Design of a containerised biodiesel production plant

An abstracted report from the Biofuels for the Fishing Industry project

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The Sea Fish Industry Authority

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Non-Technical Summary

This report details work carried out in assembly of a prototype containerised batch production plant that is portable and suited to deployment quayside to support fishermen that wish to self-manufacture biodiesel.

The biodiesel batch plant has a maximum production capacity of approximately 210,000 litres per annum when working one shift and approximately 420,000 litres per annum with 24 hour working. It is set up for an alkali catalysed (sodium hydroxide) tranesterification process that uses a pressurised reaction vessel and elevated reaction temperatures. These conditions make the reaction faster and produce bio-diesel of higher yield and purity in comparison to the process in similar plants where the reaction occurs at atmospheric pressure. Another key advantage of the plant design is that it uses a solid washing agent called magnesol that adsorbs remnant reactants, catalyst and many reaction by-products from the fuel after it has been separated out from the other product of the reaction (glycerol). This is not to say that difficulties were not encountered with the use of a solid washing agent: it proved necessary to carefully control and monitor the filtration process used to remove the pregnant magnesol from the fuel.

Other similar batch reactors frequently wash the fuel with water that then requires discharge. This increases the scope of pollution control permitting and sets a requirement for water supply and drainage infrastructure (reducing portability), not present in the plant that has been designed. The infrastructure requirements comprise the provision of: i) a 32 amp, 3 phase power supply, ii) adequate exclusions of unauthorised personnel, iii) adequate movement areas for materials handling and iv) suitable mechanised handling equipment (a fork lift). The containerised reactor unit is self-bunded to contain inevitable spillages that occur while processing the fuel, and it is recommended that it be deployed with a sister container unit used to provide safe and secure storage of feedstock oils, reagents and other consumable items.

Within this document the design is fully specified, the production process is outlined and the costs of production are presented. The measures to control risks appraised through a formal risk assessment translate into operational procedures that are detailed within Appendix 1: *Operational Procedures* and Appendix 2: *Plant Maintenance*. The reactor vessel is considered a pressure vessel and in the context of UK legislation and therefore must be inspected and insured accordingly. Options for handling co-products and waste products of the process are presented.

While the plant has been successful in realising many of the design objectives, material handling and filtration problems were experienced with the prototype and these were exacerbated during cold weather.

Production experience with the plant allowed estimation of the cost of production. Before taking into account the value of labour (estimated at around 5 per litre), the production cost per litre of bio-diesel produced was at least 23 pence per litre when feedstock was locally obtained free of charge, and at least 53 pence per litre when commercially sourced recovered vegetable oil was used.

Fishermen could readily be trained to use the existing plant as it exists in its prototype state at the time of writing; improvements to the process and the plant equipment have been identified as being desirable to implement in the first design revision before this stage.

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Introduction

Document Context

This report details work carried out in design and assembly of a prototype containerised biodiesel batch production plant. The work was carried out at the Camborne School of Mines (CSM), an academic department of the University of Exeter. The work was commissioned by the Sea Fish Industry Authority (SeaFISH) with the aim of developing a portable fuel plant for quayside deployment to support fishermen that wish to self-manufacture fuel for their vessel's diesel engines.

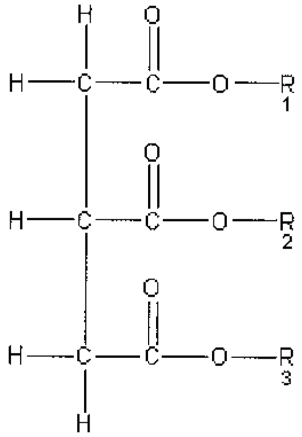
This work was conducted in parallel with other work on Biofuels for the Fishing Industry, also commissioned by SeaFISH, and was reported to SeaFISH in December 2007. At the request of SeaFISH, materials of specific relevance to the design, operation and maintenance of the plant are separately reported herein by means of abstracting the December 2007 report.

Thus the aim of this report is to provide full technical details of the biodiesel plant without the reader being unnecessarily burdened with detail concerning testing of the biofuels produced either in the CSM engine dynamometer test facility or at sea in FV Ma Gandole. The target audience of this report are thus individuals, possibly skippers, working within the fishing industry, that require full technical detail concerning the fuel plant. Readers of this report also interested in the wider biofuels scope should obtain a copy of the full December 2007 report submitted to SeaFISH.

Process description

Reaction chemistry

The reaction employed in this scale of biodiesel production is termed a transesterification reaction. Consider new vegetable oil which is comprised of triglyceride molecules.



A triglyceride molecule is shown to the left. It consists of three hydrocarbon chains, shown as R_1 R_2 R_3. These chains might be of different lengths, saturated, mono-unsaturated and poly-unsaturated which is why the shorthand notation is used.
The triglyceride molecule is a triester because there are three esters in the molecule. An ester is a molecule that has a hydrocarbon chain attached to the single bonded oxygen atom of the functional group.

