

Biofuels Production through Oil Sludge Gasification Coupled to Fischer-Tropsch Configuration

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Resumo

Para este trabalho, a gaseificação da borra de petróleo (BP) e posterior síntese Fischer-Tropsch foram modelados utilizando o software Aspen-Hysys®. Misturas de ar e vapor superaquecido foram utilizadas como agentes de gaseificação. Os resultados mostraram que a conversão termoquímica da BP requer uma temperatura de gaseificação acima de 1300 °C, visando garantir uma conversão elevada (> 90 %) dos hidrocarbonetos presentes na matéria-prima. O poder calorífico inferior (PCI) do gás de síntese variou entre 7,0 e 11,1 MJ/Nm³. Com relação à síntese Fischer-Tropsch, obteve-se uma taxa de produção de combustíveis líquidos sintéticos de 0,48 L de nafta/kg-BP a 15 bar. Conclui-se que o aumento da temperatura de gaseificação favorece reações de craqueamento térmico e reforma com vapor de hidrocarboneto genérico (C_xH_y), o qual pode favorecer a formação de H₂, CO e CH₄ no gás de síntese e o seu PCI. Além disso, aumentos na pressão operacional (acima de 15 bar) na síntese Fischer-Tropsch não levam a aumentos significativos na conversão da reação de síntese.

Palavras-chave: Conversão termoquímica; Resíduo de petróleo; Fischer-Tropsch; Bicombustíveis.

Abstract

For this work, oil sludge (OS) gasification and subsequent Fischer-Tropsch synthesis were modeled using Aspen-Hysys® software. Air and superheated steam mixtures were used as gasification agents. The results showed that OS thermochemical conversion requires a gasification temperature above 1300 °C, aiming to guarantee a high conversion (> 90 %) of the hydrocarbons present in the feedstock. The lower heating value (LHV) of syngas varied between 7.0 and 11.1 MJ/Nm³. Regarding the Fischer-Tropsch synthesis, the production rate of synthetic liquid fuels was 0.48 L of naphtha/kg-OS at 15 bar. It is concluded that increasing the gasification temperature favors thermal cracking and reforming reactions with generic hydrocarbon vapor (C_xH_y), which could favor the formation of H₂, CO, and CH₄ in the syngas and its LHV. Additionally, increases in operating pressure (above 15 bar) in the Fischer-Tropsch synthesis do not lead to significant increases in the conversion of the synthesis reaction.

Keywords: Thermochemical conversion; Petroleum waste; Fischer-Tropsch; Biofuels.

1. Introduction

The petroleum industry's upstream and downstream operations can generate various oily waste, such as oil sludge (OS). As oil refining capacity increases, more

OS production is expected, with approximately 1.0 tons of this residue generated for every 500 tons of oil processed (0.2 % by weight) [1]. According to an investigation conducted by the Environmental Protection Agency (EU-EPA), the United States

produces an annual average of 4.5 million tons of OS. In comparison, China has a yearly production of 3.0 million tons of OS from the oil refining industry [2]. The OS pH value is in the range of 6.5 to 7.5, while its chemical composition varies depending mainly on the origin of the oil, the processing scheme, the equipment, and the reagents used in the refining process. Thus, it is observed that the total content of petroleum hydrocarbons present in the oily residue can vary between 5 and 86 % (by weight). In comparison, the water and solids contents are in the range of 30 – 85 % (by weight) and 5 – 46 % (by weight), respectively [3]. According to SARA (saturates, aromatics, resins, and asphaltenes) analysis, the OS chemical composition may contain 40 – 52 % (by weight) saturated compounds (alkanes, cycloalkanes), aromatics in the range of 28 – 31 %, asphaltenes between 8 – 10 % and resins in the order of 7 – 22.4 % (by weight) [1]. In turn, asphaltenes and resins, together with water, could be responsible for the stability of the oil-water emulsion present in OS, given that these components contain hydrophilic functional groups and can act as lipophilic emulsifiers [4]. Different physicochemical, thermal, and biological methods are used to treat petroleum residues, with the majority of low-temperature physicochemical and thermal systems (pyrolysis) oriented towards recovering the main organic fractions with high potential for co-processing or production of fuels in the refinery [5]. However, OS could be treated, together with solid waste generated after the recovery of fuel oils, to guarantee comprehensive environmental management and adequate final disposal of these, with gasification being an attractive technology [6].

The gasification process transforms the carbon compounds in the treated raw material into syngas, which is rich in H_2 and CO , with a high ratio H/C . In contrast, in other processes, such as combustion/incineration, the hydrogen and carbon present in the raw material are oxidized, forming water vapor and CO/CO_2 , respectively [7]. The syngas' chemical composition and energy content depend on the raw material used, the operating conditions, the type of gasifier, and the used gasification agent [8]. The syngas can be burned to generate thermal and electrical energy or obtain chemical products with superior added value.

