CONCEPTUAL DESIGN OF AN INTEGRATED MICRO-ALGAL BIOMASS-TO-LIQUIDS PROCESS

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ABSTRACT: A new integrated biomass-to-liquids conceptual process was developed to produce 2.6 million litres of biodiesel per year from harvested micro-algal biomass. Three unconventional harvesting methods, a thermochemical liquefaction process to extract oils from micro-algal biomass, and a process to produce biodiesel through the acid-catalyzed transesterification of micro-algal oil, were combined into an integrated BtL process. The new process combined four renewable energy sources to produce biodiesel from micro-algal biomass. Wind power is utilized indirectly, as prevailing south-easterly winds concentrate micro-algal biomass against the dam wall of the Hartbeespoort Dam. The hydraulic head of 583 kPa of the 59.4 meter high dam is utilized for transportation of the biomass through the facility, which is located down-stream of the dam. Solar energy is used to dry the microalgae, which in turn is combusted in a furnace to release its 18,715 kW of bio-energy, which is used for heating in the energy-intensive extraction unit of the processing facility.
Keywords: biodiesel, biomass to liquid (BtL), microalgae

1 INTRODUCTION

Renewable energy sources such as biomass are becoming more and more important as alternative to fossil fuels. One of the most exciting new sources of biomass is microalgae. The Hartbeespoort Dam, located 37 km west of Pretoria, has one of the dense populations of microalgae in the world, and is one of the largest reservoirs of micro-algal biomass in South Africa. The Dam has great potential for micro-algal biomass production and beneficiation, due to its high nutrient loading, stable climatic conditions, size and close proximity to major urban and industrial centres.

2 METHODS & MATERIALS

The design of a biomass-to-liquids (BtL) conceptual process consisted of the following steps: (1) conducting a series of screening experiments to determine the most suitable methods for harvesting micro-algal biomass from the Hartbeespoort Dam; (2) combining current knowledge on extracting oils from microalgae and production of biodiesel from these oils into a holistic conceptual process. The screening studies described by Brink and Marx [1] identified three methods with great potential to harvest micro-algal biomass from the Hartbeespoort Dam sustainably and environmentally friendly. One method utilized the natural buoyancy of Hartbeespoort Dam microalgae to concentrate it from 1.5 to 3.0% TSS, while the second and third methods use gravity settling and a combination of sand filtration and renewable solar energy to dry and harvest the concentrated micro-algal biomass. Barnard [2] extracted oils successfully from microalgae harvested from the Hartbeespoort Dam with a small laboratory-scale pilot plant. Miao and Wu [3] produced biodiesel successfully through the acid-catalyzed transesterification of micro-algal oil.

3 RESULTS & DISCUSSION

3.1 Process description

The BtL process (Fig.1) consists of three sections: (1) a cultivation section where microalgae grows abundantly in the 20 km^2 Hartbeespoort Dam to a concentration of 160 g/m^2 during the six warmest months of the year [4], due to stable climatic conditions and the influx of large quantities of nitrates and phosphates into the Dam, from the run-off of fertilized agricultural land and effluent from sewage plants from the northern suburbs of Johannesburg [5]; (2) a harvesting section where excess water is removed from the micro-algal biomass; (3) and a reaction section where fatty acid oils are extracted from the microalgae and converted to biodiesel, and dry biomass rests are combusted to supply heat for the reaction section.

Micro-algal biomass in the Hartbeespoort Dam (Unit 100) is concentrated against the dam wall (U-200) at 1.5% TSS through prevailing south-easterly winds.

Micro-algal biomass is drained from the topside of the dam wall at a calendar-year flow rate of 930 ML/a into the concentration dam (U-300) were the biomass is concentrated to 3.0% TSS (Fig. 2) due to the natural buoyancy of the Hartbeespoort Dam's microalgae [1].

Biomass then flows to the Filtration Unit (U-400) where it is dewatered to 16% TSS through a drum filter. Excess water is recovered from Units 300 and 400 by draining it back into the river, down-stream of the dam wall. The biomass is then pumped into the reactor (R-501) at 15,000 kPa, where liquefaction occurs at 300^{o}C, to release fatty acid oils in the microalgae to a maximum content of 15.6% (wt.) [2].

