CONVERSION OF FAECAL SLUDGE TO LIQUID FUELS. WHY AND HOW COULD IT WORK FOR SMALL-SCALE APPLICATIONS?

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ABSTRACT

Waste to energy conversion is a promising route for reducing the fossil fuel dependency of the world. Fermentation, chemical processing, pyrolysis and gasification have been the main processes used for transforming biomass and other "burnable" wastes into useful fuels like ethanol, methanol, biogas, bio-diesel, bio-oil, bio-hydrogen etc. Most works on the subject are focused on power generation or on the production of alternative fuels, while few consider the option of producing gasoline or diesel.

Gasoline and diesel can be produced from bio-waste through gasification, a process that produces a mixture of hydrogen and carbon monoxide known as syngas, and a method known as the Fischer-Tropsch (FT) process. FT has been implemented by some companies (Sasol, PetroSA, Shell,...) for the production of high value hydrocarbons from coal and natural gas. These plants are normally large with production capacities of thousands of barrels per day. But for a plant with such production rates, converting high water content biomass such as faecal sludge into hydrocarbons would require large quantities of sludge to be transported to the processing plant. At a smaller, local scale it may be economically attractive to process faecal sludge for the production of liquid fuels. Although small scale FT has not yet been commercialized, there are new developments in reactor technologies that can offer economically viable small-scale FT processing.

Here we present an overview of the progress made in our theoretical study for the small-scale production of diesel fuel from faecal sludge and municipal solid waste mixtures through the use of gasification and FT technology. A low cost simplified version of a gasification + FT plant is presented along with an energy balance that shows the viability of the process.

THE PROCESS DIAGRAM

Fischer-Tropsch processing can be quite complex if the intention is to have a robust and flexible plant capable of delivering specific refined hydrocarbons. The complexity of such plants is due mainly to the refining of the products exiting the FT reactor. Assuming that it is possible to obtain hydrocarbon fractions directly from the FT reactor that can be blended with regular gasoline and diesel in order to obtain usable fuels, a simple Gasification + Fischer-Tropsch plant can be designed. Figure 1 presents such a plant where, in principle, the main equipment would be: a gasifier, a FT reactor, and a distillation column.

Besides the reduced complexity of the process, it is possible to lower the capital cost of the plant by using Micro-Reactor or Monolith-Reactor technologies for the FT reactor. These technologies have proved that it is possible to design small production FT reactors (refs).

In order to estimate the solid waste needed for transforming faecal sludge into liquid fuel, the mass and energy balance must be made for two key equipment: the gasifier and the FT reactor.
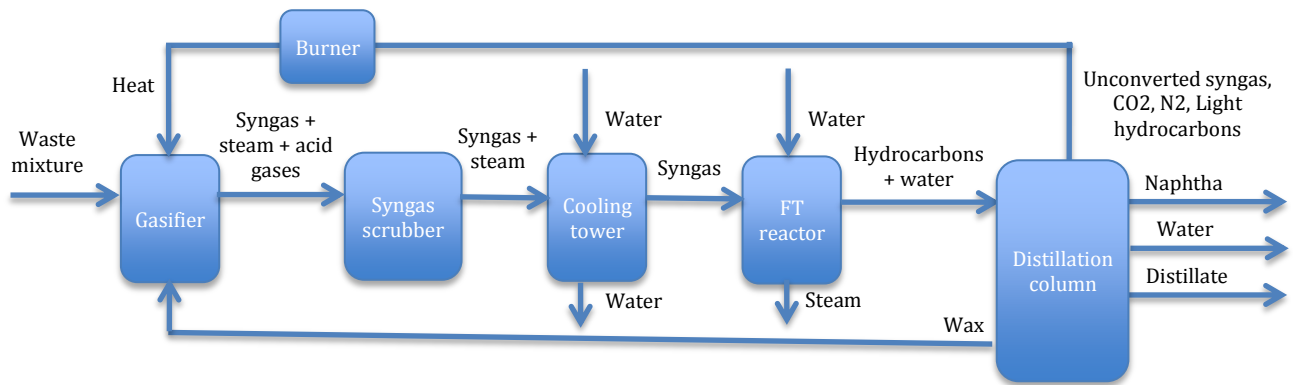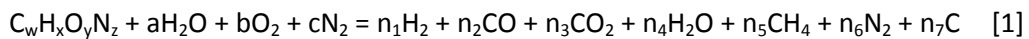
Figure 1. Schematic diagram of a simple Gasification + Fischer-Tropsch plant

