Design of Biodiesel Plant using Transesterification process for Non-edible oil seeds

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Abstract*— Fossil fuels are the most prominent energy source for rapid growth of nations economy and fast developing industrialization since many decades. Stringent environmental norms and energy security has forced researchers to think for alternatives energy resources. Biodiesel is one of the alternative that can replace conventional fossil fuel and can used in any conventional engine, without any design modifications. Several technologies are developed to reduce harmful gases emitted by gasoline engine but if fuel itself is not clean, then all this design modifications are not affordable and sustainable. So the main aim of this research is to incorporate suitable design modifications in biodiesel plant to improve oil recovery and good quality of fuel from Jatropha, Cotton seeds and Undi oil using transesterification process. Also it deals with validation of synthesized biodiesel as per ASTM D-6751 standards. Result showed that modified biodiesel plant has oil recovery above 90% for jatropha and undi oil, properties of synthesized biodiesel are also validated as per standards.

Keywords: Biodiesel plant, Design Modifications, Oil Recovery, transesterification process.

I.INTRODUCTION

Fossil fuel consumption level is predicted to increase by 60% by 2030 mainly because of population growth, industrialization and exposure to better living standards. Stringent environmental norms are present day problem for all automotive manufacturers since diesel fuel is not capable of meeting standards. Also, technology to reduce harmful green house emissions is not affordable to customers. Biodiesel as fuel has the capability of meeting stringent environmental norms which is purely renewable and eco-friendly fuel. Biodiesel is renewable fuel consisting of short chain alkyl esters made by transesterification process from various edible, non-edible oil seeds, animal fats and waste vegetable oils. Although edible oil seeds are in controversy since due to food security in many of nations. Non edible oil is highly recommended since its Free Fatty Acid (FFA) is high not suitable for human consumption and it has capability of significant oil recovery. Government of India has taken initiatives to cultivate Jatropha in 1.72 million hectare of total land and land is already allocated to some public sectors. Considering draught conditions in Maharashtra and to provide some income source for farmers non-edible like Jatropha, Cotton seed and Undi are selected as feedstock oil in this research.

II. LITERATURE REVIEW

The Jatropha curcas Linnaeus plant is a hardy shrub that can grow on poor soils and areas of low rainfall. The oil content of Jatropha seed ranges from 25% to 30% by weight. Fresh Jatropha oil is slow-drying, odorless and color less oil, but it turns yellow after aging. Non-edible oil generally contains about 3-4 %wax and gum. De-waxing and degumming of plant oils is required not only for smooth running of the CI engine but also to prevent engine failure even if plant oils are blended with diesel. It is therefore necessary to remove wax and gum from the fresh oil before it could be used in CI engine. [1-2].

Undi is a species of family Guttifereae (Clusiaceae), native to India, East Africa, South east Asia, Australia and South Pacific. Commonly it is called as Indian laure, Alexandrian Laurel, Beach calophyllum.[3] The oil content of undi seed ranges from 55% to 60% by weight. The greenish yellow oil with disagreeable odour contains 28.08mg of KOH/gm FFA. The undi oil obtained from the calophyllum seeds was used as alternative to candlenut oil in lamps. Selected feedstock oil has potential to grow in bare land and one rainfall is sufficient to yield seeds. Also, the life of selected feedstock plant is more than 100 years except cotton plant which has a life of about 70years.[2-3]

Transesterification process is conversion of ester and glycerol to form methyl ester(biodiesel) in presence of a catalyst. So the selection of catalyst is one of the important parameter for transesterification process.[3] Reaction time is greatly affected by type of catalyst used in transesterification process. Generally homogeneous catalyst such sodium and potassium oxide is usually preferred at wide scale. In this research homogeneous catalyst was replaced by heterogeneous catalyst aluminum trioxoide which is ecofriendly and reusable for various batch production.[4] Also it is comparatively non corrosive and non-toxic which is important parameter for selection of material for reactor vessel. Reaction time is greatly affected by type of catalyst used in transesterification process.[5]

Lab scale studies was carried out to study existing process at Indian Biodiesel Corporation (IBDC), Baramati. Study of existing design at IBDC was carried out to set design conditions for commercial biodiesel production process. Biodiesel production process was studied and experimentation to set reaction time, temperature, pressure, molar ratio and stirrer speeds was done on lab scale basis. Many researchers has given priorities to optimize various parameters of biodiesel production process but this research was extensively carry out to effect of various design parameters involved in design of biodiesel plant.