Among the modeling studies on the gasification of waste from the petroleum industry, Martínez et al. (2018) [9] is one of them who studied the gasification of petroleum sludge using air/steam mixtures as a gasification agent and determined that the syngas yield was $2.28 \text{ Nm}^3/\text{kg}$ sludge, with an H_2 content close to 25 mol%, for a potential production of $1.84 \text{ Nm}^3 H_2/\text{kg}$ -sludge. Bader et al. (2017) [10] also evaluated the gasification of heavy oil numerically, using mixtures of O_2 and steam as gasification agents, obtaining syngas with 50.55 % CO , 42.71 % H_2 , 3.55 % CO_2 , and 0.54 % CH_4 at 1599 K, demonstrating that the impact of

syngas composition on oil conversion is lesser when fuel moisture content decreases. Also, Banisaeed and Rezaee-Manesh (2016) [11] developed a kinetic model of heavy oil gasification to investigate the influence of oxygen as a gasification agent, where the results showed that an increment of 0.4 to 1.0 in the oxygen ratio leads to increases in the higher heating value (HHV) and in the cold efficiency of the gasification process, which increases from 8.0 to 10.0 MJ/Nm^3 and from 35 to 70 %, respectively.

Therefore, the present work proposes the study of the thermochemical conversion of petroleum residues through gasification, aiming mainly at producing syngas rich in H_2 and CO . Subsequently, the syngas produced will be used to produce liquid fuels through Fischer-Tropsch synthesis. The study of OS gasification will allow to establish possible routes for the energy recovery of petroleum wastes by obtaining products and raw materials with superior added value.

2. Materials and methods

2.1. Gasification model

For the gasifier simulation, four zones were defined, which cover the thermochemical conversion process of oily residues: (i) oxidation zone, (ii) pyrolysis-gasification zone, (iii) char/coke gasification zone, and (iv) reduction zone, as shown in Figure 1.

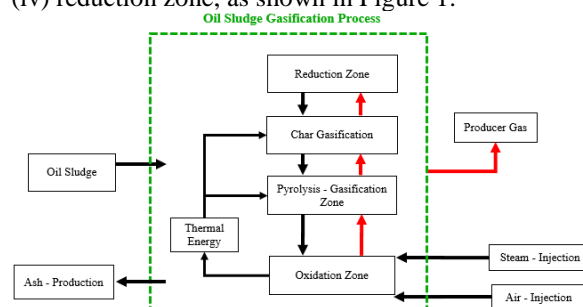


Figure 1. Gasification process scheme. Source: the authors.

Once the air/steam mixture (Air – Injection and/or Steam – Injection) is supplied as a gasification agent, the thermal energy required in the endothermic reactions of pyrolysis-gasification zone is provided by the oxidation zone (exothermic reactions). Subsequently, the products derived from these two stages enter the char/coke gasification zone, where the char, through heterogeneous reactions, is mainly converted into non-condensable gases such as CH_4 , CO , CO_2 , and H_2 . Thus, the gaseous products of this phase enter the last reduction zone, where some homogeneous reactions could occur. Finally, two streams are produced in the gasifier: syngas (Producer Gas) and a solid stream that corresponds to ash and non-gasified char (Ash – Production).

2.1.1. Chemical compounds for the process

The OS stream supplied in the process must be defined by designating chemical compounds available in the simulation software database. Thus, Table 1 shows the defined model components for their chemical characterization, corresponding to a mixture of high molecular weight aromatic hydrocarbons, such as BTX (benzene, toluene, and xylene) and some compounds with 2 and 3 aromatic rings [4].

Table 1. Oil sludge composition.

Chemical compound	Mass fraction (%)
Benzene: C ₆ H ₆	10
Toluene: C ₇ H ₈	10
Naphthalene: C ₁₀ H ₈	10
Phenol: C ₆ H ₆ O	10
Xylene: C ₈ H ₁₀	10
Anthracene: C ₁₄ H ₁₀	5
Pyrene: C ₁₆ H ₁₀	5
Phenanthrene: C ₁₄ H ₁₀	5
Chrysene: C ₁₈ H ₁₂	5
Water: H ₂ O	20
Sulfur: S	1
Solids: CaO	9

Source: adapted of [4].

2.2. Validation of the gasification model

Considering that few experimental works on OS gasification have been carried out and the need to validate the simulation model of the proposed OS gasification process, it was necessary to expand and adapt the present model for the thermochemical conversion of extra-heavy oils, mainly the so-called Orimulsion® (heavy oil with an API grade of around 8 and 10). Table 2 presents the operating conditions of the gasifier and the main characteristics of the raw material to be gasified, as described by Ashizawa et al. (2005) [12].

Table 2. Parameters for the gasification model validation.

Parameter	Value
Gasifier Pressure	18.75 atm
Gasification Agent	Oxygen
Orimulsion HHV	29.75
Orimulsion Ultimate Analysis	
C (%)	84.28
H (%)	10.33
O (%)	0.55
N (%)	0.64
S (%)	3.95
Orimulsion Proximate Analysis	
Moisture (%)	28.80
Ash (%)	0.18
Fixed Carbon (%)	12.84
Total sulfur (%)	2.81

Source: the authors.

On the other hand, Table 3 presents a comparison of the results obtained by the simulation model discussed

in this work and the experimental study developed by Ashizawa et al. (2005) [12].

Table 3. Comparison for the validation model.