GASIFIER MODEL

Gasification consists basically in an incomplete combustion reaction that can be expressed as follows:

$$C_wH_xO_yN_z + aH_2O + bO_2 + cN_2 = n_1H_2 + n_2CO + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6N_2 + n_7C \quad [1]$$
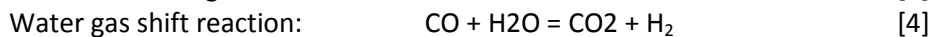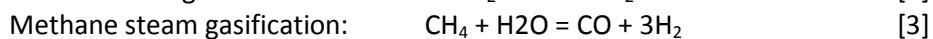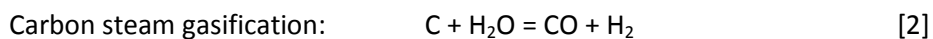
where

$C_wH_xO_yN_z$ is the empirical chemical formula of the total mass to be gasified, including wax from the FT reactor, Municipal Solid Waste, and faecal sludge.

x, y and z are the number of moles of elemental hydrogen, oxygen and nitrogen respectively per w moles of carbon present in the waste mixture.

a, b, c, and n_i are stoichiometric coefficients of the gasification reaction which can also be interpreted as the flow rate in moles/s of each species.

The gasification reaction above assumes that Sulphur, Chlorine and Fluorine, which may be present in both MSW and faecal sludge, are transformed into H_2S, HCl and HF. In addition, due to the high temperatures and low oxygen levels, the formation of sulphur dioxide (SO_2) and Nitrogen oxides (NOx) is considered negligible.

Inside a gasifier, there are many different chemical processes that occur during the transformation of the waste being gasified. It is not necessary to know all of this processes in order to predict the final yield of the different gases coming out of the gasifier. One can consider that the exiting gases are in chemical equilibrium (i.e. chemical reactions have stopped), which is a reasonable assumption for the typical gasification temperatures which are above 800 C. This allows to simplify the reaction model to a set of three main independent equilibrium reactions such as:

Carbon steam gasification:	$C + H_2O = CO + H_2$	[2]
Methane steam gasification:	$CH_4 + H2O = CO + 3H_2$	[3]
Water gas shift reaction:	$CO + H2O = CO2 + H_2$	[4]

It is possible however, to further simplify the gasifier reaction model by considering that the amount of oxygen and water being fed into the gasifier are in the right proportions in order to avoid the formation of methane (CH_4) and solid carbon (C). This leaves only the water gas shift reaction (WGSR) as the equilibrium reaction that will allow to predict the proportions of CO, CO_2, H_2 and H_2O at the gasifier exit. The resulting mass balance equations for the gasifier, which can be solved analytically, are:

Carbon balance:	$w = n_2 + n_3$	[5]
Hydrogen balance:	$x + 2a = 2n_1 + 2n_4$	[6]
Oxygen balance:	$y + a + 2b = n_2 + 2n_3 + n_4$	[7]

Water gas shift equilibrium relation:
$$K_1 = \frac{P_{H_2} P_{CO_2}}{P_{H_2O} P_{CO}} \qquad [8]$$

with

$$K_1 = e^{-\frac{\Delta G_R°}{RT}} \qquad [9]$$

where

K_1 is the WGSR equilibrium constant at the exit gases temperature.

$P_{H_2}, P_{H_2O}, P_{CO}, P_{CO_2}$ are the partial pressures of Hydrogen, Steam, Carbon Monoxide and Carbon Dioxide respectively, at the exit of the gasifier.

$\Delta G_R°$ is the Gibbs Free Energy of the Water Gas Shift Reaction = -952.25 J/mole

R is the ideal gas constant = 8.314 J/(mole.K)

T is the temperature of the gases at the gasifier exit (K).

The energy balance of the gasifier can be written as follows:

$$Q_R = n_4 \Delta H_{fH2O}° + n_2 \Delta H_{fCO}° + n_3 \Delta H_{fCO2} + n_8 \Delta H_{fH2S} + n_9 \Delta H_{fHCl} + n_{10} \Delta H_{fHF}$$
$$- w \Delta H_{fwaste}° - a \Delta H_{fH2O}° \qquad [10]$$

$$Q_{evap} = n_4 \lambda_{H2O} \qquad [11]$$

$$Q_h = n_4 \Delta H_{hH2O} + n_2 \Delta H_{hCO} + n_3 \Delta H_{hCO2} + n_8 \Delta H_{hH2S} + n_9 \Delta H_{hHCl} + n_{10} \Delta H_{hHF} \qquad [12]$$

$$Q_G = \frac{1}{\eta_G} (Q_R + Q_{evap} + Q_T) \qquad [13]$$

with

$$\Delta H_{hi} = Cp_i (T - 298\ K) \qquad [14]$$

where

Q_G is the calorific power input necessary for the gasification process.