Quality of biodiesel is key factor when it is used as alternative to conventional diesel fuel. Quality of biodiesel fuel should meet ASTM D6751 standards within recommended limits so that it can be used in modern engines without modifications maintaining engine durability and maintainability. Another major problem of biodiesel fuel is poor oxidation stability which is of main concern behind not using biodiesel as fuel i.e. it alter its properties with time. Based on design modification done at IBDC results has showed good oxidation stability for set design conditions and parameters. Also oil recovery above 90% of selected oil is achieved without affecting quality of synthesized biodiesel. Design modifications were done considering economic and sustainability of biodiesel plant for various feedstock oil. However it was found that undi oil has shown maximum oil recovery about 93% for designed biodiesel plant. Designed reactor vessel volume has showed good triglyceride conversion which is important parameter of esterification process. Biodiesel synthesizes from designed biodiesel plant has shows that 100% blending can be achieved as per ASTM D6751 standards.

III. METHODOLOGY

A. Design of Biodiesel plant

Biodiesel production process is carried out in three steps pre-treatment, biodiesel production process and purification. Since this project deals with design modifications of existing plant at IBDC to oil recovery and quality of fuel. Following are the design parameters which has maximum influence on oil recovery.

1. Design of Reactor Vessel

Biodiesel reactor vessel design was modified with eliminating pre-treatment vessel and carrying out esterification and biodiesel production process in same reactor vessel without affecting quality of methyl ester produced.

i. Sizing of reactor unit

50 litres capacity of reactor vessel suitable for batch production system was designed. Sizing calculation for reactor vessel is done according to equation 1

$$v_r = \pi \frac{D^2}{4} H \quad (1)$$

H/D = height to diameter ratio is taken as 1.5

H= 525 mm

D= 350mm

Therefore reactor vessel was designed to handle volume of 50.511 litres of reactant volume.

ii. Design conditions for reactor vessel

a. Design Pressure

According to standards, design pressure (internal) should be equivalent to pressure set for relief valve.

Internal pressure (gauge) (P_g) is taken as 25kpa and hydrostatic pressure is calculated using equation 2 assuming average density of feedstock oil as 920 kg/m^3 and liquid height approximately 500mm.

$$\text{Hydrostatic pressure, } P_h = \rho g H \quad (2)$$

$$= 0.5\times920\times9.81$$

$$= 4512.6 \text{ Pa}$$

$$(P_h) = 4.5126 \text{ Kpa}$$

Therefore as per standards design pressure is calculated as,

$$P_d = P_h + P_g$$

$$= 4.5126+25$$

$$P_d = 29.5126 \text{ Kpa}$$

b. Design Temperature

Generally transesterification process is carried out at temperature range of 60-120°C. Maximum operating temperature of reactor vessel was taken as 85°C with 10°C additional safety margin. Therefore design temperature was taken as 95°C which facilitate in selection of design of heating element.

iii. Material Selection

Selection of material for biodiesel production process was done according to design conditions. Also material should be capable to withstand chemical reactivity during process. SS304L material is selected according to manufacturers recommendation for the design of reactor vessel and carbon steel for the structure of biodiesel plant structure.

iv. Selection of Design Stress

According to British standard PD500, the design stress or allowable stress σ_{all} of selected fabricating material SS304L at operating temperature 95°C is taken as 145 N/mm^2.

v. Calculation for reactor vessel thickness

Let,

σ_{all} = allowable tensile stress for cylindrical vessel shell =145 N/mm^2

Pi = Design Pressure (internal pressure) = 29.512 Kpa

Di = inner diameter of the cylindrical vessel shell = 350mm

t = thickness of the shell without corrosion allowance, mm

Therefore,

$$t = \frac{P_i \times D_i}{2\times\sigma_{all} - P_i}. \quad (4)$$

$$t = \frac{29.5126\times 0.350}{2\times145 - 29.5126}$$

t = 2 mm, minimum allowable thickness was selected according to pressure vessel design standards.

vi. Design of end closure for reactor vessel

Considering economic feasibility and ease maintainability flat plate head closure with bolted cover was selected for designed reactor vessel. Minimum thickness required for plate was estimated using equation 5

$$t_e = C_P D_e \sqrt{\frac{P_i}{\sigma_{all}}} \qquad (5)$$

where,

C_p = design constant dependent on edge constant = 0.4

D_e = effective diameter = 0.390 mm

Therefore thickness of end closure was estimated to 4mm.