Property (unit)	Ashizawa et al. (2005) [12]	This work
Syngas composition		
CO (% vol.)	38.70	40.57
CO ₂ (% vol.)	8.67	8.71
H ₂ (% vol.)	39.40	45.64
CH ₄ (% vol.)	0.08	1.96
Others (% vol.)	0.38	0.27
Others properties		
HHV(MJ/kg)	10.5	12.1
LHV (MJ/kg)	9.7	11.1
H ₂ /CO ratio	1.02	1.12

Source: the authors.

It can be observed that the volumetric concentration of CO and CO₂ in the syngas obtained in the simulation model showed a low dispersion, where the heating value and the H₂/CO molar ratio of the syngas either did not show significant differences. However, considerable differences were observed in H₂ and CH₄ contents of syngas, which may be associated with the type of adopted conversion model to simulate the chemical reactions.

2.3. Fischer-Tropsch synthesis

Figure 2 shows the structure used to simulate the liquid fuel production process through Fischer-Tropsch synthesis, where the syngas produced from OS thermochemical conversion pass through a cleaning and cooling system. This process is simulated using a cyclone separator to remove the solid particles, while cooling is simulated considering a heat exchanger operating with an external fluid, which allows the syngas temperature to be reduced to 50 °C, as recommended by Valderrama et al. (2018) [13]. Subsequently, the H₂/CO mixture is separated from previously conditioned syngas. This step is simulated using a low-temperature (20 – 80 °C) selective polymeric membrane separator. Thus, a mixture rich in hydrogen and CO can be obtained [14].

To achieve a molar ratio H₂/CO > 2.0, which guarantees adequate performance of the Fischer-Tropsch synthesis reaction for the synthetic naphtha production, an additional amount of hydrogen is considered, which is calculated based on the availability of CO after separation of the H₂/CO mixture. In this way, H₂/CO-rich gas and additional hydrogen streams are mixed and subsequently compressed to a pressure in the range of 15 – 30 bar, as suggested by Duti, Maliha, and Amin (2015) [15]. However, the appropriate pressure of the Fischer-Tropsch synthesis reaction is demonstrated in the following section, considering its effect on the

performance of the synthesis reaction in terms of of the equivalence ratio (ER) and the ratio of

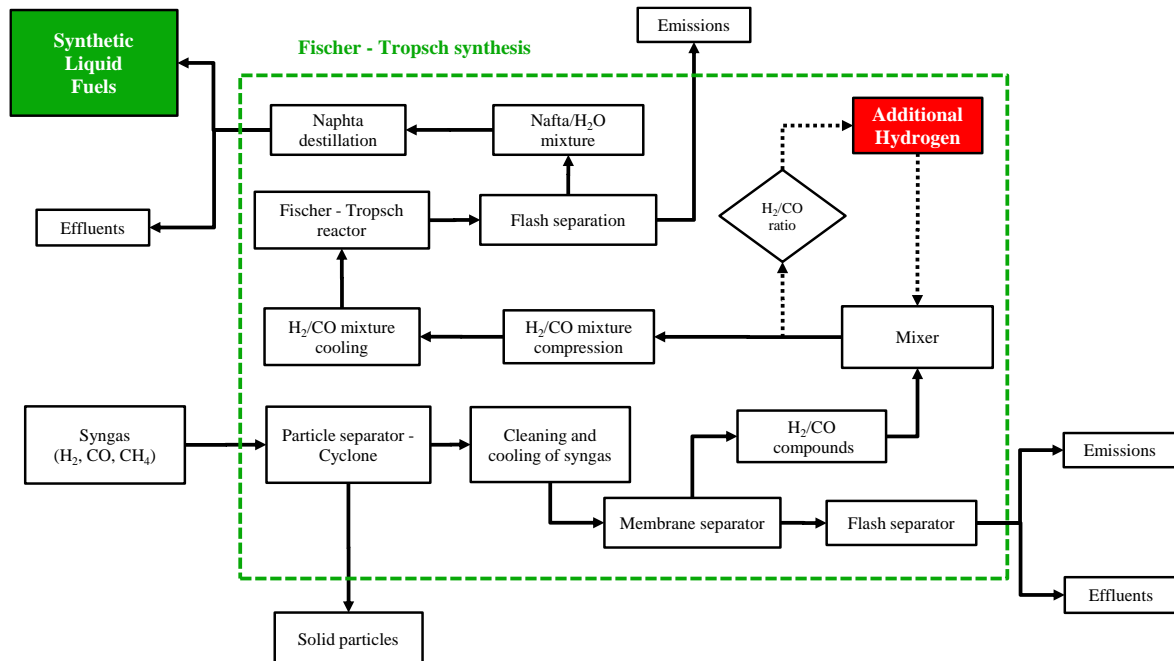


Figure 2. Fischer-Tropsch unit scheme. Source: the authors

H_2/CO conversion into synthetic naphtha.