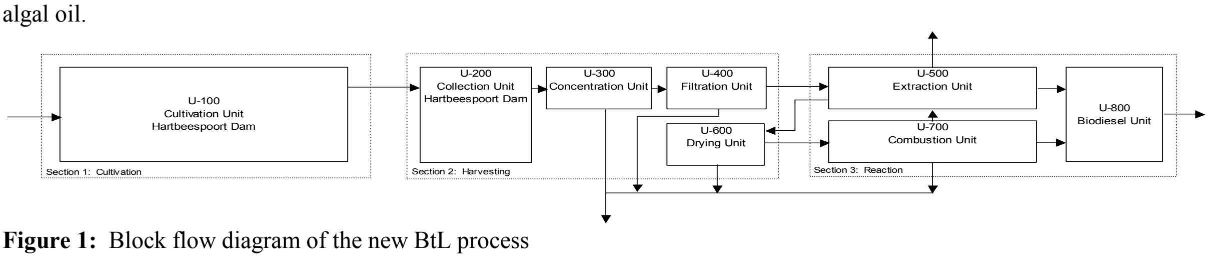

Figure 1: Block flow diagram of the new BtL process

Figure 2: Hartbeespoort Dam microalgae separating to the top of the measuring cylinders after 3.5 hours at a concentration of 3% TSS

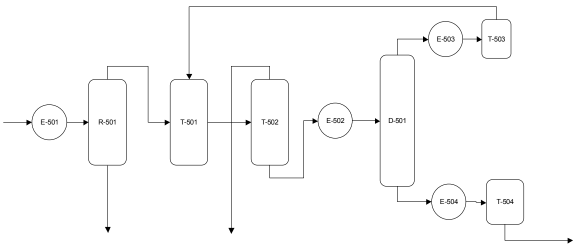

Figure 3: Process flow diagram of the Extraction Unit (U-600)

The oil-water-biomass mixture flows to a mixing tank (T-501) where chloroform solvent is added to extract the oils (Fig. 3). The contents are then sent to a separation tank (T-502) where the hydrocarbon chloroform-oil phase settles to the bottom, and the aqueous biomass phase accumulates at the top of the tank. The hydrocarbon layer is send to a distillation column (D-501) where chloroform exits the top of the column into a solvent storage tank (T-503) and purified oils leaves the bottom of the column into an intermediate feedstock storage tank (T-504) with 24 hours storage capacity. The solvent chloroform is recycled from the intermediate storage tank back into the mixing tank (T-501). The oils are then sent to the Biodiesel Unit (U-800) where fatty acids are converted into fatty acid esters through acidic-catalyzed transesterification [3]. The process of Haas et al. [6] could be used to produce biodiesel from micro-algal oils, if the sodium methoxide catalyst is replaced with sulfuric acid, as recommended by Miao and Wu [3]. The top aqueous biomass layer in the separation tank (T-502) is irrigated onto a field of cleared soil (U-600), where it is allowed to dry for 24 hours, yielding 157.6 grams of dried micro-algal biomass per square meter (Fig. 4, 5, 6) [1]. The dried biomass is harvested with solar-powered riding lawnmowers, which is fitted with rake-ends, to gather the dried biomass flakes.

Figure 4: 4 m^2 patch of cleared soil containing a layer of harvested wet Hartbeespoort Dam micro-algal biomass

Figure 5: Sun-dried patch of micro-algal biomass from the Hartbeespoort Dam after 24 hours of drying

Figure 6: Manually harvested sand-filtered, sun-dried Hartbeespoort Dam micro-algal biomass flakes