2. Design of Mixing / agitator mechanism

Design of mixing mechanism is a critical parameter since it affects reaction time need to complete the transesterification process and ultimately quality of biodiesel fuel. Mechanical agitator or stirrers are commonly used for mixing purposes but with the aid of an electric motor. Considering economic feasibility and safety constraints as mechanical agitators are more prone to ignition and electric spark it may cause explosion. Mechanical agitators were replaced by Jet mixing mechanism as shown in fig has significant oil recovery in comparatively less reaction time. Design of Jet mixing mechanism includes calculation of various design parameters such as jet nozzle diameter d_i, critical velocity V_c to estimate jet velocity and minimum circulation rate Q_c.

i. Jet nozzle diameter

According to [3] geometry of single side entry nozzle was selected according,

$$0.25 \le \frac{H}{D} \le 1.5$$

where,

H = Liquid height in tank

D = Diameter of reactor vessel = 350 mm

According to [3] it was reported that liquid height in the tank should be within 0.25 to 1.5 times diameter of the reactor vessel. Generally higher H/D ratio is recommended for better mixing ability. Therefore the liquid height of reactor H was estimated to 490mm.

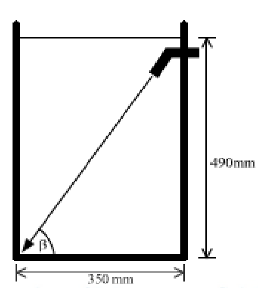

Fig.1 Dimension selected for jet mixing mechanism

X as shown in Fig 2 was calculated using geometrical relationship, $X = \sqrt{H^2 + D^2}$

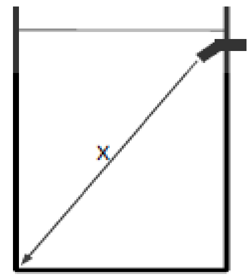

Fig 2 Jet length X for side entry

Therefore X = 609mm

According to above relationship and jet nozzle diameter, d_j is estimated using relationship given in equation,

$50d_j \le X \le 400d_j$ is selected within 1.36 and 10.88mm.

Therefore diameter of nozzle is selected as 10mm.

2. Critical jet velocity V_c

The critical velocity V_c which is necessary to estimate jet velocity is estimated using relation 6,

$$V_c = \left[\frac{2gGH\left(\frac{\rho_2 - \rho_1}{\rho_2}\right)}{\sin^2\theta} \right]^{0.5} \qquad (6)$$

where,

$\theta = (\beta + 5)^{o}$,

β = angle of inclination of jet nozzle to horizontal

ρ_2 = density of heavy liquid

ρ_1 = density of light liquid

G = constant based on stratification data for jet mixing

Therefore V_c is estimated as 5.21 m/s.

3. Minimum liquid circulation rate Q_c

Minimum circulation rate Q_c was estimated using relation,

Q_c = Area of nozzle × liquid velocity

Therefore, circulation pump selected for pumping capacity equivalent to Q_c = 2.213 m^3/ hr

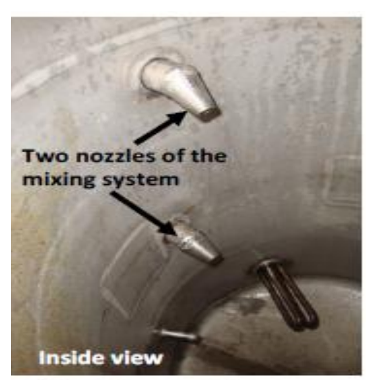

Fig 3 Jet nozzle arrangement for reactor vessel

3.Design of Heating element

Generally a temperature range of 55-120°C is desired to carry out transesterification process and temperature has significant effect on total reaction time needed to complete the process. Also it is ensured that properties of synthesizes biodiesel should meet norms while selecting appropriate temperature range. A heating element has been designed to meet temperature requirement of transesterification process. Considering controllability and safety of system it was recommended to use electric heating system to meet process requirement as shown in Fig 4.

Fig 4 2KW electric heating element

4. Design of settling unit

Settling unit or storage tank design was modified to equip with air spraging system to carry out biodiesel washing process. Maximum volume of settling tank was designed to handle 50 litres of reactants. It was recommended to design settling tank with additional 10 % volume (i.e 5 litres) to accommodate liquid variations during biodiesel washing process.