Once pressurized, the H_2/CO reactant mixture goes through a cooling process, simulated by selecting a heat exchanger. Thus, the previously pressurized H_2/CO mixture is cooled to 200 °C before entering the Fischer-Tropsch reactor, favoring the chemical equilibrium of the synthesis reaction (exothermic reaction) as the temperature decreases [16]. To simulate the chemical reaction system, an isothermal plug flow tubular reactor was selected, which exchanges heat with the external environment to maintain the reaction temperature around 200 °C, ensuring a high conversion of CO and H_2 into synthetic naphtha (98 % conversion using Co catalysts supported on TiO_2) [17]. After the synthesis reactor, a vapor phase stream is generated, consisting mainly of H_2 , CO, n-octane (selected model compound to simulate naphtha), and steam. This mixture is sent to a flash separator, where the lighter gases (CO and H_2) are separated at atmospheric pressure (1.0 bar) and an ambient temperature of 25 °C, with some traces of steam and n-octane [18]. Subsequently, the water/n-octane liquid mixture goes through an atmospheric distillation process (1.0 bar) to separate the naphtha from the denser components, particularly the water content.

3. Results

In this section, the influence of gasification agents on the performance of the thermochemical conversion process of oily residues is evaluated, mainly the effect

superheated steam per OS (SOS) on the syngas. Aiming to achieve an internal gasification temperature of around 1,300 °C, which in turn allows achieving a conversion above 90 % of the organic compounds in OS, it was necessary to perform a sensitivity study of the ER in the range of 0.05 – 0.60, as well as the SOS in the range of 0.2 – 1.0 kg steam/kg-OS.

3.1. Thermochemical conversion process

Figure 3 shows a sensitivity analysis between the gasification temperature and the percentage of OS thermochemical conversion in the pyrolysis-gasification zone (Figure 1). The main chemical reactions in this gasifier section correspond to the reforming and thermal cracking of the hydrocarbons in the oily residues. This analysis considered a constant ER of 0.3, a SOS of 0.5 kg/kg-OS, and a gasification temperature range between 100 – 1,400 °C. Thus, the simulation results showed a temperature range between 1,200 – 1,400 °C, which makes it possible to obtain a considerable conversion of the heavy hydrocarbons present in OS, varying between 70 and 98 %. However, the reactor must operate under a suitable mixture of gasification agents so that the exothermic reactions occurring in the oxidation zone can provide the required thermal energy in the pyrolysis-gasification zones. Most of the reforming and cracking reactions occur above 800 °C in a similar way, with the exception of the shift reaction, which begins at 100 °C, and the benzene reforming starts to occur at 300 °C and reaches its maximum at 600 °C.

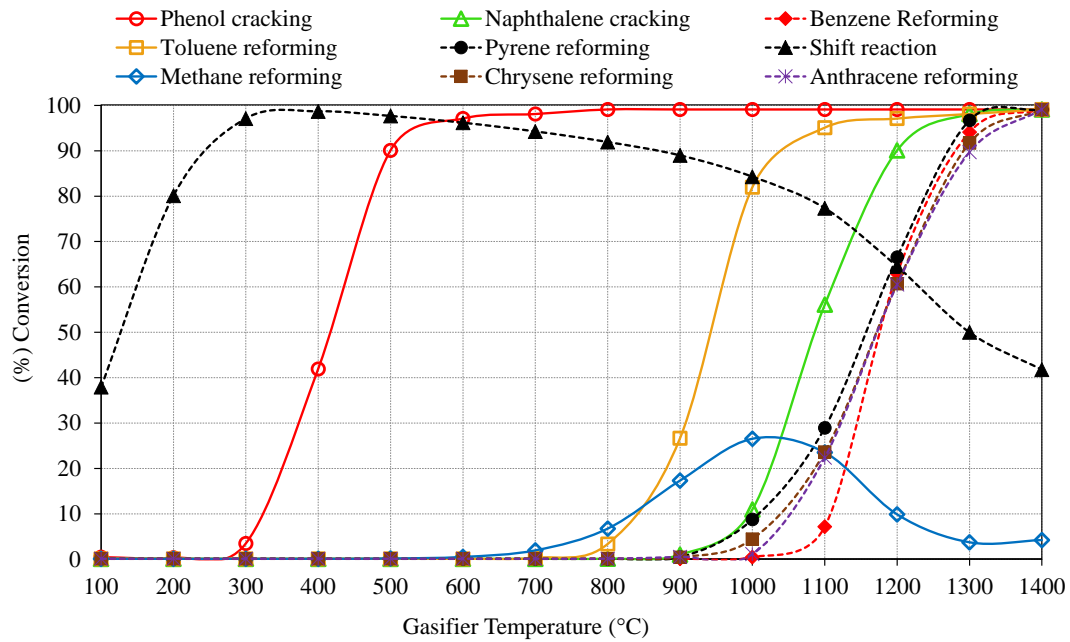


Figure 3. Syngas molar concentration profile as a function of temperature. Source: the authors.

Regarding the syngas LHV, a decreasing trend was observed as the ER was increased until reaching a value that oscillates in the range of 5 and 10 MJ/Nm³ for values of ER > 0.30 and SOS between 0.2 and 1.5 kg steam/kg-OS, as indicated in Figure 4. This can be explained by the addition of steam to the gasifier, which favors the reforming and thermal cracking reactions of the heavier organic fractions in the OS, in turn producing lighter hydrocarbons with lower energy content, generating a mixture of less dense combustible gases and with minor LHV [19]. The simulation results

showed that for an ER of 0.30 and SOS of 0.20, there is a gas LHV value of 9.7 MJ/Nm³. Otherwise, the LHV decreases to 7.7 MJ/Nm³ when the SOS remains 0.5 and 1.5 steam/kg-OS (Figure 4). Thus, the syngas has a considerable LHV to be sent as fuel to the Fischer-Tropsch process.