As the term transesterification suggests, the reaction used to make biodiesel from vegetable oil changes the esters in the oil (glyceryl esters) into alternative esters (methyl esters). In so doing the triesters become esters and by splitting the three chains apart in this manner, the viscosity of the biodiesel fuel is markedly less than that of the original oil.

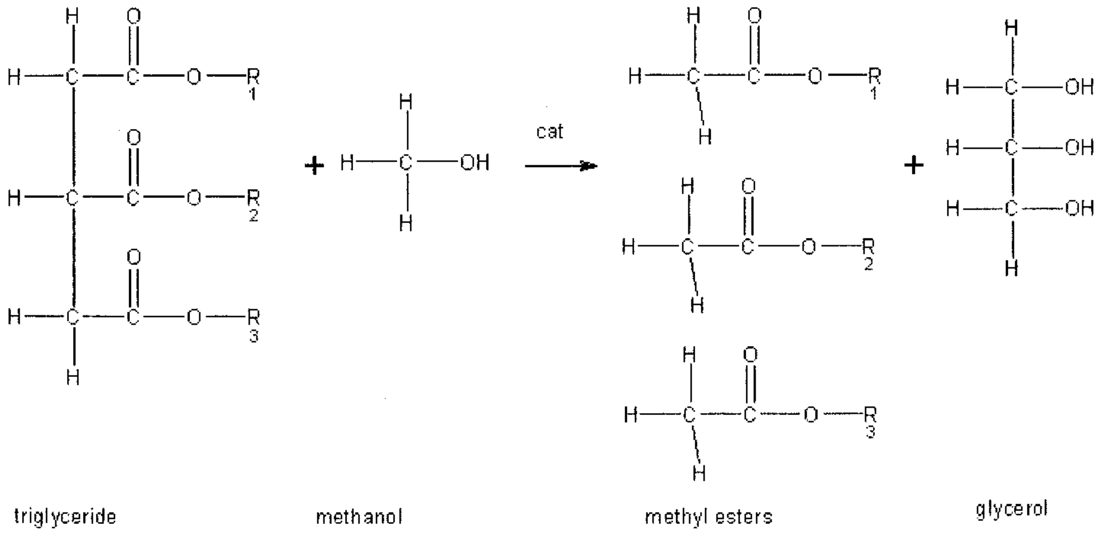


Figure 1: The transesterification of vegetable oil using methanol.

In the reaction shown above in *Figure 1*, it is evident that the methanol has replaced the glycerol “backbone” creating the three separate methyl esters and releasing the glycerol.

The transesterification reaction is reversible and as the triglycerides are separating, releasing glycerol and forming methyl esters, so the methyl esters are forming triglycerides and releasing methanol. The way in which we bias the equilibrium position well to the right (in small scale production) is to ensure the presence of a great excess of methanol.

An alternative transesterification of vegetable oil can be performed with ethanol rather than methanol hence producing ethyl esters rather than methyl esters. This is favoured by some because although the calorific value of the fuel is less than for fatty acid methyl ester fuel, the ethanol is more readily available as a carbon neutral reagent, unlike the methanol which is almost exclusively produced from petroleum.

In use as cooking oil, the triglycerides of the vegetable oil can break down and form fatty acids. Being unattached these are known as free fatty acids. These free fatty acids are undesirable in fuel due to their acidity and will not take part in the transesterification as they are not esters. One way to deal with the free fatty acids is to esterify them prior to the transesterification. However, this adds a chemical process to the production of the fuel and for small scale production the free fatty acids are simply neutralised with sodium hydroxide (or potassium hydroxide) to form soaps which are then removed.

The level of free fatty acids present in used cooking oil will depend on how much use the oil has had and what temperatures it was heated to; the more severe the use of the oil, the greater the concentration of free fatty acids. A titration is performed to assess the acidity of the oil and hence to determine how much alkali to add to neutralise it.

The production process

This section gives a brief outline of the production process with the batch reactor installed at CSM's Holmans Test Mine. The process is detailed in a stage by stage manner in the operating procedures given as *Appendix 1*. A schematic diagram of the production process is given as *Figure 2.*

There are five key stages to the production process, these are:

Stage 1	Vegetable oil conditioning and preheating. (1 hour)
Stage 2	The transesterification reaction. (1 hour)
Stage 3	Separation of the waste by-product, glycerine. (1 + 6 - 8 hours)
Stage 4	The Magnesol wash. (1 hour)
Stage 5	Final filtration. (5 hours)

The techniques and equipment employed for stage 1 will vary depending on the type and quality of the feedstock oil being used. The requirement is to deliver oil to the reactor at 55 – 60° C and for this oil to be free of water, free of solids and of known free fatty acid content. Water if present in too high a proportion, will affect the reaction by reducing the action of the catalyst and hence the reaction will not achieve the same degree of completion. Also water will form an emulsion with the soaps that are formed and this will cause difficulties in the subsequent washing and filtering operations.

