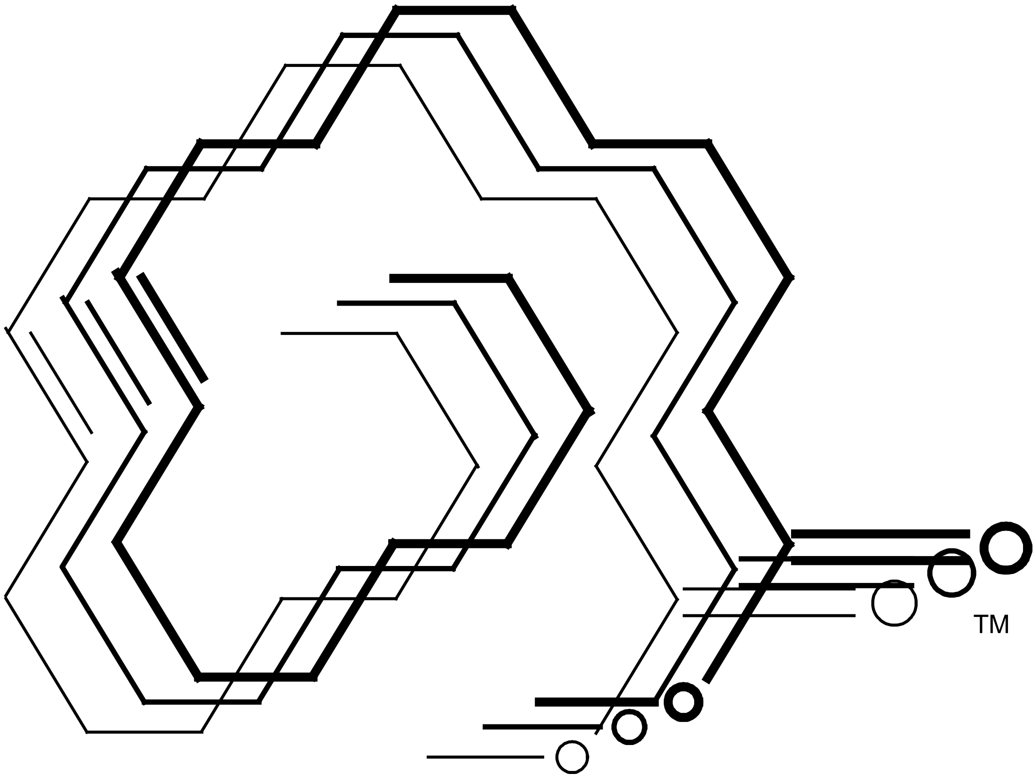
DEPARTMENT OF CHEMICAL & BIOLOGICAL ENGINEERING

The Design of a Portable Biodiesel Plant

CHBE 452/453/454



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THE UNIVERSITY OF BRITISH COLUMBIA

DEPARTMENT OF CHEMICAL & BIOLOGICAL ENGINEERING

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CHBE 452/453/454 FOURTH YEAR DESIGN PROJECT
FINAL REPORT

THE DESIGN OF A PORTABLE BIODIESEL PLANT

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Executive Summary

The main goal of this project is to design a mobile biodiesel production plant, which is capable of producing 3000 L of biodiesel per week. The design constraints specify that the biodiesel production plant must be sized to fit into a standard truck-trailer with dimensions 8 feet wide by 40 feet long by 9.5 feet tall. The plant is to be self sufficient in one form of energy (provided by the client), adaptable to different grades of waste vegetable oil (WVO), environmentally friendly, and economically feasible.

This report presents the final design of the mobile plant in two-dimensional Process Flow Diagrams (PFD's) and three-dimensional AutoCAD renderings. The main reaction, the pre-treatment, and the purification stages are described in detail and the proposed process, including equipment design specifications, is introduced. The feasibility of this design was evaluated through an environmental impact assessment and economic analysis. Although the contents of wastewater are unsuitable for discharge, the economic analysis, including wastewater disposal costs, proves the design to be economically feasible. With the production rate of 156,000 L biodiesel annually, a profit of $20563 each year is realized.

For the continuation of this project, future groups are encouraged to collect data specific to biodiesel and determine the demand for a such a mobile plant.

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1.0 Introduction

The purpose of this project is to design an economically feasible mobile biodiesel plant capable of processing different grades of waste vegetable oil (WVO) to produce 3000 L of biodiesel per week. The mobile biodiesel production unit will travel to locations such as cruise ship ports and small communities, where the clients are participating in the Biodiesel~*In Motion* program. The clients are provided with two tanks, one for WVO collection and storage and the other for the biodiesel product. It is desired that the mobile plant operate to meet the production requirements of 3000 L of biodiesel per week at the end of a 40-hour work week, such that the plant requires two full-time operators. The biodiesel produced can then be sold back to the client to fuel their diesel-engined machinery. In addition, the only client requirements are that they must provide electrical energy, water, and steam for the mobile plant process.

This final report details the plans and decisions that were made leading up to the completion of the design of the mobile plant. Section 2.0 will present the main reaction that was chosen to convert WVO to biodiesel, including the rationale and consequences for this choice. The process which takes WVO through pre-treatment, reaction, and finally, purification is described in Section 3.0 and illustrated in Process Flow Diagrams and Piping and Instrumentation Diagrams attached in Appendix B. The equipment that this process requires is sized and shown in Section 4.0. Section 5.0 discusses the environmental impacts of this mobile plant. Finally, based on equipment cost estimates, the feasibility of this mobile plant is evaluated in an economic analysis in Section 6.0. Finally, recommendations have been proposed for the continuation of this project.

2.0 Concept

2.1 Choice of Reaction

The most common method to produce biodiesel is by an esterification reaction of vegetable oils. Esterification refers to the catalyzed chemical reaction of vegetable oil and alcohol to form fatty acid methyl esters (FAME, or biodiesel) and glycerol. The catalyst can be either enzymes, acids, or bases. In this project, waste vegetable oil (WVO) is considered to be the primary reactant.

The main components of WVO is triacylglycerol (TAG), which consists of three long fatty acid chains esterified to a glycerol backbone[27]. When TAG reacts with an alcohol, the fatty acid chains are released from the glycerol backbone to yield fatty acid methyl esters. Figure A-1, in Appendix A, shows how the TAG's in vegetable oil react with methanol to produce biodiesel and glycerol.

2.1.1 Enzymatic Catalyzed Reaction

Enzyme-catalyzed esterification is a promising alternative to traditional esterification methods. It uses little organic solvents, and requires little downstream treatment. The most common enzyme for the esterification reaction is lipase. A methanol to WVO molar ratio of 4:1 and 30 wt% of lipase[6], results in an acceptable conversion of 85% TAG to FAME. The major disadvantages of enzyme-catalyzed esterification however, include the high cost of lipase, and the slow reaction rates, making this method unfavourable for this project.

2.1.2 Acid-Catalyzed Esterification Reaction

Acid catalysts such as sulphuric acid are used to esterify WVO to biodiesel. A molar ratio of methanol to WVO of 30:1 to convert 90% of TAG is required. At 65ºC the reaction time is approximately 69 hours[27]. The advantage of the acid-catalyzed esterification is that the reaction is insensitive to the free fatty acid (FFA) content in the WVO; therefore no FFA pre-treatment is required. Nonetheless, since the methanol requirement is very high, larger reactors and downstream separation units would be necessary. In effect, the sizing requirements and process time constraints of the mobile unit operation does not justify this method for optimal biodiesel production.

2.1.3 Transesterification Reaction

Alkali-catalyzed transesterification (also known as alcoholysis) uses an alkali such as NaOH or KOH as catalyst to convert TAG into biodiesel. The preferred methanol to WVO molar ratio is 6:1. At 65ºC, a 93-98% conversion of the TAG is achieved within one hour[26]. In comparison to both the enzyme- and acid-catalyzed esterification reactions, the high yield in a relatively short reaction time makes the transesterification reaction the method of choice in this project.

Methanol and NaOH are suggested as reactant and catalyst, respectively, because of their relatively low cost. In addition, no significant process enhancement has been reported in literature by use of heavier alcohols. Methanol to WVO molar ratio of 6:1 and 0.5% w/w NaOH is chosen in agreement with literature suggestions.

The transesterification reaction requires a low water (<0.06% w/w) and FFA content (<0.5% w/w)[17] in the WVO. Thus, pre-treatment of the crude WVO must be implemented. Employing a WVO pre-treatment section inherits the benefit of making the mobile biodiesel unit more flexible toward varying grades of WVO, thereby maximizing the client-base.

Finally, due to the presence of excess methanol and glycerol by-product, post-treatment of the biodiesel mixture is required. The method of choice of WVO pre-treatment and biodiesel purification will be addressed in the following sections.

2.2 Narrowing Down of Pre-treatment Reaction

The FFA contained in WVO is mostly oleic acid. Used frying oil from restaurants and food service establishments usually contain 1.5-5.4 wt% FFA, whereas combined mixed greases such as frying oil, acidulated soap stock, tallow, yellow grease, animal/vegetable blended grease may contain up to 16.9 wt% FFA[18]. The FFA content should be below

0.5 wt% for the alkali transesterification process to be efficient since the presence of FFA competes with the transesterification reaction by consuming alkali to produce soaps and water, which subsequently causes emulsion formation[2]. The presence of emulsions will then create problems in the downstream processing and purification of biodiesel.

Several options are available to treat FFA contained in the WVO. These include: caustic stripping, steam stripping, solvent extraction, grease hydrolization to 100% FFA, and conversion of FFA into methyl esters. Caustic stripping uses centrifugation with the addition of NaOH to remove FFA. However, this method is only suitable for WVO with a lower percentage of FFA (<10 wt%) since clean oil would be significantly lost above this percentage[19]. Grease containing 10 wt% FFA might lose 30% of its clean oil to the conversion of FFA to soap. Steam stripping can remove up to 95% FFA[24], but this process has four basic steps: degumming, bleaching, deacidification, and thermal quenching before proceeding to FFA esterification. The steam stripping process is very energy intensive[18] and is not suitable for a mobile unit. Another alternative is to use isopropanol solvent extraction, which separates TAG from other contaminants such as FFA, but the solvent can be very costly and the vapour is very toxic. Hydrolyzing grease to 100% FFA and then proceeding with acid esterification might be cost effective but long reaction times are expected. A more efficient approach is to convert FFA into methyl ester by means of an esterification reaction, therefore reducing FFA content to below the suggested limit of 0.5 wt%[2], and then proceeding to the alkali-catalyzed transesterification reaction.

In the FFA pre-treatment reactor, methanol and sulphuric acid are added to the WVO depending on the FFA content. Yellow grease (<15 wt% FFA) is treated with 20:1 methanol to FFA molar ratio and 5 wt% H_2SO_4[2]. Brown grease (>15 wt% FFA) requires a methanol to FFA molar ratio of 40:1 and 15 wt% acid catalyst[2]. Due to the different acid catalyst dosages, a titration step will need to be included prior to FFA pre-treatment to determine FFA content and the degree to which pre-treatment is required.

The sulphuric acid catalyst and methanol added to the reactor converts FFA into methyl esters. After a one-hour reaction time, only about 2.5 wt% FFA should remain. To further reduce FFA content, water produced from the esterification must be removed along with excess methanol. Another dosage of fresh sulphuric acid and methanol must again be added to the reactor for the second esterification reaction. After another hour of treatment time, the pre-treated WVO should contain less than 0.5% FFA[2]. The pre-treated WVO will then be pumped to a distillation column to remove water and excess methanol prior to being pumped to the main reactor.

The water and methanol produced from the two-step esterification reactions are then distilled to recover methanol for recycling back through the process, while the water is pumped to a wastewater reservoir. Three batch reactors are used to remove the FFA content in the WVO. The reason for implementing this strategy is to ensure that the distillation column is run continuously, and to produce two batches simultaneously.

2.3 Narrowing Down of Post-Treatment Reaction

The unrefined biodiesel, along with excess reactants and by-products, are pumped to a reservoir from the main reactor. From the reservoir, the raw biodiesel is pumped into a separator, in which glycerol is separated out from the raw biodiesel.

The first separation technique, separation by gravity settling, will employ either a drum or a vertical gravity separator. The relatively cheap and mechanically simple drum can be easily maintained, although maintenance includes monthly manual cleanings. Since the drum operates by gravity, the biodiesel must be allowed to settle for at least one hour before it can be extracted; the settling time can be improved by a greater surface area or by adding additional drums.

The second separation operation, the vertical gravity separator, also depends on gravity for separation. The vertical gravity separator is more advantageous because it is capable of varying the temperature, pressure, and flow rate to enhance the settling time. However, for this portable plant, its size and energy requirements are areas of concern.

The third separation option is a hydrocyclone. The design of a hydrocyclone for the separation of two immiscible liquids (glycerol and biodiesel) using a standard cyclone is more flexible in terms of size, cost, and ease of maintenance compared with the first two separation methods. The liquid-liquid hydrocyclone operates by separating the heavy component and the light component based on the density difference. In this case, biodiesel is lighter than water so it is possible for the hydrocyclone to perform the separation. The hydrocyclone will garner energy considerations because it requires a pump to perform separations; however, it contains no moving parts which greatly simplifies the maintenance.

The biodiesel, coming out as the continuous phase from the hydrocyclone, will be sent to a distillation column to separate out methanol. The methanol separated here will be pumped into the methanol purification unit and be recycled through the process.

After methanol separation the biodiesel continues to flow into a neutralization reactor where sulphuric acid is added to neutralize the caustic biodiesel. The reactor will be equipped with an impeller and baffles to ensure complete mixing. The treated and purified biodiesel is now ready to be pumped to storage tanks.

The extraction column appears immediately after the neutralization reactor The feed stream entering the extraction column is composed of biodiesel, salt and soap. Since the concentration of salt and soap in the feed stream is less than 1 %, as determined by the mass balance, this system is dilute. Water sprayed from the top of the column will be used as the solvent to remove the salt and soap contaminants from the biodiesel. The extraction column will be operated in counter-current mode. An 85 mol% biodiesel stream will exit the top of the column, while water, soap, and salt will exit the bottom as a wastewater stream.

3.0 Process

3.1 Process Flow Diagram

The biodiesel production plant is separated into five sections as follows: Section 000: Reactant Preparation, Section 100: Pre-treatment, Section 200: Transesterification Reaction, Section 300: Purification, and, Section 400: Solvent Recovery and Product Storage. The corresponding Process Flow Diagrams (PFD's) are presented in Appendix B.

Section 000 is concerned with the storage, heating, and distribution of chemicals required for the other sections of the plant and consists of six unit operations: three storage tanks, T001, T002, and T003, one mixer, M001, and two filter screens, F002 and F003.

The WVO is stored in storage tank T001 at the client's location and has a capacity of approximately 5000 L. In order for the WVO to flow easily prior to being pumped to Section 100 for pre-treatment, a heating coil through which electrical energy is supplied is installed to heat the WVO to approximately 65ºC. Two filter screens on tank T001 are required, one 1 cm mesh screen (F001) at the top of the tank to filter large debris present in the WVO and one 20 μm mesh screen (F004) at the tank outlet to further filter any remaining smaller particles in the WVO prior to being sent to the pre-treatment section. Sulphuric acid, stored in tank T002 with a capacity of 4 L, is pumped and heated by heater H001 to either Section 100 or Section 300. Methanol, supplied by a manufacturer or distilled and recycled by the distillation column in Section 400, is stored in tank T003 with a capacity of approximately 4700 L and then heated to 40ºC prior to being sent to Section 100 or Section 200. In addition, solid sodium hydroxide is solubilized in methanol in mixer, M001, which is then pumped and heated prior to being sent to the transesterification reactor in Section 200. The solubility of sodium hydroxide in methanol is 1 g NaOH in 4.2 mL CH_3OH. Finally, water, supplied by the client, is passed through one of two filters in order to remove ions that would interfere in the biodiesel production process, and is pumped and heated to the extraction column in Section 300.

Section 100 is the part of the process where WVO is treated in two one-hour reaction steps in order to reduce the free-fatty acid (FFA) content of the WVO to 0.5 wt% or less since the presence of FFA in WVO inhibits the transesterification reaction. This section consists of five unit operations: three reactors, R101, R102, and R103, a distillation column, D101, operating at 61^{o}C and 0.1 atm, and one storage tank, T101, for the treated WVO.

The final design for the pre-treatment section was based on the continuous operation of the distillation column and minimizing the number of reactors required. The pre-treatment sequencing is broken down into the hour into the operation. Reactors R101, R102, and R103 (each approximately 1200L capacity) are sealed and steam is injected into the heating jackets outside each vessel early in the batch run to pre-heat the reactants and to obtain the optimal temperature for the esterification reaction to occur. At the beginning of the first hour, R101 and R102 are filled with the appropriate amounts of WVO, methanol, and sulphuric acid for the first FFA treatment step (20:1 molar ratio of methanol to WVO and 5 wt% sulphuric acid) leaving R103 empty at this time. During the first hour, both reactors R101 and R102 are undergoing the first FFA treatment step at 60^{o}C and 1 atm. During the second hour, the WVO, water, FFA, along with the methanol and sulphuric acid in R101 is distilled through the distillation column and discharged into empty reactor R103. At the beginning of the third hour, the appropriate amount of methanol and acid for the second FFA treatment step (40:1 molar ratio of methanol to WVO and 5 wt% sulphuric acid) is added to R103. During the third hour, R103 is now undergoing the second FFA treatment for one hour while the contents of reactor R102 is distilled through the distillation column into reactor R101. At the beginning of the fourth hour, the appropriate amounts of methanol and acid for the second FFA treatment step for R101 are added (40:1 molar ratio of methanol to WVO and 5 wt% sulphuric acid). During the fourth hour, the contents of R103 is distilled and directed into the holding tank, T101, with a capacity of 500 L. The WVO is now fully treated and is ready to be pumped into the reaction stage, Section 200, of the plant. Meanwhile, the contents of R101 are undergoing the second stage of FFA treatment. During the fifth hour, the contents of R101 are now distilled through the distillation column into the holding tank, T101. Following this step, 600 L of treated WVO is available, enough for supplying Section 200 for the rest of the day.

It is desired to operate the FFA pre-treatment unit for a second time at the end of the working day in order to prepare the WVO for the transesterification reaction step to operate at the beginning of the next working day. The treated WVO will be stored overnight in tank T101 and will be heated to 60^{o}C at the beginning of the working day to allow easy pumping into the main reactors.

Section 200 is the part of the process where the treated WVO from the pre-treatment section along with methanol and sodium hydroxide catalyst react to form the main product, biodiesel, and by-product, glycerol, by means of a transesterification reaction. The main unit operations in this section include the reaction vessel, R201, and the biodiesel storage tank, T201.

The reactants entering the reaction vessel, R201, include the sodium hydroxide in methanol mixture from mixer M001, methanol from tank T003, both from Section 000, and the treated WVO from T101 in Section 100. Reactor R201 has a capacity of 320 L and is equipped with heating jackets where steam and cooling water are applied to maintain a reaction temperature of 65^{o}C. The biodiesel, produced by the transesterification reaction, is pumped to the storage tank, T201 (with a capacity of 270 L), which acts as a reservoir for the next continuous separation process in the subsequent section.

Section 300 is concerned with the product purification of biodiesel from by-products and excess reactants. This section consists of six unit operations: two hydrocyclones, HC301 and HC302, two distillation columns, D301 and D302, one reactor, R301, and one extraction column, E301.

The basic biodiesel/glycerol/methanol/soaps mixture at 65°C from the transesterification reactor is pumped into two hydrocyclones in series, HC301 and HC302, where the glycerol is separated as the bottoms product and sent to tank T403 for storage. The light component from the hydrocyclones, which contains the biodiesel, methanol, and soaps, is sent to a distillation column, D301, operating at 85^oC and 1 atm, where methanol is boiled off and sent to Section 400 for further treatment. The basic bottoms stream from the distillation column consisting of biodiesel and trace amounts of soap, is pumped continuously into a continuous stirred tank reactor, R301, where it is rapidly neutralized with the addition of sulphuric acid. To remove the salt and soap produced from the neutralization reaction, the mixture is then pumped into the bottom inlet of the counter-current liquid-liquid extraction column, E301, operating at 73^oC and 1 atm. When the salt content of the biodiesel is low enough as determined from its conductivity, the washed biodiesel is sent to distillation column, D302, operating at 215.1°C and 1 atm, to remove entrained water, then condensed and sent to the wastewater storage tank T402 with a capacity of 6964 L. The purified biodiesel is pumped and stored in storage tank T404 in the subsequent section.

Section 400 is the storage system network to store spent reactants, glycerol, wastewater, and the purified biodiesel product. This section consists of five unit operations: four storage tanks, T401, T402, T403, and T404, and one distillation column, D401.

The wastes that are produced during the biodiesel production process are glycerol, methanol (contaminated with water), and wastewater (containing sodium sulphate, sulphuric acid, methanol, and soap). Tank T401, with a capacity of 1203 L, is a spent methanol storage tank which supplies a distillation column, D401, at a constant flowrate to distil the methanol, then condensed in condenser C401 and is either refluxed back into distillation column D401 or recycled to tank T003 to be reused in the process. The bottoms from the distillation column is mostly water, and is either reboiled and returned back into the bottom of the column, or is disposed of into the wastewater tank T402. Wastewater from the extraction column, E301, and distillation column, D302, in Section 300 are also sent to tank T402 for storage. Glycerol from the hydrocyclones is stored in tank T403 and the purified biodiesel is stored in storage tank T404.

3.2 Piping and Instrumentation Diagram

The Piping and Instrumentation Diagrams (PID's) are based on the PFD's and presented in Appendix B.

The governing controller for our entire plant is a Programmable Logic Controller (PLC) that controls all pumps and valves to direct the flow of various reactants and products throughout the plant.

The localized transmitters and controllers are implemented to maintain level, temperature, and pressure set-points, as well as to monitor viscosity (as a measure of purity), pH, and salt content of various unit operations. A detailed description of these localized transmitters and controllers is discussed in this section.

To prevent restating recurring features in the PID drawings, features that are general to all sections are summarized. Level transmitters, level alarms, and pressure relief valves are installed on all tanks, reactors, and distillation columns. Level transmitters and controllers are installed to monitor and adjust the liquid level in a vessel. all tanks and reactors are equipped with a temperature sensor and controller, with the exception of T003 and M001 and the tanks in Section 400, to control the steam in/condensate out streams into and out of a heated jacket fitted around the vessels to maintain the vessels at the set-point temperature. For streams that carry condensate from a heating jacket or heat exchanger, steam traps are installed to prevent heat and energy losses from expelling steam. The valve fail-safe positions have been included and placed underneath the valve designation.

The temperature of the sulphuric acid stream 003 is measured using transmitter TT0304. The controller, TC0304, is used to control the flow of steam passing through the heat exchanger. A simple feedback control loop is used to control the flow rates of streams 003 and 004. The stream of methanol that leaves T003 and enters M001 is controlled by a feedback loop to ensure that the NaOH is fully solubilized by the methanol. The temperatures of all of the exiting methanol streams (006 through 008) are controlled using feedback loops to adjust the flow rates of steam through the heat exchangers (H002 to H004). The water passes through one of two filters. Pressure transmitters are located on the filters for early detection of clogging. In the event that a filter is clogged or requires cleaning or maintenance, the flow controller will manipulate the three-way valve to direct the water to the other filter. A feed forward controller is then used to vary the steam flow rate through the heat exchanger, H005, based on the flow rate of water. Metering pumps P001, P002, and P003 pump a fixed volume of reactants to Section 100.

The valves that control the supply of reactants into the three reactors R101, R102, and R103, are shown as “XV” to designate that these valves are simply on/off valves and are only required to either be open or closed at specified times. No-flow transmitters are needed for the reactant streams from Section 000 since the metering pumps in Section 000 supply the required volumes and ratios of reactants for pre-treatment.

