 10 CO --> C <sub>10</sub> H <sub>22</sub> + 10 H <sub>2</sub> O |
| 11      | CONVERSION         | 23 H <sub>2</sub> + 11 CO --> C <sub>11</sub> H <sub>24</sub> + 11 H <sub>2</sub> O |
| 12      | CONVERSION         | 25 H <sub>2</sub> + 12 CO --> C <sub>12</sub> H <sub>26</sub> + 12 H <sub>2</sub> O |
| 13      | CONVERSION         | 27 H <sub>2</sub> + 13 CO --> C <sub>13</sub> H <sub>28</sub> + 13 H <sub>2</sub> O |
| 14      | CONVERSION         | 29 H <sub>2</sub> + 14 CO --> C <sub>14</sub> H <sub>30</sub> + 14 H <sub>2</sub> O |
| 15      | CONVERSION         | 31 H <sub>2</sub> + 15 CO --> C <sub>15</sub> H <sub>32</sub> + 15 H <sub>2</sub> O |
| 16      | CONVERSION         | 33 H <sub>2</sub> + 16 CO --> C <sub>16</sub> H <sub>34</sub> + 16 H <sub>2</sub> O |
| 17      | CONVERSION         | 35 H <sub>2</sub> + 17 CO --> C <sub>17</sub> H <sub>36</sub> + 17 H <sub>2</sub> O |
| 18      | CONVERSION         | 37 H <sub>2</sub> + 18 CO --> C <sub>18</sub> H <sub>38</sub> + 18 H <sub>2</sub> O |
| 19      | CONVERSION         | 39 H <sub>2</sub> + 19 CO --> C <sub>19</sub> H <sub>40</sub> + 19 H <sub>2</sub> O |
| 20      | CONVERSION         | 41 H <sub>2</sub> + 20 CO --> C <sub>20</sub> H <sub>42</sub> + 20 H <sub>2</sub> O |
| 21      | CONVERSION         | 43 H <sub>2</sub> + 21 CO --> C <sub>21</sub> H <sub>44</sub> + 21 H <sub>2</sub> O |
| 22      | CONVERSION         | 45 H <sub>2</sub> + 22 CO --> C <sub>22</sub> H <sub>46</sub> + 22 H <sub>2</sub> O |
| 23      | CONVERSION         | 47 H <sub>2</sub> + 23 CO --> C <sub>23</sub> H <sub>48</sub> + 23 H <sub>2</sub> O |
| 24      | CONVERSION         | 49 H <sub>2</sub> + 24 CO --> C <sub>24</sub> H <sub>50</sub> + 24 H <sub>2</sub> O |
| 25      | CONVERSION         | 51 H <sub>2</sub> + 25 CO --> C <sub>25</sub> H <sub>52</sub> + 25 H <sub>2</sub> O |
| 26      | CONVERSION         | 53 H <sub>2</sub> + 26 CO --> C <sub>26</sub> H <sub>54</sub> + 26 H <sub>2</sub> O |
| 27      | CONVERSION         | 55 H <sub>2</sub> + 27 CO --> C <sub>27</sub> H <sub>56</sub> + 27 H <sub>2</sub> O |
| 28      | CONVERSION         | 57 H <sub>2</sub> + 28 CO --> C <sub>28</sub> H <sub>58</sub> + 28 H <sub>2</sub> O |
| 29      | CONVERSION         | 59 H <sub>2</sub> + 29 CO --> C <sub>29</sub> H <sub>60</sub> + 29 H <sub>2</sub> O |
| 30      | CONVERSION         | 61 H <sub>2</sub> + 30 CO --> C <sub>30</sub> H <sub>62</sub> + 30 H <sub>2</sub> O |
| 31      | CONVERSION         | CO + H <sub>2</sub> O --> CO <sub>2</sub> + H <sub>2</sub>                          |

The growth of the hydrocarbon chain in the Fischer-Tropsch process depends on the

operating conditions and the catalyst, it can also lead to heavier hydrocarbons than the C<sub>30</sub>, but because the software database does not contain hydrocarbons heavier than C<sub>30</sub>, therefore, chemical reactions are defined as C<sub>30</sub>.

The syngas input stream of unit with the exhaust stream from the heat exchange reactor exchange heat and then enters the Fischer-Tropsch reactor. Due to the large heat generated by the process for proceeding the isothermal process, saturation water is used to control the temperature of the reactor. The generated heat in the reactor leads to vaporize the saturation water and the conversion of it into water vapor, which can later be used to generate power.