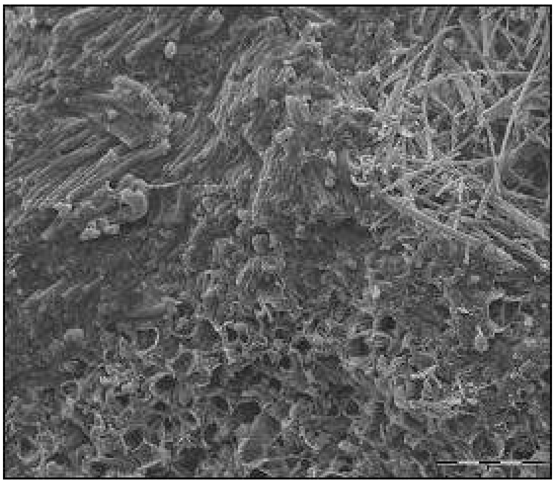

Figure 7: Microphotograph of sun-dried Hartbeespoort Dam micro-algal biomass at 20 microns (SEM Laboratory, 2009)

The biomass (Fig. 6, 7) is then fed into a furnace (U-700) and combusted to release its 19.27 MJ/kg of combustion bio-energy [7]. The hot combustion flue gas is used for heating in the Extraction and Biodiesel Units (U-500 and U-800).

3.2 Mass balance

The following mass balance was calculated (Table I), using actual design parameters achieved by screening and laboratory-scale experiments from literature. The second column lists the total suspended solids concentration (TSS) of micro-algal biomass on a dry weight basis. The third column shows the total calendar-year flow rates of the feeds entering Units 300 to 800. The last three columns show the flow rates of the water, biomass and oil fractions of these feed streams, respectively.

Table I: Mass balance across the BtL process

Unit	TSS	Total Flow	Water Flow	Biomass Flow	Oil Flow
#	wt. %	t/a	t/a	t/a	t/a
U-100	<1.5	-	-	-	-
U-200	1.5	-	-	-	-
U-300	1.5	933,525	919,242	14,283	2,228
U-400	3	536,952	522,669	14,283	2,228
U-500	16	87,841	73,558	14,283	2,228
U-600	44	32,672	18,389	12,055	0
U-700	100	12,055	0	12,055	0
U-800	0	2,228	0	0	2,228

4 CONCLUSIONS

A new integrated biomass-to-liquids conceptual process was developed to produce biodiesel from harvested micro-algal biomass from the Hartbeespoort Dam. A holistic approach was followed to incorporate all the resources available in and around the Dam. The new integrated BtL process combined four renewable energy sources to produce 2.6 million litres per year of carbon net zero biodiesel, which will reduce greenhouse gases by 22 kilotons of carbon dioxide per year. Wind power is utilized indirectly, as prevailing south-easterly winds concentrate micro-algal biomass against the dam wall of the Hartbeespoort Dam. The hydraulic head of 583 kPa of the 59.4 meter high dam is utilized for transportation of the biomass through the facility. Solar energy is used to dry the microalgae, which in turn is combusted in a furnace to release its 18,715 kW of bio-energy, which is used for heating in the energy-intensive extraction unit of the processing facility. Three unconventional harvesting methods, which utilize the natural buoyancy of Hartbeespoort Dam microalgae, gravity settling and a combination of sand filtration and solar drying, to concentrate, dewater and dry the micro-algal biomass, were incorporated into the design to minimize the energy required to harvest the micro-algal biomass sustainably and environmentally friendly.

The new process sets a benchmark for other related ones with regards to its net energy efficiency. The new process is thermodynamically viable, exporting 18 times more energy than it imports, with a net power output of 5,483 kilowatts. The Extraction and Drying units (U-500 and U-600) are the most energy-intensive units of the new process, each consuming 14,752 kW and 3,103 kW, respectively. The Extraction Unit requires 14,036 kW of heating, 491 kW of cooling, and 225 kW of electricity.

Heating is supplied by hot flue gas from the dry micro-algal biomass combusted in the Furnace Unit (U-700). Cooling is supplied by excess water from the process, and electricity is supplied by external suppliers.

The Drying Unit utilizes renewable solar energy to dry the micro-algal biomass. Except for the electricity requirements needed for pumping and agitation in the Extraction Unit, and the irrigation pumps of the Drying Unit, all energy required by the process to produce biodiesel from harvested micro-algal biomass from the Hartbeespoort Dam were supplied by renewable energy sources.

5 REFERENCES

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6 ACKNOWLEDGEMENTS

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