The extent of WVO transesterification to biodiesel in Section 200 is determined by monitoring the viscosity of the biodiesel product using an on-line viscometer implemented on R201. Once the viscosity reaches the set-point value, valve V202 opens and the contents of R201 are directed into Section 300. There are two safety controls loops using flow transmitters and controllers. The flow transmitters, FT2105 and FT2107 detect any flows in streams 201 and 202, respectively, and sends signals to the flow controllers FC2105 and FC2107, which shut off valves V203 and V204, respectively. These safety control systems prevent any biodiesel in the storage tank from flowing in and out at the same time. The third flow control loop is designed for the outlet biodiesel stream 205 going to the hydrocyclones in Section 300. This control loop prevents an overflow of biodiesel in the storage tank by controlling the valve V205 to allow a certain flow rate of biodiesel in the stream entering the hydrocyclone, HC301, in Section 300.

A viscometer is implemented on the bottoms streams for the two distillation columns D301 and D302 to ensure the separation is satisfactory before moving on to the following step in the process. The viscometer controller takes the input from the viscometer transmitter and controls a three-way valve that sends the bottoms stream back into the column if the mixture is not pure enough. Because of this feature, in contrast to the other distillation columns in the plant, the pump for the bottom stream is placed before the reboiler to prevent pump cavitation. For the mixer R301, a pH meter continuously measures the pH of the mixture in the vessel. If the pH is above the set-point, the flow controller will open valve V308 to allow more sulphuric acid into the reactor. Stream 310 acts only as a overflow prevention valve that allows the biodiesel in the extraction column to flow back to stream 322 and does not have anything to do with the pH set-point. A conductivity meter CT3607 measures the salt content in the wastewater stream 316 and compares it to the salt content in the wash water stream entering the extraction column, E301. If the difference in salt concentration is above the set point, valve V312 will direct the flow to stream 314 where the biodiesel is washed again in the extraction column. When the correct salt concentration difference has been reached, valve V312 will direct flow via stream 315 into distillation column D302.

To ensure a steady flow rate into distillation column D401, the flow into D401 is controlled with a feedback control loop which controls valve V404. The instrumentation for D401 follows the same principles as that for D101. The level transmitters that are installed on the tanks in this section are for monitoring purposes only and are not connected to any controllers.

3.3 Start-up, Shutdown and Emergency Procedures

The start-up sequence takes place as six consecutive steps. The detailed start-up outline is presented in Table C.1-1. The start-up procedure for the mobile biodiesel plant is based on “back-to-front” principles. It should be noted that this procedure relies on the fact that an appropriate amount of liquid volume remains within the unit operation after shut-down the previous day thereby streams are present and available to proceed at start-up.

The first step of the start-up procedure is to turn on utilities such as electricity, cooling water to condensers as well as water for the extraction column, E301, and steam to the reboilers. A start-up program *startupBiodiesel.exe* is initiated to connect and receive on-line data from all controllers and alarms. This program allows for initial conditions different from operating conditions to occur without tripping any alarms. For example no-flow alarms may be temporarily deactivated during the start-up procedure. The second step includes start-up of effluent streams and unit operations. Reboiler H401 is started to bring the distillation column D401 to the set-point temperature at which point the feed to D401 may commence. The third step is to start the purification section. Start-up of condenser C302 and reboiler H302 precedes start-up of condenser C301 and reboiler H301. Reactor R301, extraction column E301, followed by distillation columns D302 and D301 are started respectively. The tanks and mixer M001 of the reactant feed section is started as the fourth step of the start-up procedure. Fifth step is the start-up of condenser C101, reboiler H101, and distillation column D101 in the pre-treatment section. Pre-treated WVO storage tank T101 is made accessible. Finally, the pre-treatment reactor sequencing R101/R102/R103 is activated via the *startupBiodiesel.exe* start-up program and start-up of reactors R201 and tank T201 is initiated.

The step-wise shut-down procedure (Table C.1-2) is essentially the reverse of the start-up procedure and will therefore not be commented on further. As during start-up, a program *shutdownBiodiesel.exe* is activated and ensures proper shut-down sequencing.

Emergency shut-down is accommodated by the installation of an emergency shut-down button. In case of emergency, the technician enforces shut-down by pushing the emergency shut-down button. This will stop all pumps and force all valves to fail close/open according to definitions before shut-down electricity is effectuated. The emergency procedures are detailed in Table C.1-3 (please refer to Table C.1-4 for the trip matrix). It is emphasized that all cooling water valves fail open. After activation the technician must contact the fire department.

3.4 Mass Balance

The mass balances for each species have been derived for the individual unit operations per batch. In order to achieve the required total weekly production of 3000L biodiesel, an output of 150 L/batch biodiesel and a total number of 20 batches/week is defined.

The principles of the design of the WVO pre-treatment operation are presented in Section 2.2. As a consequence of the choice of process design, the batch size in the pre-treatment section is defined to be the double of the batch size in the transesterification reaction section. This mass ratio ensures a continuous succession of the transesterification reactions, which ultimately results in a constant continuous flow into the purification section after the initial downtime required for processing the first batch of pre-treated WVO. Therefore, stream 107B, the amount of pre-treated WVO per batch accumulated in tank T101, is equivalent to two times stream 108, the amount of pre-treated WVO used for each batch in the transesterification reaction.

The pre-treatment section reduces the FFA content to 0.5 wt% and the water content to 0.0 wt%, thereby meeting the requirements for assuring an optimal conversion of TAG to methyl esters in the transesterification process[27]. To account for the individual streams within each pre-treatment cycle, labelling of [A] and [B] referring to the 1st and the 2nd cycle, respectively, has been applied as a suffix to the relevant stream numbers. For instance stream 101A refers to stream 101 of the esterified WVO mixture leaving reactor R101 in the first pre-treatment cycle, whereas stream 101B refers to the exit stream 101 from reactor R101 after the second pre-treatment cycle.

A 6:1 molar ratio methanol to TAG is defined for the transesterification reaction[1] as described in Section 2.1.3.

Effectively, after post-treatment, a product yield of 135.94 kg/batch biodiesel is produced and an equivalent total formation of 12.4 kg/batch glycerol by-product is realized.

In general, various assumptions have been refined in agreement with computational simulations and rules of thumb; in particular the distillation processes have been correlated to results obtained using ASPEN® (refer to Appendix C.2). The degree of conversion of WVO to biodiesel in the transesterification reaction operating at 60°C and 1 atm with rapid stirring is 85%.

3.5 Energy Balance, Heat Integration and Pinch Analysis

The energy balance of the entire biodiesel plant is carried out by calculating enthalpies for all the streams present in the process. This is achieved by simulating each of the streams in ASPEN®. TAG was modeled as triolein ($C_{57}H_{104}O_6$), biodiesel was modeled as methyl oleate ($C_{19}H_{36}O_2$), and FFA was modeled as trioleic acid ($C_{18}H_{34}O_2$). Meanwhile, soap is modeled with its molecular structure $C_{18}H_{33}O_2Na$.

From the mass balance, three streams are identified to be the cold streams that require heating. These streams come from the holding tank in Section 000 containing methanol (stream 006), methanol/sodium hydroxide mixture (stream 008), and water (stream 010). These streams are assumed to have initial temperatures of 18°C, which is the average outside temperature, and need to be heated to 40°C. The final temperature of 40°C is chosen so as to prevent boiling of methanol (boiling point of methanol is 65°C) when those streams come into contact with methanol in the reactors. Please refer to Appendix C.3 for the heat integration tables.

Six streams are identified to be able to give off heat even though they are not required to be cooled down. Stream 402 containing methanol/water from the distillation column, D401, can be cooled to 20°C, stream 403 containing 98.5% methanol can also be cooled to 20°C. Stream 204 containing biodiesel/glycerol mixture can be cooled only to 30°C, to ensure that glycerol will flow easily. Glycerol in stream 305 can also be cooled to 30°C as it goes to the waste tank; however, it will not be used again in the process. Stream 323 contains water at 100°C and is available to give off heat to the cold streams. Stream 326 containing the final biodiesel product coming from distillation column D402 can be cooled as low as 20°C; however, this is not crucial since it is only being stored in the end.

Two streams are identified to be hot streams that require cooling. Stream 110A which contains the waste vegetable oil after the first cycle's distillation has a temperature of 101°C which requires cooling to a temperature of 65°C before entering the pre-treatment reactor for the second cycle in order to prevent methanol vaporization. Stream 322 contains biodiesel from distillation column D401, going to the neutralization reactor

R301 and has a temperature of 130°C. This stream requires cooling to below 100°C in order to prevent evaporation of water in the liquid-liquid extraction step.

A pinch analysis was conducted for the biodiesel production plant. A minimum temperature approach of 10°C was assumed for this process and the value of mCp (mass times heat capacity) for all of the streams are assumed to be constant over the range of initial and final temperatures. Since there are two cycles for stream 006 at different times, the cycle with a higher mCp value is used to ensure enough heat is supplied into the stream. Since there are two cycles for stream 110 at different times, the cycle with a lower mCp value is used to ensure enough heat is available to be exchanged. Please refer to Appendix C.3 for the Pinch Analysis tables and equations.

The pinch point is found to be at 40°C. Heat exchangers between streams 403 and 006A, 403 and 008, 403 and 010, 402 and 006A, 402 and 008, and between streams 402 and 010 are needed to heat up the three cold streams. Utilities have to be used to cool down the hot stream 403. The finalized pinch analysis is presented in Figure C.3-1. Based on the result, a heat exchanger network involving six heat exchangers and one cooler can be implemented to satisfy all the heating requirements. With this network, approximately 3.17 kW of energy will be conserved and around 3.43 kW of cooling energy is required. From the point of view of conservation of energy, heat integration will maximize heat recovery and minimize utility consumption[18]. The energy possessed by the hot streams will not only dissipate into the atmosphere, but also be utilized to heat the cold streams. In this case, the biodiesel production plant will be built on skid, so the inclusion of six heat exchangers will occupy a tremendous amount of space compared to if electrical heaters are used. It was decided to opt for electrical heaters based on the space limitation argument.

4.0 Equipment Design and Specifications

There are six main pieces of equipment in the biodiesel production plant: storage tank, reactor, packed distillation tower, heat exchanger, hydrocyclone, and extraction column. One common design constraint is that the mobile biodiesel plant will be installed and housed in the back of a 40 ft. trailer (Figure D.1-1). This trailer has a containing height of 2.896 m. Thus the heights of the equipment were designed to meet this constraint.

4.1 Storage Tanks

The volumes of the tanks were determined based on the mass balances. Some of the tanks are meant to hold a week's worth of reactants, products, or wastes. Tanks T101, and T201 are meant to act as equalization basins, and therefore, are sized to hold one batch of mixture which leaves reactors R101, (R102, or R103) and R201, respectively. The tanks for WVO (T001), H_2SO_4 (T002), wastewater (T402), glycerol (T403), and biodiesel (T404) are sized to hold a week's worth of volume.

The energy required to heat up the waste vegetable oil from ambient temperature of 18^oC to 65^oC is calculated to be 571.2 MJ. A helical heating coil with a diameter of 0.05 m and a total length of 65.4 m constructed from carbon steel along with impellers to improve heat transfer are implemented. The impeller is necessary since the WVO solidifies upon cooling. Figure D.1-2 shows a schematic diagram of the WVO storage tank T001. It will take about 2.6 hours to heat 6604.71kg of WVO with a power of 158.67 kWh. In order to save time, it is advised that the client heat the storage tank prior to the arrival of the biodiesel trailer.

The waste methanol tank however, is sized to hold one batch of pre-treatment waste, and two batches of post-treatment waste. The distillate from D401 is recycled back to the pure methanol storage tank, T003. Detailed sample calculations regarding the design of storage tanks are found in Appendix D.2-1. The storage tank heights and diameters were determined using equations (1) and (2). The ratio of the height to diameter was varied to ensure that the heights of the tanks were below 9 feet. Refer to Table D.1-1 for the dimension specifications and materials of construction for each of the storage tanks.

4.2 Reactors

To design the reactor for this process, the volumes were first determined using the mass balance. The volumes of all of the components entering the reactor were added together to give the total liquid volume of the reactor (equivalent to one batch). To prevent the chance of overflow, the reactors were designed to 70% fill capacity; therefore, the reactor sizes are 1.43 times greater than the liquid volume. Detailed sample calculation regarding the design of reactors can be found in Appendix D.2-2. Please refer to Table D.1-2 for the dimension specifications and materials of construction for each of the reactors.

Since the pre-treatment reactors (R101, R102, and R103) contain corrosive sulphuric acid, stainless steel was chosen as the material of construction. Stainless steel was also chosen for the transesterification reactor, R201, because of the corrosive caustic being used as a catalyst. For the neutralization reactor, R301, carbon steel was chosen as the material of construction because the corrosive components will quickly be neutralized to prevent corrosion. Figure D.1-3 shows a schematic diagram of the transesterification reactor.

To mix the components in the reactors, Rushton turbines were chosen as impellers. The diameter of the impeller, by convention, is 1/3 the tank diameter, and the impeller width is 0.2 times the impeller diameter. The length of each blade is 0.25 the impeller diameter. The impeller is placed two impeller diameters above the bottom of the tank. Three impellers were used, each spaced a distance equivalent to one impeller diameter apart. To promote mixing within the reactor, four baffles (of width 0.1 times the tank diameter) were added to each reactor. The power requirement to drive the impeller is 5 Hp/1000 Gallons[22] for the mixing of immiscible liquids for liquid-liquid reactions. Refer to Table D.1-3 for the impeller specifications for each of the reactors.

Based on thermodynamic analysis, the temperature in the main reactor R201 will increase by 3.39°C due to the exothermic effect of the transesterification reaction. This means that the maximum energy that should be supplied by the steam through the jacket is 992.7 kJ. Meanwhile, the temperature in the FFA pre-treatment reactors, R101, R102, and R103, will increase by 3.12°C due to the exothermic effect of the esterification reaction, which means that it will require at most 652.2 kJ of energy to maintain the optimum temperature in the reactor of 60°C.

4.3 Packed Distillation Tower

D401 purifies the methanol that is used during the process. The feed to D401 consists of methanol, water, and a trace amount of sodium hydroxide and soap. Since carbon steel (CS) is compatible with all of these substances[4], CS is the material of construction chosen for this unit operation. With the tower operating at 70% flooding, the flooding velocity is found to be 2.13 m/s and the tower diameter is calculated to be 0.25 m. Since the tower diameter is less than 0.67 m, packings will be more economical to use compared to plates[20].

From simulating the distillation procedure using ASPEN®, 98.5% pure methanol can be produced with three theoretical stages. Based on mass transfer calculation, the packed height of the column is found to be 2.01 m. This packing height is supported by a 0.10 m thick support plate. A schematic of the distillation tower is shown in Figure D.1-4.

The packing chosen is polypropylene Berl saddle with a nominal diameter of 1 inch, as shown in Figure D.1-5. The Berl saddle is chosen based on two main considerations; one is due to its simple design that will prevent plugging due to foaming that might occur because of the presence of soap, and two is due to economical reasons compared to other types of packings[20]. The packing's nominal diameter is dictated based on the small diameter of the tower. With a 10 to 1 ratio of tower diameter to nominal diameter of the packing, surface area for mass transfer can be maximized.

The trough type liquid distributor, as shown in Figure D.1-6 is used to distribute the feed evenly onto the packing. This distributor was chosen mainly because of its common use in the industry.

4.4 Heat Exchangers

Shell-&-tube heat exchangers are chosen as type of heat exchangers for condensers and reboilers in Sections 100 through 400. Shell-&-tube heat exchangers are convenient when dealing with potentially fouling material such as biodiesel and WVO. The plate heat exchangers for pure reactants in Section 000 are chosen, as these require minimum space requirements. The material of construction for all heat exchanger units were chosen to be carbon steel 304 as recommended in literature.

The fluid properties were obtained from literature and ASPEN® simulations. A cooling water temperature of 10.0°C was assumed. The heat duty, *Q*, was determined from ASPEN® simulations. In cases where an ASPEN® simulation was not available and no phase changes occur, the heat exchanger duties were determined using Equation 14. Sample calculations are presented in Appendix D.2-3 for the design of the condenser C401. The tube-side fluid is steam; the shell-side fluids are WVO and biodiesel.

The overall heat transfer coefficients, *U*, for all the heat exchangers were found in literature. The process flowrates were found from the mass balances. The cooling water and superheated vapour mass flowrates were determined from energy balances. Allowable pressure drops were determined according to rules of thumb. It should be noted that superheated vapour was assumed to be the source of heat. However, the high temperatures required particularly in the reboilers, H101A, H101B, and H302, such that electrical heating should be considered as an alternative.

The condensation inside the tubes was assumed to be vertical upflow. This geometry was suggested as method of condensation in literature as the preferred arrangement for refluxing hot condensate. Standard reflux condensers typically vary between 2 to 3 m in length. For the mobile unit, a horizontal arrangement with only a slight vertical gradient was assumed for installing the condensers. The vertical gradient will ensure that the condensate is returned to the distillation column by gravity. In addition, the near-horizontal arrangement minimizes the overall heights of the distillation unit.

Kettle reboilers were chosen over horizontal shell side thermosiphons, vertical thermosiphons, and forced circulation reboilers. Kettle reboilers, in general, require less temperature difference as the driving force of heat transfer and generate larger vapour fractions relative to the other reboiler types.

4.5 Hydrocyclones

The design of a hydrocyclone for the separation of two immiscible liquids (glycerol and biodiesel) using a standard cyclone was analyzed. Such a separation system requires two liquid-liquid hydrocyclones to achieve an approximate efficiency of 99%.

As a result of the internal geometry of the cyclone and with the assumption of pressure settings, it is possible to bring about an axial reversal of the central oil core. The glycerol droplet diameter is the main factor for the design of hydrocyclone. It was assumed that the diameter of glycerol droplet is between 100 μm ($1x10^{-6}$m) to 1 mm ($1x10^{-3}$m). The pressure drop over the hydrocyclone was assumed to be 100 Pa. Consequently, the high density FAME can be removed from the centre of the hydrocyclone head, as the continuous phase, while the bulk of the liquid including glycerol, plus residual contaminants, flows out of the tail section at the underflow, as the reject phase.

The probability of removing an oil droplet in the feed depends mainly upon the defined glycerol droplet diameter, $d_{p,50}$[*] and the differential density between the two liquids. The physical properties of glycerol and biodiesel are listed in Table D.1-4.

Using the hydrocyclone correlations between separation characteristics shown in Figure D.1-7[21], the resulting average diameter and height of the hydrocyclone was determined to be 1.25 m and 2.14 m, respectively. Other dimensions of the hydrocyclone were

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[*] The term $d_{p,50}$ refers to the particle size at which the hydro-cyclone is 50% efficient. It is stressed that the cut point size does not refer to overflow products as this is dependant on the feed solids particle size analysis

calculated using geometric ratios (Figure D.1-8[21]) and shown in the sample calculations in Appendix D.2-4.

Stainless steel is the most appropriate material for the hydrocyclone design as it resists higher degrees of corrosion.

4.6 Counter-Current Liquid-Liquid Extraction Column

The purpose of the extraction column (E301) is to remove the salts and soaps produced in the process. The extraction column appears immediately after the neutralization reactor (R301). Refer to PFD Section 300 in Appendix B. A schematic is shown in Figure D.1-9.

The feed stream entering the extraction column is composed of biodiesel, salt and soap. Since the concentration of salt and soap in the feed stream is less than 1 %, as determined by the mass balance, this system is dilute. Water sprayed from the top of the column will be used as the solvent to remove the salt and soap contaminants from the biodiesel. The extraction column will be operated in counter-current mode. An 85 mol% biodiesel stream will exit the top of the column, while water, soap and salt will exit the bottom as a wastewater stream.

The factors taken into account during the extraction column design process include: the flowrates of the streams entering the column, the operating temperature and pressure, the density difference between two phases, the phase viscosities, and the interfacial tension. These considerations are discussed in detail in Appendix D.2-5. Based on the properties of these two components, the biodiesel stream was chosen as the continuous phase, while the water was chosen as the dispersed phase. In column extractors, the phase with the lower viscosity (lower flow resistance) is generally chosen as the continuous phase. Also, the phase with the higher flowrate can be dispersed to create more interfacial area and turbulence. In addition, the height of the extraction column cannot exceed the height of the trailer, 2.75 m.

An ethanol-water-ester mixture ternary phase diagram was used to model the biodiesel-water equilibrium. Using the phase diagram in Figure D.1-10, it was determined that there is one equilibrium stage.

Detailed calculations for the determination of column height and diameter are presented in Appendix D.2-5. These calculations assume column operation at 50% flooding velocity to ensure maximum performance. The height of the extraction column was determined to be 2.53 m. The diameter of the column was determined to be 0.21 m. This is within the design constraint of 2.75 ft. The material of construction selected for the extraction column is stainless steel 304, which is compatible with all the components in the column.

4.7 Pumps

The various pumps in all sections have been sized according to Sulzer Pump Selector. The selector requires various input parameters, such as the composition of the fluid, piping sizes, surface pressures of the tanks that are at the suction and discharge side of the pump, the elevation head both at the suction and discharge side, etc. See Appendix D.3 for complete pump specifications.

The fluid used in this case is ethanol because it has a very similar density as biodiesel and was easier to model on the pump selector. The temperature of the process fluid used to size the pump was taken to be 60 °C.

The inlet piping size was taken as 50 mm whereas the outlet piping size was taken to be 25 mm. It was observed that while sizing, the best possible configuration was obtained when we considered the outlet pipe to be smaller than the inlet piping. The tank surface pressure at both the suction and discharge was assumed to be 1 atm. This results in a large Net Positive Suction Head (NPSH) available and a small NPSH required. Due to this, the efficiency of the pump decreased. Nonetheless, the size of the pumps were sufficient for the required flow rates and applications.

The mass flow rates of the individual streams were converted to the volumetric flow rates by dividing the stream with the density of the most abundant material in the stream. The density of ethanol was used to model biodiesel because of the ease of modeling and availability of the necessary data.

Some of the volumetric flow rates obtained were very small, especially for Section 300. These flow rates were not sufficient for pump usage. Therefore, it has been suggested to disregard the entire set of initially present pumps, which have a very small volumetric flow rate at the suction side. Upon further research it was also found that it would not be efficient to include pumps in lines which have a very small volumetric flow rate. This would lead to cavitation which would ultimately damage the pump and would lead to expensive overhauling and maintenance costs. A secondary tank after each unit having a small flow rate can be added to store all the fluid. This will develop a sufficient volumetric flow rate to justify the inclusion of pumps in these lines.

The electric motor chosen was a High Torque – HT type induction motor that is energy efficient. It is manufactured by Crompton Greaves Ltd.[5] A standard motor that is sized for one pump can be used for all pumps because of close proximity in the flow rates and the head developed. The same motor has a specific operating range and hence can be used for all the pumps. The metering pumps were selected from LMI catalogue.[5] The pumps have a maximum flow output capacity of 10 GPM.

4.8 Piping

The goal of this section is to select the most appropriate size and material of piping for the main streams in the mobile biodiesel plant. Four piping materials were considered: PVC (Poly Vinyl Chloride), CPVC (Chlorinated PVC), Carbon Steel, and Stainless Steel 304. Appendix D.4 describes each piping material. The costs for different materials of construction of piping vary widely from different sources depending on the supplier, and the additional cost of fittings, welding, and installation can easily be more than ten times the basic cost for the pipe. The factors considered when choosing the piping material were based on the material's collective ability to handle the process conditions, such as temperature and pressure, as well as chemical compatibility.

The pipes were sized according to the maximum flow rate that occurs in their respective streams. A basic 1" inner diameter schedule 40 pipe can handle the volumetric flow rate and pressure stresses for all streams, and thus it is suitable for most circumstances in this plant. Because of its strength, a schedule 10 will suffice for stainless steel 304. The complete pipe material and size selection for all streams in the process is shown in Table D.4-1.

4.9 Plant Layout

The biodiesel production plant is contained in a 40 foot Hicube trailer[7], mounted on the back of a flat bed 18-wheeler truck. The trailer's external dimensions are 12.192 m long, 2.438 m wide, and 2.896 m high; the internal dimensions are 12.024 m long, 2.353 m wide, 2.692 m high. Figure D.5-1 in Appendix D.5 shows a diagram of the plant contained inside the trailer.

The front end (1.5 m in length) of the trailer will serve as the control room. This section is separated from the rest of the trailer. Entrance to the control room is via a side door located on the driver's side of the truck.