Output products from the Fischer-Tropsch reactor by helping of gradual cooling in the three separators, are converted to lightweight, heavyweight (wax) and associated gases hydrocarbons. Lightweight and heavy liquid hydrocarbons are the main products of the process, and associated gases are sent to the power plant to enter the gas turbine and produce power. The following Fig. (1) shows the flow diagram of the Fischer-Tropsch unit.

In this presented integrated structure, natural gas is composed of: 5.45% N<sub>2</sub>, 89.5% CH<sub>4</sub>, 5.79% C<sub>2</sub>H<sub>6</sub>, 3.65% C<sub>3</sub>H<sub>8</sub>, and 2.6 % C<sub>4</sub>H<sub>10</sub><sup>+</sup>.

After simulating the process, the thermodynamic condition like temperature, pressure, molar flow rate of each stream, consumed power of compressors and pumps, the heat transfer rate in heat exchangers, generated power of gas and steam turbines are derived. This process can be analyzed and optimized through aforementioned thermodynamic properties,

The total power produced by gas and steam turbines is 9417.8 kW, while, the power consumption of compressors and pumps for producing liquid fuel from synthesis of Tropsch-Fischer is about 110 kW. A portion of production capacity of gas turbine and steam turbine (1.23%) with 0.95 efficiency ratio in the generator convert into required power consumed in compressors and pumps in the new integrated process and the remaining portion is utilized for industrial and residential use.

The specifications of Shell and Tube exchangers in this newly developed integrated structure, are tabulated in Table 3.