Q_R is the calorific power input necessary for the reaction to take place, or the calorific output power produced by the gasification reaction.

Q_{evap} is the calorific power necessary for evaporating the water exiting as steam from the gasifier.

Q_h is the calorific power necessary for heating the produced gases from standard temperature (298 K) to the gasifier exit temperature T.

n_8, n_9, n_{10}, are the molar flow rates of hydrogen sulphide (H2S), Hydrogen chloride (HCl) and hydrogen Fluoride (HF), which are equal to the molar flow rates of elemental Sulphur, Chlorine and Fluorine that enter the gasifier.

$\Delta H_{fi}°$ is the standard enthalpy of formation of the component i (kJ/mol).

ΔH_{hi} is the energy per mole of component i for heating it from standard temperature (298 K) to the gasifier exit temperature T.

Cp_i is the heat capacity of component i

η_G is the thermal efficiency of the gasifier

The chemical composition that was proposed for the Municipal Solid Waste and for the Faecal Sludge is presented in the following table:

Table 1. Model composition of Faecal Sludge and Municipal Solid Waste. Estimated using data from Refs.

Species	Faecal Sludge % weight	MSW % weight
H	0.23	3.24
O	1.25	15.84

N	0.74	0.91
S	0.01	0.06
C	1.30	19.97
Cl	0.00	0.32
F	0.00	0.0013
H_2O	94.55	42.76
Ash	1.92	16.90

FISCHER-TROPSCH REACTOR MODEL

As mentioned above, the product obtained from the FT process is a mixture of hydrocarbons that can go from methane, with one carbon per molecule (nc = 1), to waxes with 50 or more carbons per molecule (nc > 50). These products can be grouped into four main fractions: Light Hydrocarbons, Naphta, Distillate, and Wax. The relative abundance of each hydrocarbon fraction at the exit of the reactor depends on the type of catalyst used, the reactor configuration, and the main process variables, namely: operating temperature, operating pressure, and feed composition. The dependence of the fraction yield on the reactor configuration is due mainly to the mass transport properties of the reactor, which directly influences the concentration of reactants near the catalysts surface. For simplicity, the model used here was based on the Anderson-Schulz-Flory distribution assuming that it is possible to design a reactor whose operating conditions and catalyst characteristics can deliver similar results to those shown in the results section. The mathematical expression known as the Anderson-Schulz-Flory distribution is:

$$\omega_{nc} = nc(1 - \alpha)^2 \alpha^{(nc-1)} \qquad [15]$$

where
ω_{nc} is the weight fraction of a hydrocarbon with nc number of carbons per molecule.
nc is the number of carbons per molecule of a hydrocarbon exiting the FT reactor.
α is the chain growth probability which has a value between 0 to 1. Here, we used $\alpha = 0.84$

The mass balance equations for determining the flow rates of the different fractions are:

$$M_{fr} = M_T \omega_{fr} \qquad [16]$$

with

$$M_T = n_2 \varepsilon \left[\sum_1^{nc_{max}} \frac{nc(\omega_{nc})}{W_{nc}} \right]^{-1} \qquad [17]$$

$$W_{nc} = 14nc + 2 \qquad [18]$$

$$\omega_{fr} = \sum_{nc_{frmin}}^{nc_{frmax}} \omega_{nc} \qquad [19]$$

where
M_{fr} is the mass flow rate of the fraction fr exiting the FT reactor.
M_T is the total mass flow rate of hydrocarbons exiting the FT reactor.
ω_{fr} is the mass fraction of the hydrocarbon fraction fr in the mixture of hydrocarbons exiting the FT reactor.
n_2 is the molar flow rate of carbon monoxide entering the FT reactor.
ε is the conversion of carbon monoxide entering the FT reactor (values between 0 and 1).
nc_{max} is the maximum number of carbons per molecule that is found at the exit of the FT reactor for which $\omega_{ncmax} \approx 0$
W_{nc} is the molecular mass of the alkane $C_{nc}H_{2nc+2}$

nc_{frmin} and nc_{frmax} are the lower and upper limits of the number of carbons per molecule found in the fraction fr.