The remaining 10.692 m length of the trailer houses the biodiesel plant .The equipment is arranged such that the reactant and product tanks are located at the rear end of the truck, for ease of filling/emptying. The rear panel of the trailer opens outward as a set of doors. The trailer is roughly divided into four sections: pre-treatment, main reaction, purification, and reactant and product storage. The equipment is arranged sequentially to follow the flow of the biodiesel production process. The entrance to the plant is on the passenger side of the truck, midway down the length of the trailer.

Since the plant is constrained to a restricted space, the equipment is arranged 40 cm apart. The current trailer design presents limitations in manoeuvrability around the plant. To maximize space, equipment was stacked where possible. For each distillation column, its respective pump, reboiler, and condenser were stacked directly adjacent to it. The pumps for each of the storage tanks, mixers, and reactors were placed directly beneath each respective unit.

To contain any spills or leaks, catch basins were placed beneath each major piece of equipment. Four safety vents were placed on the upper perimeter of the trailer to release any hazardous methanol fumes should a leak occur. Refer to Figure D.5-2 through D.5.5 for different views of the complete plant layout.

5.0 Environmental Assessment

The environmental impact assessment is concerned with the necessary actions required to minimize the environmental impact of the waste streams from the biodiesel production process. The biodiesel production process creates two waste streams: glycerol, and wastewater (containing large quantities of methanol, soap, and sodium sulphate, and trace amounts of sodium hydroxide). The compositions of the waste streams were examined and compared to environmental regulations to determine the appropriate actions required for disposal. This section will also include the secondary effects due to the biodiesel plant being mobile, and the HAZOPs study which was performed for Section 200 of the process.

5.1 Environmental Assessment of Wastewater

The wastewater from the biodiesel production facility originates from the washing of the biodiesel in the extraction column and from the methanol distillation column (D401). The composition of the wastewater is summarized in Table E.1. According to the Sewer Use Bylaw No.164 for the GVRD, several specifications are required to be met prior to discharging the wastewater. The specifications are summarized and compared to the wastewater values in Table E.2.

To discharge the wastewater, the sulphate, soap, and methanol concentration must be reduced, along with the pH. To reduce sulphate concentrations, (which exceeds the maximum level specified by the GVRD by 359 mg/L), the sulphate may be treated by either precipitating with barium ions (at a low pH), or through anaerobic digestion. The pH can be reduced through the addition of an acid, such as HCl. Methanol, which is flammable, odourous, and poisonous, is present in the wastewater at approximately 42% by weight and therefore must be treated prior to discharge as it is a “prohibited waste”. The methanol concentration could be reduced to approximately 5% by weight, if the bottoms from D401 were recycled back to the waste methanol tank; however, the methanol would still need to be removed from the wastewater to meet discharge regulations. Methanol can be removed by anaerobic digestion, where bacteria consume methanol as a substrate. The BOD of this soap, which is soluble in water, is unknown, and would need to be determined by means of experimental methods. Since the concentration of soap would be 7820 mg/L, the BOD will be very high, and would need to be reduced. BOD reduction can be accomplished by anaerobic digestion.

For sewer discharge, the most efficient treatment method would be anaerobic digestion, which would remove the sulphates, methanol, soap, and BOD in the wastewater. For anaerobic digestion, the pH would first need to be neutralized, through the addition of an acid. Anaerobic digestion would require another reactor, and a clarifier to gravitationally separate the sludge from the effluent. As the biodiesel plant is skid-mounted, the treatment of the wastewater by anaerobic digestion would not be feasible due to space limitations. The wastewater will therefore have to be collected over the duration of the week, and will disposed of at a treatment facility capable of processing it. Likely, there will be a cost for disposal.

5.2 Environmental Assessment of Glycerol

Glycerol is produced as a by-product in the main transesterification reaction. Approximately 248 kg of glycerol is produced in one week, which will contain amounts of biodiesel, unreacted methanol, sodium hydroxide, and soap, (which are not included in the mass balance). The impurities will likely be present after the hydrocyclones, since the separation is not 100% efficient. The glycerol would have to be purified to greater than 90% for pharmaceutical use. This would involve a neutralization step, and the separation of excess methanol, and salts through a washing step. Due to space limitations of our facility, it was decided that the glycerol by-product will not be purified, instead, the glycerol will be sent, at a cost, to a specialty waste facility for proper purification.

5.3 Environmental Assessment of Secondary Effects

The biodiesel production process is based on the concept of bringing the mobile plant to the source of the waste vegetable oil. The negative environmental impact of gasoline consumption, exhaust, and road erosion (to a lesser effect) are consequently unavoidable, but can be minimized through proper logistical route planning. Optimizing the accessibility (and cost) of the reactants will most likely help to determine the best logistical plan.

The locations of processing will typically be next to the source of WVO (restaurants, cruise ships, etc.), therefore the mobile biodiesel manufacturing facility is not expected to cause any additional damage to the property, natural environment, or wild life. Due to the possible methanol vapour emissions into the environment, the locations of nearby air intake systems should be identified prior to process start up. Noise pollution may restrict the operation of the facility at certain times. In the case that noise abatement is recommended, installation of attachable sound barriers may be considered.

5.4 HAZOPs

Section 200, the main transesterification reaction section, was chosen as the subject of the HAZOPs study because of its importance to the biodiesel plant. To perform the hazard analysis, a "hazard matrix" was constructed for each stream, and each unit operation. For each stream or unit operation, the process parameters such as flows, pressures, and temperatures were examined to determine possible deviations which could lead to ultimate hazards. For each deviation, the HAZOPs study identified all the possible causes for that deviation. The consequences for each deviation were then listed, and recommendations were made to minimize the effect or to prevent the consequence. Common recommendations from the HAZOPs study included the installation of high and low alarms (to warn the operator of minor deviations), and high-high and low-low alarms, (to respond to a significant deviation which would result in a health or safety hazard). The causes, consequences, and recommendations for streams and unit operations are presented in Appendix E.

6.0 Economic Assessment

6.1 Cost Implementation

An estimate of the implementation cost was obtained by calculating the sum of all materials and labour expenses. For the estimate to hold true, the working environment must first be safe in order to operate. Safety devices such as ventilation items are not included in the economical analysis.

The total equipment capital cost is $141,941. Installation cost is assumed to be 35% of the capital cost, except for pumps as it is assumed to be 20% of the capital cost due to easier installation based on industrial approximations. The trailer cost is assumed to be $25000 ($18000 for the trailer plus $7000 for customized modifications). Piping cost is estimated to be 10% of the capital cost as this is a mobile plant and pipe length would be minimal as compared to industrial sized plants. Instrumentation cost is estimated to be 20% of the capital cost as there are some complex automated sequencing requirements in the pre-treatment section, which would require extra costs to implement not to mention programming requirements as well.

The Total Capital Investment (TCI) is estimated to be $296,417, which is the start-up cost of the *Biodiesel In Motion* production plant. This amount includes all proper over-run costs, such as the 5% contingency fund, and a 10% working capital.

6.2 Production Cost

Based on Weekly production rate of 3000L of biodiesel per week.

The raw materials used in the production stage include: methanol, sulphuric acid, and sodium hydroxide, with methanol being the primary reactant. Although the purification stage does extract and return a major portion of used methanol, some methanol is lost. The average tranesterification reaction consumption rate of methanol is 20% by volume of biodiesel produced, this equates to 30L per batch. With additional methanol lost in the glycerol and waste streams, an additional 5% by volume is adjusted. This equates to 53.3 L of methanol per batch or 1066L per week of methanol. Three litres of sulphuric acid and 9.3 kg of sodium hydroxide are required per week; therefore, the average weekly cost of raw materials used is approximately $378.55.

Utility cost is estimated to be 62.4 kWh per batch which results in a weekly power consumption of 1284 kWh. At the current BC Hydro rate of 0.067$/kWh, the total utilities cost is 86$ per week.

Labour costs for two operators working 40 hours per week each at $20/hr is $1600 per week. There are estimates for a weekly maintenance cost of $200 and $100 for miscellaneous supplies required on a weekly basis. This brings the total production cost for the week to $2365.

The production rate of biodiesel is 3000L per week, and according to the current diesel price of $0.92/L, a weekly revenue of $2760 is realized. This provides a net profit of $395 per week and is estimated to be a profit of 13 cents per litre of biodiesel produced. With the production rate of 156,000L biodiesel annually, a profit of $20563 each year is realized. By considering the initial Total Capital Investment of $296,417, this equates to a Return on Investment (ROI) of 6.94%, and the biodiesel production plant will break even at approximately 14.4 years.

The resulting Return on Investment of 14.4 years seems quite high for such a mobile plant. The exploration of cost cutting on Total Capital Investment results in few recommendations. The implementation of a glycerol purification process at an off-site location to purify the glycerol by-product could result in additional revenue for the production process. The implementation of an additional wastewater process would also reduce our wastewater disposal costs. As the major portion of our expenses for the plant is based on high equipment capital costs, there is the possibility of reducing the capital cost by employing used equipment for the biodiesel production plant. By conducting a complete analysis through further investigation of these alternatives, the Return On Investment could be significantly reduced; however, it will require additional ground site disposal facilities as the space of the mobile plant does not allow for such a facility.

Please refer to Appendix F, Tables F-1 to F-9 for a break-down of the equipment costs and a summary of the total capital investment required.

7.0 Conclusions and Recommendations

The final design of the mobile biodiesel plant encompasses many elements ranging from the principles of Chemical Engineering to the basics of economics. The Chemical Engineering aspect of this design chose the transesterification reaction, the pre-treatment and the purification processes, while the economic element determined the feasibility of this design. Based on the economic analysis, this design will breakeven in 14.4 years; however, this may be reduced if alternative means of revenue were pursued, such as the purification and selling of the by-product, glycerol. Nonetheless, this design is profitable, with a profit of $20563 each year for a production rate of 156,000 L biodiesel annually.

The following proposes several recommendations for groups who wish to continue this project.

Since many communities and government agencies have shown keen interest in biodiesel, it would be beneficial to assess the demand for a mobile unit in comparison to a permanent plant.

Although all necessary equipment has been fitted into the 40 foot trailer, there is minimal space for maintenance and repairs. Continuation of the project may focus on resizing the equipment so as to allow less head space and perform experiments to collect data that is specific to biodiesel, transesterification, and other species involved.

From an economic stand-point, additional revenue may be generated by purifying and selling the glycerol by-product or enhancing the methanol recovery to lower operational costs. Capital cost may be reduced with used equipment and obtaining government funding.

With greater exposure, this mobile plant will surely be a leap towards a feasible alternative fuel.

8.0 Nomenclature

A_c	column cross sectional area
C	capacity parameter
C_D	drag coefficient
CPVC	chlorinated polyvinyl chloride
CS	carbon steel
°C	degrees Celsius
D	tank diameter
D_i	impeller diameter
$D_{P,50}$	droplet diameter
D_T	column diameter
FAME	Fatty acid methyl esters
ϕ_D	volume fraction of dispersed liquid phase in column
g	acceleration due to gravity
H	tank height
η	viscosity
HETS	height equivalent to theoretical stage
k_2	proportionality constant
M_c	mass flow rate of continuous phase
M_D	mass flow rate of dispersed phase
μ_c	viscosity of continuous phase
μ_D	viscosity of dispersed phase
N_i	impeller speed
P	power requirement
PLC	Programmable Logic Controller
PVC	Polyvinyl chloride
ρ	density
ρ_c	density of continuous phase
ρ_D	density of dispersed phase
ρ_M	density (volumetric mean)
SS	stainless steel
σ_{avg}	interfacial tension average
σ_c	interfacial tension of continuous phase
σ_D	interfacial tension of dispersed phase
TAG	triacylglycerol
u_c	actual average velocity of the continuous liquid phase
u_D	actual average velocity of the dispersed (droplet) liquid phase
u_o	characteristic rise velocity for a single droplet
u_r	average droplet rise velocity relative to the continuous phase
U_c	superficial velocity of the continuous liquid phase
U_D	superficial velocity of the dispersed liquid phase
WVO	Waste Vegetable Oil
V	volume

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Appendix A: Concept

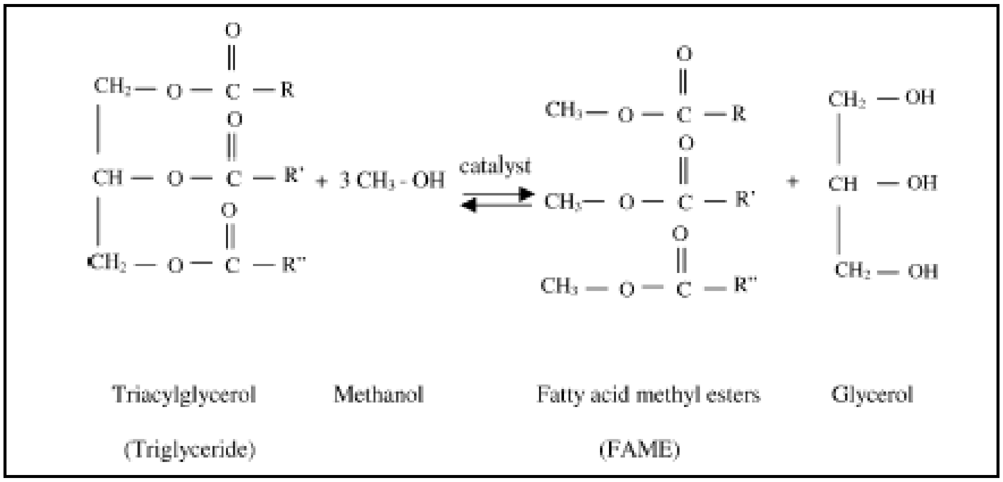


Figure A-1. Esterification reaction. Triacylglycerols (TAG) reacts with methanol to produce fatty acid methyl esters (FAME, or biodiesel)

Appendix B: Process Flow Diagrams and Piping and Instrumentation Diagrams

cover

000

000

100

100

200

200

300

300

400

400

Appendix C: Process

Appendix C.1: Start-up, Shutdown and Emergency Procedures

Table C.1-1. Start-up Procedures

1	**Utilities**
	1) electricity 2) open cooling water 3) start computer start-up program: *startupBiodiesel.exe* 4) open water stream to extraction column E401 5) open steam to reboilers
2	**Section 400: Solvent Recovery and Product Storage**
	1) start condenser C401 and reboiler H401 2) open product storage tanks 3) start distillation column D401
3	**Section 300: Purification**
	1) start reboiler H302 and condenser C302 - check online 2) start R301 impeller 3) start extraction column E301 (feed) 4) start reboiler H301 and condenser C301 - check online 5) start distillation column D301 (feed) 6) start distillation column D302 (feed)
4	**Section 000: Reactant Preparations**
	1) start mixer M001 2) start inventory tanks
5	**Section 100: Pre-treatment**
	1) start reboiler H101 and condenser C101 - check online 2) start distillation column D101 (feed) 3) open tank T101 4) open pretreatment reactor sequencing R101/R102/R103 (feed from T001)
6	**Section 200: Transesterification Reaction**
	1) start inventory in reactor R201 and tank T201 2) open tank T201 3) feed reactor R201

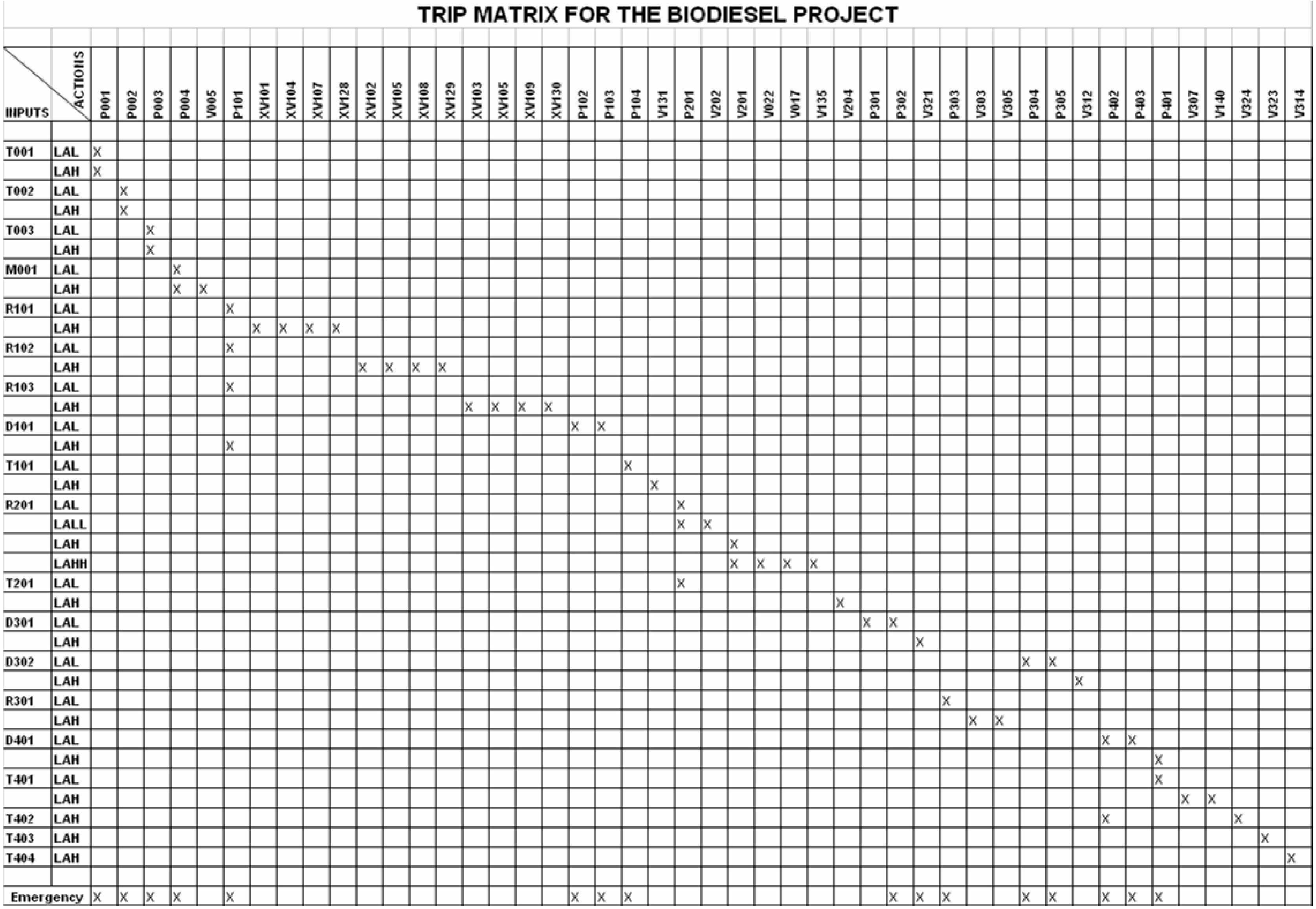
Table C.1-2. Shutdown Procedures

1	**Section 200: Transesterification Reaction**
	1) stop inventory in reactor R201 and tank T201 2) close tank T201 3) stop inventory in reactor R201 and tank T201
2	**Section 100 Pre-treatment**
	1) close pretreatment reactor sequencing R101/R102/R103 (feed from T001) 2) close tank T101 3) shut-down distillation column D101 (feed) 4) shut-down reboiler H101 and condenser C101 - check online
3	**Section 000: Reactant Preparations**
	1) shut-down inventory tanks 2) shut-down mixer M001
4	**Section 300: Purification**
	1) shut-down distillation column D302 (feed) 2) shut-down distillation column D301 (feed) 3) shut-down reboiler H301 and condenser C301 - check online 4) shut-down extraction column E301 (feed) 5) shut-down R301 impeller 6) shut-down reboiler H302 and condenser C302 - check online
5	**Section 400: Solvent Recovery and Product Storage**
	1) shut-down distillation column 2) close product storage tanks 3) shut-down condenser and reboiler
6	**Utilities**
	1) close steam to reboilers 2) close water stream to extraction column E401 3) shut-down computer shut-down-up program: *shut-downBiodiesel.exe* 4) close cooling water 5) electricity

Table C.1-3. Emergency Procedures

Case	**Methanol Spill**
	1A) methanol flow HHA/LLA triggers: shut-down electricity - see Trip Matrix 1B) visual inspection: manual electrical shut-down button - see Trip Matrix
Case	**Explosion**
	1) shut-down electricity - see Trip Matrix 2) call Fire Department

Table C.1-4. Trip Matrix



TRIP MATRIX FOR THE BIODIESEL PROJECT

INPUTS	ACTIONS	P001	P002	P003	P004	V005	P101	XV101	XV104	XV107	XV128	XV102	XV105	XV108	XV129	XV103	XV105	XV109	XV130	P102	P103	P104	V131	P201	V202	V201	V022	V017	V135	V204	P301	P302	V321	P303	V303	V305	P304	P305	V312	P402	P403	P401	V307	V140	V324	V323	V314
T001	LAL	X																																													
	LAH	X																																													
T002	LAL		X																																												
	LAH		X																																												
T003	LAL			X																																											
	LAH			X																																											
M001	LAL				X																																										
	LAH				X	X																																									
R101	LAL						X																																								
	LAH							X	X	X	X																																				
R102	LAL						X																																								
	LAH											X	X	X	X																																
R103	LAL						X																																								
	LAH															X	X	X	X																												
D101	LAL																			X	X																										
	LAH						X																																								
T101	LAL																					X																									
	LAH																						X																								
R201	LAL																							X																							
	LALL																							X	X																						
	LAH																									X																					
	LAHH																									X	X	X	X																		
T201	LAL																							X																							
	LAH																													X																	
D301	LAL																														X	X															
	LAH																																X														
D302	LAL																																				X	X									
	LAH																																						X								
R301	LAL																																	X													
	LAH																																		X	X											
D401	LAL																																							X	X						
	LAH																																									X					
T401	LAL																																									X					
	LAH																																										X	X			
T402	LAH																																							X					X		
T403	LAH																																													X	
T404	LAH																																														X
Emergency		X	X	X	X		X													X	X	X										X	X	X			X	X		X	X	X					

Appendix C.2: Aspen Simulation Results

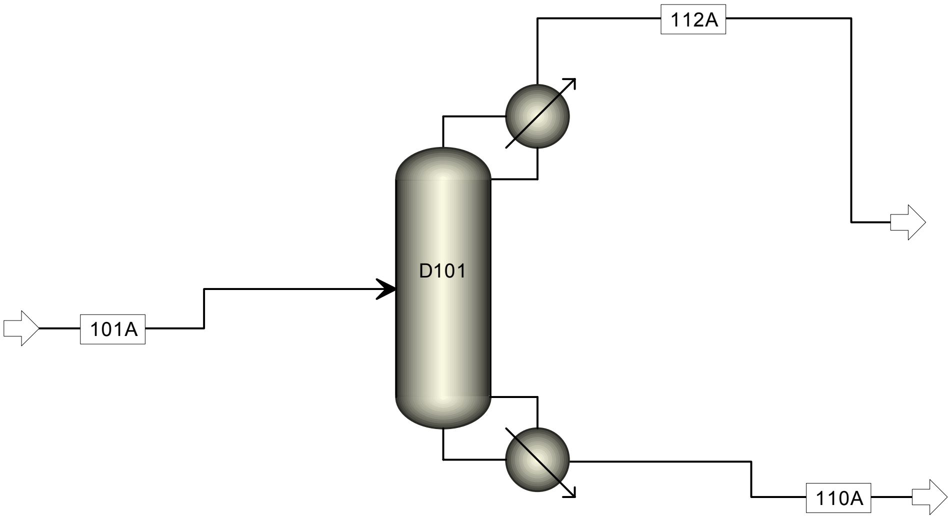


Figure C.2-1. First Treatment Aspen Distillation Column Unit D101

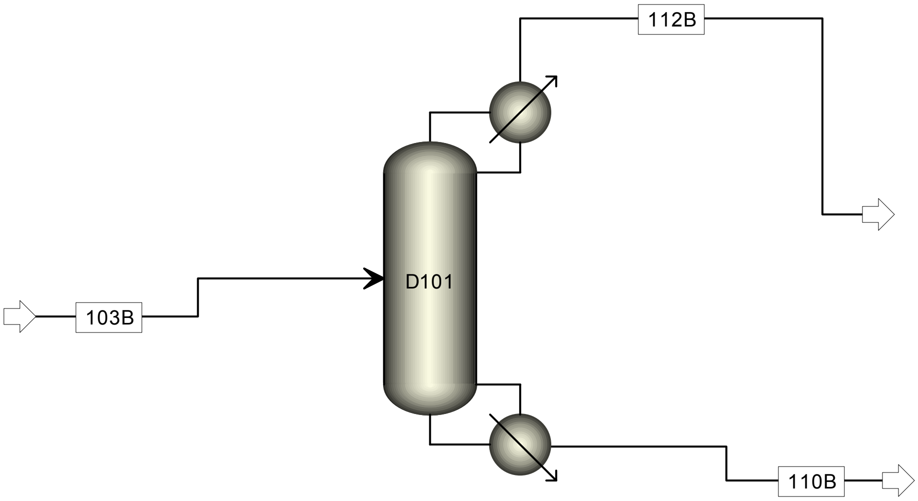


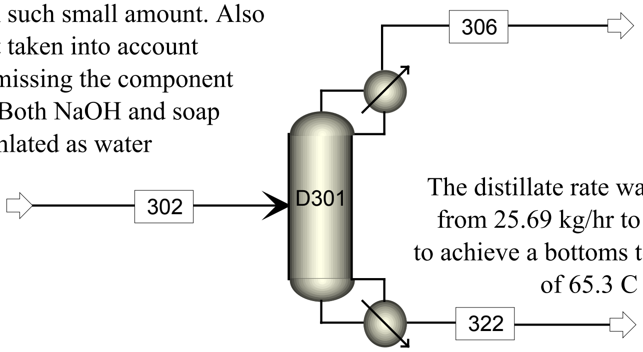
Figure C.2-2. Second Treatment Aspen Distillation Column Unit D101