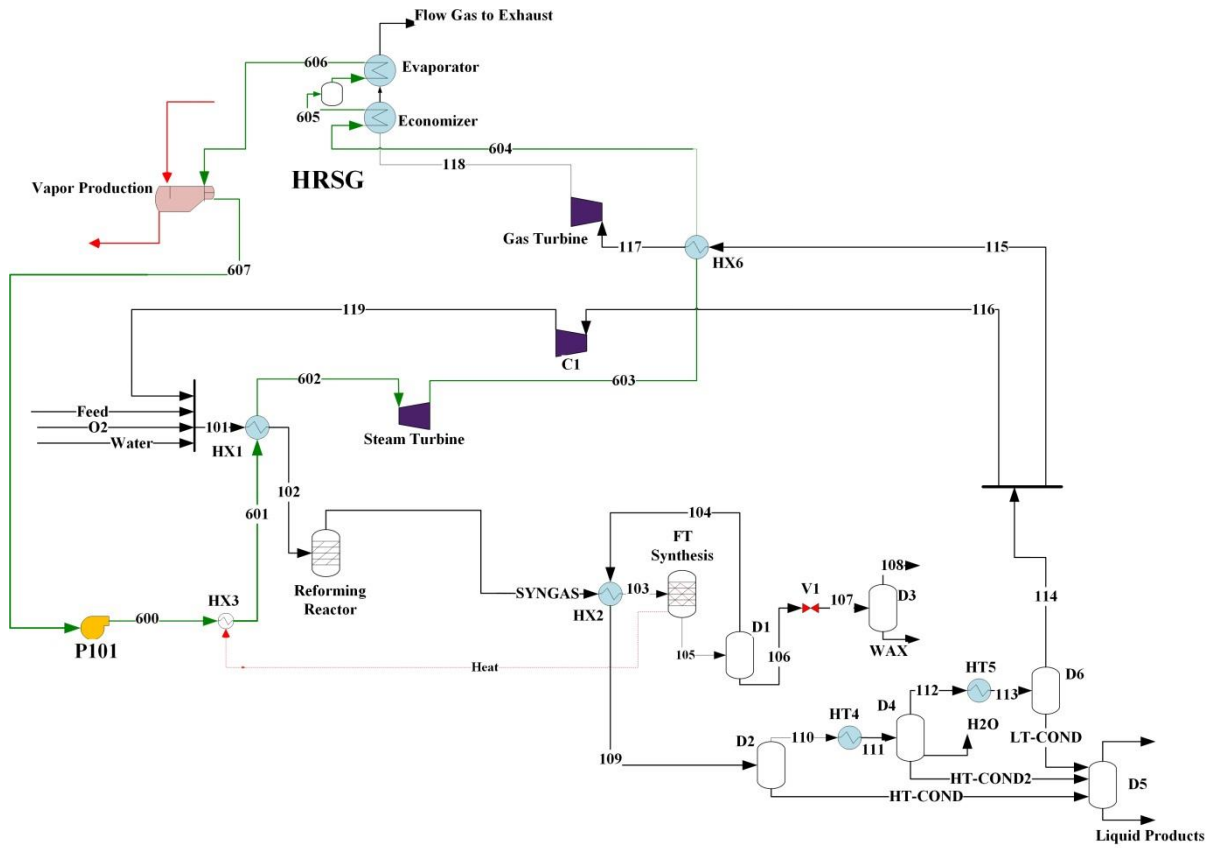


Figure 1. Schematic of process flow diagram of integrated structure

Table 2. Properties of equipment used in the integrated structure

| Unit | Pressure ratio | Inlet P (kPa) | Adiabatic Efficiency (%) | Electrical power consumption (kW) |
|------|----------------|---------------|--------------------------|-----------------------------------|
| C1   | 1.156          | 3200          | 75                       | 0.047                             |
| P101 | 20             | 500           | 75                       | 110.14                            |
| GT   | 0.062          | 3200          | 75                       | 344.715                           |
| ST   | 0.05           | 10000         | 75                       | 9074                              |

Table 3. Specifications of heat Exchangers Applied in the Integrated Structure of CHP and heavy hydrocarbons liquids from Natural Gas through Fischer-Tropsch Synthesis

| <i>Shell and Tube exchanger</i> |                    |                   |          |                              |
|---------------------------------|--------------------|-------------------|----------|------------------------------|
|                                 | Min. Approach (°C) | $\Delta T_m$ (°C) | Duty(kW) | Hot/ Cold Utility(kg.mole/h) |
| HX1                             | 6.95               | 16.73             | 10415963 | -                            |
| HX2                             | -                  | -                 | 710.513  | Cooler                       |
| HX3                             | -                  | -                 | 39990    | Heater                       |
| HX4                             | -                  | -                 | 5147     | Cooler                       |
| HX5                             | -                  | -                 | 3256     | Cooler                       |
| HX6                             | 11.57              | 27.03             | 468477   | -                            |

#### 4. Exergy Analysis

The maximum work obtained for the system in case of reaching the environment conditions is called exergy. Dead state is at 25°C and 1 atmosphere (Sheikhi, Ghorbani, Shirmohammadi, & Hamed, 2014). The difference between reversible and irreversible work is equal to irreversibility, Eq.10:

$$Ex_d = |(W_{rev} - W_{real})| \quad (10)$$

As a matter of fact, the variance between two works is to the loss of exergy. And the volume of entropy production is greater than or equal to zero, where exergy destruction is obvious. Therefore, the exergy loss low is equal to the entropy generation or second law of thermodynamic (Bejan & Tsatsaronis, 1996; Pattanayak, Sahu, & Mohanty, 2017).

$$E_{destroyed} = T_0 S_{gen} \quad (11)$$

Exergy is consist of physical and chemical status:

$$e = e^{ph} + e^{ch} \quad (12)$$

Physical Exergy is obtained by Eq. (13):

$$e^{ph} = (h - h_0) - T_0(S - S_0) \quad (13)$$

The chemical exergy is also achieved by Eq. (14):

$$e^{ch} = \sum x_i e_0^i \quad (14)$$

Equation 15 is applied for real mixture. Difference of intermolecular forces must also be considered.

$$e^{ch} = \sum x_i e_0^i + \Delta G^{mix} \quad (15)$$

Gibbs free energy is acquired by following equation:

$$\Delta G^{mix} = RT_0 \sum x_i \gamma_i \quad (16)$$

Exergy balance for a component is acquired by Eq. (17):

$$Ex_i + Ex_{Qi} = Ex_o + Ex_{Qo} + W_{sh} + Ex_d \quad (17)$$

Where,  $Ex_d$  is the irreversibility in the system. Using this equation, the losses in each equipment can be obtained.