3.2. Fischer-Tropsch

In order to obtain a significant conversion of CO and H₂ into naphtha, an analysis of the reactor pressure effect on the conversion of CO through the Fischer-

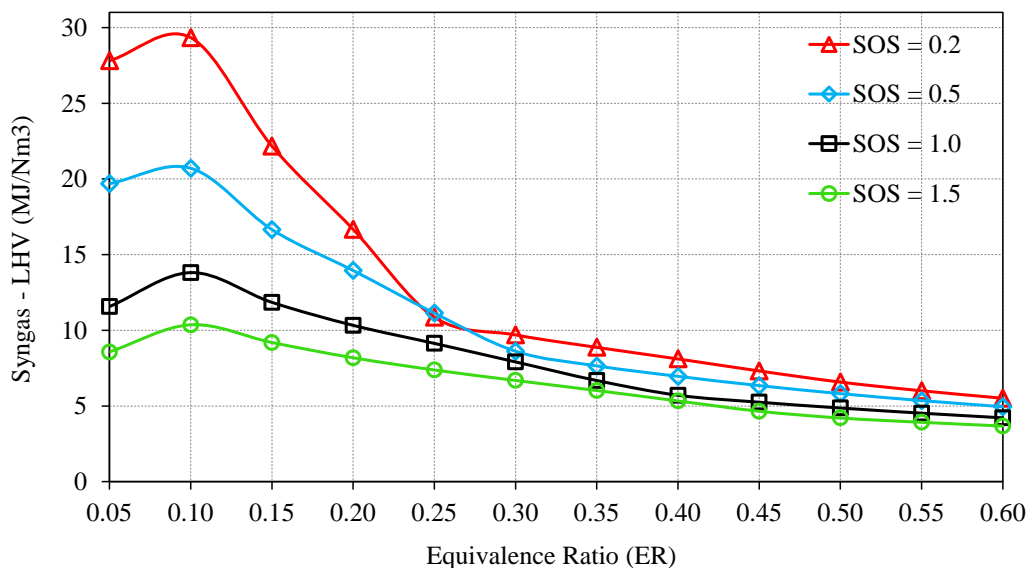


Figure 4. Syngas LHV. Source: the authors.

Tropsch synthesis reaction was performed (Figure 5). It is observed that for operating pressures of the

synthesis reactor, which would be equivalent to a potential production of 4205 m³ naphtha/year,

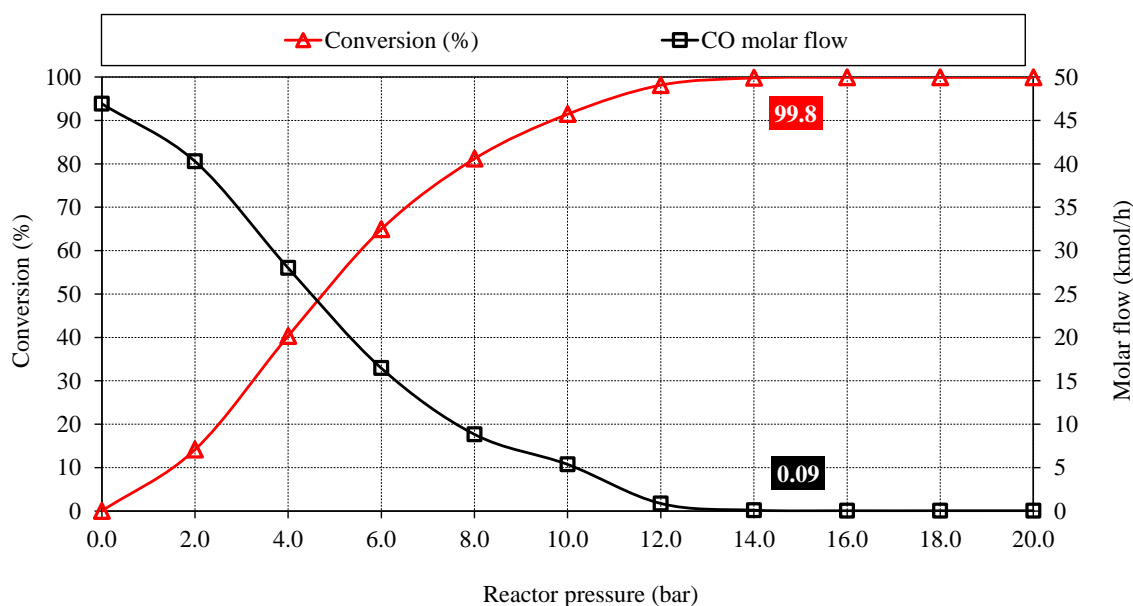


Figure 5. Fischer-Tropsch synthesis conversion reaction as a function of pressure. Source: the authors.