Table C.2-1. First Treatment Aspen Simulation Results for D101

Design				
Stream ID		101A	112A	110A
From			D101	D101
To		D101		
Phase		LIQUID	VAPOR	LIQUID
Substream: MIXED				
Mole Flow	kmol/hr			
TRIOL-01		.3170148	5.09512E-6	.3170097
METHA-01		6.233285	6.230409	2.87527E-3
SULFU-01		1.42647E-3	8.4645E-16	1.42647E-3
METHY-01		.1069740	7.4210E-16	.1069740
WATER		1.023440	.9891443	.0342953
OLEIC-01		9.93747E-3	8.1934E-19	9.93747E-3
Mass Flow	kg/hr			
TRIOL-01		280.7005	4.51147E-3	280.6960
METHA-01		199.7279	199.6358	.0921297
SULFU-01		.1399076	8.3020E-14	.1399076
METHY-01		31.71712	2.2003E-13	31.71712
WATER		18.43755	17.81971	.6178406
OLEIC-01		2.807005	2.3144E-16	2.807005
Mass Frac				
TRIOL-01		.5261195	2.07462E-5	.8880818
METHA-01		.3743518	.9180345	2.91485E-4
SULFU-01		2.62230E-4	3.8177E-16	4.42647E-4
METHY-01		.0594476	1.0118E-15	.1003484
WATER		.0345576	.0819447	1.95476E-3
OLEIC-01		5.26120E-3	1.0643E-18	8.88096E-3
Total Flow	kmol/hr	7.692077	7.219559	.4725183
Total Flow	kg/hr	533.5300	217.4600	316.0700
Total Flow	cum/hr	.8783212	1749.580	.4263466
Temperature	K	333.1500	295.3334	374.1280
Pressure	N/sqm	1.01325E+5	10132.50	10132.50
Vapor Frac		0.0	1.000000	0.0
Liquid Frac		1.000000	0.0	1.000000
Solid Frac		0.0	0.0	0.0
Enthalpy	J/kmol	-3.1418E+8	-2.0666E+8	-1.3740E+9
Enthalpy	J/kg	-4.5296E+6	-6.8610E+6	-2.0541E+6
Enthalpy	Watt	-6.7130E+5	-4.1444E+5	-1.8034E+5
Entropy	J/kmol-K	-2.8610E+6	-95844.25	-4.3149E+7
Entropy	J/kg-K	-41247.50	-3181.979	-64506.49
Density	kmol/cum	8.757704	4.12645E-3	1.108296
Density	kg/cum	607.4429	.1242927	741.3452
Average MW		69.36098	30.12095	668.9053
Liq Vol 60F	cum/hr	.6183614	.2691601	.3492013

Table C.2-2. Second Treatment Aspen Simulation Results for D101

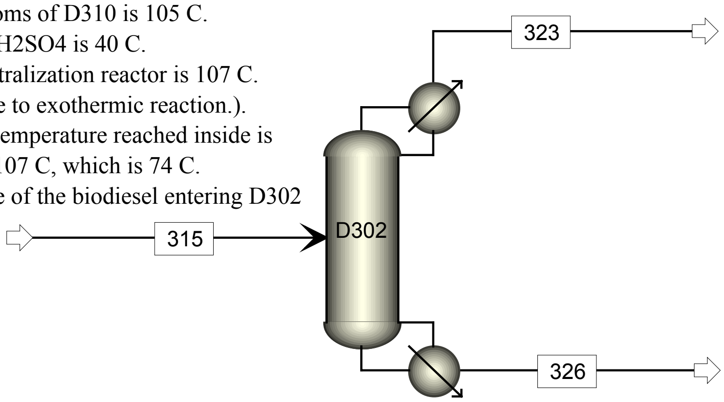
Design				
Stream ID		103B	112B	110B
From			D101	D101
To		D101		
Phase		LIQUID	VAPOR	LIQUID
Substream: MIXED				
Mole Flow	kmol/hr			
TRIOL-01		.3170091	4.86042E-6	.3170042
METHA-01		12.67822	12.66793	.0102808
SULFU-01		4.75008E-3	4.1193E-16	4.75008E-3
METHY-01		.1119426	6.5848E-17	.1119426
WATER		.0392760	.0381743	1.10172E-3
OLEIC-01		4.96864E-3	2.7756E-20	4.96864E-3
Mass Flow	kg/hr			
TRIOL-01		280.6954	4.30366E-3	280.6911
METHA-01		406.2374	405.9080	.3294192
SULFU-01		.4658857	4.0402E-14	.4658857
METHY-01		33.19027	1.9524E-14	33.19027
WATER		.7075696	.6877217	.0198478
OLEIC-01		1.403477	7.8402E-18	1.403477
Mass Frac				
TRIOL-01		.3883982	1.05845E-5	.8879820
METHA-01		.5621107	.9982980	1.04214E-3
SULFU-01		6.44646E-4	9.9365E-17	1.47386E-3
METHY-01		.0459253	4.8017E-17	.1049993
WATER		9.79064E-4	1.69140E-3	6.27897E-5
OLEIC-01		1.94199E-3	1.9282E-20	4.43998E-3
Total Flow	kmol/hr	13.15616	12.70611	.4500481
Total Flow	kg/hr	722.7000	406.6000	316.1000
Total Flow	cum/hr	1.143051	3012.871	.4152808
Temperature	K	333.1500	288.9729	378.7986
Pressure	N/sqm	1.01325E+5	10132.50	10132.50
Vapor Frac		0.0	1.000000	0.0
Liquid Frac		1.000000	0.0	1.000000
Solid Frac		0.0	0.0	0.0
Enthalpy	J/kmol	-2.7760E+8	-2.0146E+8	-1.4243E+9
Enthalpy	J/kg	-5.0535E+6	-6.2957E+6	-2.0279E+6
Enthalpy	Watt	-1.0145E+6	-7.1106E+5	-1.7806E+5
Entropy	J/kmol-K	-1.7746E+6	-1.1135E+5	-4.5284E+7
Entropy	J/kg-K	-32305.40	-3479.708	-64472.67
Density	kmol/cum	11.50969	4.21728E-3	1.083720
Density	kg/cum	632.2551	.1349543	761.1717
Average MW		54.93244	32.00034	702.3694
Liq Vol 60F	cum/hr	.8608280	.5116498	.3491782



NaOH was not taken into account NaOH is present in such small amount. Also soap was not taken into account since Aspen in missing the component sodium oleate. Both NaOH and soap were simlated as water

The distillate rate was reduced from 25.69 kg/hr to 23 kg/hr to achieve a bottoms temperature of 65.3 C

Figure C.2-3. Aspen Distillation Column Unit D301



Assume that the temperature of cooling water is 40 C.
Temperature from bottoms of D310 is 105 C.
Temperature of H2SO4 is 40 C.
Assume temperature in Neutralization reactor is 107 C.
(stream heats up a little due to exothermic reaction.).
Assume that in E301 that the temperature reached inside is the average of 40 and 107 C, which is 74 C.
This will be the inlet temperature of the biodiesel entering D302

Figure C.2-4. Aspen Distillation Column Unit D302

Table C.2-3. Aspen Simulation Results for D301

Substream: MIXED	**302**	**306**	**322**
Mole Flow kmol/hr	**(FEED)**	**(TOPS)**	**(BOTTOMS)**
TRIOLEIN	0.02377532	2.18E-08	0.0237753
METHANOL	0.86383158	0.70935607	0.15447551
H2SO4	0	0	0
M-OLEATE	0.46014918	6.00E-13	0.46014918
WATER	0.00776408	0.00195982	0.00580425
SALT	0.00237519	1.59E-35	0.00237519
GLYCEROL	8.08E-05	4.59E-14	8.08E-05
SOAP	0.04198377	0.01059764	0.03138613
NAOH	0.00977553	0.00246756	0.00730796
Mole Frac			
TRIOLEIN	0.01686509	3.01E-08	0.03469052
METHANOL	0.61276146	0.97925808	0.22539509
H2SO4	0	0	0
M-OLEATE	0.32640817	8.28E-13	0.67140328
WATER	0.00550747	0.00270552	0.00846898
SALT	0.00168485	2.20E-35	0.00346564
GLYCEROL	5.73E-05	6.33E-14	0.00011794
SOAP	0.02978131	0.01462992	0.04579547
NAOH	0.0069343	0.00340644	0.01066305
Mass Flow kg/hr			
TRIOLEIN	21.0518392	1.93E-05	21.0518199
METHANOL	27.6790296	22.7293005	4.94972912
H2SO4	0	0	0
M-OLEATE	136.431305	1.78E-10	136.431305
WATER	0.13987212	0.03530684	0.10456528
SALT	0.33738057	2.26E-35	0.33738057
GLYCEROL	0.00744451	4.22E-12	0.00744451
SOAP	0.75634945	0.19091949	0.56542996
NAOH	0.17610893	0.04445382	0.1316551
Mass Frac			
TRIOLEIN	0.1128305	8.40E-07	0.12869487
METHANOL	0.14834993	0.98823046	0.03025889
H2SO4	0	0	0
M-OLEATE	0.73122411	7.73E-12	0.83403756
WATER	0.00074966	0.00153508	0.00063923
SALT	0.00180824	9.82E-35	0.00206248
GLYCEROL	3.99E-05	1.84E-13	4.55E-05
SOAP	0.00405376	0.00830084	0.00345661
NAOH	0.00094388	0.00193277	0.00080483
Total Flow kmol/hr	1.4097355	0.72438112	0.68535438
Total Flow kg/hr	186.579329	23	163.579329
Total Flow cum/sec	6.64E-05	0.00558859	5.99E-05
Temperature C	55	65.3253369	104.09236
Pressure atm	1	1	1
Vapor Frac	0	1	0
Liquid Frac	1	0	1
Solid Frac	0	0	0
Enthalpy J/kmol	-421066059	-199967326	-592259137
Enthalpy J/kg	-3181444.4	-6297937.2	-2481410.1
Enthalpy Watt	-164886.6	-40236.821	-112752.05
Entropy J/kmol-K	-1818178.7	-121065.56	-3437339.6
Entropy J/kg-K	-13737.594	-3812.9395	-14401.549
Density kmol/cum	5.89624559	0.03600495	3.17960439
Density kg/cum	780.3716	1.14320217	758.903084
Average MW	132.350593	31.7512417	238.678461
Liq Vol 60F cum/sec	6.00E-05	8.02E-06	5.20E-05
*** ALL PHASES ***			
H J/kmol			
TRIOLEIN	-1.83E+09	-1.79E+09	-1.75E+09
METHANOL	-235373915	-199109678	-229484688
H2SO4			
M-OLEATE	-709929681	-607189404	-680532419
WATER	-283542452	-240455988	-279747049
SALT	-1.33E+09		-1.32E+09
GLYCEROL	-661765373	-573060320	-651387060
SOAP	-283542452	-240455988	-279747049
NAOH	-283542452	-240455988	-279747049
CP J/kmol-K			
TRIOLEIN	1453055.1	1472628.82	1619855.79
METHANOL	111287.641	46843.6189	129971.756
H2SO4			
M-OLEATE	566650.942	490308.83	630875.267

Table C.2-4. Aspen Simulation Results for D302

Substream: MIXED **Mole Flow kmol/hr**	**315 (FEED)**	**323 (TOPS)**	**326 (BOTTOMS)**
TRIOLEIN	0.02377529	1.33E-08	0.02377528
M-OLEATE	0.45794778	1.21E-09	0.45794777
WATER	0.00754462	0.0063807	0.00116392
GLYCEROL	8.08E-05	7.39E-12	8.08E-05
Mole Frac			
TRIOLEIN	0.04858561	2.08E-06	0.04922747
M-OLEATE	9.36E-01	1.90E-07	9.48E-01
WATER	0.01541768	0.99999773	0.00240993
GLYCEROL	0.00016518	1.16E-09	0.00016737
Mass Flow kg/hr			
TRIOLEIN	21.0518171	1.18E-05	21.0518054
M-OLEATE	135.778603	3.60E-07	135.778602
WATER	0.13591847	0.1149501	0.02096836
GLYCEROL	0.00744451	6.81E-10	0.00744451
Mass Frac			
TRIOLEIN	0.1341104	1.02E-04	0.13420862
M-OLEATE	8.65E-01	3.13E-06	0.86561025
WATER	0.00086586	0.99989462	0.00013367
GLYCEROL	4.74E-05	5.92E-09	4.75E-05
Total Flow kmol/hr	0.48934853	0.00638071	0.48296781
Total Flow kg/hr	156.973783	1.15E-01	156.85882
Total Flow cum/sec	5.59E-05	5.43E-05	7.02E-05
Temperature C	74	100.228053	330.211392
Pressure atm	1	1.00E+00	1
Vapor Frac	0	1	0
Liquid Frac	1	0.00E+00	1
Solid Frac	0	0.00E+00	0
Enthalpy J/kmol	-745968135	-239275792	-545114404
Enthalpy J/kg	-2325473.7	-13280455	-1678405.5
Enthalpy Watt	-101399.56	-424.09739	-73131.31
Entropy J/kmol-K	-4788612.2	-3.69E+04	-4412288.4
Entropy J/kg-K	-14927.973	-2047.3237	-13585.422
Density kmol/cum	2.43315708	0.03263928	1.91038179
Density kg/cum	780.510922	5.88E-01	620.45591
Average MW	320.781148	18.0171377	324.781105
Liq Vol 60F cum/sec	4.98E-05	3.20E-08	4.98E-05
*** ALL PHASES ***			
H J/kmol			
TRIOLEIN	-1.80E+09	-1.73E+09	-1.31E+09
M-OLEATE	-698926718	-589359337	-506130168
WATER	-282121041	-239272616	-251662580
GLYCEROL	-6.58E+08	-568551614	-5.93E+08
CP J/kmol-K			
TRIOLEIN	1518891.83	1592418.24	2255138.93
M-OLEATE	591568.173	531208.01	912463.45
WATER	76291.5605	34030.3895	221341.472
GLYCEROL	209515.905	133518.413	300906.419
Enthalpy J/kmol	-421066059	-199967326	-592259137
Enthalpy J/kg	-3181444.4	-6297937.2	-2481410.1
Enthalpy Watt	-164886.6	-40236.821	-112752.05
Entropy J/kmol-K	-1818178.7	-121065.56	-3437339.6
Entropy J/kg-K	-13737.594	-3812.9395	-14401.549
Density kmol/cum	5.89624559	0.03600495	3.17960439
Density kg/cum	780.3716	1.14320217	758.903084
Average MW	132.350593	31.7512417	238.678461
Liq Vol 60F cum/sec	6.00E-05	8.02E-06	5.20E-05
*** ALL PHASES ***			
H J/kmol			
TRIOLEIN	-1.83E+09	-1.79E+09	-1.75E+09
METHANOL	-235373915	-199109678	-229484688
H2SO4			
M-OLEATE	-709929681	-607189404	-680532419
WATER	-283542452	-240455988	-279747049
SALT	-1.33E+09		-1.32E+09
GLYCEROL	-661765373	-573060320	-651387060
SOAP	-283542452	-240455988	-279747049
NAOH	-283542452	-240455988	-279747049
CP J/kmol-K			
TRIOLEIN	1453055.1	1472628.82	1619855.79
METHANOL	111287.641	46843.6189	129971.756
H2SO4			
M-OLEATE	566650.942	490308.83	630875.267

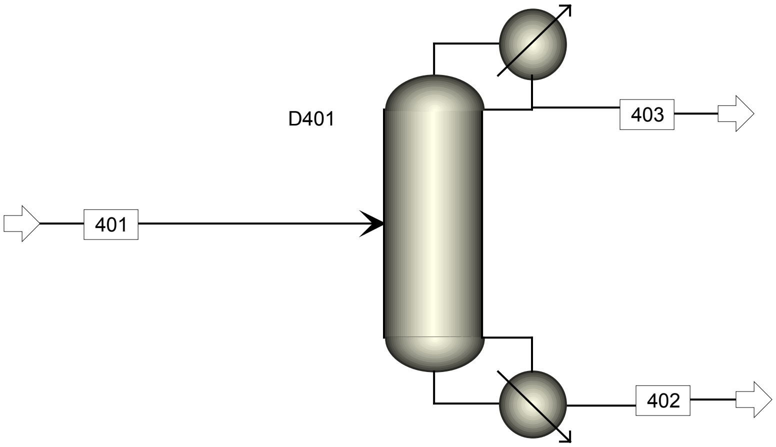


Figure C.2-5. Aspen Distillation Column Unit D401

Table C.2-5. Aspen Simulation Results for D401

Heat and Material Balance Table				
Stream ID		401	402	403
From			D401	D401
To		D401		
Phase		LIQUID	LIQUID	LIQUID
Substream: MIXED				
Mole Flow	kmol/hr			
METHANOL		10.99551	1.933650	9.061863
WATER		.5578598	.3153802	.2424796
SOAP		8.66330E-4	8.66330E-4	4.1321E-15
H2SO4		0.0	0.0	0.0
WVO		0.0	0.0	0.0
NAOH		0.0	0.0	0.0
Mass Flow	kg/hr			
METHANOL		352.3200	61.95834	290.3617
WATER		10.05000	5.681662	4.368338
SOAP		.2100000	.2100000	1.0016E-12
H2SO4		0.0	0.0	0.0
WVO		0.0	0.0	0.0
NAOH		0.0	0.0	0.0
Mass Frac				
METHANOL		.9717028	.9131664	.9851785
WATER		.0277180	.0837385	.0148214
SOAP		5.79183E-4	3.09506E-3	3.3985E-15
H2SO4		0.0	0.0	0.0
WVO		0.0	0.0	0.0
NAOH		0.0	0.0	0.0
Total Flow	kmol/hr	11.55424	2.249897	9.304343
Total Flow	kg/hr	362.5800	67.85000	294.7300
Total Flow	l/min	8.019761	1.502700	6.588709
Temperature	C	60.00000	66.72768	64.93227
Pressure	atm	1.000000	1.000000	1.000000
Vapor Frac		0.0	0.0	0.0
Liquid Frac		1.000000	1.000000	1.000000
Solid Frac		0.0	0.0	0.0
Enthalpy	J/kmol	-2.3726E+8	-2.4126E+8	-2.3556E+8
Enthalpy	J/kg	-7.5606E+6	-8.0001E+6	-7.4362E+6
Enthalpy	Watt	-7.6148E+5	-1.5078E+5	-6.0880E+5
Entropy	J/kmol-K	-2.2471E+5	-2.1507E+5	-2.2514E+5
Entropy	J/kg-K	-7160.823	-7131.704	-7107.356
Density	kmol/cum	24.01202	24.95394	23.53608
Density	kg/cum	753.5137	752.5345	745.5431
Average MW		31.38069	30.15694	31.67661
Liq Vol 60F	l/min	7.563701	1.398978	6.164723

Appendix C.3: Heat Integration Tables and Pinch Analysis Equations

Table C.3-1. Heat Exchanger Stream Data

Main Component	Stream		T_i	T_f	mCp	Q	T_i^*	T_f^*
		mass balance	(°C)	(°C)	kW/K	KW	(°C)	(°C)
MeOH	$C1_A$	006A	18.00	40	0.1323	2.9106	23	35
	$C1_{Bx}$	006B	18.00	40	0.2633	5.7922	23	35
MeOH/NaOH	C3	008	18.00	40	0.0007	0.0156	23	35
Water	C4	010	18.00	40	0.1559	3.4299	23	35
Glycerol/BioD	H1	204	60.00	30	0.0848	2.5432	55	35
Glycerol	H2	305	55.00	25	0.0069	0.2073	50	30
Methanol	H3	403	67.00	20	0.0258	1.2124	62	25
Methanol/Water	H4	402	65.00	20	0.1093	4.9203	60	25
WVO	H5	110A	100.85	65	0.0003	0.0092	96	70
Biodiesel	H6	322	130.00	40	0.0782	7.0355	125	45
Water	H7	323	100.25	15	0.0001	0.0120	95	20
Biodiesel	H8	326	323.98	20	0.0907	27.5762	319	25

***NOTE: Dark font signifies cold streams, gray font signifies hot streams**

Table C.3-2. Shifted Temperatures and Ranks

Main Component	**Stream**		**T_i**	**T_f**	**T_i^***	**T_f^***	**Rank ordered**	**mCp**
		mass balance	**(°C)**	**(°C)**	**(°C)**	**(°C)**		**kW/K**
MeOH	$C1_A$	006A	18.00		23		18	0.1323
				40		35	10	0.132301
MeOH/NaOH	C3	008	18.00		23		19	0.00071
				40		35	11	0.00071
Water	C4	010	18.00		23		20	0.155907
				40		35	12	0.155907
Glycerol/BioD	H1	204	60.00		55		7	0.084774
				30		35	13	0.084774
Glycerol	H2	305	55		50		8	0.006911
				25		30	14	0.006911
Water	H3	402	67		62		5	0.025796
				20		25	17	0.025796
Methanol/Water	H4	403	65		60		6	0.109339
				20		25	15	0.109339
WVO	H5	110A	100.85		96		2	0.0003
				65		70	4	0.0003
Biodiesel	H6	322	130.00		125		1	0.0782
				40		45	9	0.0782
Water	H7	323	100.25		95		3	0.0001
				15		20	21	0.0001
Biodiesel	H8	326	323.98		319		0	0.0907
				20		25	16	0.0907

Stream		**T_i**	**T_f**	**Ti***	**Tf***	**Rank ordered**	**mCp**
	mass balance	**(°C)**	**(°C)**	**(°C)**	**(°C)**		**kW/K**
$C1_{Bx}$	006B	18		23		12	0.263283
			40		35	6	0.263283

***NOTE: Since there are two cycles for stream 005 at different times, the cycle with higher mCp value is used to ensure enough heat is supplied into the stream**