**Table 4.** Exergy Destruction of CHP and heavy hydrocarbons liquids from Natural Gas using Fischer-Tropsch Synthesis

| Equipment         | $\dot{E}_F(kW)$ | $\dot{E}_p(kW)$ | $\dot{E}_D(kW)$ | $Y_D(\%)$ |
|-------------------|-----------------|-----------------|-----------------|-----------|
| HX1               | 149237.1        | 148346.8        | 890.3           | 2.21      |
| HX2               | 280.9           | 54.4            | 226.5           | 0.56      |
| HX3               | 21552.6         | 15813.2         | 5739.4          | 14.2      |
| HX4               | 2406.9          | 2035.4          | 371.5           | 0.92      |
| HX5               | 1424.7          | 1710.7          | 286.3           | 0.71      |
| HX6               | 29078.6         | 29075.5         | 3.1             | 0.007     |
| C1                | 18.0.0495       | 18.00           | 0.0495          | 0.00012   |
| ST                | 26287.9         | 24972.3         | 1315.6          | 3.26      |
| GT                | 18044.5         | 17924.4         | 120.1           | 0.29      |
| P101              | 10515.5         | 9490.4          | 1026            | 2.51      |
| FT Synthesis      | 111157.1        | 96104.1         | 15053           | 37.34     |
| Reforming Reactor | 122058.9        | 111157.1        | 10901.8         | 28.48     |
| D1                | 86611.9         | 86197.1         | 414.8           | 1.02      |
| D2                | 23943.8         | 21735.9         | 2207.9          | 5.47      |
| D3                | 52798.1         | 51967.1         | 831.1           | 2.06      |
| D4                | 26779.5         | 25983.5         | 796.3           | 1.97      |
| D5                | 104054.2        | 103934.2        | 12.6            | 0.3       |

The performance of equipment in terms of energy consumption should be assessed with respect to irreversibility and exergetic efficiency. Among the heat exchangers, HX3 with 5739.4 kW has the highest amount of

exergy destruction, while HX6 with 3.1 kW has the lowest amount of exergy destruction, Table 4.

The HX5 with 98.74% has the highest amount of exergetic efficiency, and HX1 with 64.12%

has the lowest amount of exergetic efficiency among the heat exchangers, Table 5.

Among compressors, pumps, and turbines, ST with the exergetic efficiency of 86.81% has the highest amount of exergetic efficiency, and P101 with 50.34% has the lowest exergetic efficiency. Among the equipment, ST with 1315.6 kW has the highest amount of exergy destruction, while C1 with 0.0495 kW has the lowest amount of exergy destruction.

The distribution of exergy destruction in a pie chart for the integrated structure of CHP and liquid fuels from natural gas through Fischer-Tropsch synthesis is shown in Fig. (2). Reactor of FT Synthesis with 37.3% has the highest amount of exergy destruction and gas turbine

with 0.29% has the lowest amount of exergy destruction. The distribution of exergy destruction for heat exchangers in a pie chart for the integrated structure of CHP and liquid fuels from natural gas through Fischer-Tropsch synthesis are shown in Fig. (3). This chart illustrates that HX3 among heat exchangers has the highest amount of exergy destruction. Since, HX5 has the highest exergetic efficiency, it can be deduced that the simulation of equipment in the integrated structure is correct.

Overall efficiency of the integrated structure is calculated based on high and low heat values through equation presented in Table 5.

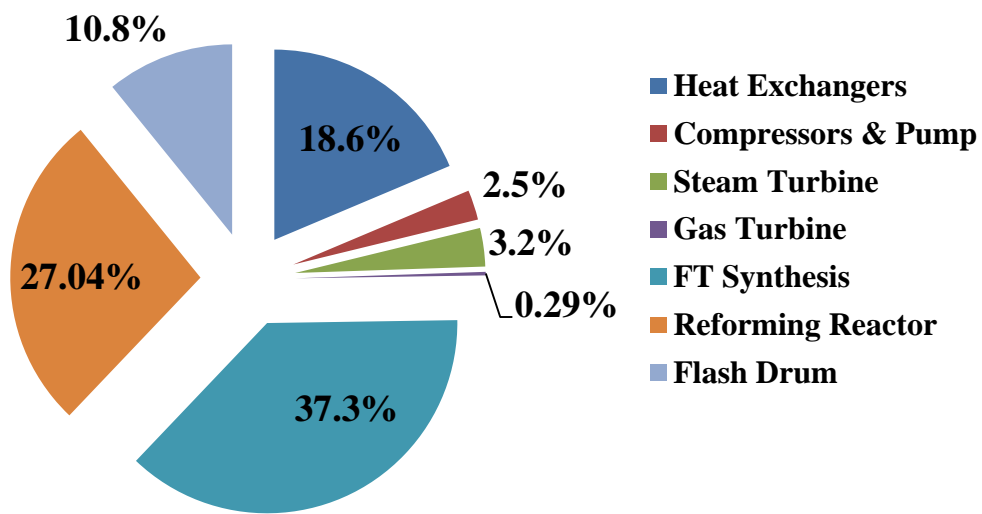


Figure 2. Distribution of Exergy Destruction in this Developed Integrated Structure