Fischer-Tropsch reactor above 15 bar and 50 kmol/h, no significant increases were evident in the synthesis reaction conversion, while the CO molar flow rate at the reactor exit (unreacted CO) tends to a minimum equilibrium value [18].

On the other hand, Figure 6 presents the simulation results of the specific naphtha production as a function of the operating pressure in the synthesis reactor. Thus, a production rate for synthetic liquid fuels close to 0.48 L of naphtha/kg-OS is expected, particularly for pressures above 15 bar in the Fischer-Tropsch

considering an OS mass flow of 1,000 kg/h in the gasification process. Finally, Figure 7 presents the Sankey diagram for the evaluated process, indicating the specific energy flows (in terms of kWh/ton-OS) associated with all processes and mass streams considered in the synthetic liquid fuels production from the OS gasification and Fischer-Tropsch synthesis, including the final separation of the produced fuel. In this way, the obtained synthetic naphtha corresponds to

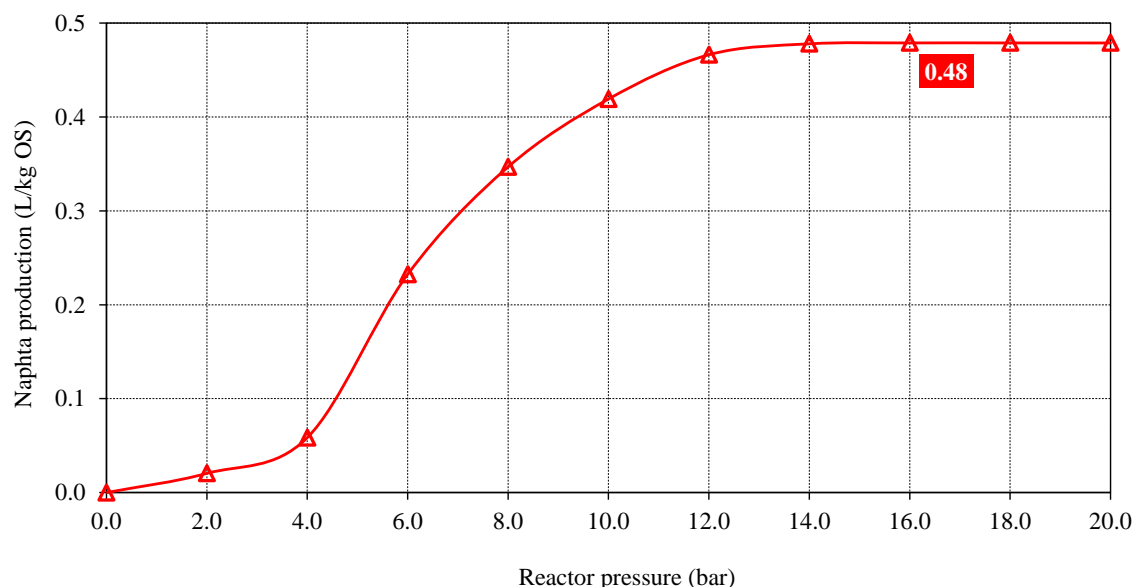


Figure 6. Specific naphtha production as a function of reactor pressure. Source: the authors.

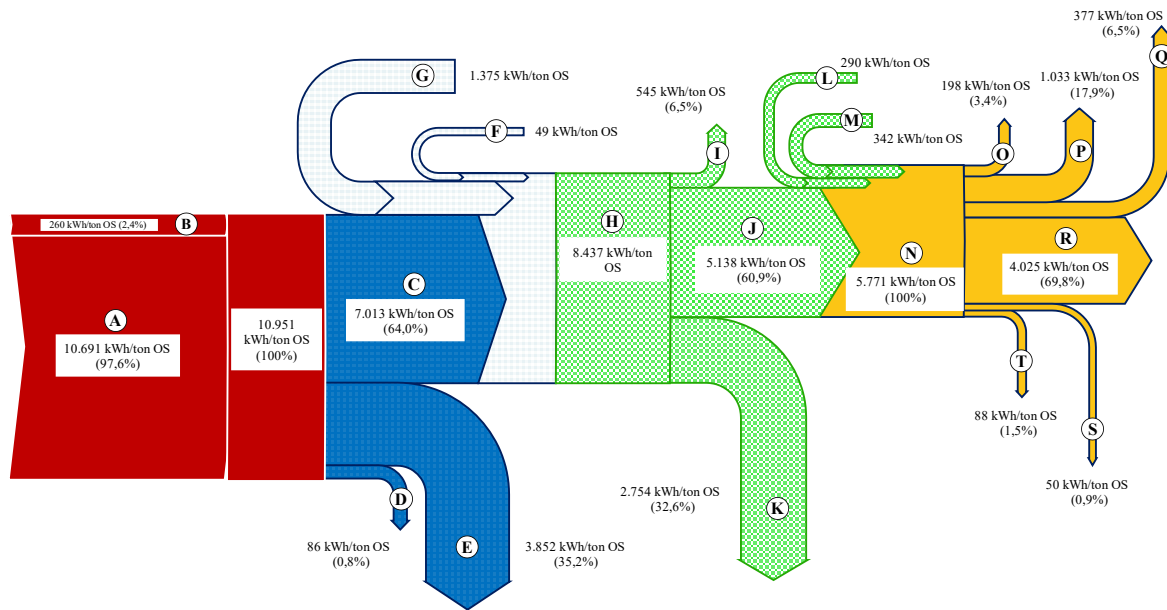


Figure 7. Sankey diagram of the synthetic liquid fuels production from OS gasification. Source: the authors.