5. Design of air spraging system

Air spraging system designed for settling/ storage tank is used for biodiesel washing process. It consist of mesh like tibe structure which can be submerged horizontal to bottom of the vessel and a vertical tube mesh from outside as shown in fig. Complete system was fabricated using 152.4mm and 76.2mm SS304L tubes with 2mm holes drilled to bottom side of tube mesh to allow escaping pressurizes air as tiny bubbles as shown in Fig 5.

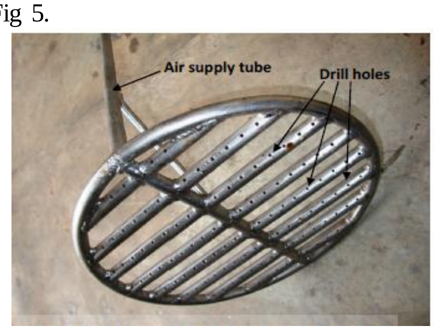

Fig 5 Tube structure for air spraging system

6. Selection of piping system

Piping system suitable for design conditions for transferring reactants was selected replacing stainless steel pipes with flexible clear PVC tubing. It allowed transparency to allow operator visually inspect process and it is flexible for assembling and dismantling whenever required.

B. Biodiesel production process

Due to design modifications esterification is carried out in reactor vessel inspite of pretreatment vessel. Esterification process is carried out to reduce free fatty acid (FFA) value of selected oil. Jatropha oil first heated to 50°C then 1.7% (by wt. of oil) sulfuric acid was to be added to heated oil and methyl alcohol about 1:8 molar ratio (by wt of oil) added afterwards in 50litres designed reactor. The reaction started with stirring speed about 950 rpm and temperature was controlled at 55-60°C for 60 min with regular analysis of FFA every after 25-30 min. Finally the FFA was reduced upto 1.5% then the excess methyl alcohol was removed by distillation and esterified oil was transferred into settling tank. The trace quantity of moisture was formed in this step, which was removed. The major obstacle to acid catalyzed esterification for FFA is the water formation. Water can prevent the conversion reaction of FFA to esters from going to completion [28]. Afterwards the esterified oil was now used to carry out transesterification process [29].

1.2wt % of aluminium trioxide was added in reactor vessel to dissolved with methyl alcohol (8 mol of that oil) at 40^0C, then this mixture was slowly added to heated oil & reaction started for 90 min with stirring speed about 650 rpm and at 55-60^oC temperature. After reaction completion i.e. when FFA reduced up to 0.7% the transesterified oil was again transferred to settling/storage tank. The three distinct layer of methyl ester, glycerol and unreacted oil were formed. The glycerol settled at bottom of storage tank due to gravity and jatropha methyl ester were settled at the top of storage tank. The unreacted oil settled in between glycerol and methyl ester layer. The glycerol was separated manually. Then the product i.e. jatropha methyl ester was washed with the help of air designed air sprager to remove dissolved sulphric acid, sodium, methyl alcohol and glycerol. The wasted biodiesel were dried over anhydrous sodium sulphate. The purified methyl ester were proceeded for quality testing.The undi methyl ester and thumba methyl ester were synthesized as per protocol using aluminium trioxide as a strong base catalyst and methyl alcohol [17], [20]. Same process was carried out to synthesize biodiesel from cotton seeds oil and undi oil.

C. Experimental Set-up at IBDC

Designed 50 litres capacity of biodiesel plant with suitable design modifications at IBDC is shown in Fig 6.

Fig 6 Designed Biodiesel Plant at IBDC

IV. RESULTS AND DISCUSSIONS

Biodiesel synthesized from modifications in design of Biodiesel plant has shown significant results as discussed below.

A. Effect of various design parameters

1. Effect of internal pressure on reactor vessel thickness

Reactor vessel used for biodiesel production process generally designed to withstand pressure between 20-40 N/m^2. However increase of internal pressure has to incorporate with increase in thickness of pressure vessel. Designed reactor vessel with 29.515 N/m^2 pressure is optimum and safe against design conditions set for biodiesel plant.