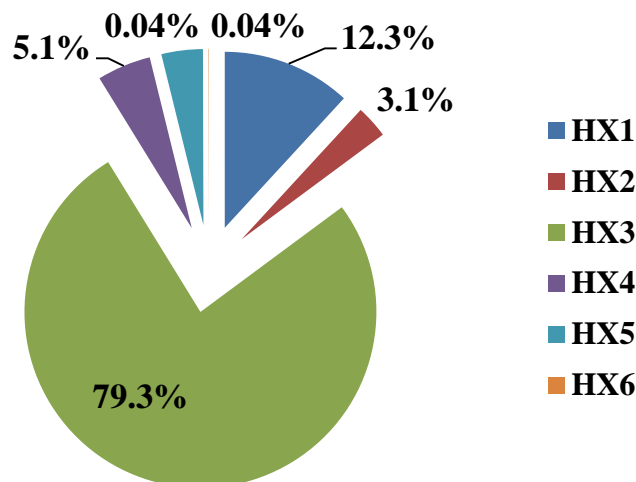


Figure 3. Distribution of Exergy Destruction among Heat Exchangers in the Developed Integrated Structure

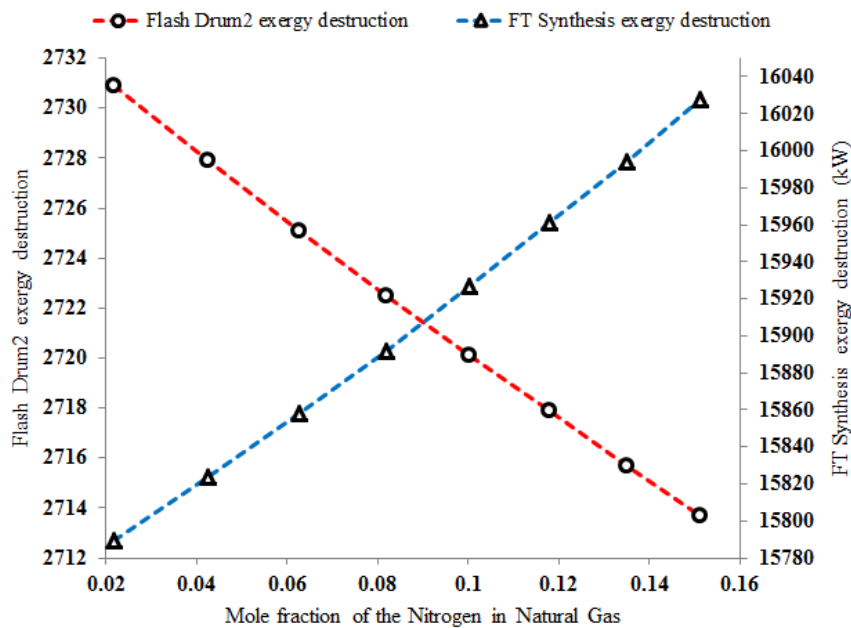


**Table 5.** Exergetic Efficiency of Equipment for CHP and heavy hydrocarbons liquids from Natural Gas through Fischer-Tropsch Synthesis