A: oil sludge, B: gasification agents, C: synthesis gas produced, D: ashes, E: energy losses in the gasifier, F: syngas cleaning, G: additional hydrogen, H: total syngas treatment, I: syngas cooling, J: H₂/CO mixture, K: energy losses in treatment, L: H₂/CO mixture compression, M: naphtha distillation, N: total Fischer-Tropsch reactor, O: cooling H₂/CO mixture, P: Fischer-Tropsch reactor (FT), Q: flash separation, R: synthetic naphtha, S: naphtha cooling, and T: FT synthesis energy losses

an equivalent energy index of gasified 4,025 kWh/ton-OS. Furthermore, it is worth highlighting the gasification process energy losses (3852 kWh/ton-OS), which are associated with the cold gas efficiency, affected by the dilution effect of the N₂ present in the air used as a gasification agent. Other energy losses highlighted are those of the syngas conditioning process (2754 kWh/ton-OS) and syngas cooling (545 kWh/ton-OS) due to the limited efficiency of the cleaning technologies and heat exchangers, respectively. Similar losses through gasification and syngas cleaning processes have been previously reported by Martínez et al. (2018) [9].

4. Conclusions

The present work studied the possibility of using solid waste from the oil refinery, particularly the case of OS and its thermochemical conversion into chemical products or inputs of superior economic value. According to the results obtained in the present work, it can be concluded that the thermal conversion of the oily waste requires high gasification temperatures (above 1,300 °C) to guarantee an adequate conversion percentage (> 90 %) of the heavy organic fractions in OS into gaseous compounds of smaller molecular size (syngas rich in H₂ and CO, mainly). Also, a high thermal requirement is necessary to reach the high temperatures required by the OS gasification process. Regarding gasification agents, mixtures of air and

superheated steam lead to obtaining syngas with high quality in terms of energy content (with a heating value varying between 7.0 and 11.1 MJ/Nm³), with the 0.25 – 0.37 of ER and 0.20 – 1.50 kg of steam/kg-OS leading to promising results. Finally, it is possible to achieve a synthetic liquid fuels production rate around 0.48 L/kg-OS (3.02 barrels of naphtha/ton-OS) from OS gasification syngas. Finally, increasing the operating pressure (above 15.0 bar) in the Fischer-Tropsch synthesis reactor does not lead to significant increases in the conversion of the synthesis reaction and the specific index of naphtha production.

5. Acknowledgments

The authors acknowledge the Research Support Foundation of the State of Rio de Janeiro (FAPERJ), the Human Resources Program of the National Agency of Petroleum, Natural Gas, and Biofuels (PRH-ANP 51.1), the National Council for Scientific and Technological Development (CNPq), and Research Support Foundation of the State of Minas Gerais State (FAPEMIG).

6. References

- [1] A. Martínez González, E. E. Silva Lora, and J. C. Escobar Palacio, "Syngas production from oil sludge gasification and its potential use in power generation systems: An energy and exergy