The free fatty acid content must be assessed so that the correct amount of sodium hydroxide can be determined. The sodium hydroxide performs two functions, firstly that of a catalyst for the transesterification reaction and secondly as a neutralizing agent for the free fatty acids.

In stage 2 the methanol is pumped by hand into the reactor followed by the sodium hydroxide and then the oil. A circulating pump mixes and agitates the reagents and electric elements raise the temperature resulting in a rise in pressure within the sealed vessel. Once 85° C is reached the reaction completes within 25 minutes after which the pressure is released and the products are pumped immediately to the separation vessel. Significant separation occurs quite soon after the transfer is complete and an initial drain off of the glycerine is performed after 1 hour. The final drain off of glycerine can be performed 6 – 8 hours later if 2 or 3 separation vessel batches are required per 24 hour day but overnight separation yields a higher grade of product and reduces the consumption of subsequent filter elements. When the glycerine is removed, the biodiesel is pumped to the Magnesol ‘wash’ tank.

Magnesol R60 powder is mixed into the biodiesel and mechanically agitated for 15 – 20 minutes. The Magnesol powder is described by its manufacturers, The Dallas Group of America inc., as a synthetic, amorphous, hydrous form of magnesium silicate with a porous internal structure and an enormous activated surface. It adsorbs the water, soaps, and residual methanol present in the biodiesel allowing them to be filtered out. The pump unit is used to circulate the colloidal mixture through the diffuser which removes solids above 1 micron in diameter. Periodic agitation is necessary during this time to prevent the Magnesol from settling out on to the bottom of the tank. When sufficient washing has been achieved, the biodiesel returning to the tank from the diffuser is diverted into the filtration tank. This method of transfer eliminates the risk of some unfiltered fluid being picked up by a separate suction hose in the Magnesol wash tank.

Final filtration employs a simple multi–pass pumped filtration circuit through 1 micron filters. Four or five passes through the filters are recommended which will take approximately 5 hours for a full batch of around 700 litres. When the filtration is complete the filter return line is diverted to send the finished biodiesel into a clean IBC for storage and use.