The lower and upper limits of the number of carbons per molecule in each fraction are listed in the following table:

Table 2. Defined minimum and maximum number of carbons per molecule for Light Hydrocarbons, Naphtha, Distillate and Wax.

Hydrocarbon Fraction exiting the FT reactor	nc_{frmin}	nc_{frmax}
Light hydrocarbons (Gaseous at Temp > 0°C)	1	4
Naphtha (Gasoline compatible)	5	10
Distilate (Diesel compatible)	11	20
Wax (Solid at Temp < 40°C)	21	50+

Fischer-Tropsch is an exothermic process, which means that excess heat must be removed in order to avoid overheating. Here we did not analyse the cooling requirements of the FT reactor, as it does not affect directly on the FT product yield. We simply assumed that the reactor has an appropriate cooling system for ensuring a constant operation temperature.

RESULTS

The overall energy and mass balance of the modelled process showed that it is possible to produce hydrocarbons from the gasification of Faecal Sludge and Municipal Solid Waste mixtures, with a liquid products yield from 10 to 55 Litres per metric ton of waste. Water content, oxygen feed, mixture composition and several other variables can be optimized in order to increase the liquid products yield.
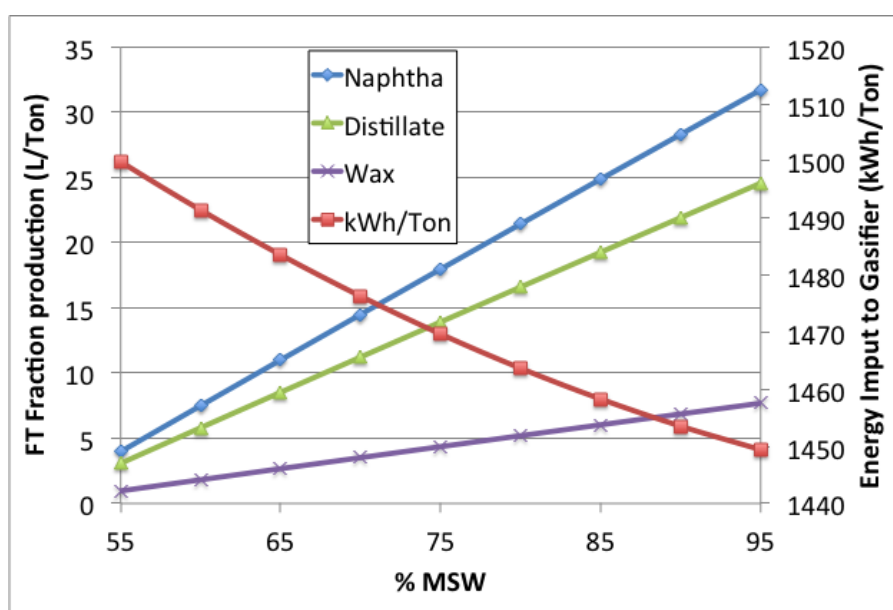

Figure 2. Fischer-Tropsch products yield and Gasifier energy requirements per metric ton of waste for different mixtures of Municipal Solid Waste (MSW) and Faecal Sludge. Oxygen feed ratio: 0.1 moles O2 /moles of C. No recirculation of Wax.

The higher the water content in the waste mixture, the higher the energy input required for the waste gasification. Mixing Faecal Sludge with MSW reduces the water content per ton of waste, which reduces the energy requirements of the gasifier (figure 2). The yield of FT products is also affected by the proportion of Faecal Sludge and MSW in the mixture, resulting in a higher yield per metric ton of waste for higher MSW content in the mixture. Feeding oxygen to the gasifier also reduces the external energy requirements of the gasifier. This is due to the fact that oxygen reacts inside the gasifier, which releases