- analysis,” *Energy*, vol. 169, pp. 1175–1190, 2019, doi: <https://doi.org/10.1016/j.energy.2018.11.087>.
- [2] Y. Castillo Santiago, A. Martínez González, O. J. Venturini, and D. M. Yepes Maya, “Assessment of the energy recovery potential of oil sludge through gasification aiming electricity generation,” *Energy*, vol. 215, p. 119210, 2021, doi: [10.1016/j.energy.2020.119210](https://doi.org/10.1016/j.energy.2020.119210).
 - [3] R. A. Tahhan, T. G. Ammari, S. J. Goussous, and H. I. Al-Shdaifat, “Enhancing the biodegradation of total petroleum hydrocarbons in oily sludge by a modified bioaugmentation strategy,” *Int. Biodeterior. Biodegrad.*, vol. 65, no. 1, pp. 130–134, 2011, doi: [10.1016/j.ibiod.2010.09.007](https://doi.org/10.1016/j.ibiod.2010.09.007).
 - [4] G. Hu, J. Li, and G. Zeng, “Recent development in the treatment of oily sludge from petroleum industry: A review,” *J. Hazard. Mater.*, vol. 261, pp. 470–490, Oct. 2013, doi: [10.1016/J.JHAZMAT.2013.07.069](https://doi.org/10.1016/J.JHAZMAT.2013.07.069).
 - [5] P. I. Murungi and A. A. Sulaimon, “Petroleum sludge treatment and disposal techniques: a review,” *Environ. Sci. Pollut. Res.*, vol. 29, no. 27, pp. 40358–40372, 2022, doi: [10.1007/s11356-022-19614-z](https://doi.org/10.1007/s11356-022-19614-z).
 - [6] Z. Chu, Y. Li, C. Zhang, Y. Fang, and J. Zhao, “A review on resource utilization of oil sludge based on pyrolysis and gasification,” *J. Environ. Chem. Eng.*, vol. 11, no. 3, p. 109692, 2023, doi: <https://doi.org/10.1016/j.jece.2023.109692>.
 - [7] Y. Castillo Santiago, J. F. Pérez, and L. A. Sphaier, “Reaction-front and char characterization from a palm kernel shell – Oil sludge mixture under oxygen lean regimes in a fixed-bed gasifier,” *Fuel*, vol. 333, p. 126402, 2023, doi: <https://doi.org/10.1016/j.fuel.2022.126402>.
 - [8] G. Maitlo *et al.*, “Thermochemical Conversion of Biomass for Syngas Production: Current Status and Future Trends,” *Sustainability*, vol. 14, no. 5, 2022, doi: [10.3390/su14052596](https://doi.org/10.3390/su14052596).
 - [9] A. Martínez González, E. E. Silva Lora, J. C. Escobar Palacio, and O. A. Almazán del Olmo, “Hydrogen production from oil sludge gasification/biomass mixtures and potential use in hydrotreatment processes,” *Int. J. Hydrogen Energy*, vol. 43, no. 16, pp. 7808–7822, 2018, doi: [10.1016/j.ijhydene.2018.03.025](https://doi.org/10.1016/j.ijhydene.2018.03.025).
 - [10] A. Bader, M. Hartwich, A. Richter, and B. Meyer, “Numerical and experimental study of heavy oil gasification in an entrained-flow reactor and the impact of the burner concept,” *Fuel Process. Technol.*, vol. 169, no. September 2017, pp. 58–70, 2018, doi: [10.1016/j.fuproc.2017.09.003](https://doi.org/10.1016/j.fuproc.2017.09.003).
 - [11] M. Banisaeed and A. Rezaee-Manesh, “A parametric study for gasification of liquid fuels,” *Pet. Sci. Technol.*, vol. 34, no. 11–12, pp. 976–979, Jun. 2016, doi: [10.1080/10916466.2016.1181652](https://doi.org/10.1080/10916466.2016.1181652).
 - [12] M. Ashizawa, S. Hara, K. Kidoguchi, and J. Inumaru, “Gasification characteristics of extra-heavy oil in a research-scale gasifier,” *Energy*, vol. 30, no. 11–12 SPEC. ISS., pp. 2194–2205, 2005, doi: [10.1016/j.energy.2004.08.023](https://doi.org/10.1016/j.energy.2004.08.023).
 - [13] M. L. Valderrama Rios, A. M. González, E. E. S. Lora, and O. A. Almazán del Olmo, “Reduction of tar generated during biomass gasification: A review,” *Biomass and Bioenergy*, vol. 108, pp. 345–370, 2018, doi: <https://doi.org/10.1016/j.biombioe.2017.12.002>.
 - [14] M. Peer, S. Mehdi Kamali, M. Mahdeyarfar, and T. Mohammadi, “Separation of Hydrogen from Carbon Monoxide Using a Hollow Fiber Polyimide Membrane: Experimental and Simulation,” *Chem. Eng. Technol.*, vol. 30, no. 10, pp. 1418–1425, Oct. 2007, doi: <https://doi.org/10.1002/ceat.200700173>.
 - [15] I. J. Duti, M. Maliha, and R. Amin, “Analysis of Petroleum Production From Coconut Husks and Shellsby Fischer-Tropsch process,” in *Proceedings of the International Conference on Mechanical Engineering and Renewable Energy 2015*, 2015, pp. 1–6.
 - [16] K. Keyvanloo, S. J. Lanham, and W. C. Hecker, “Kinetics of Fischer-Tropsch synthesis on supported cobalt: Effect of temperature on CO and H₂ partial pressure dependencies,” *Catal. Today*, vol. 270, pp. 9–18, 2016, doi: <https://doi.org/10.1016/j.cattod.2016.03.019>.
 - [17] S. S. Ail and S. Dasappa, “Biomass to liquid transportation fuel via Fischer Tropsch synthesis – Technology review and current scenario,” *Renew. Sustain. Energy Rev.*, vol. 58, pp. 267–286, 2016, doi: <https://doi.org/10.1016/j.rser.2015.12.143>.
 - [18] K. Aasberg-Petersen *et al.*, “Synthesis gas production for FT synthesis,” in *Fischer-Tropsch Technology*, 1st ed., vol. 152, A. Steynberg and M. B. T.-S. in S. S. and C. Dry, Eds. Amsterdam: Elsevier, 2004, pp. 258–405.
 - [19] H. D. Z. S. Oliveira, Y. C. Santiago, A. M. González, I. F. Pinheiro, K. P. Barbosa, and L. A. Sphaier, “OIL SLUDGE THERMOCHEMICAL CONVERSION: GASIFICATION AND AMMONIA SYNTHESIS CASE,” *Brazilian J. Pet. Gas*, vol. 17, no. 2–3, pp. 63–73, 2023, doi: [10.5419/bjpg2023-0004](https://doi.org/10.5419/bjpg2023-0004).