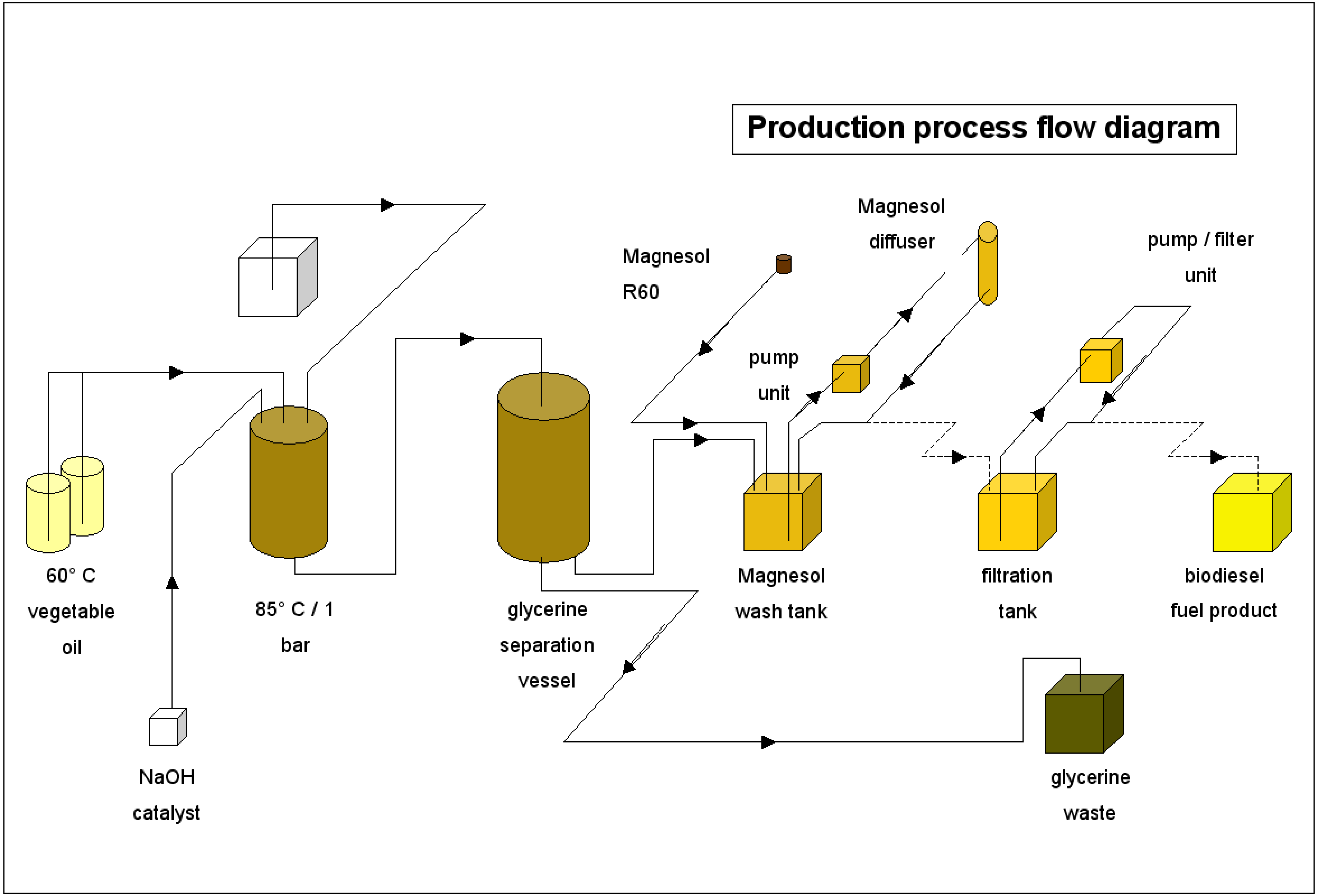
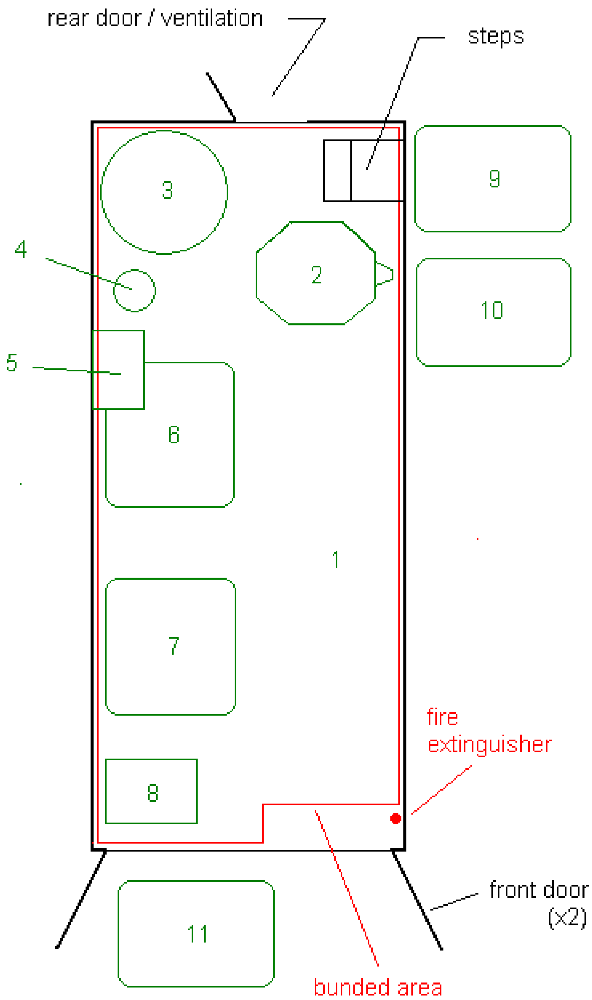


Figure 2: Production process flow diagram

Plant specification

Containerised plant layout

The production unit comprises the equipment required for the 5 stages of the process, pumps and pipework to effect the fluid transfer from stage to stage, an electrical distribution system and suitable lighting. This equipment is rigidly assembled into a specially modified steel shipping container providing a secure, safe and bunded operating environment that can be relocated to any suitable site. *Figure 3* below shows the layout of the process equipment within the container and the positioning of methanol, glycerine and the fuel product outside of the container.



1	Area for feedstock oil preparation	7	Filtration tank
2	Transesterification reactor	8	Filtration unit
3	Glycerine separation vessel	9	IBC containing methanol
4	Magnesol wash diffuser	10	IBC receiving waste glycerine
5	Magnesol wash pump unit	11	IBC receiving final fuel product
6	Magnesol wash tank		

Figure 3: Plan view of process equipment layout

Figure 4: Containerised biodiesel batch reactor plant, close to commissioning stage.

Plant specifications

Production unit

External dimensions:	6.0 m x 2.4 m x 2.5 m high
Internal dimensions:	5.5 m x 2.25 m x 2.3 m high
Gross dry weight:	~ 3.75 tonnes
Electricity supply requirement:	3 phase (32 amp) + neutral + earth
Electricity supply connection:	Armoured cable terminating in a 32 amp 5 pin socket
Maximum daily fuel output:	~ 700 litres (overnight separation phase). Up to ~ 1400 litres (7 hour separation phase with 24 hour working).