2. Effect of Reactor Volume on Triglyceride Conversion

Reactor vessel volume has significant effect on triglyceride conversion i.e. conversion FFA on methyl ester. According to ASTM standards triglyceride conversion should be not more than 0.30 (wt%), designed reactor vessel has meet norms for selected oil from different feedstock as shown in Fig. 7

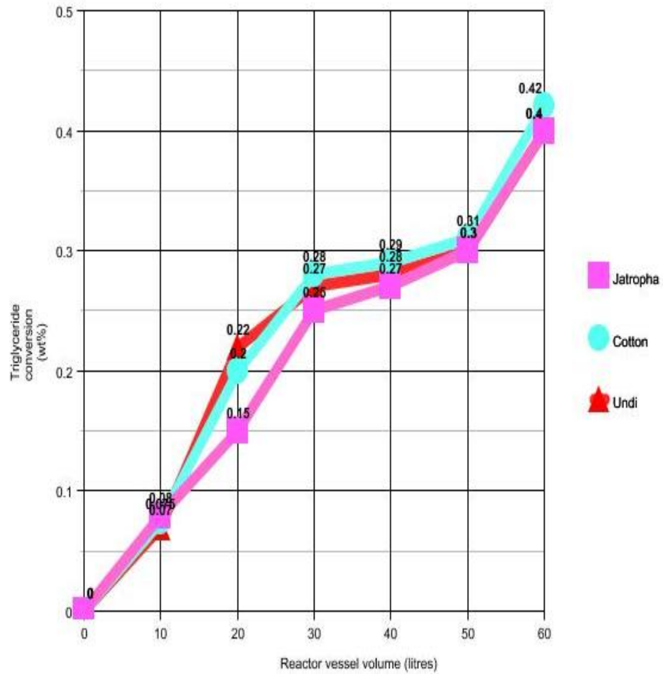

Fig 7 Reactor volume (litres) vs Triglyceride conversion (wt%)

3. Effect of Modifications of mixing mechanism.

Replacement of mechanical agitators with jet mixing mechanism has reduced total reaction time required to carry out biodiesel production process. Synthesizes biodiesel was obtained in just 55 minutes of reaction times without affecting quality of fuel. Also it was not necessary to equip separate motor which ultimately led to cost saving.

4. Effect of Modification in design of settling/storage tank.

Air spraging system designed for storage tank unit has reduced settling time and loss of oil recovery during washing process was completely eliminated. Due to which results has showed upto 90% oil recovery for selected feedstocks.

B. Oil Recovery

Oil recovery of existing plant at IBDC was 70-75% and due to design modifications incorporated oil recovery for selected feedstocks oil is increased as shown in Table i

TABLE I OIL RECOVERY OF DESIGNED BIODIESEL PLANT

Sr. No	**Non-edibleoil seeds**	**Oil Recovery(%)**
1	Jatropha	90
2	Undi	93
3	Cotton Seeds	85

C. Validation ofSynthesized Biodiesel as per ASTM standards

Validation of synthesized biodiesel is important parameter in deciding quality of synthesized. Results have showed that approximately all properties of synthesized biodiesel are as per norms.

TABLE II PROPERTIES OF SYNTHESIZED BIODIESEL

Properties	**ASTM Standards**	**Properties of synthesized biodiesel Methyl Ester**		
		Jatropha	**Undi**	**Cotton**
Density (g/cm^3)	0.860-0.900	0.872	0.892	0.87
Viscosity (cst)	3.5-5	3.82	3.87	3.8
Calorific Value (MJ/kg	35-45	38	37.18	37
Flash point (°C)	160-190	164	176	164
Fire point (°C)	160-190	171	182	172
Cetane Number	51	48	51	51

V. CONCLUSION

Design reactor vessel is safe against design conditions and has shown good triglyceride conversion rate for selected capacity. Also cost associated with selection of material is comparatively low since SS304L material is cheaply available with manufacturer due to its good corrosive properties. Also SS304L is material which does not take into account corrosion allowance for design of reactor vessel. Modification in mixing mechanism has reduced settling time required to obtain methyl ester. Also good oxidation stability upto 8 hours is achieved using jet mixing mechanism. Electric heater employed is capable of controlling process temperature within limits with aid of temperature controller. Design plant is compact since pre-treatment vessel was completely eliminated carrying out esterification and transesterification process in main reactor vessel.

Biodiesel plant designed at IBDC has shown increase in oil recovery for selected non-edible oil seeds like Jatropha (90%), Undi (93%) and cotton seeds oil (85%) using transesterification process. Generally Undi oil has shown recovery upto 90%. Also heterogeneous catalyst (Aluminium trioxide) used for designed plant is reusable and eco-friendly, which is one of the additional benefits in economical concern. Also properties of synthesized biodiesel are validated as per ASTM D6751 standards which shows that 100% blending of synthesized biodiesel is possible in conventional engine without any design modifications.

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