Table C.3-3. Temperature Interval Heat Balance

Ranks	**$T_{intervals}$**	C_P	**$deltaT_{intervals}$**	**C_{PH}-C_{PC}**	**$deltaH_{int}$**
	(°C)		**(°C)**	**kW/K**	**kW**
0	319	0.0907			
1	125	0.0782	193.98	0.0907	17.5940
2	96	0.0003	29.15	0.1689	4.9234
3	95	0.0001	0.6	0.1692	0.1015
4	70	0.0003	25.25	0.1693	4.2748
5	62	0.0258	8	0.1690	1.3520
6	60	0.1093	2	0.1948	0.3896
7	55	0.0848	5	0.3042	1.5208
8	50	0.0069	5	0.3889	1.9447
9	45	0.0782	5	0.3959	1.9793
10	35	0.1323	10	0.3177	3.1768
11	35	0.0007	0	0.1316	0.0000
12	35	0.1559	0	-0.1552	0.0000
13	35	0.0848	0	0.0711	0.0000
14	30	0.00691065	5	0.0222	0.1108
15	25	0.10933904	5	-0.0629	-0.3146
16	25	0.0907	0	0.0186	0.0000
17	25	0.02579604	0	0.0649	0.0000
18	23	0.1323	2	-0.2888	-0.5776
19	23	0.00071024	0	0.1316	0.0000
20	23	0.15590682	0	-0.1552	0.0000
21	20	0.0001	3	0.0001	0.0004

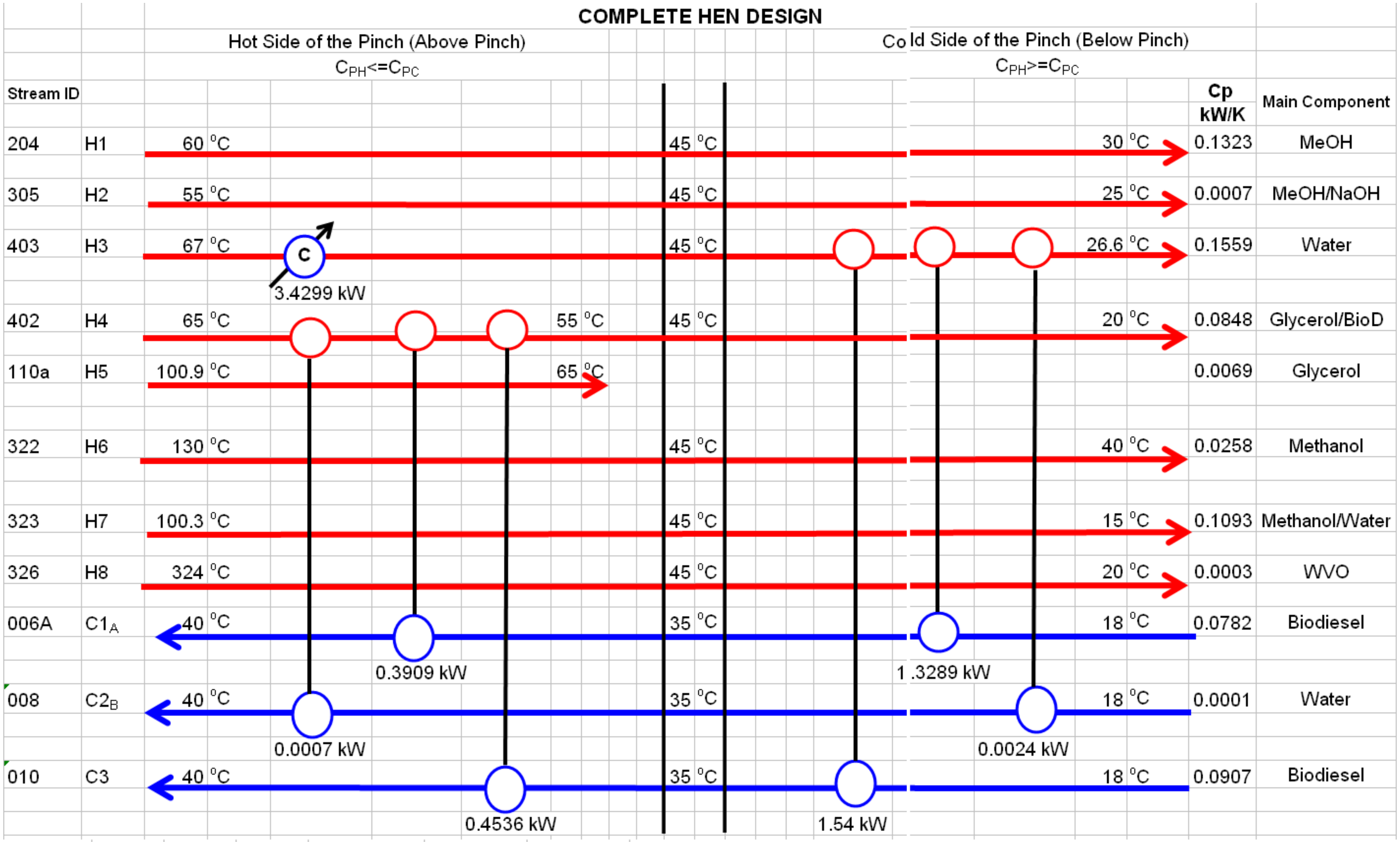
Table C.3-4. Energy Flow Between Intervals

Temperature	**delta H**	**Initial Pass**	**Final Pass**	
(°C)	**kW**	**Q (kW)**	**Q (kW)**	
319		0	37.3677	
125	17.5940	-17.5940	19.7737	
96	4.9234	-22.5174	14.8503	
95	0.1015	-22.6189	14.7488	
70	4.2748	-26.8938	10.4739	
62	1.3520	-28.2458	9.1219	
60	0.3896	-28.6354	8.7324	
55	1.5208	-30.1562	7.2115	
50	1.9447	-32.1009	5.2668	
45	1.9793	-34.0801	3.2876	
35	3.1768	-37.2569	0.1108	
30	0.1108	-37.3677	0.0000	← **PINCH**
25	-0.3146	-37.0531	0.3146	
23	-0.5776	-36.4755	0.8922	
20	0.0004	-36.4760	0.8918	

Assumptions:

1.Heat capacity is constant over the range of initial and final temperatures

2. deltaTmin = 10 °C



Energy Saving and Requirements				
Cooling Required	3.430	kW	12348	KWh
Heating Required	0.000	kW	0	kWh
Energy Saved	3.617	kW	13019	kWh

Figure C.3-1. Heat Exchanger Network

Equations for Heat Integration and Pinch Analysis

$$T_{i}^{*}{}_{,coldstream} = T_i + \frac{\Delta T_{\min}}{2}$$

$$T_{f}^{*}{}_{,coldstream} = T_f - \frac{\Delta T_{\min}}{2}$$

$$T_{i}^{*}{}_{,hotstream} = T_i - \frac{\Delta T_{\min}}{2}$$

$$T_{f}^{*}{}_{,chotstream} = T_f + \frac{\Delta T_{\min}}{2}$$

$$C_p = \dot{m}C_p$$

$$\Delta T_{\text{int}} = T_j - T_{j+1}$$

$$C_{P_C} - C_{P_H} = C_{p,j} - C_{p,j+1}$$

$$\Delta H_{\text{int}} = (C_{PC} - C_{PH}) * \Delta T_{\text{int}}$$

$$Q = H_{T_j} - H_{T_{j+1}}$$

Appendix D: Equipment Design and Specifications

Appendix D.1: Tables and Figures

Figure D.1-1. Mobile Biodiesel Production Plant

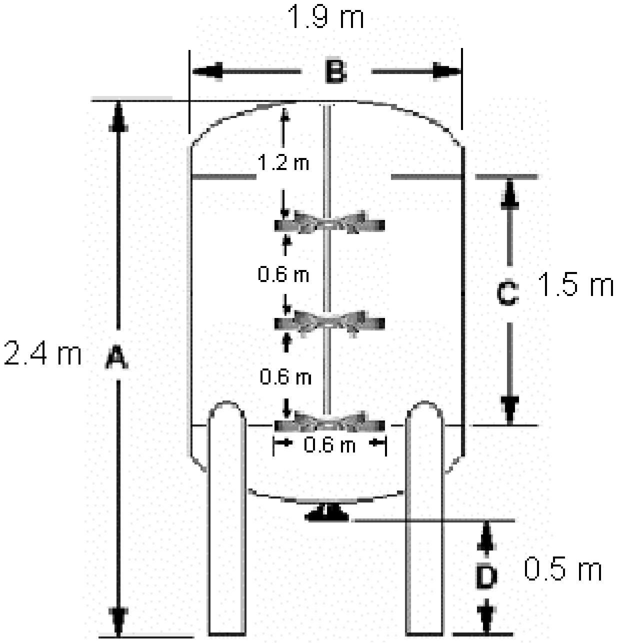


Figure D.1-2. Schematic of Waste Vegetable Oil Storage Tank T001

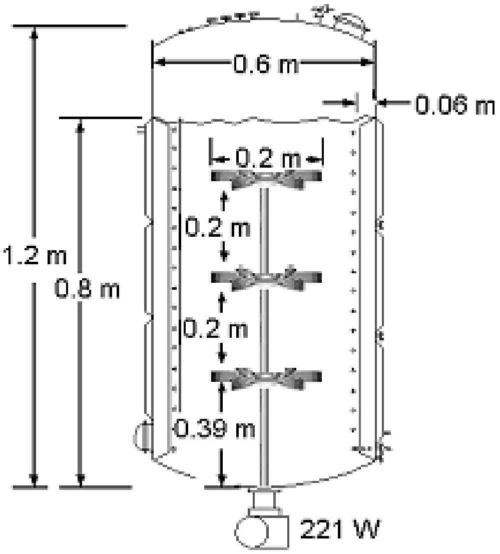


Figure D.1-3. Schematic Diagram of Transesterification Reactor R201

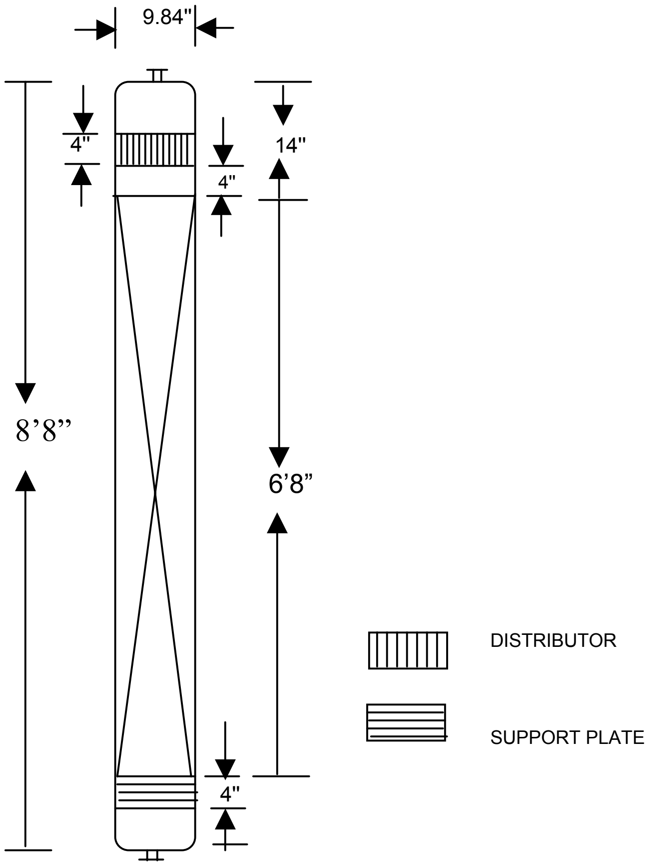


Figure D.1-4. Schematic of Methanol-Water Distillation Tower D401

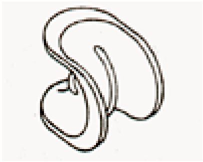


Figure D.1-5. Berl Packing[1]

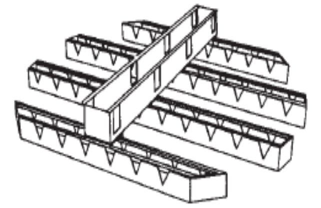


Figure D.1-6. Trough Type Distributor

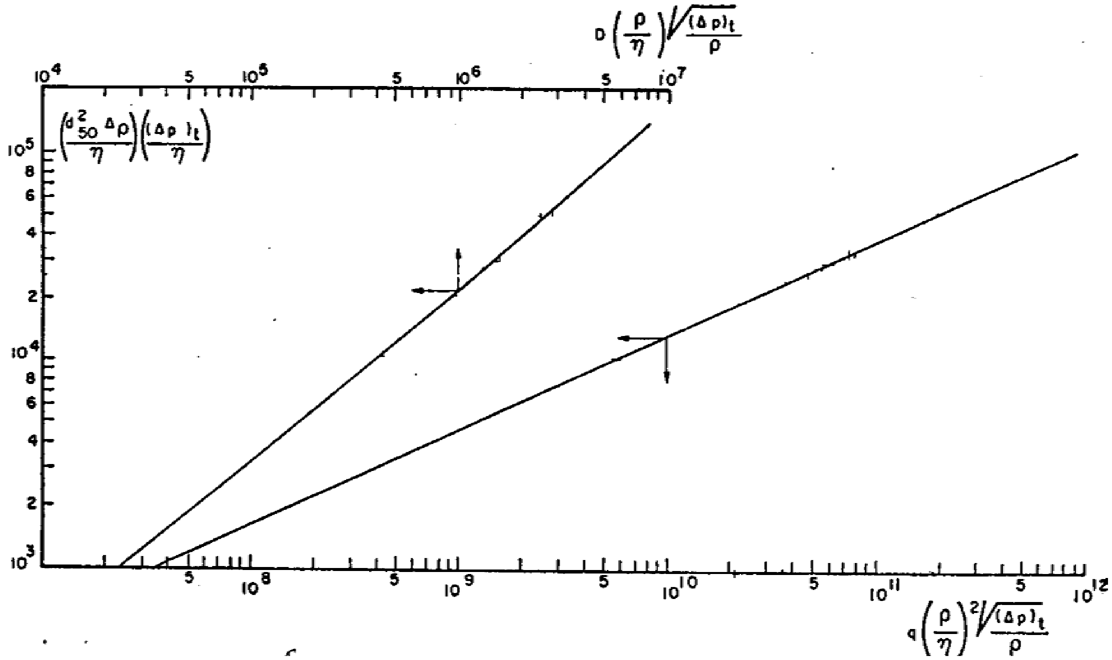


Figure D.1-7. Hydrocyclone Correlations Between Separation Characteristics, Cyclone Diameter and Cyclone Throughput if a Gas Core is Present

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[1] http://www.chinachemicalonline.com/packing/grainde_packing3.asp

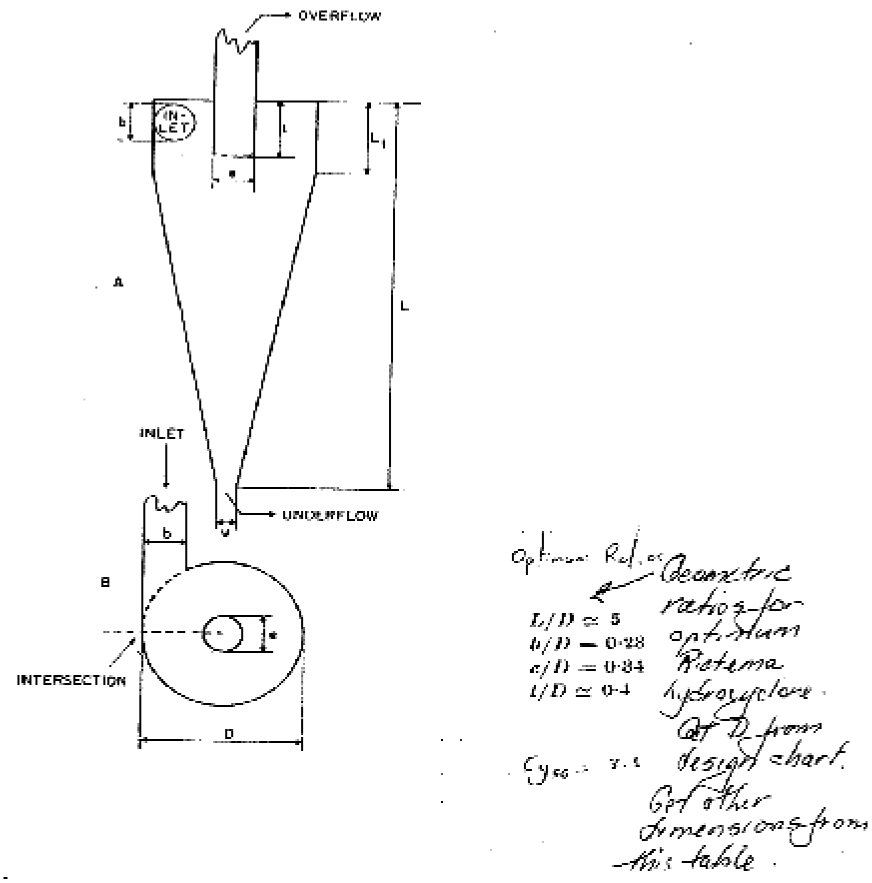

Figure D.1-8. Schematic Diagram of a Hydrocyclone

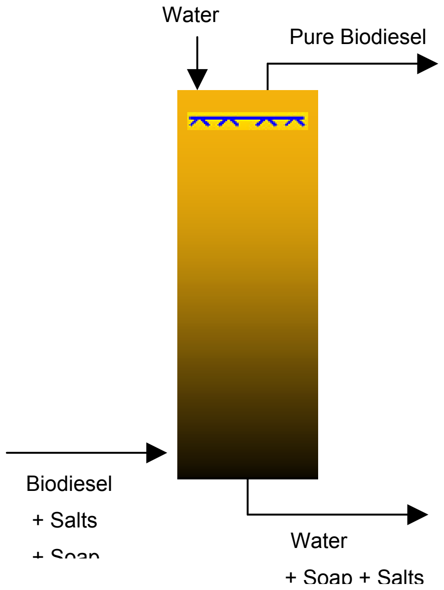

Figure D.1-9. Schematic Diagram of Extraction Column E301

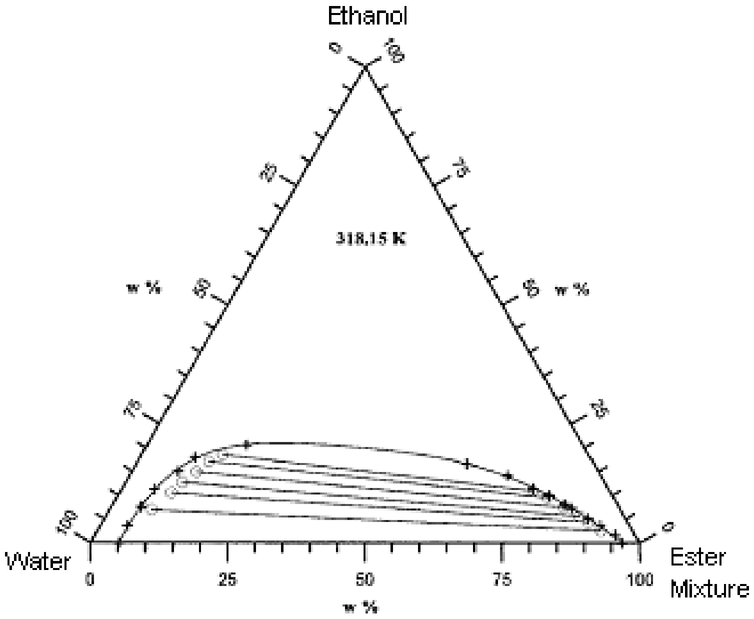

Figure D.1-10. Water-Ethanol-Ester Mixture Ternary Diagram

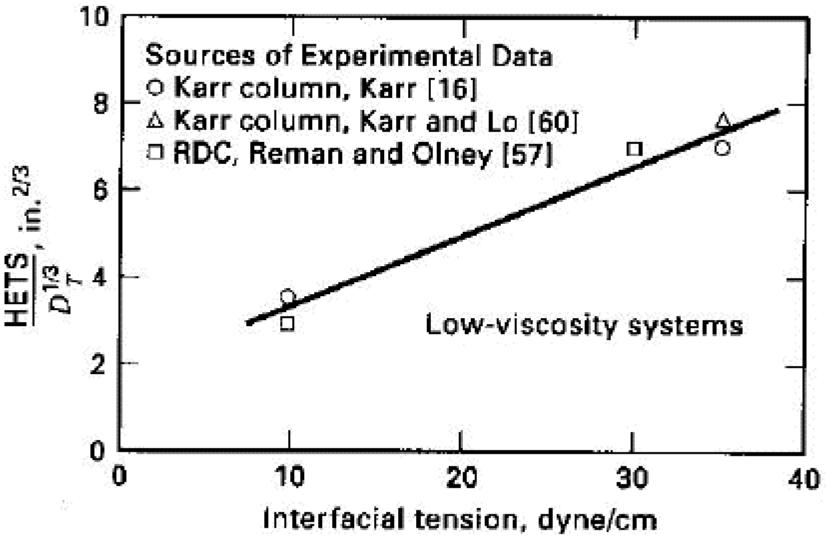

Figure D.1-11. HETS as a Function of Diameter vs. Interfacial Tension

Table D.1-1. Tank Design Specifications

Tank #	Liquid Volume (L)	Tank H:D ratio	Percent Fill (%)	Tank Volume (m^3)	Tank Diameter (m)	Tank Height (m)	Vessel Material of Construction	
T001	3583	1	70	5.12	1.9	1.9	Carbon Steel	AISI 1020
T002	3	2	70	0.004	0.1	0.3	Stainless Steel	AISI 316
T003	3281	1.1	70	5.21	1.8	2.0	Carbon Steel	AISI 1020
T101	346	2	70	0.49	0.7	1.4	Stainless Steel	AISI 304
T201	188	2	70	0.27	0.6	1.1	Stainless Steel	AISI 304
T401	482	1	70	1.32	1.2	1.2	Carbon Steel	AISI 1020
T402	4875	1	70	4.56	1.8	1.8	Polyethylene	—
T403	197	2	70	0.28	0.6	1.1	Carbon Steel	AISI 1020
T404	3586	1	70	5.12	1.9	1.9	Carbon Steel	AISI 1020

Table D.1-2. Reactor Design Specifications

Reactor #	Liquid Volume (L)	Tank H:D ratio	Percent Fill (%)	Tank Volume (m^3)	Tank Diameter (m)	Tank Height (m)	Vessel Material of Construction	
R101	860	2	70	1.23	0.9	1.8	Stainless Steel	AISI 304
R102	860	2	70	1.23	0.9	1.8	Stainless Steel	AISI 304
R103	860	2	70	1.23	0.9	1.8	Stainless Steel	AISI 304
R201	224	2	70	0.32	0.6	1.2	Stainless Steel	AISI 304
R301	207	2	70	0.30	0.6	1.1	Carbon Steel	AISI 1020
M001	43	2	70	0.06	0.34	0.68	Stainless Steel	AISI 316

Table D.1-3. Reactor Impeller Design Specifications

Reactor #	Type of Impeller	Diameter of Impeller (m)	Width of Impeller (m)	Length of Blade (m)	Impeller Placement (above bottom of tank) (m)	Width of Baffles (m)	Power required for turbine (W)	Density of fluid (kg/m3)	Rotational Speed of Impeller (rpm)
R101	Rushton Turbine	0.31	0.06	0.08	0.61	0.09	847	840	237
R102	Rushton Turbine	0.31	0.06	0.08	0.61	0.09	847	840	237
R103	Rushton Turbine	0.31	0.06	0.08	0.61	0.09	847	840	237
R201	Rushton Turbine	0.20	0.04	0.05	0.39	0.06	221	885	314
R301	Rushton Turbine	0.19	0.04	0.05	0.38	0.06	204	875	321

Table D.1-4. Physical Properties of Glycerol and Biodiesel

Glycerol:		**Biodiesel:**	
Viscosity (kg/m.s), η	1.49	Density (kg/m^3), ρ	879
Density (kg/m^3), ρ	1.26E-03	Viscosity (kg/m.s),η	4.40E-03
$d_{p,50}$, Diameter (m)	1.00E-04 to 1.00E-03	Kinematic viscosity[2] (avg) (m^2/s)	5.00E-06
Mass flow rate (kg/hr)	198.81		
Pressure Drop (Pa)	100		

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[2] Chancellor college Biodiesel Research-Biodiesel Properties
< http://www.chanco.unima.mw/physics/biodieselanaly.html>

Appendix D.2: Sample Calculations

Appendix D.2-1 Reactor and Storage Tank Design Calculations

For the reactors, the height to diameter ratio was chosen as 2:1. Therefore, the diameters and heights were determined using the following equations:

$$D = \sqrt[3]{\frac{4V}{\pi R}} \tag{1}$$

where D is the diameter (m), V is the tank volume (m^3), and R is the H/D factor.