Feedstock oil conditioning

Vessel:	Dependant on oil supply
Heating:	2 x 3 kW submersible barrel elements

Reactor vessel

Manufacturer:	UK Fueltech Ltd
Model:	BD 400
Minimum batch size:	200 litres of vegetable oil + 34 litres of methanol (17%)
Maximum batch size:	400 litres of vegetable oil + 80 litres of methanol (20%)
Operating temperature:	85° C
Operating pressure:	1 bar

Instrumentation:	Digital temperature display
	Bordon tube pressure gauge
	Fluid input volume meter
Settling vessel	
Manufacturer:	Camborne School of Mines
Material:	Steel
Capacity:	1000 litres
Instrumentation:	Fluid level sight tube
Washing equipment	
Manufacturer:	Hydrotechnik Ltd
Model:	Magnesol wash diffuser
Washing agent:	Magnesol R60 powder
	(magnesium silicate – 60 micron)
Diffuser filter grade:	1 micron
Diffuser maximum pressure:	3.5 bar
Working temperature:	20° C – 120° C
Washing tank	
Type:	Modified IBC
Capacity:	800 litres
Filtration equipment	
Manufacturer:	Hydrotechnik Ltd
Model:	BD 6000
Pre-filter grade:	10 – 50 micron
Final filter grade:	1 micron
Final filter capacity:	Up to 4 kg of particulate matter
	Up to 1.6 litres of water
Rate of filtration flow:	600 litres / hour
Filtration tank	
Type:	Modified IBC
Capacity:	800 litres
Methanol delivery pump	
Manufacturer:	Arco Ltd
Model:	950 plastic hand pump
Stage to stage transfer pumps (4)	
Manufacturer:	Clarke
Model:	Diesel delivery pump
Hot reaction products transfer hose	

Supplier: Pirtek

Type: 10 bar petroleum resistant hose

All other fluid transfer hose

Supplier: Pirtek

Type: Ribbed PVC hose

Thread sealants

In contact with methanol: Araldite 2012 epoxy resin

All others: PTFE thread tape

Ball Valves

Materials: Chrome plated brass / PTFE

Suitability for quayside operation

The containerised production plant could feasibly be located on the quayside at a fishing port. The bunding provided within the unit serves well to contain the inevitable spillages that occur whilst processing the fuel. However, it is envisaged that a second container would be required in an adjacent position providing safe and secure storage for the feedstock oils, methanol, sodium hydroxide, Magnesol, waste products, consumable items and the fuel product itself.

The exact location of such a processing plant would need to allow for the following factors:

- Safe provision of a 32 amp, 3 phase power supply
- Adequate exclusion of unauthorised personnel
- Adequate movement areas for materials handling
- Provision of suitable mechanised handling equipment (fork lift truck).

Additionally it would be necessary to comply with the relevant pollution control regulations and this is likely to require the provision of equipment suitable for containing an accidental spillage. However, it should be noted that in constrast to other biodiesel batch reactors of a similar scale, the plant described herein does not involve a washing stage with water, rather the fuel is 'washed' with magnesol. By 'washing' with a solid and filtering this solid out of the fuel, there is no need for the batch reactor to have a fresh water supply or to discharge spent water to drain. This design choice eliminates emissions to water that would otherwise have to be considered as part of the pollution control regulations and effectively increases the portability of the plant. However, it does mean that extra care needs to be taken with the magnesol filtration and fuel polishing stages.

Reagent storage and handling

Waste vegetable oil has been procured in two distinct forms, liquid waste vegetable oil purchased from dealers and solid waste palm oil freely available for collection.

The liquid waste oil is generally received in a 1000 litre IBC and contains high levels of free fatty acids which densely populate the 'whites' that settle out at the bottom of the container with time. Whilst the IBC serves well as a delivery and storage container for the oil, it is important that the 'whites' are allowed to settle and that the oil is pumped from the top of the IBC rather than the outlet port provided at the bottom.

The solid waste palm oil has been poured (warm) into 50 litre plastic drums having barrel shaped sides. It is found that the re-entrant form of the containers has made it difficult to remove the solid oil from these containers once the oil has set firm. The original plan to upturn the containers above a heat source has not been successful due to the very poor thermal conductivity of the solid fat.

Methanol has been procured in both 1000 litre IBCs and 205 litre barrels. The latter option is preferable due to the lower risks associated with smaller volume containers. It is important that any pump used for transferring methanol is intrinsically safe. In this instance there is no spark risk as the specified unit is hand operated.