| Components and exergy efficiency expression                                                                                                                                                                                                                                                                     | Component identifier | Exergy efficiency (%) | Component identifier | Exergy efficiency (%) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|-----------------------|----------------------|-----------------------|
| Heat Exchanger (Ghorbani, Hamed, Amidpour, & Shirmohammadi, 2017)<br>$\eta_{ex} = 1 - \left[ \frac{\left\{ \sum_1^n (\dot{m} \Delta e) \right\}}{\left\{ \sum_1^n (\dot{m} \Delta h) \right\}_h} - \frac{\left\{ \sum_1^m (\dot{m} \Delta e) \right\}}{\left\{ \sum_1^m (\dot{m} \Delta h) \right\}_c} \right]$ | HX1                  | 64.12                 | HX4                  | 86.41                 |
| Cooler<br>$\eta_{ex} = \frac{Q(1 - \frac{T}{T_0})}{\sum (\dot{m} \cdot e)_i - \sum (\dot{m} \cdot e)_o}$                                                                                                                                                                                                        | HX2                  | 67.18                 | HX5                  | 98.74                 |
|                                                                                                                                                                                                                                                                                                                 | HX3                  | 76.32                 | HX6                  | 79.46                 |
| Compressor, Gas Turbine and Pump (Ghorbani et al., 2017)<br>$\eta_{ex,COM \& Pump} = \frac{\sum (\dot{m} \cdot e)_i - \sum (\dot{m} \cdot e)_o}{W}$                                                                                                                                                             | C1                   | 85.73                 | P101                 | 50.34                 |
| $\eta_{ex,GT} = \frac{\sum (\dot{m} \cdot e)_i - \sum (\dot{m} \cdot e)_o}{W}$                                                                                                                                                                                                                                  | GT                   | 73.21                 | ST                   | 86.81                 |
| FT Synthesis                                                                                                                                                                                                                                                                                                    |                      |                       |                      |                       |
| $\eta_{ex} = \frac{\text{Total exergy of desired output (electricity)}}{\text{Required exergy input}}$                                                                                                                                                                                                          |                      |                       | 41.12                |                       |
| Reforming Reactor (Mehrpooya, 2016)<br>$\eta_{ex} = \frac{\sum (\dot{m} \cdot e)_o}{\sum (\dot{m} \cdot e)_i}$                                                                                                                                                                                                  |                      |                       | 86.32                |                       |
| Flash Drum<br>$\eta_{ex} = \frac{\sum (\dot{m} \cdot e)_o}{\sum (\dot{m} \cdot e)_i}$                                                                                                                                                                                                                           | D1                   | 72.31                 | D4                   | 58.12                 |
|                                                                                                                                                                                                                                                                                                                 | D2                   | 69.17                 | D5                   | 49.17                 |
|                                                                                                                                                                                                                                                                                                                 | D3                   | 72.13                 |                      |                       |

**Table 6.** Efficiency of the Integrated Structure of CHP and heavy hydrocarbons liquids from Natural Gas through Fischer-Tropsch Synthesis

| Parameter                             | Equation                                                                                                                                                                      | Value (%) |
|---------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| Overall thermal efficiency (HHV Base) | $\eta_{OverallHHV} = \frac{Q_{Steam} + \dot{m}_{FT} \times HHV_{FT} + \dot{W}_{ST} + \dot{W}_{GT} - \dot{W}_{Compressor} - \dot{W}_{Pump}}{\dot{m}_{fuel} \times HHV_{fuel}}$ | 65.55     |
| Overall thermal efficiency (LHV Base) | $\eta_{OverallLHV} = \frac{Q_{Steam} + \dot{m}_{FT} \times LHV_{FT} + \dot{W}_{ST} + \dot{W}_{GT} - \dot{W}_{Compressor} + \dot{W}_{Pump}}{\dot{m}_{fuel} \times LHV_{fuel}}$ | 61.94     |



**Figure 4.** Effect of increasing the amount of nitrogen in the natural gas feed on the amount of exergy destruction of FT Synthesis and Flash Drum2 in the structure.

Fig.(4) shows changes of surging in nitrogen content in the feed stream with respect to the amount of exergy destruction of FT Synthesis and Flash Drum2.

By surging in the flow rate of natural gas on the ratio of molar flow rate of hydrogen on syngas in the stream of syngas entering the Fischer Tropsch reactor is increased with very little velocity where the ratio remains approximately in the range of 2.

## 5. Conclusion

The necessitate of capital investment has been evidently revealed with regard to the merits of Fisher Trapsh Synthesis in order to convert natural gas to valuable products such as liquid fuels such. This issue of considering the enormous volume of gas available in shared resources in the Persian Gulf is considered as an economically vital matter. Applying this method in high capacities can generate new sources of currency at natural level. It can increase the potential of country's oil production capacity in the future. A structure of converting natural gas to valuable products like liquid fuels through Fisher Trapsh synthesis is proposed here. Since, the Fisher Trapsh synthesis process has high volume of energy and the ability to produce significant volume of the required energy, co-generation of heat and power of 21 and 9 MW volume through an offered hybrid structure is implemented or recommended.

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