The height H is given by:

$$H = D \times R \tag{2}$$

The power requirement in Watts was found by the following equation:

$$P = \frac{5Hp \times V \times 0.26417 Gal / L \times 1000 W / kW}{1000 Gal \times 1.341 Hp / kW} = (0.985 W / L)V \tag{3}$$

where V is the volume in liters. Given the power requirements, the impeller speed (N_i in rpm) was found using the correlation given by Haynes (2004):

$$N_i = \sqrt[3]{\frac{P}{k_2 \rho D_i^5}} \tag{4}$$

where k_2 is a proportionality constant (5 for Rushton turbines), ρ is the average fluid density, and D_i is the impeller diameter.

Appendix D.2-2 Distillation Column D401 Design Calculations

EQUATIONS FOR PACKED TOWER DESIGN

$$U_f = \left[Y * g * \frac{\rho_{H_2O(l)}}{\rho_G} \frac{1}{F_P * f(\rho_L) * f(\mu_L)} \right]^{0.5} \tag{5}$$

$$Y = \exp\left[-3.7121 - 1.0371 * \left(\ln F_{LG} \right) - 0.1501 * \left(\ln F_{LG} \right)^2 - 0.007544 * \left(\ln F_{LG} \right)^3 \right] \tag{6}$$

$$F_{LG} = \frac{L}{G} * \left(\frac{\rho_G}{\rho_L} \right)^{0.5} \tag{7}$$

$$F_P = Table14.1^1 \tag{8}$$

$$f(\rho_L) = -0.8787 + 2.6776 * \frac{\rho_{H_2O(L)}}{\rho_L} - 0.6313 * \left[\frac{\rho_{H_2O(L)}}{\rho_L} \right]^2 \tag{9}$$

$$f(\mu_L) = 0.96 * \mu_L^{\ 0.19} \tag{10}$$

$$D_T = \left[\frac{4 * G}{f * U_f * \Pi * \rho_G * 3600} \right]^{1/2} \tag{11}$$

$$D_T \geq 10 * D_P - 30 * D_P$$

$$\alpha = \frac{P^V_{Methanol}}{P^V_{water}} \tag{12}$$

$$Packedheight = \frac{N_T \cdot HETP}{E_o} \tag{13}$$

SAMPLE CALCULATIONS

$$U_f = \left[0.0831 * 32.2 * \left(\frac{59.34134}{0.07} \right) \frac{1}{39.3 * 1.50465 * 0.7851} \right]^{0.5} = 6.99 ft/s$$

$$Y = \exp\left[-3.7121 - 1.0371 * (\ln 0.00891) - 0.1501 * (\ln 0.00891)^2 - 0.007544 * (\ln 0.00891)^3 \right] = 0.255$$

$$F_{LG} = \left(\frac{149.5837}{649.768} \right) \left(\frac{0.07}{46.69033} \right)^{0.5} = 0.00891$$

$$F_P = 54 ft^{-1} (polypropylenepallring) = 39.3 ft^{-1} (polypropylene\,\mathrm{int}\,aloxsaddle)^5$$

$$f(\rho_L) = -0.8787 + 2.6776 * \frac{59.34134}{46.69033} - 0.6313 * \left[\frac{59.34134}{46.69033} \right]^2 = 1.50465$$

$$f(\mu_L) = 0.96 * 0.346976^{0.19} = 0.7851$$

$$D_T = \left[\frac{4 * 649.768}{0.7 * 6.99 * \Pi * 0.07 * 3600} \right]^{0.5} = 0.82 ft$$

$$HETP = 1.0 ft$$

$$\alpha = \frac{14.967}{3.63} = 4.123$$

$$Packedheight = \frac{3 * 1.0}{0.5} = 6.0 ft$$

Calculating the height of packing (HETP) in the distillation column D401

Since the two major species to be separated is methanol and water, the calculation is performed assuming a binary distillation between methanol (A), and water (B).

The Schmidt number of each of the species

$$\mathrm{Sc}_{L,A} = \frac{\mu_{L,A}}{\rho_{L,A} * D_{AB,L}} = \frac{355 * 10^{-6} Pa.s}{(756 kg/m^3) * (2.16 * 10^{-10} m^2/s)} = 2174$$

$$\mathrm{Sc}_{L,B} = \frac{\mu_{L,B}}{\rho_{L,B} * D_{AB,L}} = \frac{0.4668 * 10^{-6} Pa.s}{(983.2 kg/m^3) * (2.16 * 10^{-10} m^2/s)} = 2.19$$

$$\mathrm{Sc}_{L} = \frac{Sc_{L,A} + Sc_{L,B}}{2} = \frac{2174 + 2.19}{2} = 1088$$

In the enriching section

L’ = $\dfrac{4L}{\pi(D_c)^2} = 67.64\dfrac{kg}{hr} * \dfrac{1hr}{3600s} * \dfrac{4}{\pi(0.25m)^2} = 0.383\dfrac{kg}{m^2 s}$ L

The correlation for 1 in berl saddle

$\mathrm{H_{tL}} = 0.00129 * \left(\dfrac{L'}{\mu_L}\right)^{0.28} * Sc_L = 0.00129 * \left(\dfrac{0.383 kg/m^2 s}{3.44x10^{-4}\, Pa.s}\right)^{0.28} * 1088^{0.5} = 0.303m$

In the exhausting section

$$\overline{L'} = \frac{4\overline{L}}{\pi(D_c)^2} = 134.5\frac{kg}{hr} * \frac{1hr}{3600s} * \frac{4}{\pi(0.25m)^2} = 0.76\frac{kg}{m^2 s}$$

The correlation for 1 in berl saddle

$$\overline{H_{tL}} = 0.00129 * \left(\frac{L'}{\mu_L}\right)^{0.28} * Sc_L = 0.00129 * \left(\frac{0.99 kg/m^2 s}{3.44x10^{-4}\, Pa.s}\right)^{0.28} * 1088^{0.5} = 0.368m$$

The height of the packing in the tower

$$Z = Z_{enriching} + Z_{exhausting} = NtL * (H_{tL} + \overline{H_{tL}}) = 3 * (0.303 + 0.368) = 2.01m$$

Appendix D.2-3 Heat Exchanger Design Calculations

The following sample calculations are for the shell and tube heat exchanger of condenser C401.

The heat exchanger duty *Q* is estimated on the basis of:

$$Q = AUF(\Delta T)_{lmtd} = m_A c_{p,A} \Delta T_A = -m_B c_{p,B} \Delta T_B \tag{14}$$

Correction factor *F* for the mean logarithmic temperature difference $(\Delta T)_{lmtd}$:

$$\begin{aligned} P &= \frac{T_{w,2} - T_{w,1}}{T_{m,1} - T_{w,1}} \\ &= \frac{45-10}{65.3-10} = 0.63 \end{aligned} \tag{15}$$

$$\begin{aligned} R &= \frac{m_m c_{p,m}}{m_w c_{p,w}} \\ &= \frac{599 \cdot 1.42}{2304 \cdot 4.19} = 0.01 \end{aligned} \tag{16}$$

Thus, $F = F(P,R) = 0.98$ for a 1-2 S&T heat exchanger.

$$\left.\begin{aligned} (\Delta T)_1 &= 65.3 - 45.0 = 20.3 \\ (\Delta T)_2 &= 65.3 - 10.0 = 55.3 \end{aligned}\right\}$$

$$\begin{aligned} (\Delta T)_{lmtd} &= \frac{(\Delta T)_2 - (\Delta T)_1}{\ln\left[\frac{(\Delta T)_2}{(\Delta T)_1}\right]} \\ &= \frac{55.3 - 20.3}{\ln\left[\frac{55.3}{20.3}\right]} = 34.92°C \end{aligned} \tag{17}$$

Wall material: Carbon Steel 304, $1/h_w = 1.76 \cdot 10^{-4} \frac{m^2K}{W}$. From references it is found:

$$\begin{aligned} \frac{1}{U} &= \frac{1}{h_1} + f_1 + \frac{1}{h_{wall}} + f_2 + \frac{1}{h_2} \\ &= \frac{1}{6000} + 0.0002 + 1.76 \cdot 10^{-4} + 0.0002 + \frac{1}{3500} = 0.00185 \frac{W}{m^2K} \end{aligned} \tag{18}$$

Thus, $U = 540 \frac{W}{m^2K}$

Table 1: **Summary of Heat Transfer and Fouling Coefficients**

	Heat Transfer Coefficient h	Fouling Coefficient f
[unit]	[W/(m^{2}K)]	[(m^{2}K)/W]
1. H_2O (liq)	6000	0.0002
2. Light Organics (cond.)	3500	0.0002

Required heat exchanger area A:

$$\begin{aligned} A &= \frac{Q}{UF(\Delta T)_{lmtd}} \\ &= \frac{\left|-93.78\cdot 10^3\right|}{540\cdot 0.98\cdot 35.92} = 4.93m^2 = 53.07sqft \end{aligned} \tag{19}$$

Selected: $O.D. = 1.0in = 0.083ft$ outer diameter tubing, which is equivalent to the total tube length L_t

$$\begin{aligned} L_t &= \frac{A}{\pi D} \\ &= \frac{53.07}{0.083\pi} = 203.5ft \end{aligned} \tag{20}$$

Selected: two tube pass, triangular geometry:

$L = 6ft$ $\quad$ $Shell\ I.D. = 10in = 0.83ft$ $\quad$ $No.of\ tubes = 32$

Thus, verifying acceptable ratio: $L/D = 6ft/0.83ft = 7.2$, which is acceptable.

Determining the pressure drop:

$D_h = 1.1028\frac{P_t}{D_t} - D_t$	Hydraulic diameter for square pitch
$B = 0.83ft$	Distance between baffles
$E = 0.25in \cdot 0.083\frac{ft}{in} = 0.0208ft$	Distance between tubes
$D_s = 10in = 0.83ft$	Shell diameter
$A_s = \frac{D_s BC}{P_t}$	Flow area
$G_s = \frac{\dot{m}}{A_s}$	Flow velocity
$s = 1.0$	Specific gravity
$N = 16$	Number of baffles where: $(L/N)/D_s = (6ft/16)/0.83 = 0.45 \in [0.2, 1.0]$ - ok!
$\mathrm{Re} = \frac{D_h G_s}{\mu}$	Reynolds number

$f = 0.0121\,\mathrm{Re}^{-0.19},\ 300 < \mathrm{Re} < 10^6$ Friction factor

$\Delta P = \dfrac{f G_s^2 D_s (N+1)}{5.22 \cdot 10^{10} s D_h}$ Pressure drop. 25% segment baffles.

Insertion of know values in design equations yields:

$$\mathrm{Re} = \frac{0.0828 \cdot 24390}{2.424} = 829 < 2300$$

$$f = 0.0121 \cdot (829)^{-0.19} = 0.00337$$

$$\Delta P = \frac{0.00337 \cdot (24390)^2 (0.83)(17)}{5.22 \cdot 10^{10} \cdot 1.0 \cdot 0.0824} = \underline{\underline{0.0066 psi}} = \underline{\underline{0.046 kPa}}$$

The pressure loss is acceptable.

Appendix D.2-4 Hydrocyclone Design Calculations

Design Equations used for Standard Liquid-Liquid Hydrocyclones:

$$Y = \left(\frac{d_{50}^2 \Delta\rho}{\eta} \right) \times \left(\frac{(\Delta p)_t}{\eta} \right) \tag{21}$$

$$X = D \times \left(\frac{\rho}{\eta} \right) \times \left(\sqrt{\frac{(\Delta p)_t}{\rho}} \right) \tag{22}$$

Assumptions:

$$L / D \cong 5$$

$$b / D = 0.28$$

$$e / D = 0.34$$

$$I = D \cong 0.4$$

Sample Calculations:

For Glycerol droplet diameter 50%, $d_{p,50}$ = 0.001 m:

$$Y = \left(\frac{d_{50}^2 \Delta\rho}{\eta} \right) \times \left(\frac{(\Delta p)_t}{\eta} \right) = \left(\frac{0.001 m \times (879 - 1.26E-3) kg/m^3}{0.0044 kg/m.s} \right) \times \left(\frac{100 kg/m.s^2}{0.0044 kg/m.s} \right) = 4545.44$$

The value Y is corresponding to about X=1.6E+05

Hence, $X = 1.6E5 = D \times \left(\frac{879 kg/m^3}{0.0044 kg/m.s} \right) \times \left(\sqrt{\frac{100 Pa}{879 kg/m^3}} \right)$

$$\Rightarrow D = 2.37 m = 7.79 ft$$

$$L = D \times 5 = 2.37 \times 5 = 11.87 m$$

$$b = D \times 0.28 = 2.37 \times 0.28 = 0.66 m$$

$$e = D \times 0.34 = 2.37 \times 0.34 = 0.81 m$$

$$I = D \times 0.4 = 2.37 \times 0.4 = 0.95 m$$

Appendix D.2-5 Extraction Column Design Calculations

Design Considerations

The operating temperature is not critical in the extraction process. It is only dependent upon the streams entering the extraction column. The biodiesel feed stream enters the column at 85 °C; the water enters the column at 40 °C. The extraction column is assumed to operate isothermally at an average of these two inlet stream temperatures, at 63 °C. The operating pressure is assumed at isobaric at 1 atm. This is well below the vapour pressure of the solution, ensuring that the vapour phase will not appear and interrupt liquid equilibrium. Isobaric conditions are beneficial to the phase stability of the system. The density difference between the water and biodiesel is large enough such that the water (heavier solvent) will flow downward, and the biodiesel (lighter component) will flow to the top of the column. The concentration gradient, coupled with the higher affinity that the solutes have for water over biodiesel, drives the mass transfer, allowing the solutes to be extracted from the biodiesel and dissolved into the water, leaving the biodiesel relatively solute free. The density difference aids in the complete separation between water and biodiesel.

Viscosity is also valuable in the determination of what type of system to use for extraction. Components having a high viscosity cannot be used in packed columns. Since biodiesel has a high viscosity of 880 Pa·s (water has a viscosity of 1.129 Pa·s at 63 °C), a packed column was not used.

Design Conditions

Dispersed (light) Phase: Water

Continuous (heavy) Phase: Biodiesel

Flow rates determined from mass balance:

U_D = 41.75 m/s = 136.9688 ft/s

U_C = 43.77 m/s = 143.6041 ft/s

M_D = 0.0420 kg/s = 151.0484 kg/h

M_C = 0.0503 kg/s = 181.1195 kg/h

Fluid properties obtained from Perry's Handbook:

ρ_D = 995 kg/m^3 = 0.995 g/cm^3

ρ_C = 870 kg/m^3 = 0.870 g/cm^3

μ_D = 0.000384 Pa = 8.0156 x 10^{-6} lb$_f$s/ft^2

μ_C = 0.004882 Pa = 0.0001020 lb$_f$s/ft^2

Surface tension:

σ_D = 63.375 mN/m = 0.004342 lb$_f$/ft	*http://hyperphysics.py-astr.gsu.edu/hbase/surten.html#c3*
σ_C = 31.33 mN/m = 0.002147 lb$_f$/ft	*Lange's Handbook, at 25°C*
σ_{avg} = 47.3525 mN/m = 0.003245 lb$_f$/ft	*the average surface tension between the dispersed and continuous phase was used in place of interfacial tension due to the lack of data*

At σ_{avg}, using Figure D.1-, *HETS as a function of diameter was determined by assuming a linear relationship and calculating the equation of the line.*

$$m = \frac{3.4 - 0.6}{0 - 30} = 0.16$$

$$y = mx + b \rightarrow b = y - mx = 3.4 - (0.16 \cdot 10) = 1.8$$

$$y = 0.16x + 1.8 = 0.16 \cdot 47.35 + 1.8 = 9.38 = HETS \big/ D_T^{1/3}$$

Determining the total capacity of the column

$$u_D = \frac{U_D}{\phi_D} \tag{23}$$

Phase flow ratio

$$\frac{U_D}{U_C} = \frac{M_D}{M_C} \times \frac{\rho_C}{\rho_D} = \frac{151.0484 \frac{kg}{h}}{181.1195 \frac{kg}{h}} \times \frac{0.87 \frac{g}{cm^3}}{0.995 \frac{g}{cm^3}} = 0.729 \tag{24}$$

Using Figure 9 and the phase flow ratio

$$\frac{\left(U_C + U_D\right)_f}{u_O} = 0.3 \tag{25}$$

Determing characteristic rise velocity

$$u_O = \frac{0.01 \cdot \sigma_C \cdot \Delta\rho}{\mu_C \cdot \rho_C} = \frac{0.01 \cdot 0.002147 \frac{lb_f}{ft} \cdot (0.995 - 0.87) \frac{g}{cm^3}}{0.0001020 \frac{lb_f s}{ft^2} \cdot 0.87 \frac{g}{cm^3}} = 0.06119 \frac{ft}{s} \tag{26}$$

Determining superficial flooding velocity

$$(U_D + U_C)_f = 0.3 \times 0.06619 \frac{ft}{s} = 0.01837 \frac{ft}{s} \tag{27}$$

Superficial velocity at 50% flooding

$$(U_D + U_C)_{50\%\,flooding\,velocity} = \frac{1}{2} \cdot 0.01837 \frac{ft}{s} \times 3600 \frac{s}{h} = 33.0423 \frac{ft}{h} \tag{28}$$

Total volumetric flowrate

$$Q_{total} = \left(\frac{M_D}{\rho_D} + \frac{M_C}{\rho_C} \right) = \left(\frac{151.0484 \frac{kg}{h}}{995 \frac{kg}{m^3}} + \frac{181.1195 \frac{kg}{h}}{87 \frac{kg}{m^3}} \right) \times 35.3146 \frac{ft^3}{m^3} = 12.7129 \frac{ft^3}{h} \tag{29}$$

Determining cross sectional area

$$A_C = \frac{Q_{total}}{(U_D + U_C)_{50\%\,flooding\,velocity}} = \frac{12.7129 \frac{ft^3}{h}}{33.0423 \frac{ft^3}{h}} = 0.3847 ft^2 \tag{30}$$

Determining diameter

$$D = \sqrt{\frac{4A_C}{\pi}} = \sqrt{\frac{4 \cdot 0.3847 ft^2}{\pi}} = 0.6999 ft_{//} \tag{31}$$

Determining height of column from Figure 10 using the average interfacial tension

$$\frac{HETS}{\sqrt[3]{D}} = 9.3764 \Rightarrow HETS = 9.3764 \times \sqrt[3]{0.6999 ft} = 8.3250 ft_{//} \tag{32}$$

Appendix D.3: Pump Specifications

Table D.3-1. Centrifugal Pump Specifications

Pump ID	Speed (rpm)	Type of Liquid	Density @ 20C (kg/cub.m)	Vol Flow Rate (cub.m/hr)	NPSHa (m)	NPSHr (m)	Total Head (m)	Type/Size	Diameter (mm)	Efficiency	Power (kw)
P201	1120	Ethanol	789	1.52	23.1	2.88	8.55	APP-C 11-32 283902	205	16.7	0.157
P104	1120	Ethanol	789	12	23.1	1.5	6.08	APP-C 11-40 283903	185	58.9	0.254
P101	840	Ethanol	789	0.67	23.1	1.67	5.08	APP-O 22-32 288449	215	6.1	0.114
P103	840	Ethanol	789	0.61	24.1	1.67	5	APP-O 22-32 288449	215	5.5	0.113
P401	840	Ethanol	789	0.5	24.1	1.67	5	APP-O 22-32 288449	215	5.5	0.113
P403	840	Ethanol	789	0.8	23.1	1.67	5.08	APP-O 22-32 288449	215	6.1	0.114

***NOTE: All pumps in Table are single-stage centrifugal pumps. Material of Construction: Stainless Steel Schedule 40. Suction and Discharge pressures were assumed at 1 atm. Pump manufacturer: Sulzer Pumps.**

Table D.3-2. Pump Design Parameters

Pump ID	Shut-off head (m)	Shut-off dp (kpa)	BEP	Max Power (kW)	Test Speed	
					Min	Max
P201	6.73	0.497	60.9% @16.1 cum/hr	0.342 @ 22 cum/hr	400	3490
P104	20.5	1.52	65.1% @ 24.1 cum/hr	1.51 @ 31.4cum/hr	400	3600
P101	5.1	0.377	33.2% @ 7.28 cum/hr	0.344@ 11.1 cum/hr	400	3540
P103	5.1	0.377	33.2%@ 7.28 cum/hr	0.201 @ 9.1cum/hr	400	3540
P401	5.1	0.377	33.2% @ 7.28 cum/hr	0.344@ 11.1 cum/hr	400	3540
P403	5.1	0.377	33.2% @ 7.28 cum/hr	0.344@ 11.1 cum/hr	400	3540

*** NOTE: Pumps P102, P301, P302, P303, P304, and P402 were not sized since the volumetric flowrates were too small to achieve an efficient pump sizing.**

Table D.3-3. Metering Pump Specifications

Pump ID	Flow rate GPM	Manufacturer	Type	Max Output Flow Rate GPM	Max Output Pressure Psi	Stroke/Min	Max Current Amps
P001	1.58	LMI	Mseries - 13	10	120	120	3.05
P002	0.0003351	LMI	Mseries - 13	10	120	120	3.05
P003	0.0007881	LMI	Mseries - 13	10	120	120	3.05

The motor sized can be applied to both the centrifugal and metering pumps since the flowrates of the pumps are quite similar:

Manufacturer: Compton Greaves – Htmotor

Supply Voltage: up to 6600 V

Ouput: 100 – 1250 kW

IEC Frame Size: 315 – 450

Supply Frequency: 50 & 60 Hz

Number of poles: 4

Type: Squirrel Cage

Mounting: Horizontal Foot Mounted

Appendix D.4: Piping Data and Specifications

PVC (Poly Vinyl Chloride) 1120, Type I

Density: 1.039 g/m^3
Temperature Limits: -18 to 60 C
Pressure Limits (1" ID): 30.6 atm @ 23 C, 6.7 atm @ 60 C for schedule 40
42.8 atm @ 23 C, 9.4 atm @ 60 C for schedule 80
Cost Estimates: ~$0.50 / foot from Fabco for basic 1" inner diameter pipe
$7002 (56% carbon steel) - 2" ID 400 ft complex system installation
$5875 (86% carbon steel) - 2" ID 500 ft straight run installation
Suppliers: Fabco Plastics, Surrey, BC (604-882-1564)
Harvel Plastics, Inc

Chemical Corrosion:
- Not recommended for high concentrations of sulphuric acid (98% at 50 C) or sodium hydroxide (50%)
- Not recommended for sulphur salts
- May be damaged by ketones, aromatics, and some chlorinated hydrocarbons

CPVC (Chlorinated PVC) 4120, Type IV, Grade I

Density: 1.52 g/m^3
Temperature Limits: -18 to 99 C
Pressure Limits (1" ID): 30.6 atm @ 23 C, 6.12 atm @ 60 C for schedule 40
42.8 atm @ 23 C, 8.58 atm @ 60 C for schedule 80
Cost Estimates: ~$1.02 / foot from Fabco for basic 1" inner diameter pipe
$7822 (63% carbon steel) - 2" ID 400 ft complex system installation
$6638 (97% carbon steel) - 2" ID 500 ft straight run installation
Suppliers: Fabco Plastics, Surrey, BC (604-882-1564)
Harvel Plastics

Chemical Corrosion:
- Not recommended to handle vegetable oils or diesel fuels
- May be damaged by ketones, aromatics, and some chlorinated hydrocarbons

Carbon Steel, schedule 40

Density: 7.84 g/m^3
Temperature Limits: Not a factor
Pressure Limits: Not a factor
Cost Estimates: $12480 - 2" ID 400 ft complex system installation
$6853 - 2" ID 500 ft straight run installation
Suppliers: Bartle and Gibson Inc, Port Coquitlam, BC (604-941-7318)

Chemical corrosion:
- May embrittle when handling alkaline or strong caustic fluids
- May be damaged when exposed to high aqueous acid solutions under extreme T-P conditions
- May deteriorate when piping material is exposed to hydrogen sulfide

Stainless Steel 304, schedule 10

Density: 8.03 g/m^3
Temperature Limits: Not a factor
Pressure Limits: Not a factor
Cost Estimates: $14140 (113% carbon steel) - 2" ID 400 ft complex system installation
$8153 (119% carbon steel) - 2" ID 500 ft straight run installation
May be up to 1.6 times that of carbon steel
Suppliers: Bartle and Gibson Inc, Port Coquitlam, BC (604-941-7318)

Chemical corrosion:
- Although it resists all rusting, it will tarnish when it comes into contact with oxidizing acids
- Improper selection or application of thermal insulation may result in stress-corrosion cracking when exposed to media such as chlorides and other halides

Table D.4-1. Pipe Material and Size Specifications

Stream*	Flow Rate US gal/min	Major Components vol%	Temp C	Recommended Pipe Material and Size	Rationale
001	1.58	85% TAG, 10% FFA, 5% Water	65	CS 1" S40	PVC/CPVC not recommended since temp > 60C, organic material
001S	N/A	100% Steam/Water	~100	CS 1" S40	CPVC not recommended since temp may be > 100C
002S	N/A	100% Steam/Water	50-90	CS 1" S40	CPVC not recommended since temp may be > 100C
002	minute	100% H2SO4	18	CPVC 1/8" to 1" S40	CS not recommended since 100% Acid, SS also appropriate
005	2.26	100% Methanol	18	PVC 1" S40	
011	minute	100% NaOH	18	CPVC 1/8" to 1" S40	CS not recommended since 100% Base, SS also appropriate
008	minute	90% Methanol, 10% NaOH	18	CPVC 1/8" to 1" S40	PVC is a little riskier, high concs of acid due to accident a concern
009	0.668	100% Water	18	PVC 1/2" to 1" S40	No problem for all materials
103B	3.786	60% Methanol, 36% TAG	60	SS 1.25" to 1.5" S10	CS may work, but high concs of acid due to accident is a concern
104B	4.977	99.9% Methanol	65	CS 1.5" S40	CPVC possible, but temp may go above 100 C from a distill column
109B	2.027	88% TAG, 11% BioD	202	CS 1" S40	CS ok as long as acid concentration is low
108	0.762	88% TAG, 11% BioD	65	CS 1" S40	
203	1.822	69% BioD, 16% MeOH, 10% TAG	60	CS 1" S40	PVC/CPVC not recommended since temp > 60C, organic material
305	0.0433	100% Glycerol	55	CPVC 1/8" to 1" S40	
307	1.917	84% BioD, 12% TAG	104	CS 1" S40	
318	1.84	87% BioD, 12.8% TAG	330	CS 1" S40	
316	0.702	95% Water, 4% Methanol	70	CS 1" S40	CPVC ok as long as long as no biodiesel goes in this pipe
317	minute	99.9% Water	100	CS 1/8" to 1" S40	CPVC not recommended since temp is > 100C
306	0.128	99% Methanol	65	CPVC 1/8" to 1" S40	
405	3.598	98% Methanol, 1% Water	65	CPVC 1.25" to 1.5" S40	
402	0.371	92.9% Methanol, 6.8% Water	67	CPVC 1/2" to 1" S40	
403	1.636	99% Methanol, 1.2% Water	65	CPVC 1" S40	

Appendix D.5: Plant Layout

The plant was drawn to scale using AutoCAD. The pipes have been removed from the views of the plant layout for ease in visibility.