Both reagents should be stored within a bunded area to avoid accidental contamination to the surrounding environment. The methanol should be stored with the container sealed to prevent evaporation to the atmosphere but this necessitates shielding the container from heat sources such as sunlight. The liquid vegetable oil should be stored in such a manner as to prevent the ingress of moisture which will be absorbed by the oil.

Figure 5: Plant operations

Processing Plant operations

Required infrastructure

The infrastructure requirements for the processing plant operation are based on the safety of personnel and the public and protection of the environment as well as the practical needs of the plant. The requirements are:

1. Electrical power supply – 415 V, 3 phase + neutral +earth, rated at 32 amp maximum.
2. Mechanical handling equipment suited to the safe lifting and movement of the chosen bulk liquid containers (IBC or 205 litre barrel etc).
3. Bunding dedicated to the safe storage of the liquid reagents and products (vegetable oil, methanol, methyl ester fuel and glycerol by-product).
4. Equipment, materials and a written plan providing emergency measures in the case of accidental fluid spillages.
5. Adequate fire prevention and control measures.
6. Appropriate waste disposal streams for the glycerol by-product, the process filters and the filter cake.
7. Adequate space suited to the safe storage of the reagents, products and wastes.

Health and safety issues

The production process, equipment and the materials involved present a variety of hazards to personnel operating the plant. These hazards and the resulting risks must be recognised and understood in order that they can be controlled and reduced to acceptable levels. For this reason a full risk assessment study has been carried out. The risk assessment study is continuously reviewed and updated in the light of experience gained and to this end a member of the production team has taken ‘ownership’ of this document.

The measures to control risks determined by the study translate into procedures that are detailed within the *Operational Procedures* (reported here as Appendix 1) and the *Maintenance* (reported here as Appendix 2) sections of the plant operating manual. All safety instructions contained within the *Operational Procedures* and *Maintenance* sections appear in red.

Material safety data sheets (sometimes referred to as CoSHH sheets) are made available on site for all substances involved in the process. Suppliers are required to provide such information under the Control of Substances Hazardous to Health legislation. The substances involved in the fuel processing that require CoSHH sheets are listed below.

1. Sodium Hydroxide
2. Methanol
3. Phenolphthalein solution

4. Isopropanol
5. Magnesol R

Pressure vessel regulations

Under the current UK legislation any vessel subjected to more than 0.5 bar is regarded as a pressure vessel. Further, if the product of the maximum pressure and the internal volume is greater than 250 bar litres, the pressure vessel is subject to the regulations. In the case of the reactor vessel the maximum pressure is 1 bar and the product is around 600 - 1000 bar litres (the precise volume of the reactor is not specified). Therefore the reactor vessel is classified as a pressure vessel under the regulations and must be inspected and insured accordingly.

Feedstock collection and provenance

Recovered vegetable oil was sourced locally from several fish and chip shops, although the vast majority was acquired from The Galley Fish and Chip Shop, in Camborne. It was found that most chip shops were willing to provide their waste oil free of charge, as long as suitable barrels were supplied. Only one chip shop asked any questions about the waste transport licence. Local chip shops were found to produce between 25 litres and 100 litres of waste oil per week. The quality of oil varied between establishments and oil that had been used to fry chicken was found to be of particularly poor quality, with a high free fatty acid content.

It was found that in the local area only about half of the fish and chip shops used vegetable oil, the remainder using animal fats. Although animal fats can be converted into bio-diesel, none was collected as this requires an acid esterification process rather than the transesterification process established.

Plant operation

Successful operation of the fuel processing plant is achieved by close adherence to the operating procedures. In addition to these specific instructions the following points are made:

1. It is important that the feedstock waste vegetable oil is of adequate quality. Particular attention must be given to the exclusion of water from the oil and to the settling out of the ‘whites’ containing high levels of free fatty acids.
2. It is important that the catalyst is kept in an air tight container to prevent moisture ingress. If the granular sodium hydroxide absorbs moisture it loses effect as a catalyst for the transesterification reaction.
3. Good housekeeping within the processing plant is vital to maintain a safe working environment and to prevent unnecessary errors from being made.

Waste products

The waste products from the fuel processing include the glycerol by-product, wet catalyst retrieved from the settling vessel, magnesol filter cake, magnesol filter sock, final filter elements and the 'whites' from the feedstock waste oil. Options for disposal / use of these materials are detailed below:

The glycerol by-product can be combusted but this combustion must be achieved at high temperatures to prevent the release of acrolein, a very hazardous gas. Dedicated glycerine burners are commercially available for this purpose and these burners typically rely on the methanol remnants in the glycerine and an addition of 10 – 15% methyl ester fuel to achieve the temperature required. However, consideration should be given to whether this disposal method risks contravening waste incineration regulations.