energy. Nevertheless, there is no apparent benefit in increasing the oxygen feed ratio in the FT product yield (figure 3). Reprocessing the Wax produced in the FT reactor by feeding it to the gasifier results in a slight improvement of the FT product yield, but increases (also slightly) the energy requirements of the gasifier (figure 4).
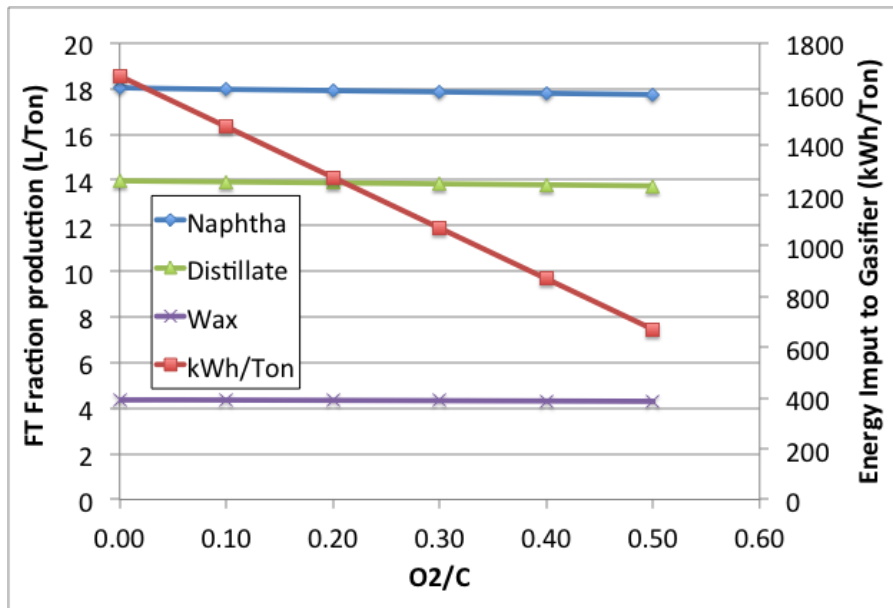

Figure 3. Fischer-Tropsch products yield and Gasifier energy requirements per metric ton of waste for different Oxygen feed ratios (moles O2 /moles of C). Waste mixture: 75 % MSW, 25% Faecal Sludge. No recirculation of Wax.
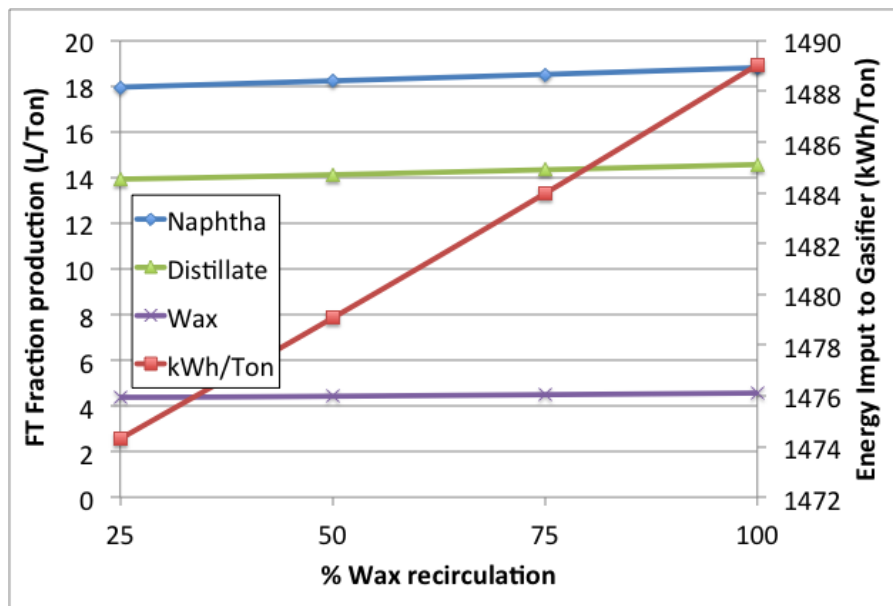

Figure 4. Fischer-Tropsch products yield and Gasifier energy requirements per metric ton of waste for different Wax recirculation values for reprocessing inside the Gasifier. Waste mixture: 75 % MSW, 25% Faecal Sludge. Oxygen feed ratio: 0.1 moles O2 /moles of C.

CONCLUSIONS

A simple design of a Gasification + Fischer-Tropsch plant was proposed for the production of gasoline and diesel compatible hydrocarbons. A model was developed whose results demonstrate that it is possible to obtain liquid hydrocarbons and wax from Municipal Solid Waste and Faecal Sludge mixtures.

The simplicity of the plant design and using Monolith FT reactors or FT Micro reactors could allow for low capital costs that would make small scale FT processing economically feasible.