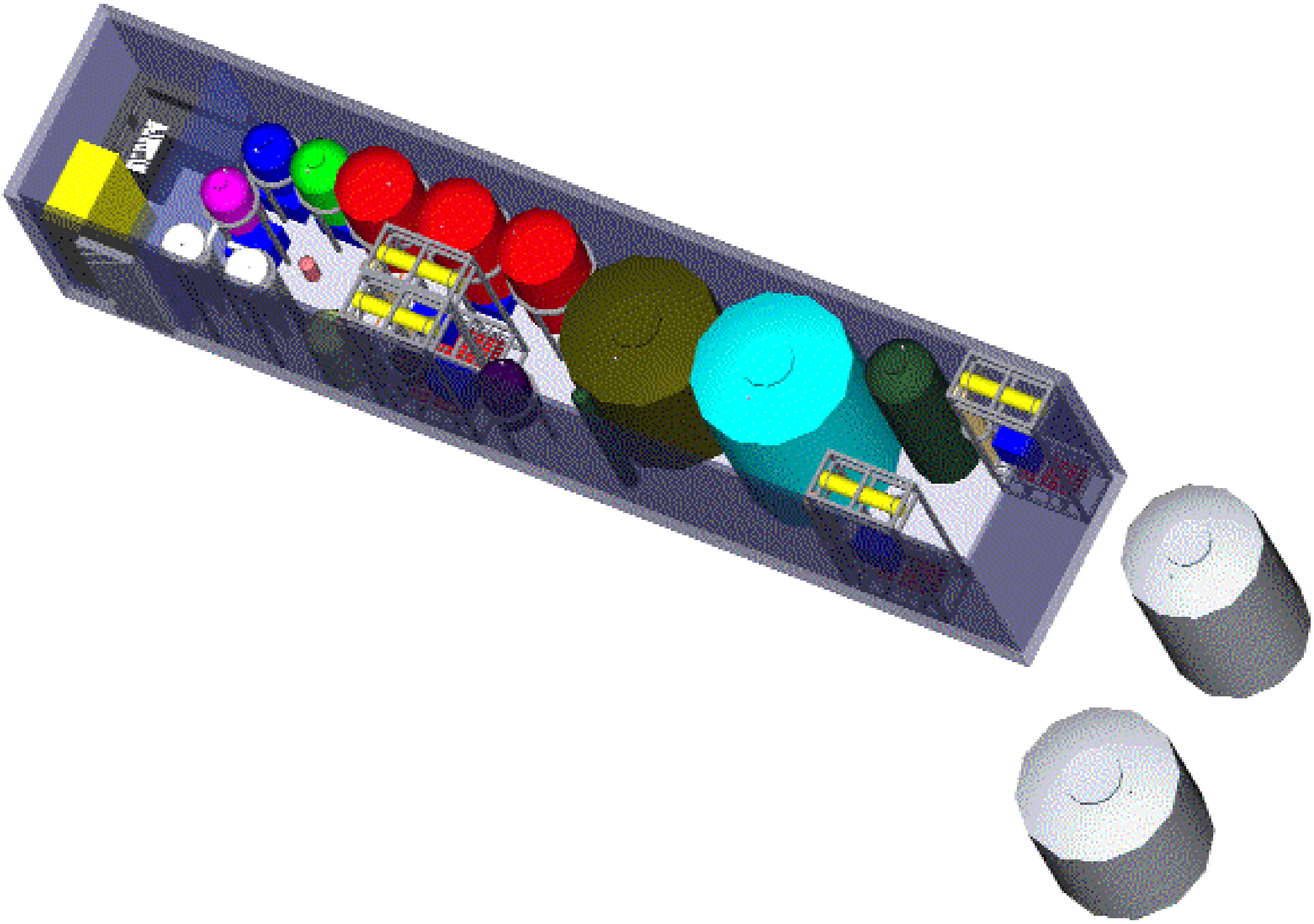

Figure D.5-1. Plant contained in a 40 ft. trailer

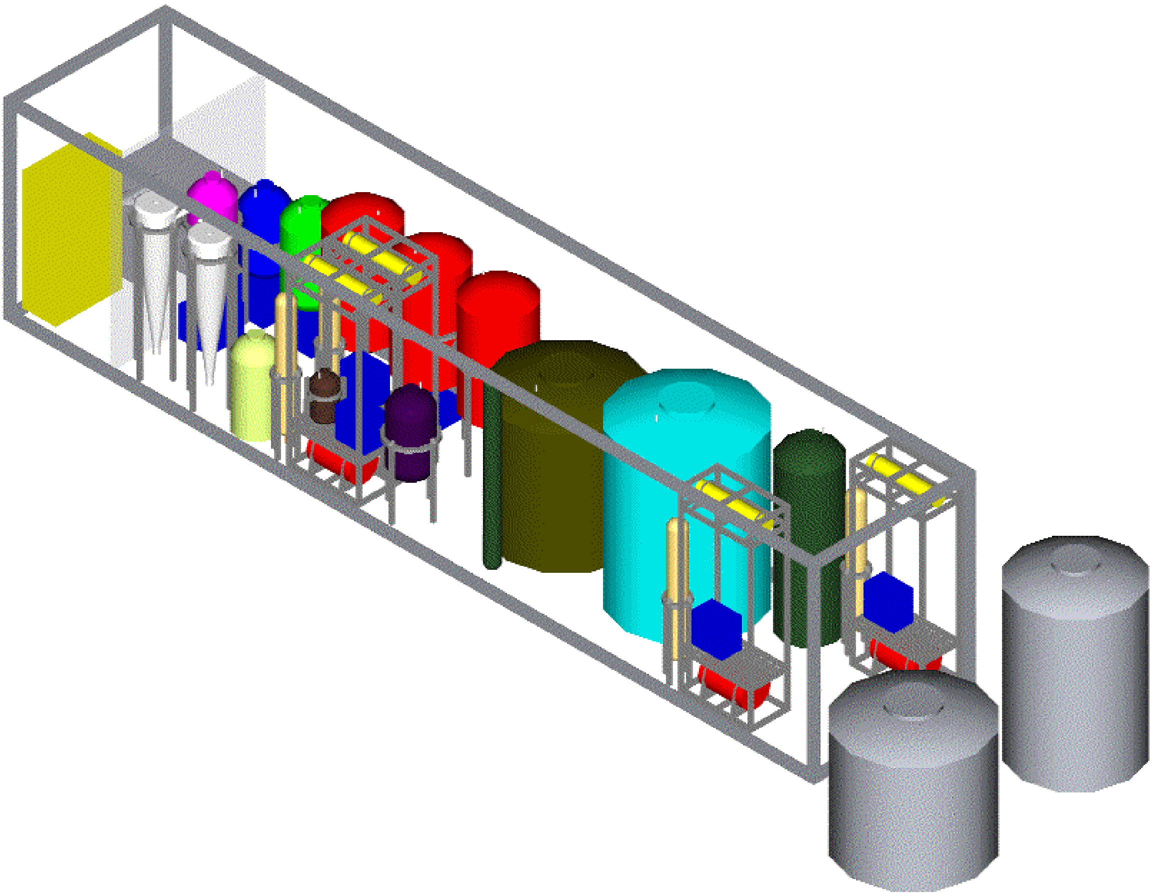

Figure D.5-2. Isometric view of plant

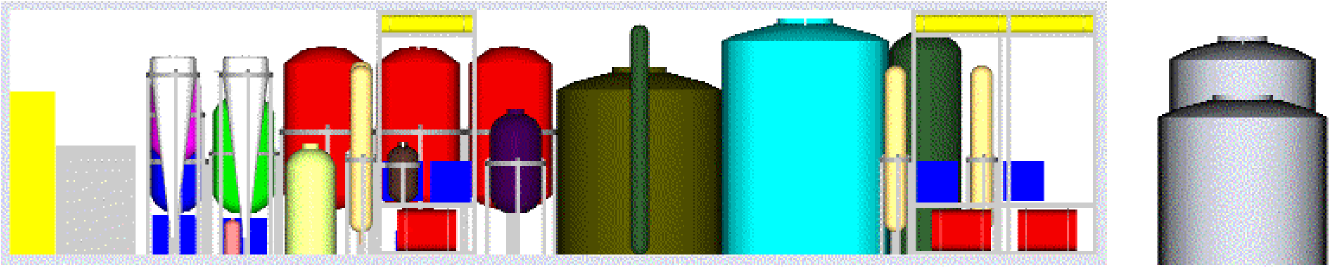

Figure D.5-3. View of plant from driver's side of truck

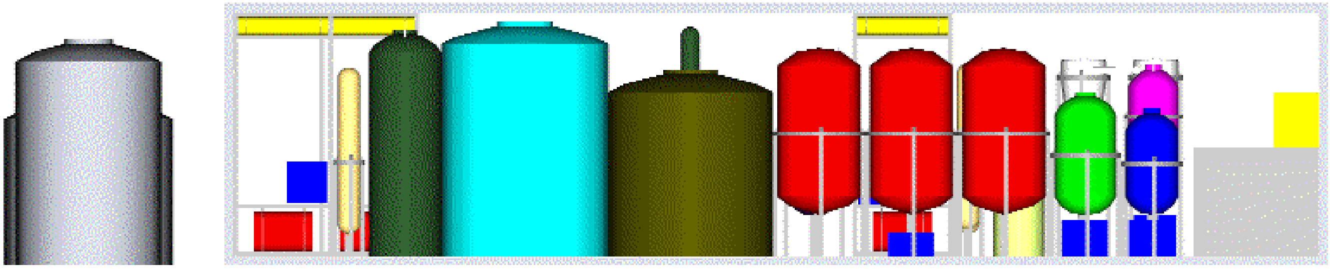

Figure D.5-4. View of plant from passenger side of truck

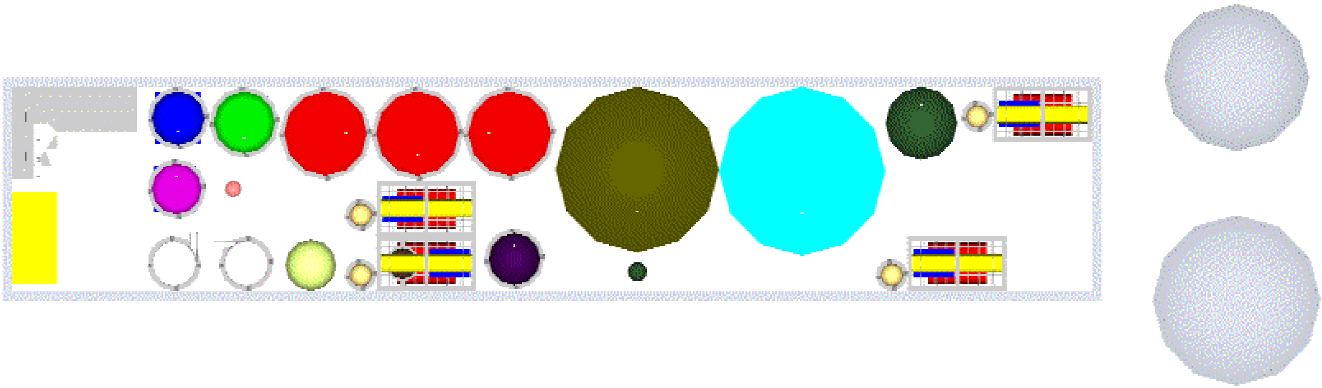

Figure D.5-5. Top view of plant

Appendix E: Environmental Assessment

Table E-1. Wastewater Composition

Component	Mass (kg)	Mass Fraction
Water	3134.8	0.6952
Methanol	1339	0.2969
Sodium Hydroxide	1	0.0002
Sodium Sulfate	9	0.0020
Soap	25.6	0.0057
Total	4509.4	1.00000

Table E.2. Related Sewer Use Bylaw Specifications for Sewer Discharge[3]

	Biodiesel Wastewater	For Sewer Discharge
Sulfate Concentration (mg/L)	1859	1500
pH	11.9	5.5-10.5
Wt% Methanol	42	no flammables, no odours, no poisons
Soap Concentration (mg/L)	7820	no specification
BOD (mg/L)	unknown	500

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[3] Greater Vancouver Sewerage and Drainage District: Sewer Use Bylaw No. 164. Bylaw introduced July 31, 1991, and last amended July 28, 2000. http://www.gvrd.bc.ca/sewerage/pdf/SewerUseBylaw164.pdf

Table E.3. HAZOPs for Stream 007

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Flow	More	Valve failure/fully open	Possible upset in downstream	Turn off pump P004
			Flow control failure	Pressure buildup in R201	Install HA
			Flow control sensor failure	R201 overflow	Regular maintenance and calibration
			Operator failure	High pH in R201	Operator training
			Pressure buildup in M001	Longer draining time of R201	Check differential pressure across valve during routine maintenance
				Increase solution volume in R201	Fail-closed mechanism
				Reverse flow 008, 108, and 007	
				Reduced stirring rate	
				Increased reaction rate	
				Higher solution temperature. R201 temperature too high	
				Pipe damage	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Flow	Less	Valve failure/closed	R201 pH not reached	Install LA
			Flow control failure	Reaction rate reduced	Regular maintenance
			Flow control sensor failure	Downstream process backed-up	Operator training
			Operator failure	Tank temperature reduced	Inspection prior to startup
			Low pressure in M001	MeOH, NaOH spill	Ventilation installed
			Plugged pipe	Health hazard	Implementation of absorbing material to avoid leaks to ground

			Plugged P004	Fire hazard	
			Pipe breakage	Corrosion of exterior surface	
				Environment contamination	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Flow	No	Valve closed	R201 pH not reached	Install check valve
			Flow control failure	No reaction	Regular maintenance
			Flow control sensor failure	Downstream process backed-up	Operator training
			Operator failure	Tank temperature reduced	
			Empty M001	MeOH spill NaOH spill	Previous HAZOP address M001
			Plugged pipe	Health hazard	
			Plugged P004	Fire hazard	Inspection prior to startup
			Pipe breakage	Corrosion of surfaces	Ventilation and absorbing material installed
				No reaction	
				Pump cavitation	
				Environment contamination	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Flow	Reverse	Pressure buildup in R201	R201 pH not reached	Install LA
			Plugged pipe	Reaction rate reduced	Regular maintenance. Inspection prior to startup
			Operator failure	Downstream process backed-up	Operator training
			Pump damage	Tank temperature reduced	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Pressure	High	Valve failure/fully open	Possible upset in downstream	Same precautions as for 007 flow deviations
			Flow control failure	Pressure buildup in R201	
			Flow control sensor	Pipe breakage	

			failure		
			Operator failure	Pump damage	
			Pressure buildup in M001		
			Plugged pipe		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Pressure	Low	Valve failure/fully open	Possible upset in downstream	Same precautions as for 007 flow deviations
			Operator failure	MeOH may partial vaporized	
			Leak in pipe	Pipe breakage	
			Plugged pipe	Pump cavitation	
			Pumps fails		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Temperature	High	Excessive heating	Increase pressure	Install HA + thermo couples
			Weather	Pipe melt	Ventilation installed
			Operator failure	MeOH boil	Operator training
			Temperature control failure in H004	Pump damage	Regular maintenance
			Temperature sensor failure in H004	Viscosity decrease	Install throttle
			Valve V014 fails and open	Higher temperature in R201	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Temperature	Low	Not sufficient heating	Reduced pressure	Install LA + thermo couples installed
			Weather		Regular maintenance
			Operator failure		Operator training
			Temperature control failure in H004		
			Temperature sensor	Viscosity increase	

			failure in H004		
			Valve V014 fails and close	Reduced temperature in R201	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Concentration	More base			Not applicable (operation at maximum solubility)
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Concentration	Less base	No supply of base to M001	See less NaOH concentration R201	Maintain adequate supply
					Operator training
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Concentration	No base	No supply of base to M001	See no NaOH concentration R201	Maintain adequate supply
					Operator training
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
007	Concentration	Additional component	Additional component(s) supplied in M001	See R201	See M001
			Operator failure		Operator training

Table E.4. HAZOPs for Stream 008

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Flow	More	Valve failure/fully open	Possible upset in downstream	Turn off pump P003
			Flow control failure	Pressure buildup in R201	Install HA Fail-closed mechanism
			Flow control sensor failure	R201 overflow	Regular maintenance and calibration.
			Operator failure	Methanol vaporize	Operator training
				Longer draining time of R201	Install high flow alarm
				Increase solution volume in R201	Check differential pressure across valve during routine maintenance
				Reverse flow 008, 108, and 007	
				Reduced stirring rate	
				Increased reaction rate	
				Higher solution temperature. R201 temperature too high	
				Pipe damage	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Flow	Less	Valve failure/closed	Reaction rate reduced	Install LA
			Flow control failure	Downstream process backup	Regular maintenance
			Flow control sensor failure	Tank temperature reduced	Operator training
			Operator failure	MeOH spill	Inspection prior to startup
			Plugged pipe	Health hazard	Ventilation installed
			Plugged P003	Fire hazard	Implementation of absorbing material to avoid leaks to ground

			Pipe breakage	Methanol vaporize	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Flow	No	Valve closed	No reaction/little reaction	Install check valve
			Flow control failure		Regular maintenance
			Flow control sensor failure	Downstream process backup	Operator training
			Operator failure	Tank temperature reduced	
			Empty T004/T003	MeOH spill/Vaporize	Refer to Hazop for T003/T004
			Plugged pipe	Health hazard	Inspection prior to startup
			Plugged P003	Fire hazard	Ventilation and absorbing material installed
			Pipe breakage	Explosion	
			Pump failure	Cavitation	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Flow	Reverse	Pressure buildup in R201	Reaction rate reduced	Install LA
			Plugged pipe	Downstream process backup	Regular maintenance and inspection prior to startup
			Pump damage	Tank temperature reduced	Operator training
			Operator failure		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Pressure	High	Valve failure/fully open	Possible upset in downstream	Same precautions as for 008 flow deviations
			Flow control failure	Pressure buildup in R201	
			Flow control sensor failure	Pipe breakage	
			Operator failure	Pump damage	
			Pressure buildup in T003		

			Plugged pipe		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Pressure	Low	Valve failure/fully open	Possible upset in downstream	Same precautions as for 008 flow deviations
			Operator failure	MeOH may be partially vaporized	
			Leak in pipe	Pipe breakage	
			Plugged pipe	Pump cavitation	
			Pumps fails		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Temperature	High	Excessive heating	Increase pressure	Install HA + thermo couples
			Weather	Pipe melt	Ventilation installed
			Operator failure	MeOH vaporize	Operator training
			Temperature control failure in H003	Pump damage	Regular maintenance
			Temperature sensor failure in H003	Viscosity decrease	Install throttle
			Valve V013 fails and open	Higher temperature in R201	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
008	Temperature	Low	Not sufficient heating	Reduced pressure	Install LA + thermo couples installed. Install throttle control?
			Weather	Viscosity increase	Regular maintenance
			Operator failure	Reduced temperature in R201	Operator training
			Temperature control failure in H003	Reaction rate decreased	
			Temperature sensor failure in H003		
			Valve V013 fails and close		

Table E.5. HAZOPs for Stream 108

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Flow	More	V113 failure/fully open	Possible upset in downstream	Turn off pump
					Install high flow alarm
					Check differential pressure across valve during routine maintenance
			Flow control failure	Pressure buildup in R201	Install HA
					Fail-closed mechanism
			Flow control sensor failure	R201 overflow	Regular maintenance/ calibration
			Operator failure	Longer draining time of R201	Operator training
				Increase solution volume in R201	
				Reverse flow 008, 108, and 007	
				Reduced stirring rate	
				Increased reaction rate	
				Higher solution temperature. R201 temperature too high.	
				Pipe damage	
				Increase in mass of unreacted treated WVO	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Flow	Less	V113 failure/closed	Reaction rate reduced	Install LA
			Flow control failure	Downstream process backup	Regular maintenance
			Flow control sensor failure	Tank temperature reduced	Operator training
			Operator failure		Inspection prior to startup

			Plugged pipe		Ventilation installed
			Plugged P003		Collection system
			Pipe breakage		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Flow	No	V113 closed	No reaction	Install check valve
			Flow control failure	Downstream process backup	Regular maintenance
			Flow control sensor failure	Tank temperature reduced	Operator training
			Operator failure	Pump cavitation	Inspection prior to startup
			Empty T101		Refer to previous HAZOP for T101
			Plugged pipe		Ventilation
			Pipe breakage		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Flow	Reverse	Pressure buildup in R201	Reaction rate reduced	Install LA
			Plugged pipe	Downstream process backup	Regular maintenance and inspection prior to startup
			Pump damage	Tank temperature reduced	Operator training
			Operator failure		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Pressure	High	V113 failure/fully open	Possible upset in downstream	Same precautions as for 108 flow deviations
			Flow control failure	Pressure buildup in R201	
			Flow control sensor failure	Pipe breakage	