An alternative to combustion is to compost the waste glycerine. This must be performed together with compostable solid matter so that the liquid waste is absorbed into a larger solid mass rather than simply running off into the water course. The wet catalyst can be added to this compost as the sodium hydroxide is recognised as a fertiliser.

A third option for disposal of the glycerine might be to use it as a simple soap, perhaps for washing down fishing boat decks. In their book, How to make biodiesel, the Low Impact Living Initiative recommend warming and filtering the glycerine and then leaving it to stand for at least a week in an open top container. This time period is required to allow any methanol remnants to evaporate.

For larger scale operations it has been financially attractive to refine the waste glycerine into its pure form however this may not be as attractive now due to the large surplus of glycerine on the market.

The whites of the waste vegetable oil can be composted in a similar manner to that described above and the magnesol filter cake can also be composted although the magnesol itself will not undergo any change and will simply add bulk to the compost. The filter cartridges from the final filtration are made from paper and can therefore be composted.
In the event that the volume of waste product exceeds that which can be dealt with as described above, commercial waste disposal will be required.

One potential disposal route worthy of further assessment but not discussed above is that of anaerobic digestion (AD). It is possible that all of the wastes suitable for composting can be processed in an 'energy from waste' anaerobic digester. Low grade glycerine is currently being used as part of the feedstock for the Holsworthy anerobic digestion power plant. Its high calorific value relative to cattle slurry and other similar components of the feedstock means that its addition to the AD process must be strictly regulated. Consequently, it is not thought that even a burgeoning AD market would provide sufficient demand for by-product glycerine from biodiesel plants.

Experience of bio-diesel production

Cold weather problems

Operation of the processing plant is made considerably more difficult by cold weather. As the plant is located within a steel container the ambient temperature within the plant closely follows the outside air temperature. The effect of the lower temperature is to increase the viscosity of the liquids involved in the process and to promote solid plugging of fluid transfer ports and pumps making transfer impossible. The problem is eased somewhat by heating the environment within the processing plant or by continuous operation which achieves the same end without additional energy input.

Pumping problems

On occasions the pump employed to lift the feedstock oil into the pre-heating vessels has been inadequate due to the viscosity of the oil and the suction head required. In such instances oil has been dosed from the bottom tapping of an IBC and consequently fuel washing and filtering operations have been severely hampered by the level of emulsified soaps present.

Fluid transfer from the settling vessel

By definition the catalyst passes through the reaction unchanged although it is dissolved in the products. As the products cool in the settling vessel, the catalyst crystallises in the bottom of the vessel and eventually blocks the outlet ports used to transfer the waste glycerine and the methyl ester from the vessel. This has necessitated the removal of hoses and rodding of the ports to clear the obstruction on several occasions.

Washing and Filtering

The pumped circuits that take the fuel through the Magnesol filter sock and the final filters have maximum pressure limits of 3.5 bar. This pressure limit is soon exceeded in cold conditions when the fuel is more viscous and this has necessitated external heating of the filter units and more recently a re-heat of the fuel itself to around 40° C. Even with this action these filtering operations have been problematic and have not been sufficiently controllable. On at least one occasion Magnesol powder has been found in the final fuel product despite multiple passes through filters that should prevent passage of this particle size. Additionally the success of the Magnesol wash in removing emulsified soaps is unpredictable. It is recognised that this problem is closely related to the issues concerning feedstock handling and ambient conditions and it is apparent that at times all factors have acted together to undermine the process.

Bio-diesel production costs

Costing basis

The costs listed below are all given excluding VAT and represent the costs that applied to the last batch of fuel processed during November 2007.

Feedstock costs

The cost of feedstock vegetable oil procured for fuel processing has varied between zero as described previously and £0.60 per litre for virgin rapeseed oil purchased direct from a local farmer. Perhaps the most representative cost to consider is the general market value of waste vegetable oil which can be purchased in a 1000 litre IBC. During the summer of 2006 this cost was £0.20 per litre but with the increasing demand this cost has risen to £0.27 per litre in September 2007. With the current transesterification only process, a quantity of this feedstock oil (the whites) is unusable and this can be as much as 10%.

Methanol and Catalyst costs

In September 2007 the cost of methanol purchased from a chemicals supplier in 200 litre barrels was £95.58 giving a cost per litre of £0.48 / litre.

The current cost of pearl granular sodium hydroxide is £16.00 per 25 Kg bag or £0.64 per Kg.

Costs of consumables

The pre-filter elements that screen larger particulates from the reactor and the final filters currently cost £5.78 each for disposable elements or £46.00 for cleanable elements. For costing purposes it is assumed that disposable elements are used.

The final filtration / polishing filter elements currently cost £15.00 each and are used in pairs.

The Magnesol filter sock currently costs £8.95 and Magnesol powder costs £2.00 per kg.

Electrical power consumption

The fuel processing plant is connected to the test site's electrical sub-system via a dedicated three phase power / energy meter which has facilitated easy measurement of electrical energy consumption. Splitting the process into three parts, the measured energy consumed for a 400 litre batch of feedstock oil is as follows:

1. Pre-heating feedstock, pumping, reacting and pumping to the settling vessel consumed 25 kWh.
2. The Magnesol wash stage consumed ~ 2 kWh.
3. The Final filtration stage consumed ~ 3 kWh.

This gives a total energy consumption of 30 kWh for a 400 litre batch of oil producing approximately 380 litres of fuel. These figures do not take into account any additional heating of the working environment that might be required in cold weather.

Assuming a cost per kWh for electricity of £0.12 this gives a cost of £3.60 to produce 380 litres of fuel.

Labour costs

The labour cost to process a single 400 litre batch of feedstock oil is not representative of economic operation because of the large amount of 'idle time'. It is therefore sensible to consider the labour cost content for a 400 litre batch assuming that the previous batch is being washed/filtered and the following batch is being prepared. Also the assumption is made here that cold weather difficulties do not apply. In this manner the following approximates to the labour input to the current production facility.

1. Stages 1, 2 and 3 combined – 2 man hours
2. Stages 4 and 5 combined – 3 man hours

Assuming a labour value of £10 per man hour gives a labour value of £50.00 to produce 380 litres of fuel.

Costs of bio-diesel production

In summary, the observed costs of bio-diesel produced for this project were as follows:

Recovered vegetable oil was obtained at a cost of 0p to 30 per useable litre (after allowing for discarded whites), which, after allowing for losses during the production process gave a feedstock cost per litre of 0p to 32p.

With the process consuming just over 1 litre of methanol for every 4 litres of bio-diesel produced, the cost of methanol per litre of product was 12.5p. It should be noted that this cost could be reduced if methanol recovery was included within the process.

The cost of the sodium hydroxide catalyst added a further 0.75p per litre to the production cost.

The magnesium silicate dry washing process employed adds up to 2p per litre to the production cost. Alternative systems would also have similar costs: water washing has a low input cost but a more significant effluent disposal cost, whilst ion exchange systems have an initial resin cost plus the cost of periodic recharging.

In order to improve the cold weather properties of the bio-diesel, a cold weather additive is required, just as it is in fossil diesel. The cost of this additive will vary upon the concentration used, which is in itself a function of the nature of the feedstock and the ambient temperature at which the fuel is to be used. A conservative cost would be 2p per litre.

The marginal cost of materials to produce 1 litre of bio-diesel was therefore either 18p or 48p depending upon whether the feedstock oil had been obtained free of charge or was purchased on the open market. However, these are not the only costs associated with bio-diesel production. Power, consumables and maintenance add a significant overhead cost. The observed power costs as outlined earlier, amount to around 1p per litre of product. The costs arising from consumables, maintenance and local collection of feedstock were highly variable from batch to batch. However, it is unlikely that these overheads would amount to less than 5p per litre. When filtration problems or other breakdowns were encountered, the costs were far higher.

Therefore, before taking into account the value of labour, the production cost per litre of bio-diesel produced was at least 23 pence per litre when feedstock was locally obtained free of charge, and at least 53 pence per litre when commercially sourced recovered vegetable oil was used.

Recommendations

Process improvements

Recommendations for improvements to the methyl ester production process are as follows:

1. Utilise an esterification reaction prior to transesterification to reduce the problematic production of soaps in the fuel product. This measure will also eliminate the requirement for a suitable waste stream for the ‘whites’ from the waste oil and produce only a small amount of filtered solids which can be composted.
2. Implement methanol recovery by condensing the methanol vapours that are expelled from the reactor at the completion of the reaction stage. This stage can be extended to allow sufficient time for significant methanol recovery.
3. Replace the Magnesol wash with a process that does not compromise the intrinsic safety of the fuel product by the addition of particulate matter.

Plant improvements

Recommendations for the improvement of plant to suit the current process are as follows:

1. The provision of a robust diaphragm type pump capable of achieving a minimum suction head of 3 metres and being unaffected by large particulate matter and tolerant of viscous fluids. This pump will be used to transfer waste vegetable oil into the processing plant and to transfer fuel and glycerol from the settling vessel.
2. The reduction in height (and thus capacity) of the settling vessel allowing for easier periodic removal of wet catalyst and other particulate matter.
3. The addition of insulation material to the steel container, perhaps on the outside. This would allow a favourable working temperature to be maintained within the processing plant. A better solution would be to locate the processing plant container within a heated environment such as a large industrial building. Better still might be to install the process equipment freely in an industrial building. If this were possible advantages would be realised by adopting a multi level process where gravity is used to transfer fluids from stage to stage.