			Operator failure	Pump damage	
			Pressure buildup in T101		
			Plugged pipe		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Pressure	Low	V113 failure/fully open	Possible upset in downstream	Same precautions as for 108 flow deviations
			Operator failure	Pipe breakage	
			Leak in pipe	Pump cavitation	
			Plugged pipe		
			Pumps fails		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Temperature	High	Excessive heating in T101	Increase pressure	Install HA + thermo couples and install throttle
			Weather	Pipe melt	Ventilation installed
			Operator failure	Pump damage	Operator training
				Viscosity decrease	Regular maintenance
				Higher temperature in R201	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
108	Temperature	Low	Not sufficient heating in T101	Reduced pressure	Install LA + thermo couples installed. Install throttle control?
			Weather	Viscosity increase	Regular maintenance
			Operator failure	Reduced temperature in R201	Operator training
				Reaction rate decreased	

Table E.6. HAZOPs for Stream 201

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Flow	More	Valve failure/fully open	T201 overflow	Check differential pressure across valve during routine maintenance
			Flow control failure	Pipe damage	Regular maintenance/ calibration.
			Flow control sensor failure		Operator training
			Operator failure		
			Pressure buildup in R201		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Flow	Less	Valve failure/closed	Downstream process backup	Install LA
			Operator failure	MeOH/biodiesel/glycerol leak	Regular maintenance
			Low pressure in R201		Operator training
			Plugged pipe	P201 cavitation	
			Pipe breakage	MeOH/biodiesel/glycerol leak	Inspection prior to startup
				Health hazard	Ventilation installed and implementation of absorbing material
				Fire hazard	
				Corrosion of exterior environment	
				Exterior ground contamination	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Flow	No	Valve closed	R201 pH not reached	Install check valve
			Operator failure	Downstream process backup	Regular maintenance

			Empty R201	MeOH/biodiesel/glycerol leak	Operator training
			Plugged pipe	Health hazard	Inspection prior to startup
			Pipe breakage	Fire hazard	Ventilation and absorbing material installed
				Corrosion of exterior environment	
				Exterior ground contamination	
				P201 cavitation	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Flow	Reverse	Pressure buildup in T201	Downstream process backup	Install LA
			Plugged pipe	R201 overflow	Regular maintenance and inspection prior to startup
			Operator failure		Operator training
			Pump P201 damage		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Pressure	High	Valve failure/fully open	Possible upset in downstream	Same precautions as for 201 high flow
			Operator failure	T201 overflow	
			Pressure buildup in R201	Pipe breakage	
			Plugged pipe	Pump damage	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Pressure	Low	Valve failure/fully open	Possible upset in downstream	Same precautions as for 201 less flow
			Operator failure	MeOH may partially vaporize	
			Leak in pipe	Pipe breakage	
			Plugged pipe	Pump cavitation	
				MeOH/biodiesel/glycerol spill	

				Health hazard	
				Fire hazard	
				Corrosion of exterior environment	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Temperature	High	See HAZOPS for R201	P201 Cavitation	See HAZOPS for R201
			Weather	Pipe melt	Ventilation installed
			Operator failure	MeOH vapour	Operator training
				Pump damage/cavitation	Regular maintenance
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201	Temperature	Low	See HAZOPS for R201	Reduced pressure	Install LA + thermo couples installed. Install throttle control?
			Weather	Viscosity increase	Regular maintenance
			Operator failure	Pump damage (reduced efficiency)	Operator training
				Pipe blockage	
				Downstream process blockage	

Table E.7. HAZOPs for Stream 201S

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201S	Flow	More	V206 fails and open	Higher solution temperature	Install HA
				R201 temperature too high	See HAZOP for high temperature of R201
				Explosion	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201S	Flow	Less	V206 fails and close	Overnight product compromised (only during cold weather)	Install HA but no critical precautions necessary
			Insufficient supply of steam from boiler	Reduced reaction rate	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201S	Temperature	High	Boiler malfunction	See high temperature for R201	See HAZOP for high temperature of R201
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201S	Temperature	Low	Boiler malfunction	See high temperature for R201	See HAZOP for low temperature of R201
			Insufficient pipe insulation		

Table E.8. HAZOPs for Stream 201WC

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201WC	Flow	More	V206 fails and open	Low reaction temperature (See low temperature for R201)	Install HA See HAZOP for low temperature of R201
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201WC	Flow	Low	V207 fails and close	See high temperature of R201	See HAZOP for high temperature of R201
			Pipe clogged		
			Filter clogged		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201WC	Temperature	High	Weather Poor insulation	See high temperature for R201	See HAZOP for high temperature of R201

Table E.9. HAZOPs for Stream 201WH

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201WH	Flow	More	V206 fails and open	High reaction temperature (See High temperature for R201)	Install HA Alarm
					See HAZOP for High temperature of R201
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201WH	Flow	Low	V206 fails and close	See Low temperature of R201	See HAZOP for Low temperature of R201
			Plug in the pipe		
			Filter clogged		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
201WH	Temperature	Low	Weather	See Low temperature for R201	See HAZOP for low temperature of R201

Table E.10. HAZOPs for Stream 202

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Flow	More	Valve failure/fully open	Possible upset in downstream	Check differential pressure across valve during routine maintenance
			Flow control failure	Pipe damage	Regular maintenance/ calibration.
			Flow control sensor failure		Operator training
			Operator failure		Install HA
			Pressure buildup in T201		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Flow	Less	Valve failure/closed	Downstream process backup	Install LA.
			Flow control failure	Pump damage/cavitation	Regular maintenance.
			Flow control sensor failure	MeOH/biodiesel/glycerol spill	Operator training.
			Operator failure	Health hazard	Inspection prior to startup
			Low pressure in T201	Fire hazard	Ventilation installed. Implementation of absorbing material to avoid leaks to ground.
			Plugged pipe	Corrosion of exterior environment.	
			Plugged P004	Exterior ground contamination	
			Pipe breakage		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Flow	No	Valve closed	Downstream process backup	Regular maintenance
			Flow control failure	Pump damage/cavitation	Operator training

			Flow control sensor failure	MeOH/biodiesel/glycerol spill	Inspection prior to startup
			Operator failure	Health hazard	Ventilation and absorbing material installed
			T201 empty	Fire hazard	
			Plugged pipe	Corrosion of exterior environment	
			Plugged P004	Exterior ground contamination	
			Pipe breakage		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Flow	Reverse	Pressure buildup in T201	Downstream process backup	Install LA
			Plugged pipe	T201 overflow	Regular maintenance. Inspection prior to startup
			Operator failure		Operator training
			Pump damage		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Pressure	High	Valve failure/fully open	Possible upset in downstream	Same precautions as for 202 flow deviation
			Flow control failure	Pipe breakage	
			Flow control sensor failure	Pump damage	
			Operator failure	MeOH/biodiesel/glycerol spill	
			Pressure buildup in T201	Health hazard	
			Plugged pipe	Fire hazard	
				Corrosion of exterior environment.	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Pressure	Low	Valve failure/fully open	Possible upset in downstream	Same precautions as for 202 flow deviation
			Operator failure	MeOH may partial vaporized	
			Leak in pipe	Pipe damage	
			Plugged pipe	Pump cavitation	
			Pumps fails	MeOH/biodiesel/glycerol spill	

				Health hazard	
				Fire hazard	
				Corrosion of exterior environment	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Temperature	High	See HAZOPS for T201	Increase pressure	Install HA + thermocouples. Install throttle
			Weather	Pipe melt	Ventilation installed
			Operator failure	MeOH vaporize	Operator training
				Pump cavitation	Regular maintenance
					Ensure Proper MOC of pipe
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202	Temperature	Low	See HAZOPS for T201	Reduced pressure	Install LA + thermocouples installed. Install throttle control
			Weather	Viscosity increase	Regular maintenance
			Operator failure	Pump damage (reduced efficiency)	Operator training
				Pipe blockage	
				Downstream process blockage	

Table E.11. HAZOPs for Stream 202S

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202S	Flow	More	V210 fails and open	Higher solution temperature. T201 temperature too high	Install HA Alarm. See HAZOP for high temperature of R201
				Explosion	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202S	Flow	Less	V210 fails and close	Overnight product compromised (only during cold weather)	Install HA Alarm. No critical precautions necessary.
			Insufficient supply of steam from boiler	Stored product has no further reaction	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202S	Temperature	High	Boiler malfunction	Explosion	See HAZOP for high temperature of R201
				MeOH Vaporization	
				Viscosity Decrease	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
202S	Temperature	Low	Boiler malfunction	Viscosity Increase	N/A
			Insufficient pipe insulation		

Table E.12. HAZOPs for Stream 203

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 18, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Flow	More	Valve V202 or V203 failure	Overflow to T201	Turn off pump P201
			Flow transmitter FT2105 or FT2107 failure	Overflow to hydrocyclones HC301 and HC302, causing incomplete separation of glycerol.	Close valve V202 and V203
			Flow controller FC2105 or FC2107 failure	Backflow to R201 and/or T201	Install high flow alarm (HA)
			Pressure buildup in R201 or T201	Damage / bursting of pipe and/or fittings	Regular maintenance/calibration
			Operator failure		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Flow	Less	Valve V202 or V203 failure	Pump damage	Install LA
			Flow transmitter FT2105 or FT2107 failure	Loss of product, insufficient flow to hydrocyclone reducing efficiency	Operator Training, emergency procedures
			Flow controller FC2105 or FC2107 failure	Fire hazard	Regular maintenance of valves, pump, piping and fittings
			Pipe streams 201, 202, or 203 plugged, leaking, or broken	Health hazard	Spill kits, spill equipment
			Pump P201 failure, not calibrated	Corrosion of exterior environment	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Flow	No	Valve V202 and V203 closed	Pump P201 damage	Install LLA
			Plugged or leaking pipe	Downstream process backup	Regular maintenance

			Operator failure	Hydrocyclone H301 damage	Operator Training
			Damaged pump P201	No product	Temporary pipe sealing material
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Flow	Reverse	Pressure buildup in T201 or HC301	Pressure buildup in R201, T201	Install LA
			Plugged pipe	Downstream process backup	Regular maintenance
			Operator failure	Overflow in T201	Operator training
			Pump damaged	Hydrocyclone H301 damage	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Pressure	High	Valve V204 and V205 fail closed	Possible upset in hydrocyclones / downstream process	Same precautions as flow deviation 203
			Valve V202 or V203 fail and open	Increased pressure to in H301	
			Flow control failure	Pump damage	
			Flow control sensor failure	Pipe / fitting breakage	
			Pressure buildup in T201		
			Plugged pipe		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Pressure	Low	Valve V203 fails and opens	Downstream process upset	Same precautions as low flow deviation 203
			Operator failure	Pump P201 cavitation	
			Leak in pipe		
			Plugged pipe		
			Pump fails		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Temperature	High	Excessive heating in R201 and/or T201	Increase pressure	See HAZOP for low temperature of R201

			Weather	Viscosity decrease	
			Operator Failure	Higher temperature to HC301, causing change in separation efficiency	
			Temperature control/sensor failure in R201 and/or T201	Piping / fitting melt	
			Valve V206 fails and open	Pump damage	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
203	Temperature	Low	Insufficient heating in R201 and/or T201	Reduced pressure	Install LA and Thermocouples. Install throttle control
			Weather	Viscosity increase	Regular maintenance
			Operator failure	Reduced temperature in T201	Operator training
			Temperature control/sensor failure in R201 and/or T201		
			Valves V206 fails and close		

Table E.13. HAZOPs for Stream 204

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 18, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Flow	More	V202/V204 fail and open	Overflow to HC301	Turn off pump P201
			Flow control fail	Back flow to R201	Install HA, alarm should recognize desired flow at time of operation
			Flow control sensor failure	Increased volume to HC301	Regular maintenance/calibration
			Pressure buildup in T201	Pipe damage	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Flow	Less	V204 fails and partially closed	Pump damage	Install LA, alarm should recognize desired flow at time of operation
			Leak in pipe 204	Loss of product, insufficient flow to hydrocyclone reducing efficiency.	Operator Training
			Flow control sensor failure	Fire hazard	Regular maintenance
			Low pressure in T201	Health hazard	Pipe sealing equipment
			Plugged pipe	Corrosion of exterior environment	
			Leaking pipe	Exterior ground contamination	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Flow	No	V204 closed	Pump P201 damage	Install LLA, alarm should recognize desired flow at time of operation
			Plugged/leaking pipe	Downstream process backup	Regular maintenance
			Operator failure	HC301 efficiency affected	Operator Training
			Damaged pump P201		Pipe sealing equipment

Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Flow	Reverse	Pressure buildup in P201	Pressure buildup in T201	Install LA, alarm should recognize desired flow at time of operation
			Plugged pipe	Downstream process backup	Regular maintenance
			Operator failure	Overflow in T201	Operator training
			Pump damaged		

Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Pressure	High	Flow control failure	Possible upset in downstream process	Same precautions as flow deviation 204
			Flow control sensor failure	Increased pressure to in HC301	
			Pressure buildup in T201	Pump damage	
			Plugged pipe	Pipe breakage	

Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Pressure	Low	Valve V203 failed and open	Downstream process upset	Same precautions as flow deviation 204
			Operator failure	Pump P201 cavitation	
			Leak in pipe		
			Plugged pipe		
			Pump fails		

Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Temperature	High	Excessive heating in T201	Increase pressure	See HAZOP for low temperature of R201
			Weather	Viscosity decrease	Check MOC of pipe
			Operator Failure	Higher temperature to H301	
			Temperature control failure in T201	Pipe melt	

			V206 fails and open		

Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
204	Temperature	Low	Insufficient heating in T201	Reduced pressure	Install LA and Thermo couples. Install throttle control.
			Weather		Regular maintenance
			Operator failure		Operator training
			Temperature control failure in T201		
			Temperature sensor failure T201	Viscosity increase	
			V206 fails and close	Reduced temperature in T201	

Table E.14. HAZOPs for Stream 205

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Flow	More	V203 fails and open	Overflow to H301	Turn off pump P201
			Flow control fail	Back flow to R201	Install high flow alarm (HA)
			Flow control sensor failure	Increased volume to H301	Regular maintenance/calibration
			Pressure buildup in T201	Pipe damage	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Flow	Less	V203 fails and close	Pump damage	Install LA
			V204 fails and open		
			Leak in pipe 205	Loss of product, insufficient flow to hydrocyclone reducing efficiency.	Operator Training
			Flow control sensor failure	Fire hazard	Regular maintenance
			Low pressure in T201	Health hazard	
			Plugged pipe	Corrosion of exterior environment	
			Pipe breakage	Exterior ground contamination	
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Flow	No	Valve closed	Pump P201 damage	Install LLA
			Plugged pipe	Downstream process backup	Regular maintenance
			Operator failure	Hydrocyclone H301 efficiency affected	Operator Training
			Damaged pump P201		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Flow	Reverse	Pressure buildup in P201	Pressure buildup in T201	Install LA

			Plugged pipe	Downstream process backup	Regular maintenance
			Operator failure	Overflow in T201	Operator training
			Pump damaged		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Pressure	High	V204 fails and open	Possible upset in downstream process	Same precautions as high flow 205
			Flow control failure	Increased pressure to in HC301	
			Flow control sensor failure	Pump damage	
			Pressure buildup in T201	Pipe breakage	
			Plugged pipe		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Pressure	Low	V204 failed and open	Downstream process upset	Same precautions as low flow 205
			Operator failure	Pump P201 cavitation	
			Leak in pipe		
			Plugged pipe		
			Pump fails		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Temperature	High	Excessive heating in T201	Increase pressure	See HAZOP for low temperature of R201
			Weather	Viscosity decrease	
			Operator Failure	Higher temperature to HC301	
			Temperature control failure in T201		
			V210 fails and open		
Stream	Process Parameters	Deviations	Possible Causes	Consequences	Action required
205	Temperature	Low	Insufficient heating in T201	Reduced pressure	Install LA and thermocouples. Install throttle control.

			Weather	Viscosity increase	Regular maintenance
			Operator failure	Reduced temperature in T201	Operator training
			Temperature control failure in T201		
			Temperature sensor failure T201		
			V210 fails and close		

Table E.15. HAZOPs for Reactor 201

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Pressure	High	Malfunctioning of relief valve V202	Explosion	Install HHA
			High flow 007, 008, 108	MeOH boils	See precautions for more flow of 007, 008, 108
				Reaction rate decrease or increase	Install pressure sensor
				Level increase	
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Pressure	Low/None	Malfunctioning of air intake valve	Vacuum and consequently no downstream	Install LA
				MeOH vaporization	Regular maintenance
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Temperature	High	Weather	Explosion	Install HA
			V207 malfunctioning	Reaction rate changes	Regular maintenance
			Temperature of 007, 008, 108 above design specifications	MeOH vaporizes	See HAZOP of high temperature of 007, 008, 108
			V206 malfunction fail and open	Viscosity increase	Operator training
			Cooling water in 201WC is too warm		See HAZOP for high temperature 201WC
			Flow of 201WC too low		See HAZOP of low flow 007, 008, 108
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Volumetric Level	High	Controller failure	Overflow	Install HA

			More flow of 007, 008, 108	Higher pressure	Regular maintenance
			V202 fails and close	Higher temperature	See HAZOP for high flow of 007, 008, and 108
			Jacket and reactor vessels corrode	Reaction rate changes	Operator training
				Contamination	
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Concentration	Low MeOH	Low flow of 008	Reduced degree of conversion	See HAZOP for low flow for 008
			V017 fail and close	Reduced reaction rate	
			Reduced purity of distillation product of D401		See HAZOP for D401
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Concentration	Low WVO	Low flow of 108	Reduced degree of conversion	See HAZOP for low flow for 108
			WVO Sources not consistent	Reduced reaction rate	
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Concentration	Low NaOH	Low flow of 007	Reduced reaction rate	See HAZOP for low flow for 007
			Mixer M001 failure		
			Degraded/impure NaOH		Operator to ensure it is fresh. NaOH solution must be prepared ASAP
			Operator error		Operator training
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Concentration	High WVO	High flow of 108	Reduced degree of conversion	See HAZOP for high flow for 108
			WVO Sources not consistent	Reduced reaction rate	

Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
R201	Reaction	Incomplete	V202 fails and open	Lower degree of conversion	Preventative
			Impeller malfunctioning	Downstream processes contaminated	Emergency storage tank
					Operator to ensure it is fresh. NaOH solution must be prepared ASAP
					Operator training

Table E.16. HAZOPs for Storage Tank 201

PROJECT NAME:		BIODIESEL IN MOTION		DATE:	FEBRUARY 8, 2005
SECTION:		TRANSESTERIFICATION REACTION SECTION 200		REFERENCE DRAWING:	P&ID SECTION 200
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
T201	Pressure	High	Malfunctioning of relief valve V211	Overflow	Install HA
			High flow 204		See HAZOP for more flow of 204
					Install pressure sensor
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
T201	Pressure	Low/None	Malfunctioning of air intake valve	Vacuum and consequently no downstream.	Install LA
				MeOH vaporization	Regular maintenance
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
T201	Temperature	High	Weather	Explosion	Install HA
			V210 malfunctioning	Viscosity increase	Regular maintenance
			Temperature of 204 above design specifications	MeOH vaporizes	See HAZOP of high temperature of 204 Operator training
Unit	Process Parameters	Deviations	Possible Causes	Consequences	Action required
T201	Volumetric Level	High	Controller failure	Overflow	Install HA
			More flow of 204	Higher pressure	Regular maintenance
			V203 fails and close	Higher temperature	See HAZOP for high flow of 204
					Ventilation and collection system installed

Appendix F: Economic Analysis

Table F-1. Hydrocyclone Capital Cost

Equipment Type	Equipment ID	Flow Rate (USGPM)	Capital Cost ($)	Installation Cost ($)
Hydrocyclone	HC 301	8	$1,240.00	$434.00
Hydrocyclone	HC 302	8	$1,240.00	$434.00
		Totals	$2,480.00	$868.00

Table F-2. Tank Capital Cost

Equipment Type	Equipment ID	Volume (m3)	Capital Cost ($)	Installation Cost ($)
TANKS	T001	5.12	$2,515.12	$880.29
TANKS	T002	0.004	$29.13	$10.20
TANKS	T003	5.21	$2,546.87	$891.41
TANKS	T101	0.49	$928.66	$325.03
TANKS	T201	0.27	$604.64	$211.62
TANKS	T401	1.32	$947.76	$331.72
TANKS	T402	4.56	$2,313.87	$809.85
TANKS	T403	0.28	$310.34	$108.62
TANKS	T404	5.12	$2,515.12	$880.29
		Totals	$12,711.51	$4,449.03

Table F-3. Heat Exchanger Capital Cost

Equipment Type	Equipment ID	Capital Cost ($)	Installation Cost ($)
Condensers	C101A	$8,050.00	$2,817.50
Condensers	C301	$8,050.00	$2,817.50
Condensers	C302	$8,050.00	$2,817.50
Condensers	C401	$8,050.00	$2,817.50
Reboilers	H101A	$9,300.00	$3,255.00
Reboilers	H301	$9,300.00	$3,255.00
Reboilers	H302	$9,300.00	$3,255.00
Reboilers	H401	$9,300.00	$3,255.00
	Totals	$69,400.00	$24,290.00

Table F-4. Reactor Capital Cost

Equipment Type	Equipment ID	Volume	Capital Cost ($)	Installation Cost ($)
Closed Vessel Reactor	R101	1.23	$5,000.00	$1,750.00
Closed Vessel Reactor	R102	1.23	$5,000.00	$1,750.00
Closed Vessel Reactor	R103	1.23	$5,000.00	$1,750.00
Closed Vessel Reactor	R201	0.32	$2,500.00	$875.00
Closed Vessel Reactor	R301	0.30	$2,250.00	$787.50
		Totals	$19,750.00	$6,912.50

Table F-5. Mixer Capital Cost

Equipment Type	Equipment ID	Volume	Capital Cost ($)	Installation Cost ($)
Mixer	M001	0.06	$2,300.00	$805.00

Table F-6. Pumps Capital Cost

Equipment Type	Equipment ID	Capital Cost ($)	Installation Cost ($)
Single Stage - Centrifugal Pump	P101	$1,700.00	$340.00
Single Stage - Centrifugal Pump	P103	$1,700.00	$340.00
Single Stage - Centrifugal Pump	P104	$1,700.00	$340.00
Single Stage - Centrifugal Pump	P201	$1,700.00	$340.00
Single Stage - Centrifugal Pump	P401	$1,700.00	$340.00
Single Stage - Centrifugal Pump	P403	$1,700.00	$340.00
LMI - Mseries Metering Pump	P001	$2,300.00	$460.00
LMI - Mseries Metering Pump	P002	$2,300.00	$460.00
LMI - Mseries Metering Pump	P003	$2,300.00	$460.00
	Totals	$17,100.00	$3,420.00

Table F-7. Distillation and Extraction Column Capital Cost

Equipment Type	Equipment ID	Capital Cost ($)	Installation Cost ($)
Distillation Column	D101	$4,200.00	$1,470.00
Distillation Column	D301	$4,200.00	$1,470.00
Distillation Column	D302	$4,200.00	$1,470.00
Liq/Liq extraction column	E301	$1,400.00	$490.00
Distillation Column	D401	$4,200.00	$1,470.00
	Totals	$18,200.00	$6,370.00

Table F-8. Direct and Indirect Cost Summary

DIRECT COST

Total Equiptment Capital Cost:	$141,941.51
Total Installation Cost	$47,114.53
Trailer Cost	$25,000.00
Piping Cost	$14,194.15
Instrumentation/Electrical Cost	$28,388.30
Total Direct Cost	$256,638.49
INDIRECT COST:	
Contingency	$12,831.92

Table F-9. Total Capital Investment Summary

FIXED CAPITAL INVESTMENT	$269,470.41	
Working Capital	$26,947.04	
TOTAL CAPITAL INVESTMENT	**$296,417.45**	**Start Up Cost**